

A.C. Machines Performance (315333)

MSBTE K-Scheme · EE Semester 5 · Model Question Paper — Set B · Model Answers

Q.1 Attempt any FIVE of the following: (10 M)

a) Slip; value at standstill and at N_s

2 M

Slip: $s = (N_s - N)/N_s$, the difference between synchronous speed and rotor speed expressed as a fraction of synchronous speed.

At standstill $N = 0 \Rightarrow s = 1$; at synchronous speed $N = N_s \Rightarrow s = 0$ (no relative motion, so no torque — the motor can never actually reach N_s).

(Definition 1 M, values 1 M)

b) Rotor frequency and rotor p.f. (running)

2 M

Rotor frequency: $f_r = s f$ (at standstill $f_r = f$; at full load only 1–3 Hz).

Rotor power factor (running): $\cos \phi_{2r} = R_2 / \sqrt{R_2^2 + (s X_2)^2}$

(R_2 = rotor resistance/phase, X_2 = standstill rotor reactance/phase, s = slip)

(1 M each)

c) Components of soft starter

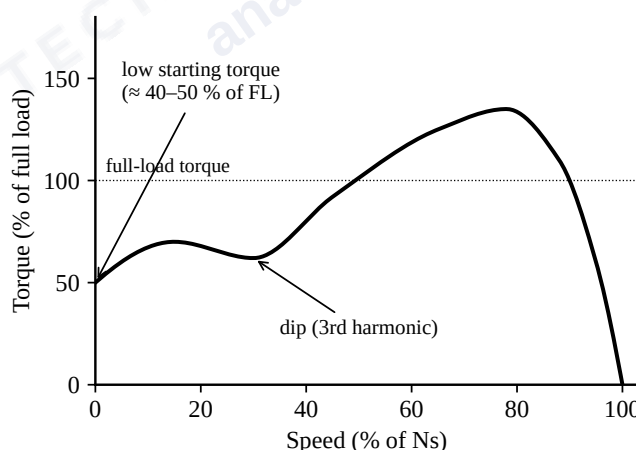
2 M

- Anti-parallel SCR pairs (or triacs) in each line, mounted on heat sinks
- Bypass contactor
- Control / firing circuit (microcontroller based)
- Current transformers for current feedback / current limit
- Protection circuits (overload, phase failure) and keypad / display for ramp settings

(Any four, ½ M each)

d) T–N characteristic of shaded pole motor

2 M



Typical torque–speed characteristic of shaded pole motor

(Correct shape with labels 2 M)

e) Types of torques in synchronous motor

2 M

- **Starting (breakaway) torque:** torque developed at standstill to start the motor (from damper winding when started as induction motor).
- **Running torque:** torque developed at synchronous speed under normal operating conditions, determined by the load.
- **Pull-in torque:** the maximum load torque at which the motor running near synchronous speed (as an induction motor) **pulls into synchronism** when DC excitation is applied.
- **Pull-out torque:** the **maximum torque the motor can develop without losing synchronism** (load angle $\delta = 90^\circ$). If load exceeds it the motor pulls out of step and stops.

(Any four, $\frac{1}{2}$ M each)

f) Factors affecting voltage regulation

2 M

- Armature resistance drop ($I R_a$)
- Armature leakage reactance drop ($I X_L$)
- Armature reaction — depends on load power factor
- Magnitude of load current
- Power factor of the load (lagging p.f. gives larger positive regulation, leading p.f. may give negative regulation)
- Field excitation and speed (frequency) of the machine

(Any four, $\frac{1}{2}$ M each)

g) Step angle

2 M

Step angle (β): the angle through which the rotor of a stepper motor turns for one input pulse.

Steps per revolution = $360^\circ / \beta$; speed $n = \beta \times f / 360^\circ$ rps (f = pulse rate).

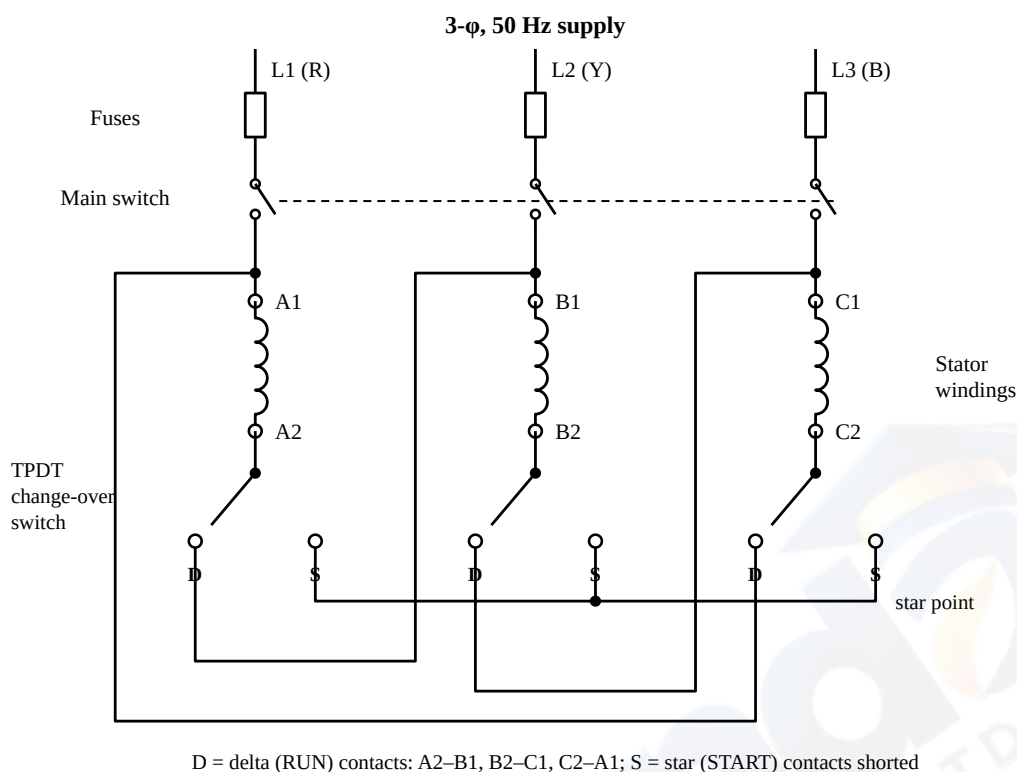
For 200 steps/revolution: $\beta = 360^\circ / 200 = 1.8^\circ$.

(Definition 1 M, calculation 1 M)

Q.2 Attempt any THREE of the following: (12 M)

a) Star–delta starter with 1/3 proof

4 M



Manual star–delta starter (TPDT change-over switch)

1. The six terminals of the stator (A1–A2, B1–B2, C1–C2) are brought out to a TPDT change-over switch. The motor is designed to run in **delta**.
2. **START position:** terminals A2, B2, C2 are shorted — the winding is in **star**. Each phase gets $V_L/\sqrt{3}$ (58 % of rated voltage), so the starting current and torque are reduced.
3. When the motor reaches about 80 % of rated speed, the handle is quickly thrown to the **RUN position:** A2–B1, B2–C1, C2–A1 are joined — the winding is in **delta** and each phase gets full line voltage.
4. The starter has no-volt release (handle returns to OFF on supply failure) and overload release.
5. Starting line current and starting torque both become **1/3** of DOL values.

Proof (Z = standstill impedance per phase):

DOL (delta): $I_{ph} = V_L/Z$, $I_L(\Delta) = \sqrt{3} V_L/Z$. Star start: $I_L(Y) = I_{ph} = (V_L/\sqrt{3})/Z$.

$$\therefore I_L(Y)/I_L(\Delta) = (V_L/\sqrt{3}Z)/(\sqrt{3}V_L/Z) = 1/3; T \propto V_{ph}^2 \Rightarrow T_{st}(Y)/T_{st}(\Delta) = (1/\sqrt{3})^2 = 1/3.$$

(Diagram 2 M, working 1 M, proof 1 M)

b) Necessity and types of starters

4 M

Necessity:

- At the instant of starting, $s = 1$, so the rotor emf and rotor current are maximum — the motor behaves like a **short-circuited transformer**.
- Direct switching draws **5 to 7 times full-load current**.

- This large current causes a heavy **voltage dip** in the supply that disturbs other consumers / loads.
- It overheats the windings and produces large electromagnetic and mechanical shocks on the motor and driven machine.
- Hence a starter is used (i) to **limit the starting current** and (ii) to give **protection** — overload (O/L) release and no-volt (under-voltage) release.

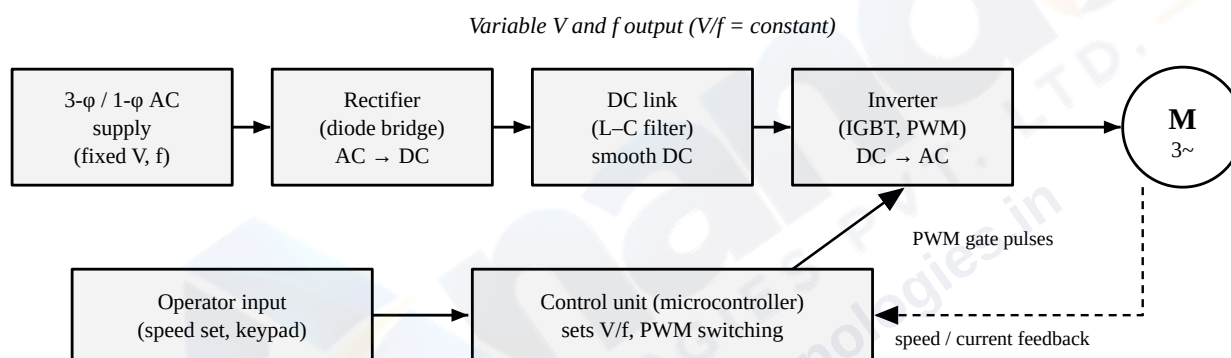
Types of starters:

1. Direct-on-line (DOL) starter (small motors up to about 5 HP)
2. Stator (primary) resistance / reactance starter
3. Auto-transformer starter
4. Star–delta starter
5. Rotor resistance starter (slip-ring motors only)
6. Soft starter (solid-state, SCR based)
7. Variable frequency drive (VFD) used as starter

(Necessity 2 M, types 2 M)

c) Variable frequency drive

4 M



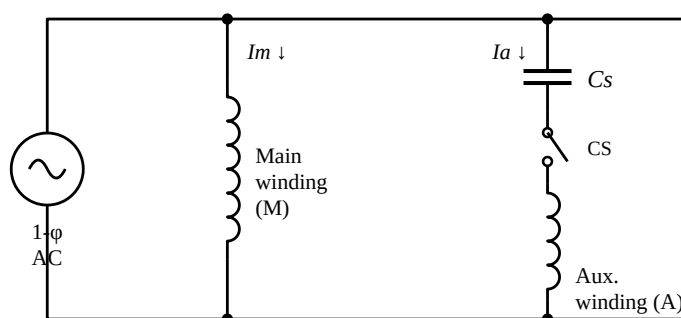
Block diagram of variable frequency drive (VFD)

1. **Rectifier:** diode bridge converts fixed-voltage, fixed-frequency AC supply into DC.
2. **DC link (filter):** capacitor (and inductor) smooth the rectified DC and store energy; gives a stiff DC voltage.
3. **Inverter:** IGBTs switched by PWM signals convert DC into 3-φ AC of **variable voltage and variable frequency**.
4. **Control unit:** microcontroller / DSP sets the output frequency from the speed reference and keeps **V/f constant** so that the air-gap flux stays constant (no saturation, full torque).
5. **Feedback & protection:** current / speed feedback, over-current, over-voltage, under-voltage, over-temperature protection.
6. Speed $N \approx N_s = 120 f / P$, so varying f gives smooth speed control from near zero to above rated speed; the VFD also works as a soft starter.

(Block diagram 2 M, function of blocks 2 M)

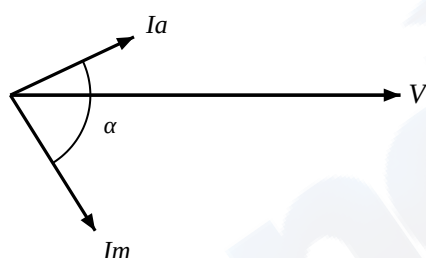
d) Capacitor start induction run motor

4 M



CS = centrifugal switch (opens at about 75–80 % of N_s)
Main and auxiliary windings are 90° (electrical) apart in space

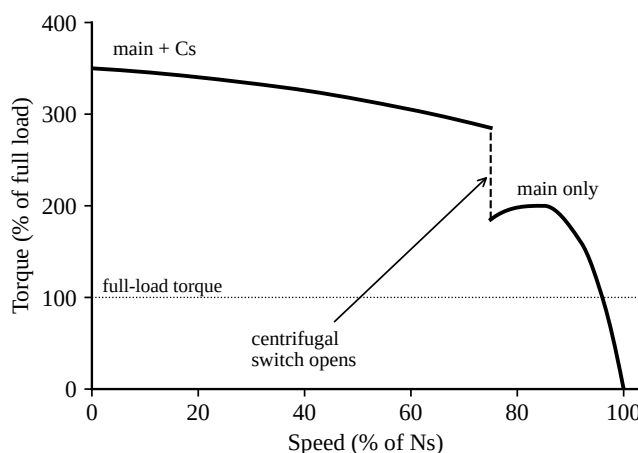
Capacitor-start induction-run motor



$\alpha \approx 83^\circ$: I_m lags V by 58° , I_a leads V by 25°
(typical values)

Phasor diagram at starting

1. **Construction:** stator carries a main winding and an auxiliary winding 90° apart in space. A **capacitor** C_s (electrolytic, large value, short-time rated) and a **centrifugal switch** are connected in series with the auxiliary winding. Rotor is squirrel cage.
2. Because of the capacitor, the auxiliary current I_a **leads** the voltage while I_m lags; the phase difference α is close to **80–90°**.
3. Nearly balanced 2-phase currents produce a strong rotating field → high starting torque (**300–400 %** of FL torque) with lower starting current.
4. At about 75 % of N_s the centrifugal switch disconnects the auxiliary winding and capacitor; the motor runs as a single-phase motor on the main winding (hence 'induction run').
5. Applications: refrigerator and air-conditioner compressors, reciprocating pumps, conveyors, machine tools — heavy starting loads.



Typical torque–speed characteristic (capacitor start)

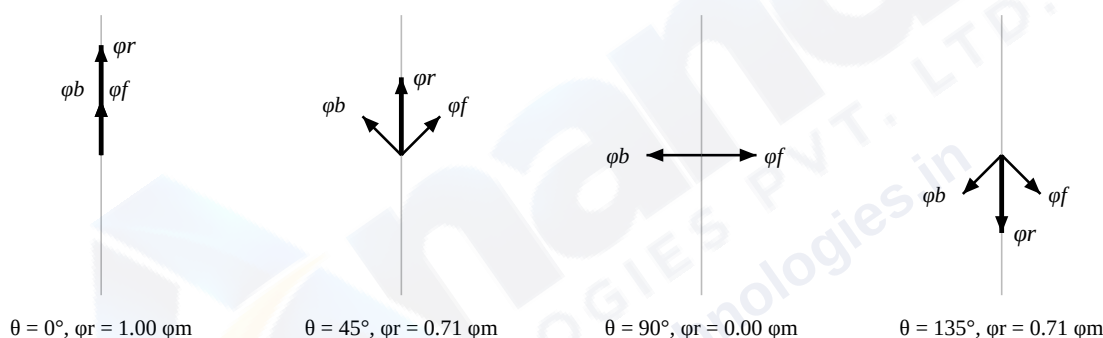
(Sketch 1 M, working 2 M, characteristic 1 M)

Q.3 Attempt any THREE of the following: (12 M)

a) Zero starting torque — DFRT

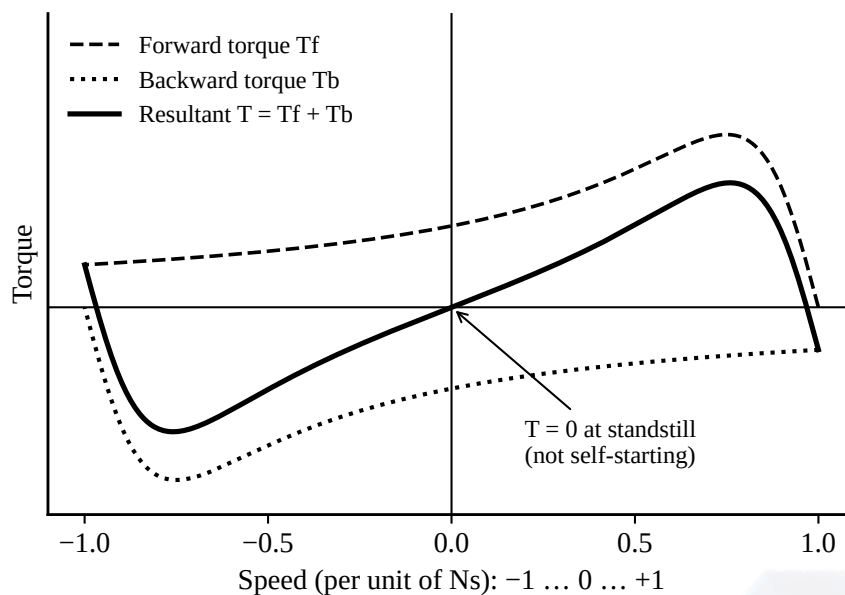
4 M

Statement: A pulsating (alternating) flux of maximum value ϕ_m can be resolved into **two rotating fluxes, each of magnitude $\phi_m/2$** , rotating at synchronous speed in **opposite directions**.



Pulsating flux $\phi_m \cos \omega t$ = two fluxes $\phi_m/2$ rotating in opposite directions

- The single-phase winding produces $\phi = \phi_m \cos \omega t$ along a fixed axis. The forward component ϕ_f and backward component ϕ_b (each $\phi_m/2$) rotate in opposite directions; their sum always lies on the winding axis and pulsates between $+\phi_m$ and $-\phi_m$.
- Each rotating field induces rotor currents and produces torque: forward field $\rightarrow$ forward torque T_f , backward field $\rightarrow$ backward torque T_b (opposite direction).
- If rotor speed is N , slip w.r.t. forward field $s_f = s$, slip w.r.t. backward field $s_b = 2 - s$.
- At standstill** $s_f = s_b = 1$, so $T_f = T_b$ and the **net torque is zero** — a single-phase induction motor is **not self-starting**.
- If the rotor is given a push in any direction, the torque due to that field becomes larger ($T_f > T_b$) and the motor keeps running in that direction.

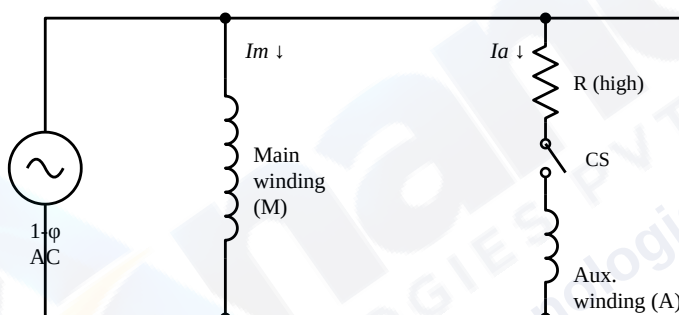


Forward, backward and resultant torque-speed curves (computed); net torque is zero at standstill

(Explanation 2 M, diagrams 2 M)

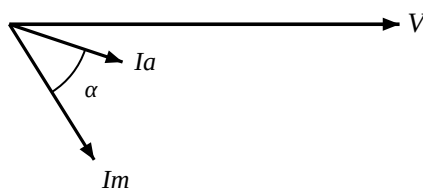
b) Resistance split-phase motor

4 M



CS = centrifugal switch (opens at about 75–80 % of N_s)
 Main and auxiliary windings are 90° (electrical) apart in space

Resistance split-phase motor



$\alpha \approx 40^\circ$: I_m lags V by 58° , I_a lags V by 18°
 (typical values)

Phasor diagram at starting

1. The stator has two windings displaced **90° electrical in space**: the **main (running) winding** of thick wire — low resistance, high reactance; and the **auxiliary (starting) winding** of thin wire with fewer turns — high resistance, low reactance.
2. Both are connected in parallel across the 1-φ supply. Main winding current I_m lags V by a large angle (about 60–80°); auxiliary current I_a lags V by a small angle (about 15–30°).
3. The two currents are displaced by $\alpha \approx 25\text{--}30^\circ$ in time, and the windings are 90° apart in space, so a (unbalanced) **rotating magnetic field** is produced and the motor starts. $T_{st} \propto I_m I_a \sin \alpha$.
4. At about 75–80 % of synchronous speed the **centrifugal switch** opens and the auxiliary winding is disconnected; the motor then runs on the main winding alone.
5. Starting torque 150–200 % of full-load torque; starting current is high. Applications: washing machines, fans and blowers, grinders, small drills, centrifugal pumps.

(Circuit 1 M, phasor 1 M, working 2 M)

c) Capacitance for maximum starting torque

4 M

Given: $V = 230\text{ V}$, $f = 50\text{ Hz}$, $Z_m = (4.0 + j7.5)\ \Omega$, $Z_a = (12.0 + j9.0)\ \Omega$

Starting torque $T_{st} \propto I_m I_a \sin \alpha$, where α = angle between I_m and I_a .

With a capacitor reactance X_c in the auxiliary winding: $Z_a' = R_a + j(X_a - X_c) = R_a + jX$. Writing T_{st} in terms of X and putting $dT_{st}/dX = 0$ gives the condition for maximum starting torque:

$\theta_a = \theta_m/2 - 45^\circ$ (θ_m, θ_a = impedance angles of main and auxiliary branches)

$$\theta_m = \tan^{-1}(7.5/4.0) = 61.93^\circ \Rightarrow \theta_a = 61.93/2 - 45 = -14.04^\circ$$

$$X = R_a \tan \theta_a = 12.0 \times \tan(-14.04^\circ) = -3.000\ \Omega$$

$$X_c = X_a - X = 9.0 - (-3.000) = 12.000\ \Omega$$

$$C = 1 / (2\pi f X_c) = 1 / (2\pi \times 50 \times 12.000) = 265.3\ \mu\text{F}$$

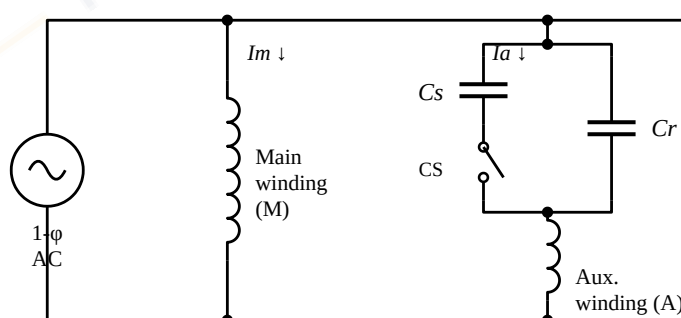
$$\text{Check: } I_m = 27.06\text{ A } \angle -61.9^\circ, I_a = 18.59\text{ A } \angle 14.0^\circ, \alpha = 76.0^\circ$$

Answer: $X_c = 12.00\ \Omega$; $C = 265.3\ \mu\text{F}$

(Condition 1 M, steps 2 M, answer 1 M)

d) Two-value capacitor motor

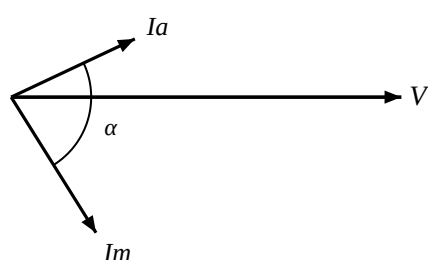
4 M



CS = centrifugal switch (opens at about 75–80 % of N_s)
Main and auxiliary windings are 90° (electrical) apart in space

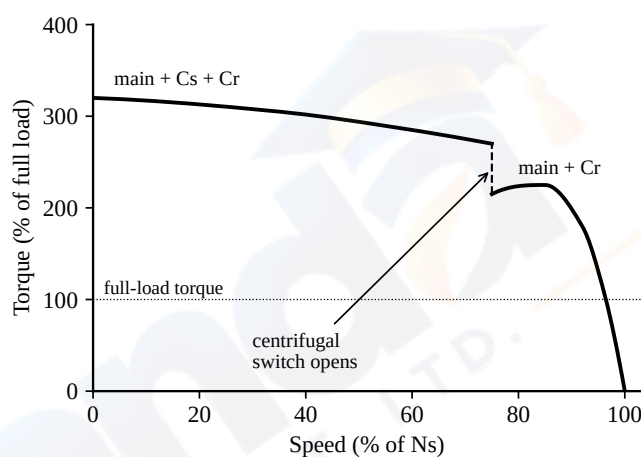
Capacitor-start capacitor-run (two-value capacitor) motor

1. The auxiliary winding has **two capacitors** in parallel: a large **starting capacitor** C_s (electrolytic) in series with a centrifugal switch, and a small **running capacitor** C_r (oil-filled paper) permanently connected.
2. At start $C_s + C_r$ give a large capacitance, so I_a leads V and the phase difference α between I_m and I_a is nearly $90^\circ \rightarrow$ **high starting torque**.
3. At about 75 % of N_s the centrifugal switch removes C_s . C_r remains, so the motor runs as a **two-phase motor** with a uniform rotating field.
4. Running performance improves: better power factor and efficiency, nearly constant torque and quiet, vibration-free operation.
5. Applications: air-conditioner and refrigerator compressors, large pumps, conveyors, ceiling-fan type loads needing both good start and good running.



$\alpha \approx 83^\circ$: I_m lags V by 58° , I_a leads V by 25°
(typical values)

Phasor diagram at starting ($C_s + C_r$ in circuit)



Typical torque-speed characteristic (two-value capacitor)

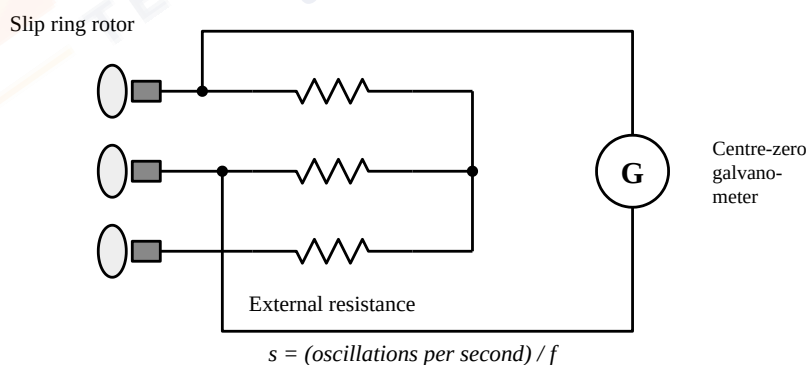
(Sketch 2 M, working and applications 2 M)

Q.4 Attempt any THREE of the following: (12 M)

a) Galvanometer method of slip measurement

4 M

Used for **slip-ring** induction motors, because the rotor circuit is accessible.



Galvanometer method (slip ring motor) — pointer swings at rotor frequency

1. A centre-zero permanent-magnet moving-coil galvanometer (or millivoltmeter) is connected across two slip rings (or across a small shunt in the rotor circuit).

2. The rotor current has frequency $f_r = s f$, which is very small (1–3 Hz), so the pointer can follow it and **swings to and fro**.
3. Count the number of complete oscillations n of the pointer in time t seconds: $f_r = n / t$.
4. Slip $s = f_r / f = n / (t f)$.
5. For a squirrel-cage motor a search coil placed near the shaft / end ring with a millivoltmeter can be used in the same way.

Why only slip-ring motors: the galvanometer must be connected in the rotor circuit to sense the rotor current of frequency $s f$; in a slip-ring motor the rotor circuit is accessible through slip rings and brushes, whereas in a cage motor the rotor bars are permanently short-circuited and not accessible.

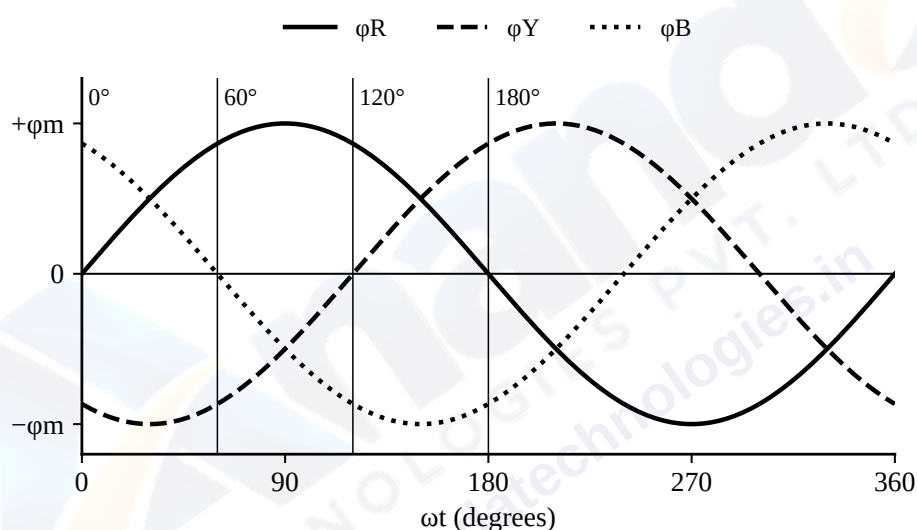
(Diagram 1 M, procedure 2 M, reason 1 M)

b) Resultant flux $1.5 \phi_m$ rotating at N_s

4 M

When a balanced 3- ϕ supply is given to three identical windings placed **120° apart in space**, the currents are **120° apart in time**. Each winding produces an alternating flux along its own axis:

$$\phi_R = \phi_m \sin \omega t, \quad \phi_Y = \phi_m \sin(\omega t - 120^\circ), \quad \phi_B = \phi_m \sin(\omega t - 240^\circ)$$

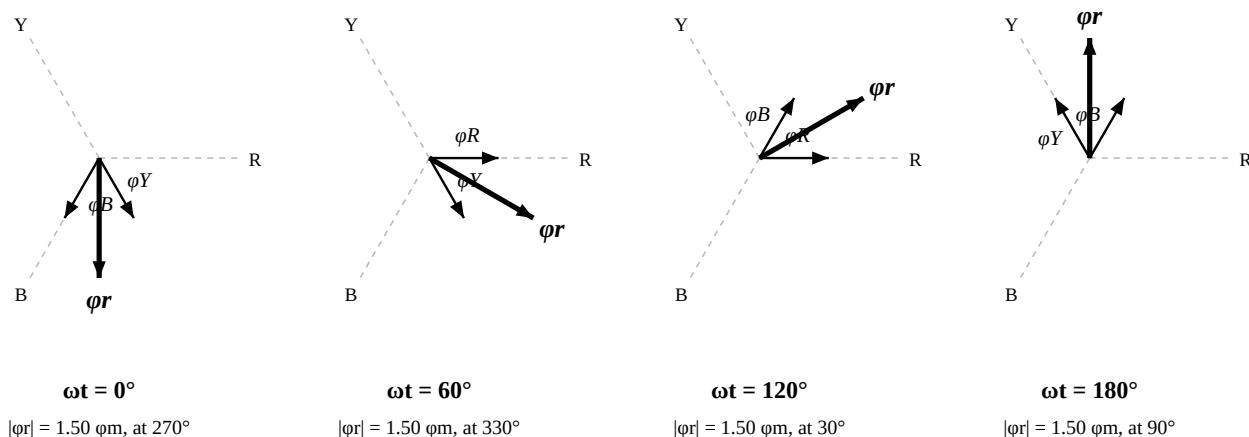


Three-phase fluxes ϕ_R, ϕ_Y, ϕ_B (120° apart) and the instants considered

The resultant flux ϕ_r is the phasor sum of the three fluxes along their space axes. Taking four instants:

ωt	ϕ_R	ϕ_Y	ϕ_B	$ \phi_r $	Direction of ϕ_r
0°	0	-0.866 ϕ_m	+0.866 ϕ_m	1.50 ϕ_m	270°
60°	+0.866 ϕ_m	-0.866 ϕ_m	0	1.50 ϕ_m	330°
120°	+0.866 ϕ_m	0	-0.866 ϕ_m	1.50 ϕ_m	30°
180°	0	+0.866 ϕ_m	-0.866 ϕ_m	1.50 ϕ_m	90°

(Values computed; space axes of R, Y, B windings taken at 0°, 120°, 240°.)



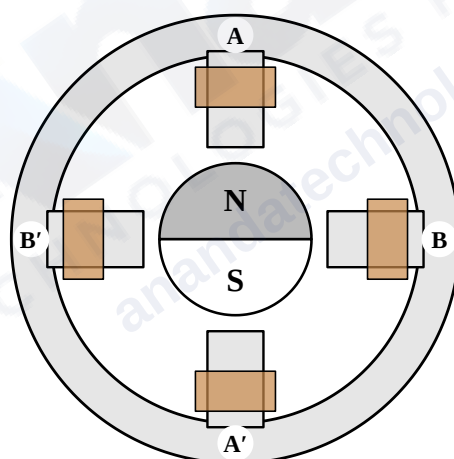
Resultant flux $\phi_r = 1.5 \phi_m$ at $\omega t = 0^\circ, 60^\circ, 120^\circ, 180^\circ$ — constant magnitude, rotating at N_s

- At every instant the resultant flux has the same magnitude **1.5 ϕ_m** .
- From $\omega t = 0^\circ$ to 180° the resultant has turned through 180° in space; i.e. it turns by the same angle as ωt .
- Hence a **rotating magnetic field of constant magnitude 1.5 ϕ_m** is produced, rotating at synchronous speed $N_s = 120 f / P$.
- Interchanging any two supply lines reverses the direction of rotation of the RMF (and of the motor).

(Phasor diagrams 2 M, explanation 2 M)

c) Permanent magnet stepper motor

4 M



$$\text{Full-step angle} = 360^\circ / (m \times N_r) = 360^\circ / (2 \times 2) = 90^\circ$$

Permanent magnet stepper motor (2-phase, 4 stator poles, 2-pole PM rotor)

- **Construction:** stator has salient poles with concentrated windings forming two phases (A–A', B–B'). Rotor is a cylindrical **permanent magnet** magnetised radially (N and S poles), with no teeth.
- **Working:** when phase A is energised (A = S pole, A' = N pole) the rotor N pole aligns with stator pole A.

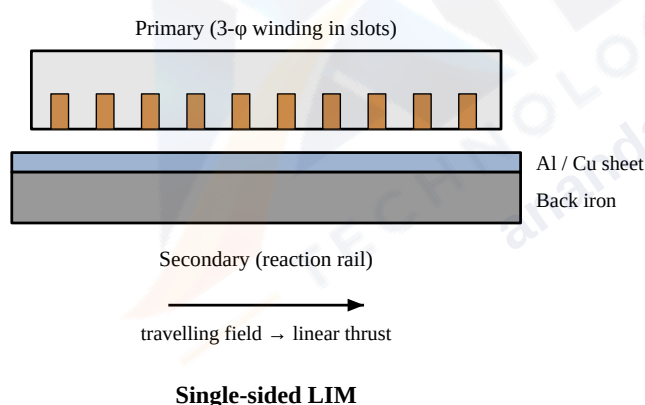
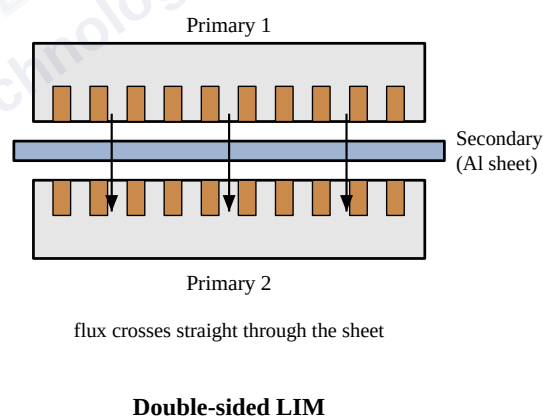
- Switching to phase B attracts the rotor to the B axis — the rotor moves one step (90°). Then –A (reversed current), –B, ... give continuous stepping.
- Direction depends on the sequence of excitation and on the polarity of current.
- Because of the permanent magnet it has **detent (holding) torque** even without excitation; step angle is large (typically 7.5°–90°); used for low-power positioning.

(Sketch 2 M, working 2 M)

d) Single-sided vs double-sided LIM

4 M

Point	Single-sided LIM	Double-sided LIM
Construction of primary	One primary (stator) on one side of the secondary	Two primaries, one on each side of the secondary
Secondary	Al / Cu sheet backed by iron (back iron) to complete the flux path	Thin Al / Cu sheet only (no back iron)
Magnetic flux path	Flux crosses air gap and sheet, returns through back iron (longer path)	Flux passes straight across from one primary to the other through the sheet
Effective air gap / leakage	Larger, more leakage	Smaller, less leakage
Efficiency	Lower	Higher
Power factor	Lower	Higher
Normal (attraction) force	Large attraction between primary and back iron	Cancels (balanced)
Applications	Linear metro / maglev trains, conveyors	Sliding doors, material handling, launching systems



Linear induction motor: single-sided (left) and double-sided (right)

(Any four points, 1 M each)

e) VR stepper motor numerical

4 M

Given: Stator teeth $N_s = 12$, rotor teeth $N_r = 10$, $f = 150$ pulses/s

Step angle $\beta = (N_s - N_r) / (N_s \times N_r) \times 360^\circ = (12 - 10) / (12 \times 10) \times 360^\circ = \mathbf{6.00^\circ}$

Steps per revolution $= 360^\circ / \beta = 360 / 6.00 = \mathbf{60}$

Speed $n = \beta \times f / 360^\circ \text{ (rps)} = 6.00 \times 150 / 360 = 2.500 \text{ rps} = \mathbf{150.0 \text{ rpm}}$

Answer: $\beta = 6^\circ$; 60 steps/rev ; N = 150 rpm

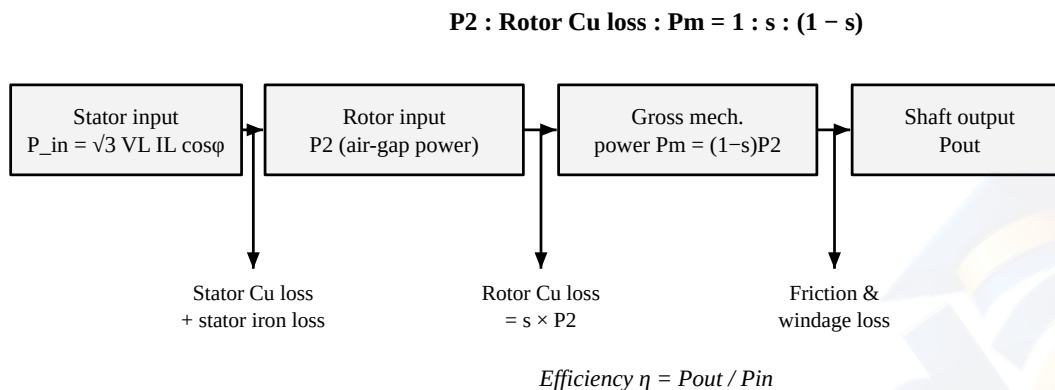
(Step angle 2 M, steps 1 M, speed 1 M)

Q.5 Attempt any TWO of the following: (12 M)

a) Power stages and P2 : Pcu : Pm

6 M

The electrical power input to the stator is converted into mechanical output in stages; at every stage some power is lost.



Power flow (power stages) diagram of 3- ϕ induction motor

1. **Stator input** $P_{in} = \sqrt{3} V_L I_L \cos \phi$.
2. **Stator losses** = stator copper loss ($3 I_1^2 R_1$) + stator iron (core) loss.
3. **Rotor input P2** = P_{in} – stator losses. This power crosses the air gap (air-gap power): $P_2 = 2\pi n_s T$.
4. **Rotor copper loss** = $3 I_2^2 R_2 = s \times P_2$ (rotor iron loss is negligible because f_r is very small).
5. **Gross mechanical power** $P_m = P_2 - \text{rotor Cu loss} = (1 - s) P_2$.
6. **Shaft output** $P_{out} = P_m - \text{mechanical losses (friction and windage)}$.

Important relation: $P_2 : P_{cu2} : P_m = 1 : s : (1 - s)$; rotor efficiency = $P_m / P_2 = (1 - s) = N / N_s$; overall $\eta = P_{out} / P_{in}$.

Proof: Rotor input $P_2 = 2\pi n_s T$ and gross mechanical power $P_m = 2\pi N T$ (N in rps). Rotor Cu loss = $P_2 - P_m = 2\pi T(n_s - N)$.

Rotor Cu loss / $P_2 = (n_s - N) / n_s = s \Rightarrow P_{cu2} = s P_2$; $P_m = P_2 - s P_2 = (1 - s) P_2$. $\therefore$ **P2 : Pcu2 : Pm = 1 : s : (1 - s).**

(Diagram 2 M, explanation 2 M, proof 2 M)

b) Alternator e.m.f. numerical (double layer, chorded)

6 M

Given: P = 6, slots = 72, $\Phi = 0.05$ Wb, N = 1000 rpm, 6 turns/coil, double layer, coil short-pitched by 2 slot(s)

Frequency $f = PN/120 = 6 \times 1000/120 = 50$ Hz

Slots per pole = $72/6 = 12$; slot angle $\beta = 180^\circ/12 = 15.00^\circ$

Slots per pole per phase $m = 72/(6 \times 3) = 4$

Pitch factor: coil short by 2 slot $\Rightarrow \alpha = 2 \times 15.00 = 30.00^\circ$; $K_p = \cos(\alpha/2) = \cos(15.00^\circ) = 0.9659$

Distribution factor: $K_d = \sin(m\beta/2) / (m \sin(\beta/2)) = \sin(30.00^\circ) / (4 \times \sin(7.50^\circ)) = \mathbf{0.9577}$

Double-layer winding $\Rightarrow$ number of coils = number of slots = 72; total turns = $72 \times 6 = 432$;
turns/phase $T = 432/3 = \mathbf{144}$

EMF per phase: $E_{ph} = 4.44 f \Phi T K_p K_d = 4.44 \times 50 \times 0.05 \times 144 \times 0.9659 \times 0.9577 = \mathbf{1,478.6 \text{ V}}$

Line voltage (star): $E_L = \sqrt{3} \times E_{ph} = \sqrt{3} \times 1,478.6 = \mathbf{2,561.0 \text{ V}}$

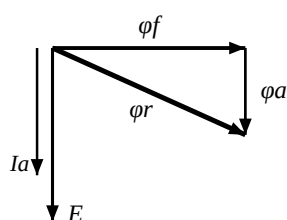
Answer: $f = 50 \text{ Hz}$; $K_p = 0.9659$; $K_d = 0.9577$; $E_{ph} = 1,478.6 \text{ V}$; $E_L = 2,561.0 \text{ V}$

(f 1 M, K_p 1 M, K_d 1 M, turns 1 M, E_{ph} and E_L 2 M)

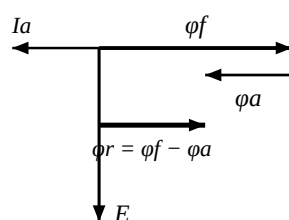
c) Armature reaction for lagging and leading loads

6 M

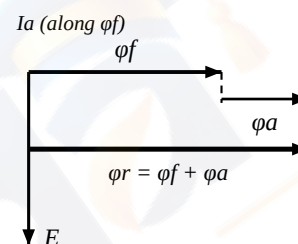
Armature reaction: the effect of the armature (stator) flux, produced by the load current, on the main field flux of the alternator. Its nature depends on the power factor of the load.



Unity p.f.
cross-magnetising (distorting)
 I_a in phase with E



Zero p.f. lagging
demagnetising
 I_a lags E by 90°



Zero p.f. leading
magnetising
 I_a leads E by 90°

Armature reaction phasor diagrams (ϕ_f = main field flux, ϕ_a = armature flux, ϕ_r = resultant flux)

- Unity p.f. load:** I_a is in phase with E . The armature flux is 90° behind the main flux (in space), i.e. along the interpolar axis. It weakens one half and strengthens the other half of each pole — **cross-magnetising (distorting)** effect; the resultant flux is almost unchanged in magnitude.
- Zero p.f. lagging load:** I_a lags E by 90° . The armature flux is directly opposite to the main flux — **demagnetising** effect. Terminal voltage falls; more field current is needed to keep voltage constant.
- Zero p.f. leading load:** I_a leads E by 90° . The armature flux is in the same direction as the main flux — **magnetising** effect. Terminal voltage rises.
- Intermediate p.f.** (e.g. 0.8 lag): partly cross-magnetising and partly demagnetising; for leading p.f. partly cross-magnetising and partly magnetising.

(Definition 1 M, lagging $2\frac{1}{2}$ M, leading $2\frac{1}{2}$ M)

Q.6 Attempt any TWO of the following: (12 M)

a) Tfl/Tmax derivation and numerical

6 M

(i) Derivation

Torque at any slip s : $T = k s E^2 R_2 / (R_2^2 + s^2 X_2^2) \dots (1)$

Maximum torque occurs at $s_m = R_2/X_2$: $T_{max} = k E^2 / (2 X_2) \dots (2)$

Dividing (1) by (2): $T / T_{\max} = 2 s R_2 X_2 / (R_2^2 + s^2 X_2^2)$

Divide numerator and denominator by X_2^2 and put $a = R_2/X_2 = \text{sm}$:

$$T_{\text{fl}} / T_{\max} = 2 a s f / (a^2 + s f^2) \quad (\text{sf} = \text{full-load slip}) \quad \text{and for } s = 1: T_{\text{st}} / T_{\max} = 2a / (1 + a^2)$$

(ii) Numerical

Given: $P = 6$, $f = 50$ Hz, s (full load) $= 0.03$, $R_2 = 0.02 \Omega$, $X_2 = 0.1 \Omega$

$$a = R_2 / X_2 = 0.02 / 0.1 = \mathbf{0.2000} \quad (= \text{slip at maximum torque, sm})$$

$$T_{\text{fl}} / T_{\max} = 2 a s / (a^2 + s^2) = 2 \times 0.2000 \times 0.03 / (0.2000^2 + 0.03^2) = \mathbf{0.2934}$$

$$\therefore T_{\max} / T_{\text{fl}} = \mathbf{3.408}$$

$$T_{\text{st}} / T_{\max} = 2a / (1 + a^2) = \mathbf{0.3846} \Rightarrow T_{\text{st}}/T_{\text{fl}} = 1.311$$

$$N_s = 120 \times 50 / 6 = 1,000 \text{ rpm}; \text{ speed at maximum torque } N = N_s (1 - \text{sm}) = 1,000 \times (1 - 0.2000) = \mathbf{800.0 \text{ rpm}}$$

Answer: $T_{\max}/T_{\text{fl}} = 3.408$; $T_{\text{st}}/T_{\max} = 0.3846$; speed at $T_{\max} = 800 \text{ rpm}$

(Derivation 3 M, numerical 3 M)

b) Regulation by synchronous impedance (O.C./S.C. test) method

6 M

Given: 200 kVA, 3300 V, star, $R_a = 0.8 \Omega/\text{ph}$, at $I_f = 4$ A: $I_{\text{sc}} = \text{full-load current}$, O.C. line voltage = 900 V

$$\text{Full-load current } I = 200 \times 10^3 / (\sqrt{3} \times 3300) = \mathbf{34.99 \text{ A}} \quad (= I_{\text{sc}} \text{ at } I_f = 4 \text{ A}).$$

$$\text{Synchronous impedance } Z_s = (\text{O.C. voltage per phase}) / (\text{S.C. current}) \text{ at the same field current} = (900/\sqrt{3}) / 34.99 = 519.62 / 34.99 = \mathbf{14.850 \Omega}$$

$$\text{Synchronous reactance } X_s = \sqrt{(Z_s^2 - R_a^2)} = \sqrt{(14.850^2 - 0.8^2)} = \mathbf{14.829 \Omega}$$

$$\text{Phase voltage } V = 3300/\sqrt{3} = 1,905.26 \text{ V, full-load current } I = 34.99 \text{ A}$$

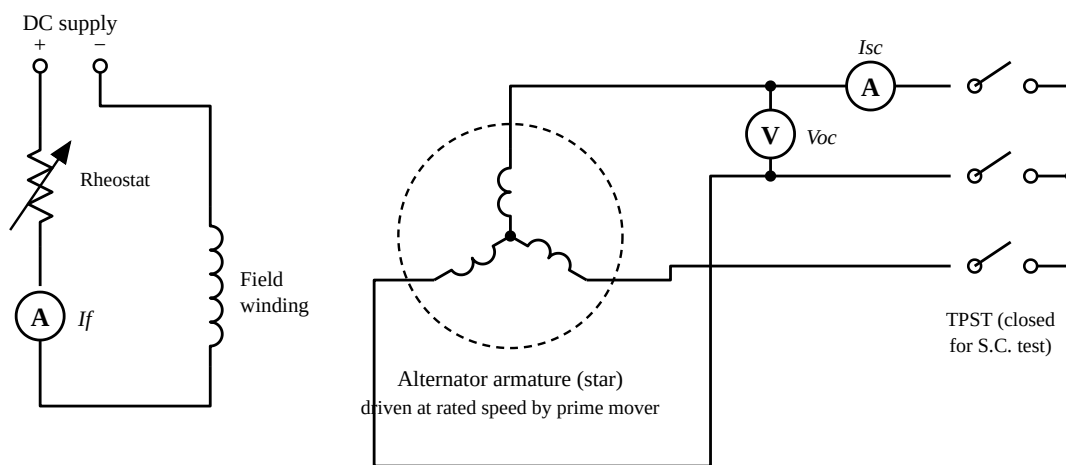
$$I R_a = 34.99 \times 0.8 = 27.99 \text{ V}; \quad I X_s = 34.99 \times 14.829 = 518.86 \text{ V}$$

$$\text{At 0.8 p.f. lagging: } E = \sqrt{(V \cos \phi + I R_a)^2 + (V \sin \phi + I X_s)^2} = \sqrt{[(1,524.20 + 27.99)^2 + (1,143.15 + 518.86)^2]} = \mathbf{2,274.12 \text{ V}}$$

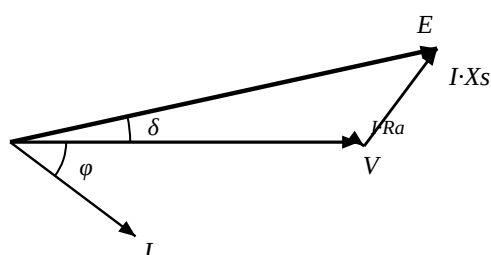
$$\% \text{ Regulation} = (2,274.12 - 1,905.26) / 1,905.26 \times 100 = \mathbf{19.36 \%}$$

$$\text{At unity p.f.: } E = \sqrt{(V + I R_a)^2 + (I X_s)^2} = \sqrt{[(1,905.26 + 27.99)^2 + 518.86^2]} = \mathbf{2,001.67 \text{ V}}$$

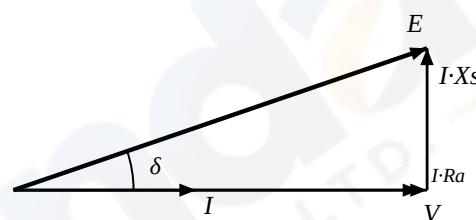
$$\% \text{ Regulation} = (2,001.67 - 1,905.26) / 1,905.26 \times 100 = \mathbf{5.06 \%}$$



Circuit for open-circuit (O.C.) and short-circuit (S.C.) tests on 3- ϕ alternator



p.f. 0.8 lagging (drops not to scale)



p.f. 1.0 (unity) (drops not to scale)

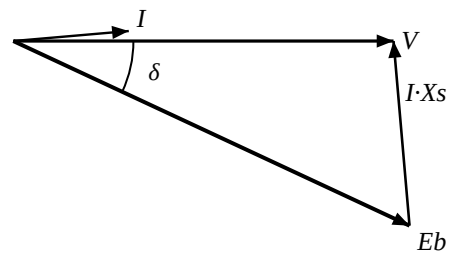
Answer: $Z_s = 14.850 \, \Omega$; $X_s = 14.829 \, \Omega$; 0.8 lag: 19.36 % ; unity: 5.06 %

(Z_s, X_s 2 M; each regulation 2 M)

c) Synchronous motor — principle, not self-starting, load angle

6 M

- **Construction:** stator has a 3- ϕ distributed winding (like an induction motor); rotor has salient (or cylindrical) poles excited by DC through slip rings; a damper (cage) winding is placed in the pole faces.
- **Principle:** the 3- ϕ supply produces an RMF rotating at N_s . The DC excited rotor poles get **magnetically locked** with the opposite stator poles and are dragged round at exactly **synchronous speed**, $N_s = 120f/P$.
- **Not self-starting:** at standstill the stator poles sweep past the rotor poles at N_s ; the torque on the heavy rotor reverses every half-cycle (average zero) and the rotor cannot follow. It is started as an induction motor using the damper winding (or by a pony motor / VFD), and DC is applied near N_s .
- **Load angle δ :** the angle by which the rotor poles fall behind the stator field axis (angle between V and E_b). It increases with load; power $P = (V E_b / X_s) \sin \delta$, maximum at $\delta = 90^\circ$ (pull-out).



$$V = E_b + I \cdot X_s \text{ (} R_a \text{ neglected), over-excited}$$

Phasor diagram of synchronous motor (load angle δ)

(Principle 2 M, not self-starting 2 M, load angle 2 M)

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