A.C. Machines Performance (315333)

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

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

a) Slip and synchronous speed — 2 M

Synchronous speed (Ns): The speed at which the rotating magnetic field produced by the 3-φ stator winding rotates. Ns = 120 f / P rpm, where f = supply frequency, P = number of poles.

Slip (s): The difference between synchronous speed and actual rotor speed, expressed as a fraction (or %) of synchronous speed: $s = (Ns - N) / Ns$. $Ns - N$ is called the slip speed. Full-load slip is usually 2 % to 5 %.

(Each definition 1 M)

b) Function of stator core and slip rings — 2 M

(i) Stator core: made of thin silicon-steel laminations; provides a low-reluctance path for the rotating flux, holds the 3-φ stator winding in its slots and reduces eddy-current and hysteresis losses.

(ii) Slip rings: copper / brass rings mounted on (and insulated from) the shaft of a wound-rotor motor; with brushes they connect the rotor winding to external resistance for starting (higher starting torque, lower starting current) and speed control.

(1 M each)

c) Advantages of soft starter over star–delta starter — 2 M

- Smooth, stepless rise of voltage — no current / torque surge at the star-to-delta change-over.
- Starting current limit and ramp time are adjustable; soft stop is also available.
- Works with any motor connection (only 3 leads), compact and with built-in electronic protection.

(Any two, 1 M each)

d) Types of single phase induction motors — 2 M

1. Split-phase (resistance start) induction motor
2. Capacitor start induction run motor
3. Capacitor start capacitor run (two-value capacitor) motor
4. Permanent split capacitor (PSC) motor
5. Shaded pole induction motor
6. Reluctance start motor

(Any four, ½ M each)

e) Pull-in and pull-out torque — 2 M

Pull-in torque: the maximum load torque at which a synchronous motor, running near synchronous speed as an induction motor, can be pulled into synchronism when DC field excitation

is applied.

Pull-out torque: the maximum torque a synchronous motor can develop at synchronous speed without losing synchronism (at load angle $\delta = 90°$).

(1 M each)

f) Pitch factor and distribution factor

2 M

Pitch factor (coil span factor) Kp: the ratio of emf induced in a short-pitched coil to the emf that would be induced in a full-pitched coil. $K_p = \cos(\alpha/2)$, where α = angle by which the coil is short of 180° electrical.

Distribution factor (breadth factor) Kd: the ratio of emf of a distributed winding (coils in several slots) to the emf of the same winding if concentrated in one slot (arithmetic sum). $K_d = \sin(m\beta/2) / (m \sin(\beta/2))$, where m = slots per pole per phase, β = slot angle.

(1 M each)

g) Applications of stepper motor

2 M

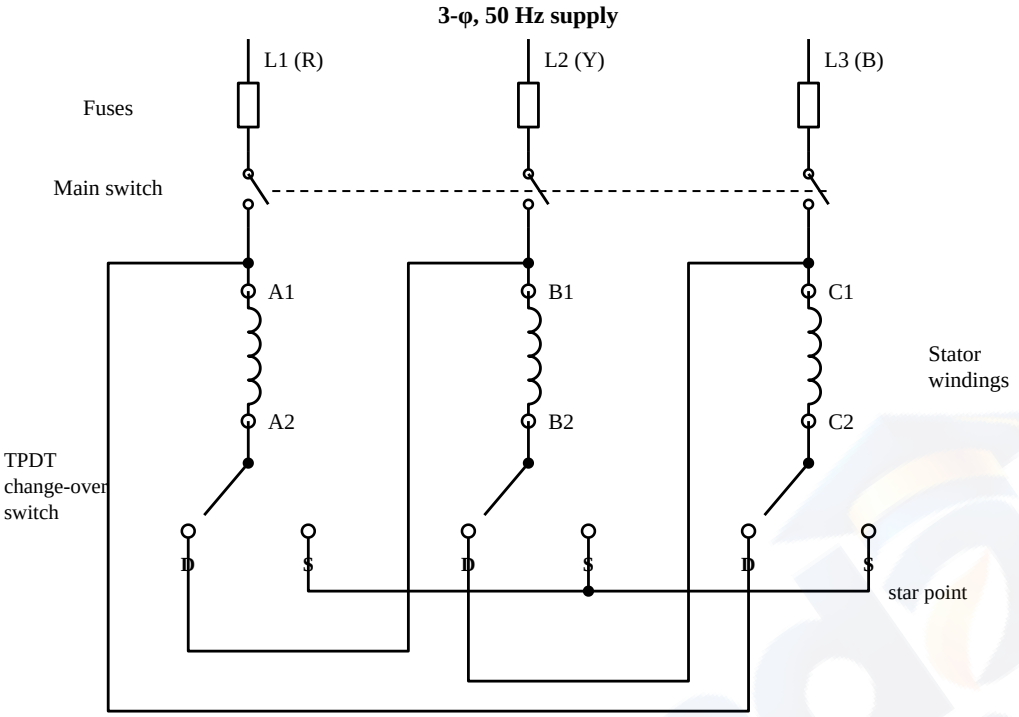
- Computer printers, plotters, scanners and disk drives
- CNC machines, 3-D printers and X–Y tables
- Robotics and pick-and-place machines
- Camera lens focusing, clocks / watches, medical equipment (infusion pumps)
- Textile machines, valve positioning, satellite antenna positioning

(Any four, ½ M each)

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

a) Manual star–delta starter

4 M



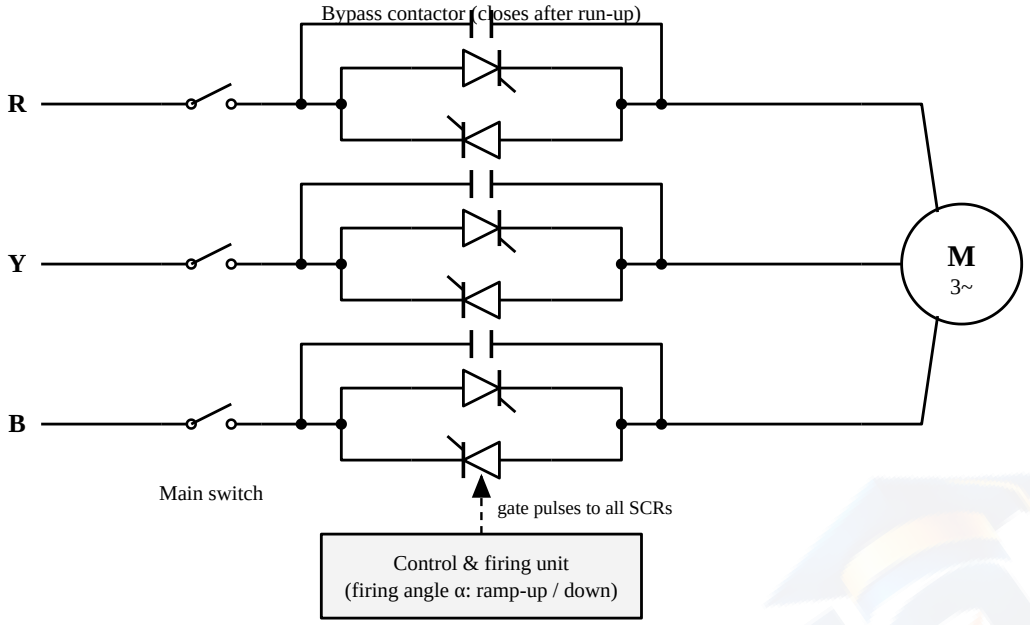
D = delta (RUN) contacts: A2–B1, B2–C1, C2–A1; S = star (START) contacts shorted

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 VL/√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.

(Diagram 2 M, working 2 M)

b) Soft starter 4 M



Soft starter: anti-parallel SCR pair in each line, bypass contactor and control unit

1. Two SCRs connected **back-to-back (anti-parallel)** are placed in series with each supply line (a triac may be used for small motors).
2. The control and firing unit varies the **firing angle α**. At start α is large, so only a part of each half-cycle reaches the motor — a low voltage is applied.
3. α is reduced gradually (ramp time set by user), so the motor voltage rises smoothly from an initial value (about 30–50 %) up to full voltage. Starting current is kept within a set current limit.
4. When the motor reaches full speed, the **bypass contactor** closes and the SCRs are removed from the circuit to avoid their losses and heating.
5. For stopping, the voltage is reduced gradually (**soft stop**) — useful for pumps (prevents water hammer) and conveyors.
6. Built-in protections: overload, phase loss, phase reversal, over-temperature.

(Diagram 2 M, working 2 M)

c) Starting currents — DOL, star–delta, auto-transformer 4 M

Given: Delta-connected motor, V = 400 V, starting phase current on DOL = 90 A, auto-transformer tapping x = 0.65

i) DOL starting: full voltage across each delta phase, so phase current = 90 A; line current $I_L = \sqrt{3} \times 90 =$ **155.88 A**

ii) Star–delta starting: in star each phase gets $V/\sqrt{3}$, so phase current = $90/\sqrt{3} =$ **51.96 A**; in star, line current = phase current = **51.96 A** (= 1/3 of DOL line current 155.88 A)

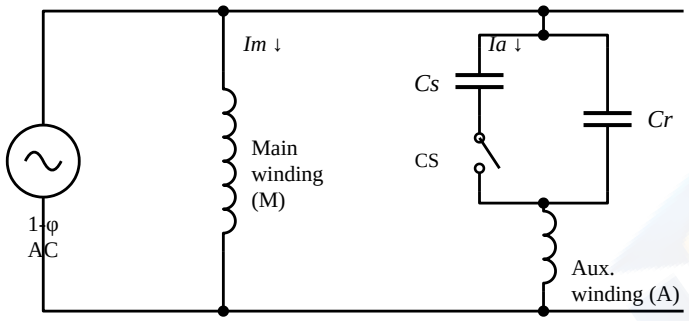
iii) Auto-transformer (65 % tap): motor phase current = x × 90 = **58.50 A**; motor line current = $\sqrt{3} \times 58.50 =$ **101.32 A**; supply line current = x × motor line current = 0.65 × 101.32 = **65.86 A** (= x^2 × DOL line current)

Method	Motor phase current (A)	Line current from supply (A)
DOL	90.00	155.88
Star–delta (start in star)	51.96	51.96
Auto-transformer, 65 % tap	58.50	65.86 (motor line current 101.32)

(Each part with steps; 1 + 1½ + 1½ M)

d) Capacitor start capacitor run motor

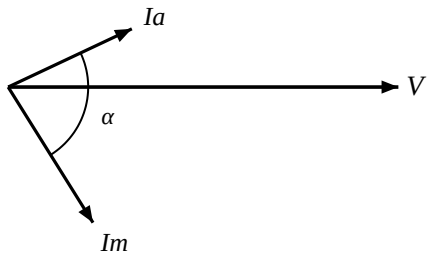
4 M



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

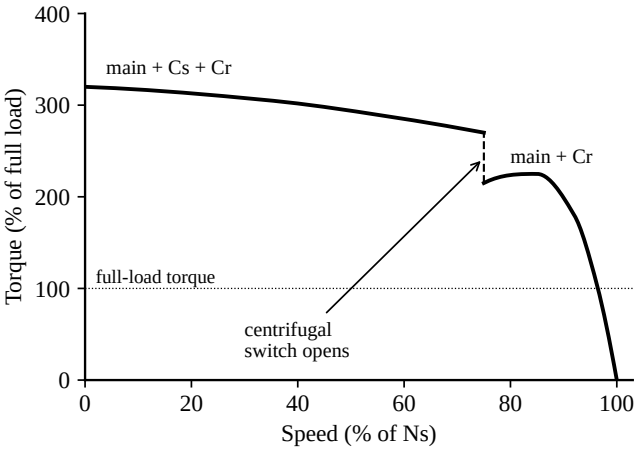
Capacitor-start capacitor-run (two-value capacitor) motor

1. The auxiliary winding has **two capacitors** in parallel: a large **starting capacitor Cs** (electrolytic) in series with a centrifugal switch, and a small **running capacitor Cr** (oil-filled paper) permanently connected.
2. At start Cs + Cr give a large capacitance, so Ia leads V and the phase difference α between Im and Ia is nearly 90° → **high starting torque**.
3. At about 75 % of Ns the centrifugal switch removes Cs. Cr 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.



α ≈ 83°: Im lags V by 58°, Ia leads V by 25°
(typical values)

Phasor diagram at starting (Cs + Cr in circuit)



Typical torque–speed characteristic (two-value capacitor)

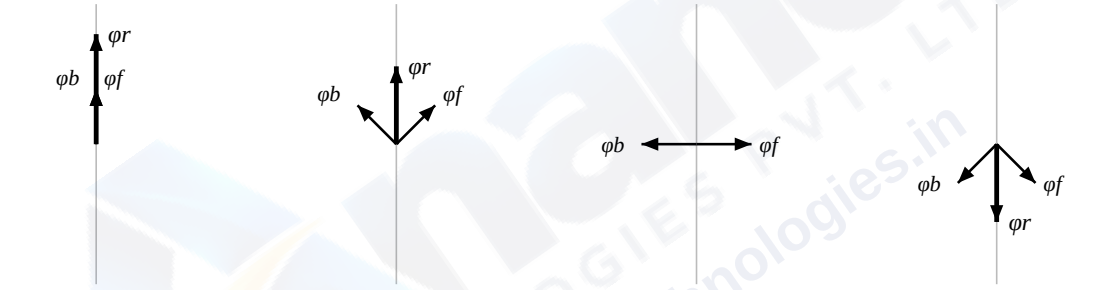
(Circuit 1 M, phasor 1 M, working 2 M)

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

a) Double field revolving theory

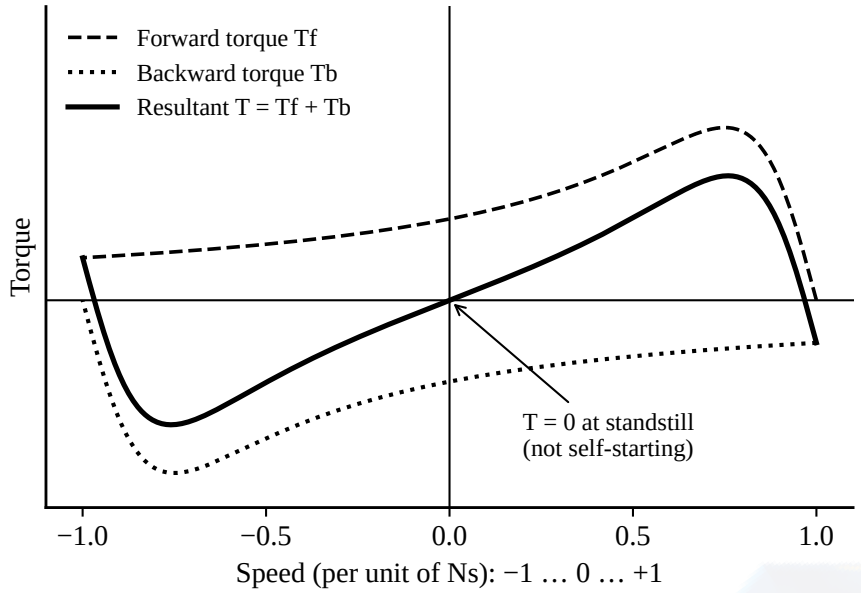
4 M

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



Pulsating flux φm cos ωt = two fluxes φm/2 rotating in opposite directions

- The single-phase winding produces φ = φm cos ωt along a fixed axis. The forward component φf and backward component φb (each φm/2) rotate in opposite directions; their sum always lies on the winding axis and pulsates between +φm and −φm.
- Each rotating field induces rotor currents and produces torque: forward field → forward torque Tf, backward field → backward torque Tb (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 Tf = Tb 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 (Tf > Tb) and the motor keeps running in that direction.

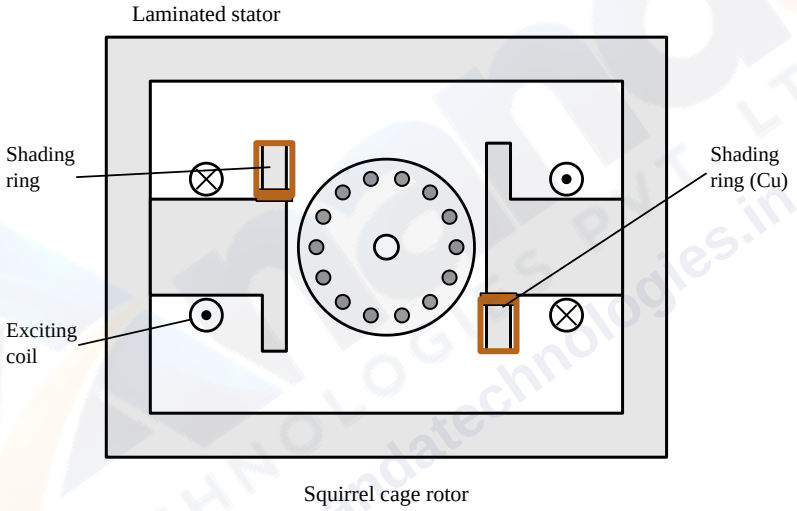


Forward, backward and resultant torque–speed curves (computed); net torque is zero at standstill

(Statement 1 M, diagram 1 M, explanation 2 M)

b) Shaded pole starting technique

4 M



Shaded pole motor — construction (two-pole)

- **Construction:** salient-pole laminated stator with a concentrated exciting coil on each pole. Each pole has a slot cut across it; the smaller part (about 1/3) is surrounded by a short-circuited copper ring called the **shading ring**. Rotor is squirrel cage.
- **Working:** when the flux in the pole is **rising**, current induced in the shading ring opposes the rise — most flux passes through the unshaded part.
- Near the **maximum** of the flux, its rate of change is nearly zero, little current flows in the ring and the flux distributes uniformly over the whole pole.
- When the flux is **decreasing**, the ring current opposes the decrease — the flux is crowded in the shaded part.
- Thus the magnetic axis **shifts from the unshaded to the shaded part** of the pole in every half-cycle — a moving (rotating) field is produced and the rotor turns in that direction.

- Low starting torque (40–50 % of FL), low efficiency and p.f.; direction cannot be reversed easily.

(Sketch 2 M, working 2 M)

c) Capacitor start vs capacitor start capacitor run

4 M

Point	Capacitor start induction run	Capacitor start capacitor run
Capacitors	One (starting, electrolytic)	Two: Cs (electrolytic) + Cr (paper / oil)
Aux. winding after start	Disconnected by centrifugal switch	Remains in circuit with Cr
Running	Runs as 1-φ motor (pulsating torque)	Runs as 2-φ motor (uniform torque)
Power factor / efficiency	Lower	Higher
Noise	More noisy	Quiet, smooth running
Cost	Less	More
Applications	Compressors, pumps, conveyors	AC compressors, refrigerators, large pumps

(Any four points, 1 M each)

d) Selection of single phase motors

4 M

Application	Suitable motor	Reason
(i) Ceiling fan	Permanent split capacitor (PSC) motor	Low starting torque is enough; quiet running, good p.f.; speed control by regulator
(ii) Air-conditioner compressor	Capacitor start capacitor run motor	High starting torque against pressure plus high running efficiency and p.f.
(iii) Small exhaust fan	Shaded pole motor	Very small power, low starting torque load; simple and cheap
(iv) Washing machine	Resistance split-phase (or capacitor start) motor	Moderate starting torque, simple and economical

(1 M each)

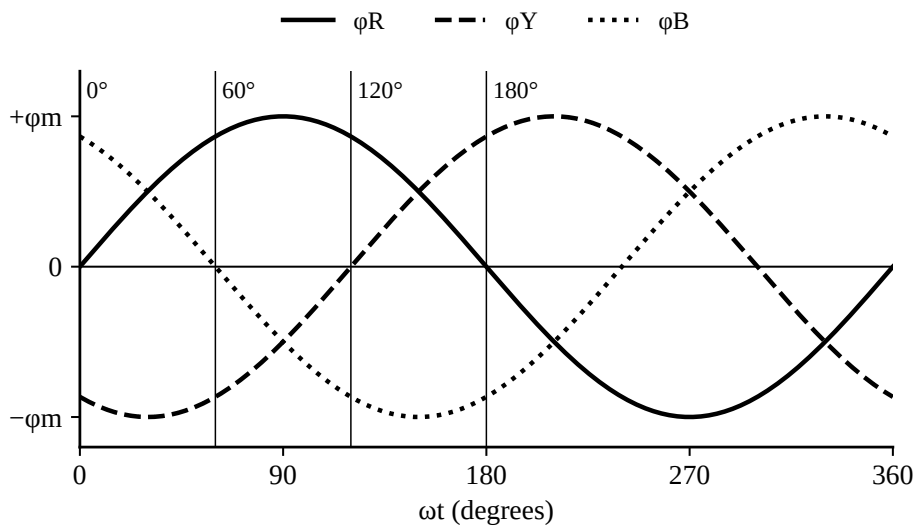
Q.4 Attempt any THREE of the following: (12 M)

a) Production of rotating magnetic field

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:

$$\varphi R = \varphi m \sin \omega t, \quad \varphi Y = \varphi m \sin(\omega t - 120°), \quad \varphi B = \varphi m \sin(\omega t - 240°)$$

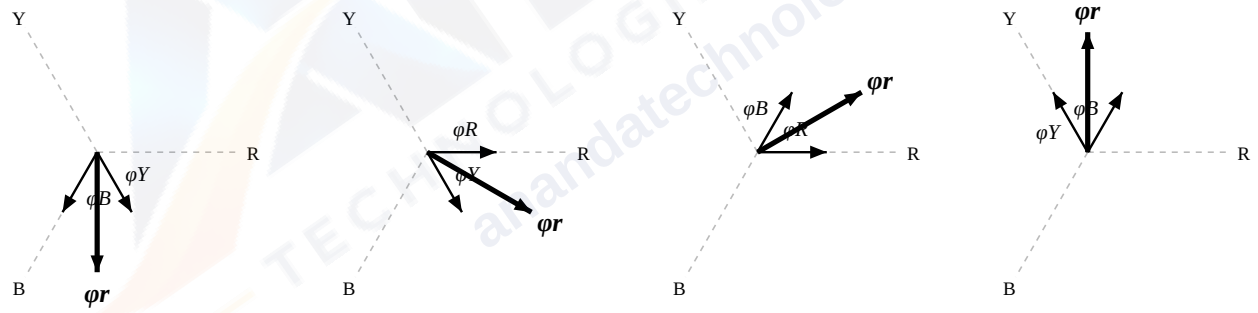


Three-phase fluxes φR, φY, φB (120° apart) and the instants considered

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

ωt	φR	φY	φB	|φr|	Direction of φr
0°	0	-0.866 φm	+0.866 φm	**1.50 φm**	270°
60°	+0.866 φm	-0.866 φm	0	**1.50 φm**	330°
120°	+0.866 φm	0	-0.866 φm	**1.50 φm**	30°
180°	0	+0.866 φm	-0.866 φm	**1.50 φm**	90°

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



ωt = 0°
|φr| = 1.50 φm, at 270°

ωt = 60°
|φr| = 1.50 φm, at 330°

ωt = 120°
|φr| = 1.50 φm, at 30°

ωt = 180°
|φr| = 1.50 φm, at 90°

Resultant flux φr = 1.5 φm at ωt = 0°, 60°, 120°, 180° — constant magnitude, rotating at Ns

- At every instant the resultant flux has the same magnitude **1.5 φm**.
- From ωt = 0° 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 φm** is produced, rotating at synchronous speed Ns = 120 f / P.

- Interchanging any two supply lines reverses the direction of rotation of the RMF (and of the motor).

(Diagrams 2 M, explanation 2 M)

b) Power stages numerical 4 M

Given: P = 4, f = 50 Hz, N = 1440 rpm, Stator input = 25 kW, Stator losses = 0.8 kW, Friction & windage loss = 0.6 kW

1) Synchronous speed: Ns = 120f / P = 120 × 50 / 4 = **1,500 rpm**

2) Slip: s = (Ns − N) / Ns = (1,500 − 1440) / 1,500 = **0.0400** = 4.00 %

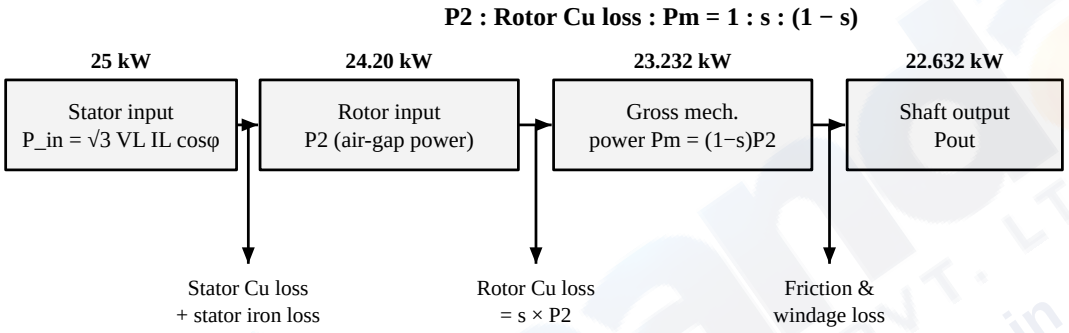
3) Rotor input (air-gap power): P2 = Stator input − Stator losses = 25 − 0.8 = **24.20 kW**

4) Rotor copper loss: Pcu2 = s × P2 = 0.0400 × 24.20 = **0.968 kW**

5) Gross mechanical power (rotor output): Pm = P2 − Pcu2 = (1 − s) P2 = **23.232 kW**

6) Shaft output: Pout = Pm − F&W loss = 23.232 − 0.6 = **22.632 kW**

7) Efficiency: η = Pout / Pin × 100 = 22.632 / 25 × 100 = **90.53 %**



Efficiency η = Pout / Pin

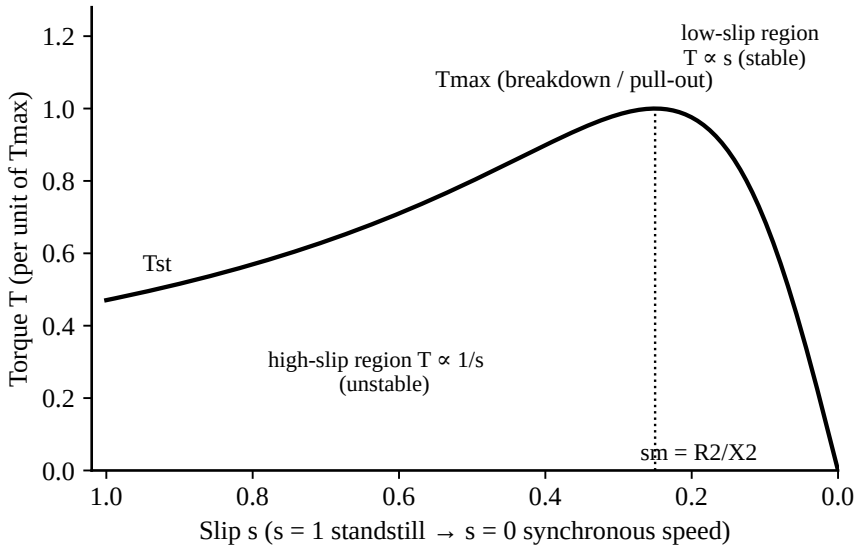
Power flow for this motor

Answer: s = 0.04 ; P2 = 24.20 kW ; rotor Cu loss = 0.968 kW ; output = 22.632 kW ; η = 90.53 %

(1 M each part)

c) Torque–slip characteristics 4 M

Torque under running condition: $T = k\, s\, E2^2\, R2 / (R2^2 + s^2\, X2^2)$.

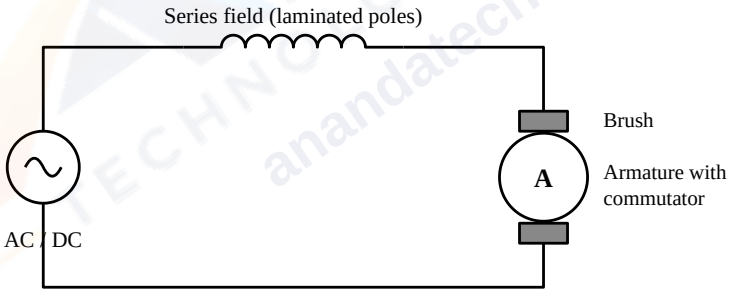


Torque–slip characteristic of 3-φ induction motor

- **Low-slip region** (normal running, s ≈ 0 to sm): sX2 ≪ R2, so T ∝ s — the curve is almost a straight line. Speed falls slightly as load increases; operation is **stable**.
- **Maximum torque** Tmax occurs at sm = R2/X2; Tmax = k E2²/(2X2). Tmax does not depend on R2, but the slip at which it occurs does.
- **High-slip region** (s > sm): sX2 ≫ R2, so T ∝ 1/s — a rectangular hyperbola. If load exceeds Tmax the motor slows down further and stops: **unstable** region.
- **Starting torque** Tst is the torque at s = 1. Adding rotor resistance (slip-ring motor) raises Tst; Tst = Tmax when R2 = X2.
- At s = 0 (N = Ns) torque is zero.

(Characteristic 2 M, explanation 2 M)

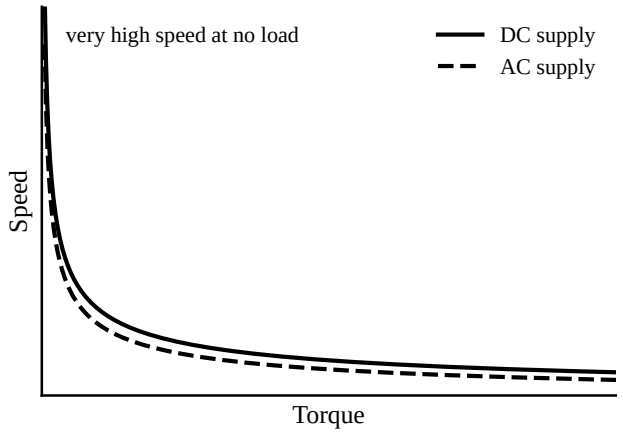
d) Universal motor 4 M



Universal motor — series field and armature, works on AC or DC

- A **series motor** designed to run on both AC and DC at about the same speed and output.
- Field poles and yoke are fully **laminated** to reduce eddy-current loss on AC; field has few turns to reduce reactance drop.
- Armature with commutator and carbon brushes, connected in series with the field; larger motors use a compensating winding to reduce armature reactance and sparking.
- On AC, field flux and armature current reverse together, so torque (T ∝ φI ∝ I²) remains unidirectional.

- High starting torque and very high no-load speed (it must not be run on no load); speed falls sharply with load.



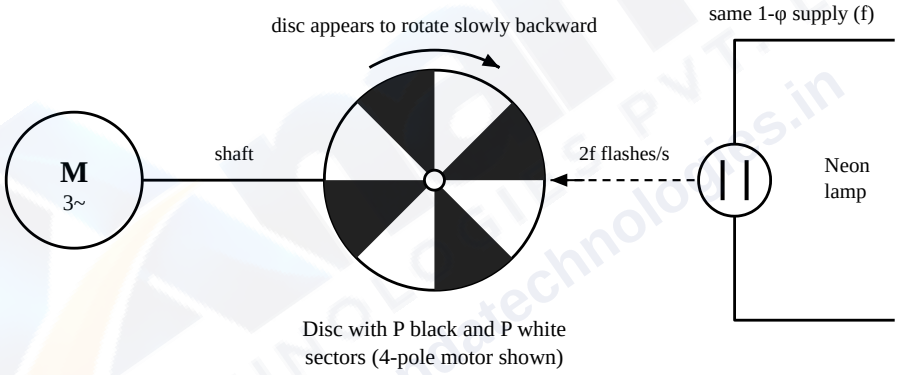
Torque–speed characteristic of universal motor (computed series-motor model)

Applications: mixer-grinders, vacuum cleaners, portable drills, hair dryers, sewing machines, food processors.

(Construction with sketch 2 M, characteristic 2 M)

e) Stroboscopic method of slip measurement 4 M

Used for accurate measurement of the small slip of an induction motor.



Stroboscopic method of slip measurement

1. Fix a circular disc on the motor shaft having **P black and P white sectors** alternately (P = number of poles).
2. Illuminate the disc with a **neon lamp** connected to the same supply of frequency f. The lamp flashes 2f times per second.
3. If the disc rotated exactly at Ns, it would move by exactly one pair of sectors between two flashes and would appear **stationary**.
4. Since N < Ns, the disc lags a little at every flash and the sectors appear to **rotate slowly backwards**.
5. Count the number of black sectors n that pass a fixed reference mark in one minute (stop-watch).
6. Slip speed Ns − N = n / P rpm, and **s = (n / P) / Ns** (or count apparent backward revolutions n′ per minute: s = n′/Ns).

(Sketch 1 M, procedure 3 M)

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

a) EMF equation and numerical 6 M

(i) Derivation

Let Φ = flux per pole (Wb), P = number of poles, N = speed (rpm), f = frequency, Z = conductors in series per phase, T = Z/2 turns per phase.

In one revolution each conductor cuts flux = PΦ webers. Time for one revolution = 60/N s.

Average emf per conductor = dΦ/dt = PΦ / (60/N) = PΦN/60 V. Since f = PN/120, PN/60 = 2f ⇒ average emf per conductor = 2fΦ V.

Average emf per turn (2 conductors) = 4fΦ V; average emf per phase = 4fΦT V.

RMS value = form factor (1.11) × average = 1.11 × 4fΦT = **4.44 f Φ T** V (full-pitch, concentrated winding).

For a short-pitched and distributed winding: **Eph = 4.44 Kp Kd f Φ T volts**, where Kp = pitch factor, Kd = distribution factor.

(ii) Numerical

Given: P = 4, slots = 48, Φ = 0.03 Wb, f = 50 Hz, 10 conductors/slot, coil short-pitched by 2 slot(s)

Slots per pole = 48/4 = 12; slot angle β = 180°/12 = **15.00°**

Slots per pole per phase m = 48/(4 × 3) = **4**

Pitch factor: coil short by 2 slot ⇒ α = 2 × 15.00 = 30.00°; Kp = cos(α/2) = cos(15.00°) = **0.9659**

Distribution factor: Kd = sin(mβ/2) / (m sin(β/2)) = sin(30.00°) / (4 × sin(7.50°)) = **0.9577**

Total conductors Z = 48 × 10 = 480; Zph = 480/3 = 160; turns/phase T = Zph/2 = **80**

EMF per phase: Eph = 4.44 f Φ T Kp Kd = 4.44 × 50 × 0.03 × 80 × 0.9659 × 0.9577 = **492.9 V**

Line voltage (star): EL = √3 × Eph = √3 × 492.9 = **853.7 V**

Answer: Kp = 0.9659 ; Kd = 0.9577 ; Eph = 492.9 V ; EL = 853.7 V

(Derivation 3 M, numerical 3 M)

b) Starting, full-load and maximum torque 6 M

Given: P = 4, f = 50 Hz, R2 = 0.03 Ω/ph, X2 = 0.18 Ω/ph, E2 = 110 V/ph (standstill), N = 1440 rpm

Ns = 120f/P = 120 × 50/4 = 1,500 rpm; ns = 1,500/60 = 25.0000 rps

Full-load slip s = (Ns − N)/Ns = (1,500 − 1440)/1,500 = **0.0400**

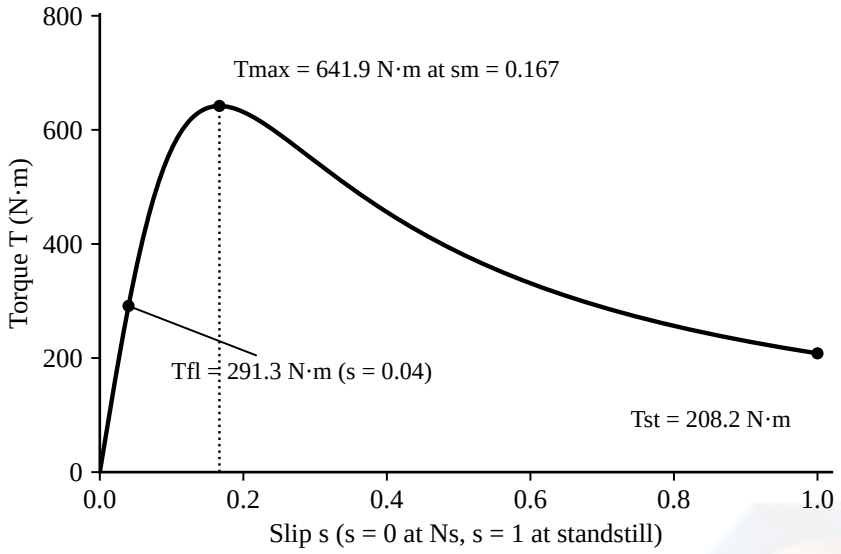
Torque equation (3-φ): $T = (3 / 2\pi ns) \times s\, E2^2\, R2 / (R2^2 + (s\, X2)^2)$ N·m; $3/(2\pi ns) = 0.01910$

i) Starting torque (s = 1): Tst = 0.01910 × 110² × 0.03 / (0.03² + 0.18²) = **208.19 N·m**

ii) Full-load torque (s = 0.0400): Tfl = 0.01910 × 0.0400 × 110² × 0.03 / (0.03² + (0.0400 × 0.18)²) = **291.34 N·m**

iii) Maximum torque: occurs at sm = R2/X2 = 0.03/0.18 = 0.167; Tmax = (3 / 2πns) × E2² / (2 X2) = 0.01910 × 110² / (2 × 0.18) = **641.92 N·m**

Speed at maximum torque: N = Ns (1 − sm) = 1,500 × (1 − 0.167) = **1,250.0 rpm**



Computed torque–slip curve for this motor

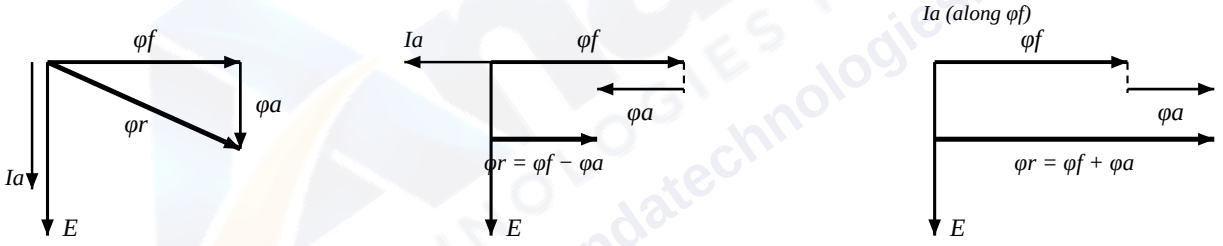
Answer: Tst = 208.19 N·m ; Tfl = 291.34 N·m ; Tmax = 641.92 N·m at 1,250.0 rpm

(2 M each part)

c) Armature reaction at various power factors

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)
Ia in phase with E

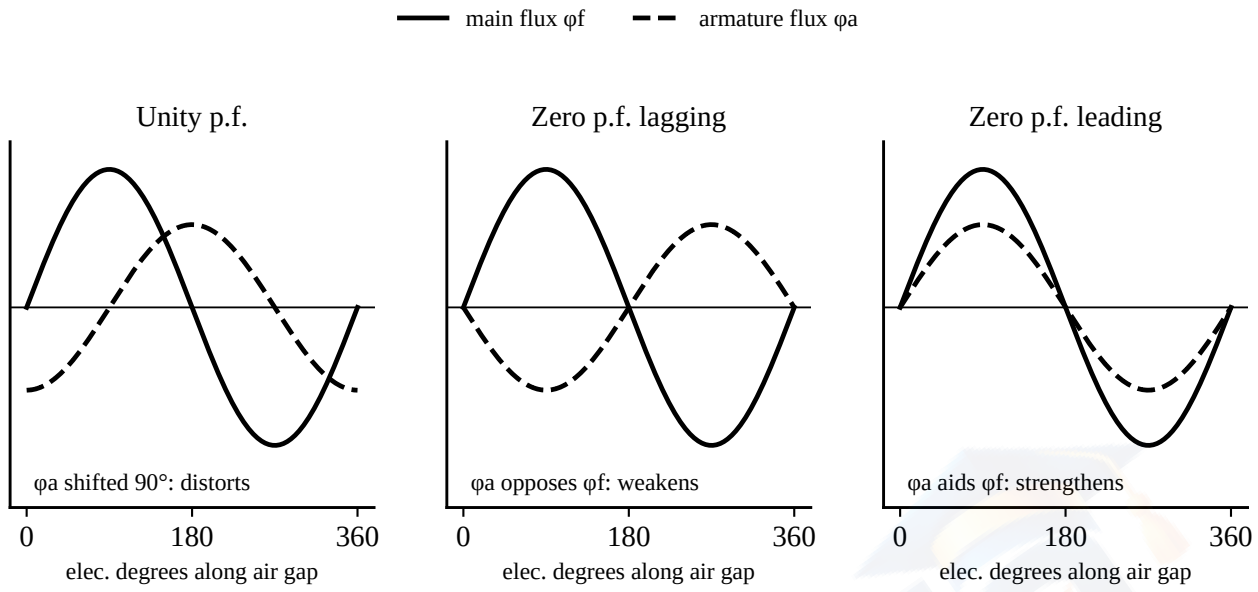
Zero p.f. lagging
demagnetising
Ia lags E by 90°

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

Armature reaction phasor diagrams (φf = main field flux, φa = armature flux, φr = resultant flux)

1. **Unity p.f. load:** Ia 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.
2. **Zero p.f. lagging load:** Ia 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.
3. **Zero p.f. leading load:** Ia leads E by 90°. The armature flux is in the same direction as the main flux — **magnetising** effect. Terminal voltage rises.

4. **Intermediate p.f.** (e.g. 0.8 lag): partly cross-magnetising and partly demagnetising; for leading p.f. partly cross-magnetising and partly magnetising.



Main field flux and armature flux along the air gap (one pole pair) at different p.f.

(Definition 1 M, three cases with diagrams 5 M)

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

a) Voltage regulation — synchronous impedance method 6 M

Given: 500 kVA, 3300 V, star, Ra = 0.3 Ω/ph, Xs = 4 Ω/ph

I Ra = 87.48 × 0.3 = 26.24 V, I Xs = 87.48 × 4 = 349.91 V; cos φ = 0.8, sin φ = 0.6. E = no-load emf per phase, V = rated phase voltage.

Phase voltage V = 3300/√3 = **1,905.26 V**

At 0.8 p.f. lagging: Full-load current I = 500×10³ / (√3 × 3300) = **87.48 A**

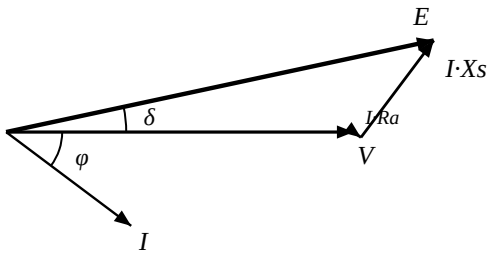
E = √[(V cosφ + IRa)² + (V sinφ + IXs)²] = √[(1,524.20 + 26.24)² + (1,143.15 + 349.91)²] = **2,152.47 V**

% Regulation = (E − V)/V × 100 = (2,152.47 − 1,905.26)/1,905.26 × 100 = **12.98 %**

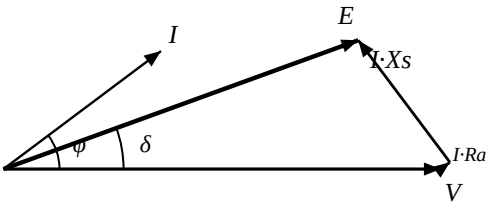
At 0.8 p.f. leading: Full-load current I = 500×10³ / (√3 × 3300) = **87.48 A**

E = √[(V cosφ + IRa)² + (V sinφ − IXs)²] = √[(1,524.20 + 26.24)² + (1,143.15 − 349.91)²] = **1,741.59 V**

% Regulation = (E − V)/V × 100 = (1,741.59 − 1,905.26)/1,905.26 × 100 = **-8.59 %**



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



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

Answer: 0.8 lag: 12.98 % ; 0.8 lead: -8.59 % (negative — terminal voltage rises on load)

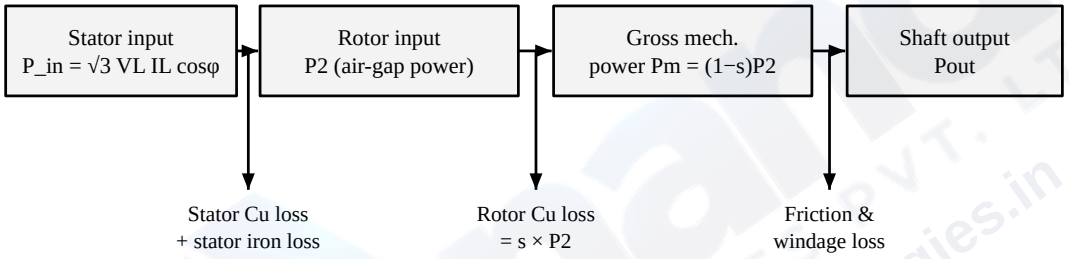
(Current & data 1 M, each case 2½ M)

b) Power stages and rotor frequency numerical

6 M

(i)

P2 : Rotor Cu loss : Pm = 1 : s : (1 − s)



Efficiency η = Pout / Pin

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

P2 : rotor Cu loss : Pm = 1 : s : (1 − s).

(ii)

Given: P = 4, f = 50 Hz, Rotor input P2 = 50 kW, rotor emf makes 90 complete cycles per minute

Rotor frequency: fr = 90 / 60 = **1.5000 Hz**

1) Slip: fr = s f ⇒ s = fr / f = 1.5000 / 50 = **0.0300** (3.00 %)

2) Rotor speed: Ns = 120 × 50 / 4 = 1,500 rpm; N = Ns (1 − s) = 1,500 × (1 − 0.0300) = **1,455.0 rpm**

3) Rotor copper loss: Pcu2 = s × P2 = 0.0300 × 50 = **1.500 kW** (total), i.e. 500.0 W per phase

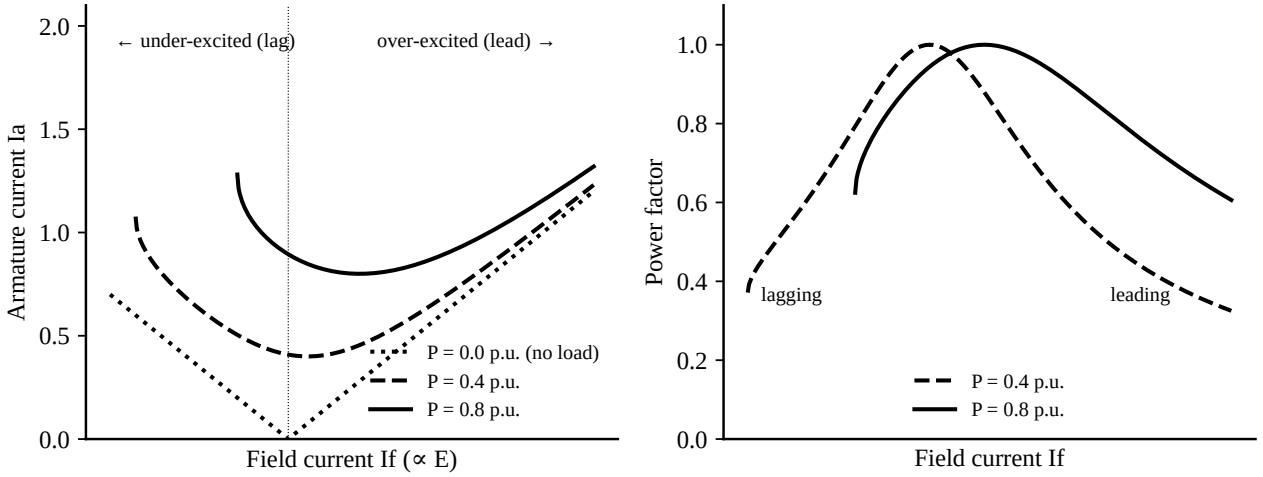
4) Gross mechanical power: Pm = (1 − s) P2 = **48.500 kW**

Answer: s = 0.03 ; N = 1,455 rpm ; rotor Cu loss = 1.50 kW ; Pm = 48.50 kW

(Diagram 2 M, numerical 4 M)

c) V-curves and p.f. improvement

6 M



V-curves and inverted-V (p.f.) curves of synchronous motor (computed: V = 1 p.u., Xs = 1 p.u.)

- V-curves are graphs of armature current Ia against field current If at constant load (constant mechanical power).
- **Under-excitation:** Eb < V; motor draws **lagging** current; Ia is high.
- **Normal excitation:** Ia is **minimum** and p.f. is **unity** (lowest point of the V-curve).
- **Over-excitation:** Eb > V; the motor draws **leading** current (behaves like a capacitor).
- Joining the minimum points gives the unity p.f. line; the p.f. vs If curves have an inverted-V shape.
- **P.F. improvement:** an over-excited synchronous motor running at no load (**synchronous condenser**) connected in parallel with lagging industrial loads supplies leading kVAR and raises the overall power factor; the correction is smooth by just varying If.

(V-curves 3 M, explanation 3 M)

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