

A.C. Machines Performance (315333)

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

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

a) Synchronous speed and slip

2 M

Given: $P = 6$, $f = 50$ Hz, $N = 960$ rpm

$N_s = 120 f / P = 120 \times 50 / 6 = \mathbf{1,000}$ rpm

$s = (N_s - N)/N_s = (1,000 - 960)/1,000 = \mathbf{0.04} = 4 \%$

(1 M each)

b) Reasons for using a starter

2 M

- At start ($s = 1$) the motor draws 5–7 times full-load current, like a short-circuited transformer; this causes a large voltage dip on the supply.
- The heavy current overheats the winding and causes mechanical shocks; the starter also provides overload and no-volt protection.

(1 M each)

c) Applications of shaded pole motor

2 M

- Table fans, small exhaust fans
- Hair dryers and small blowers
- Toy motors, record players / tape recorders
- Advertising displays, humidifiers, vending machines

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

d) E.M.F. equation of alternator

2 M

$$E_{ph} = 4.44 K_p K_d f \Phi T \text{ volts}$$

- E_{ph} = rms emf induced per phase (V)
- K_p = pitch (coil span) factor; K_d = distribution factor
- f = frequency = $PN/120$ (Hz)
- Φ = flux per pole (Wb)
- T = number of turns in series per phase ($= Z_{ph}/2$)

(Equation 1 M, terms 1 M)

e) Pull-out torque

2 M

Pull-out torque: the maximum torque that a synchronous motor can develop at synchronous speed without losing synchronism; it occurs at load angle $\delta = 90^\circ$.

If the load torque exceeds it, the rotor **falls out of step** (loses synchronism), the motor stops (or runs as an induction motor on its damper winding) and draws heavy current — the protection trips it.

(Definition 1 M, effect 1 M)

f) Applications of stepper motor and LIM

2 M

Stepper motor: printers / plotters, CNC and 3-D printers, robotics, disk drives.

Linear induction motor: Linear metro / maglev train propulsion, Conveyors and material handling, Sliding doors, curtain pulling, Pumping of liquid metals, aircraft launchers.

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

g) Conditions for synchronising

2 M

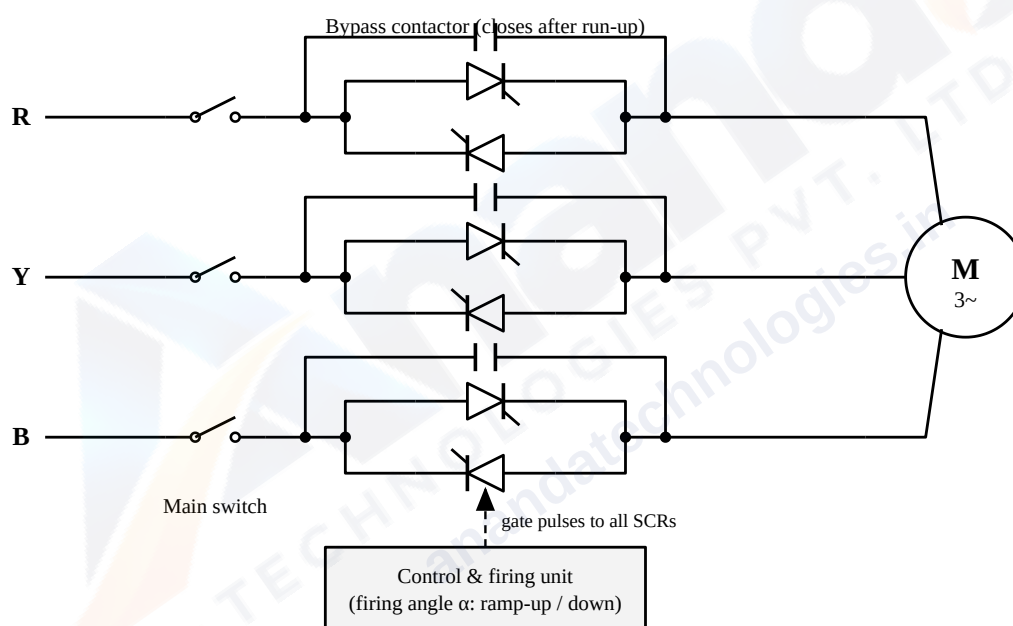
- **Equal voltage:** terminal voltage of incoming alternator = bus-bar voltage.
- **Equal frequency:** frequency of incoming alternator = bus-bar frequency.
- **Same phase sequence** (R-Y-B) as the bus-bars.
- **In phase:** the alternator voltage must be in phase with the bus-bar voltage at the instant of closing the switch (checked by synchroscope / dark lamp method).

($\frac{1}{2}$ M each)

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

a) Soft starter using SCRs and its advantages

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.

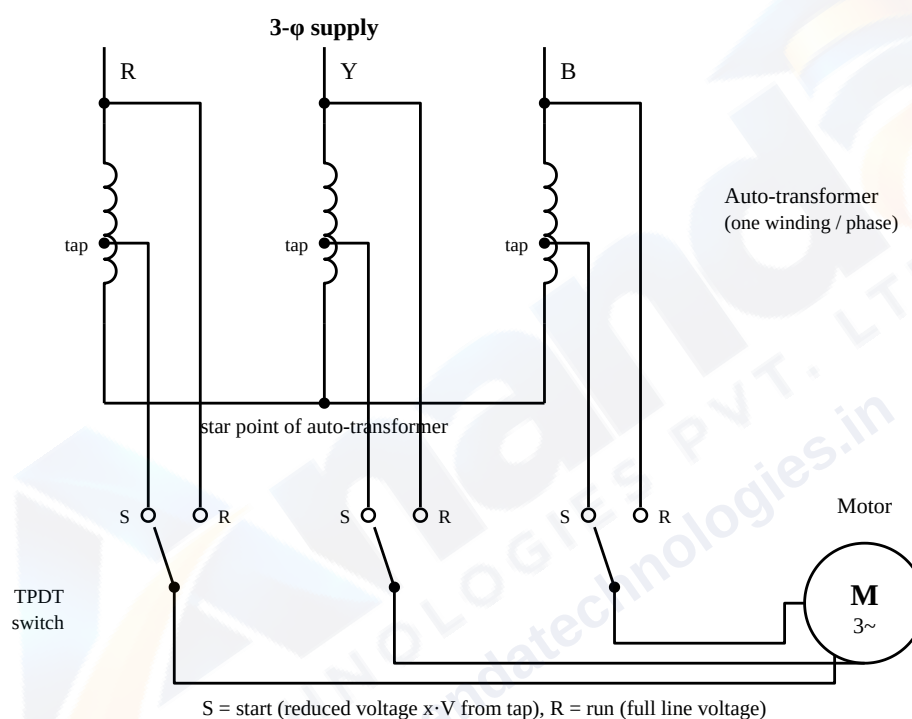
Advantages:

- Smooth, stepless acceleration — no jerks or mechanical shocks to belts, gears and couplings.
- Starting current can be limited to any set value (typically $2-4 \times \text{FL}$); no sudden voltage dip.
- Soft stop facility (prevents water hammer in pumps).
- No transition (open-circuit) current surge as in star–delta; compact, maintenance-free (no moving contacts during start).
- Built-in electronic protections and energy saving at light loads.

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

b) Auto-transformer starter

4 M



Auto-transformer starter (star-connected auto-transformer with tapping x)

1. A 3-φ star-connected auto-transformer with tapplings (50 %, 65 %, 80 %) is used. A TPDT switch connects the motor to the tapping at START and to the line at RUN.
2. At start the motor gets a reduced voltage $x \cdot V$, so motor current = $x \times (\text{DOL current})$, and **supply current = $x^2 \times \text{DOL current}$** .
3. Starting torque = $x^2 \times (\text{DOL starting torque})$.
4. After the motor accelerates (about 80 % speed) the switch is moved to RUN: full voltage is applied and the auto-transformer is cut out.
5. Usable for both star- and delta-connected motors; gives more starting torque per ampere of supply current than a resistance starter.

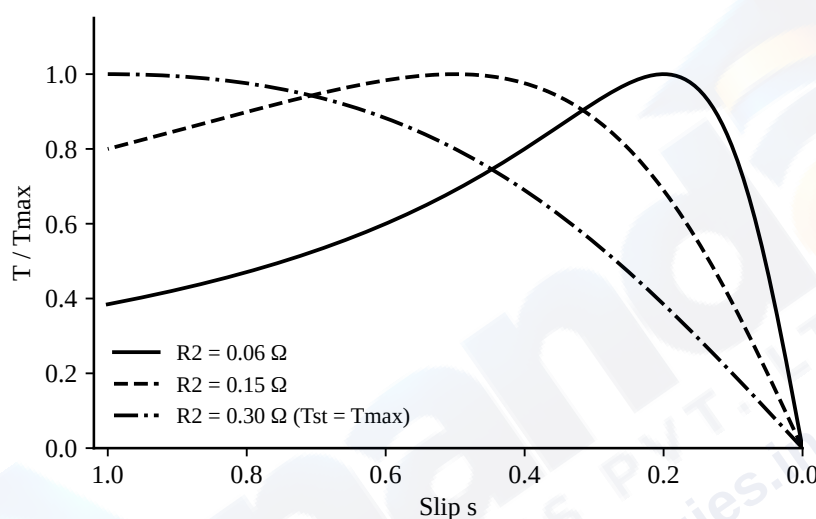
(Diagram 2 M, working 2 M)

c) Speed control by pole changing and rotor resistance

4 M

Speed $N = (120 f / P)(1 - s)$.

- **(i) Pole changing:** Since $N_s = 120f/P$, changing the number of stator poles changes the speed in steps. Methods: (a) **consequent pole method** — the current in half the coils of each phase is reversed by changing external connections, which doubles (or halves) the poles, e.g. 4/8 poles → 1500/750 rpm; (b) **multiple stator windings** — two independent windings with different poles. Used only for squirrel cage motors (cage rotor adapts to any number of poles). Gives two or more fixed speeds, good efficiency.
- **(ii) Rotor resistance control:** used for slip-ring motors. External star-connected rheostat is inserted in the rotor through slip rings. For the same load torque, higher rotor resistance gives a higher slip, so speed decreases (see curves). Simple and smooth below rated speed, high starting torque; but rotor Cu loss = $s P^2$ makes it inefficient at low speed, and speed regulation is poor.

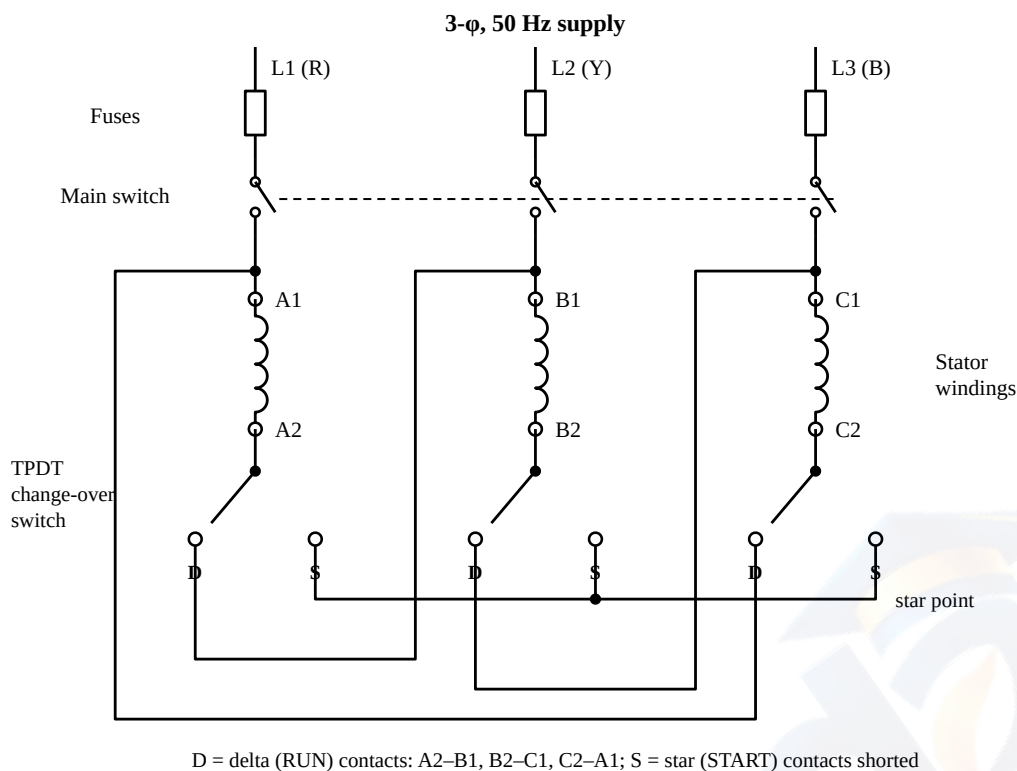


Effect of added rotor resistance on T - s curve (rotor resistance starter / speed control)

(2 M each method)

d) Star–delta starter; why only for delta-run motors

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.

Why only delta-run motors: in the RUN position the starter connects the winding in **delta** to get full voltage per phase. A motor designed for star operation would get $\sqrt{3}$ times its rated phase voltage in delta and would be damaged. Also, all six terminals of the winding must be available.

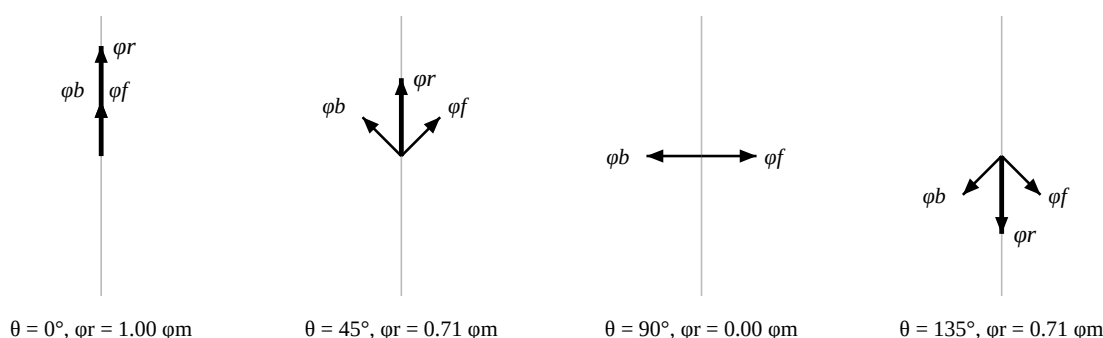
(Diagram 2 M, explanation 2 M)

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

a) Double field revolving theory

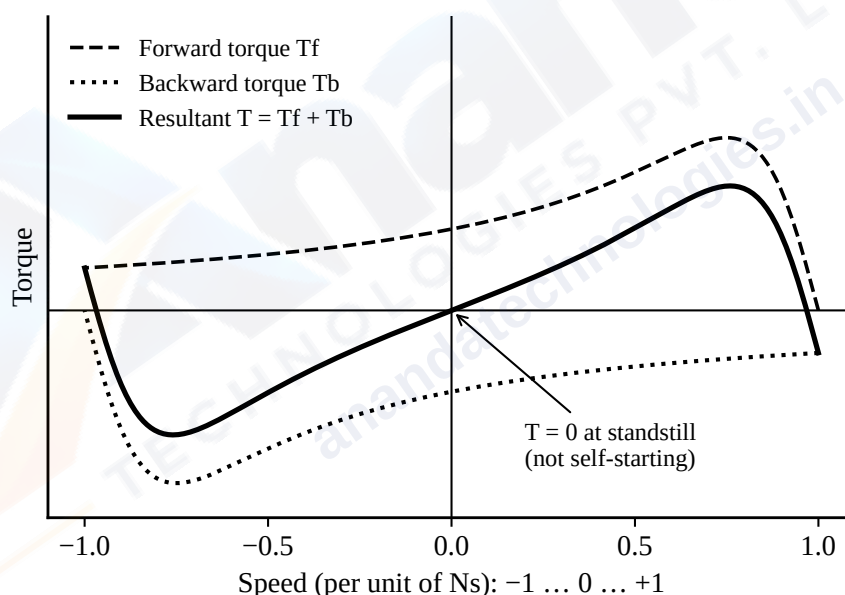
4 M

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



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

- 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.

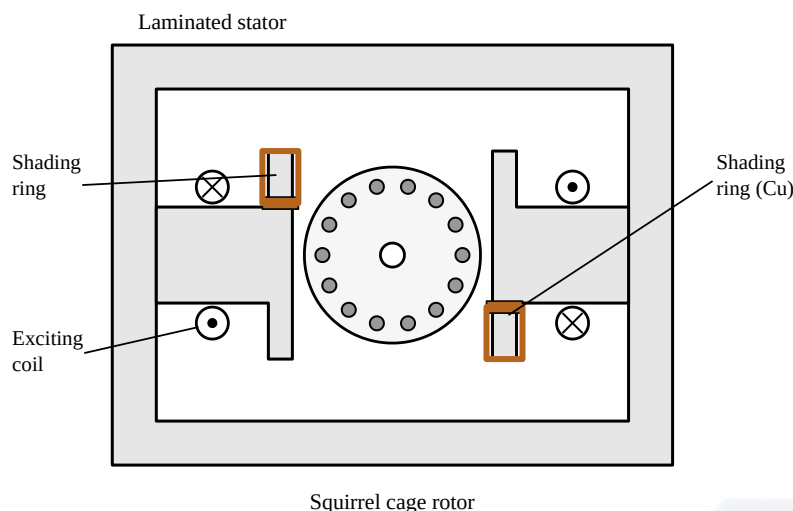


Forward, backward and resultant torque–speed curves (computed); net torque is zero at standstill

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

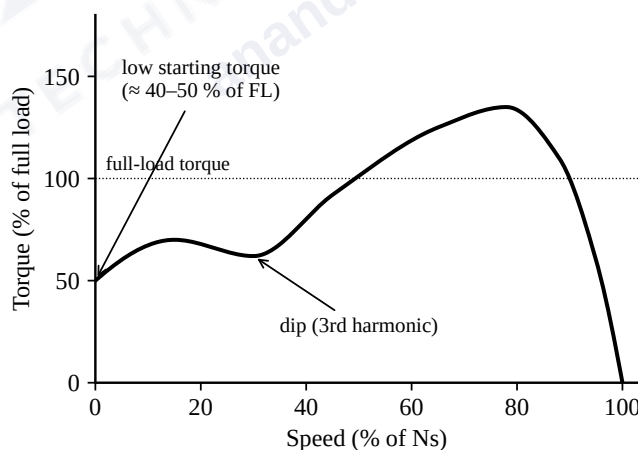
b) Shaded pole motor — construction and working

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.

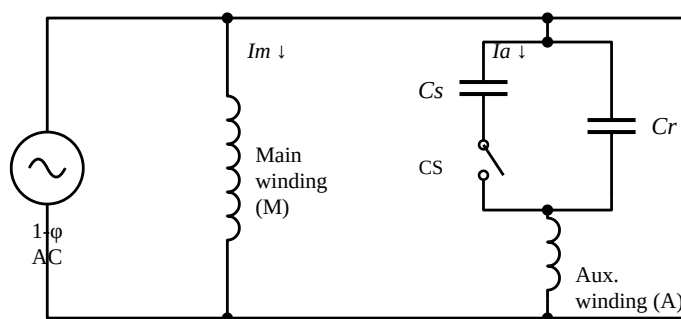


Typical torque–speed characteristic of shaded pole motor

(Sketch 2 M, working 2 M)

c) Capacitor start capacitor run motor

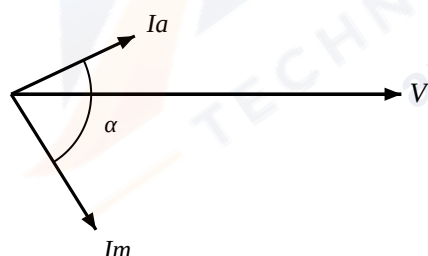
4 M



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

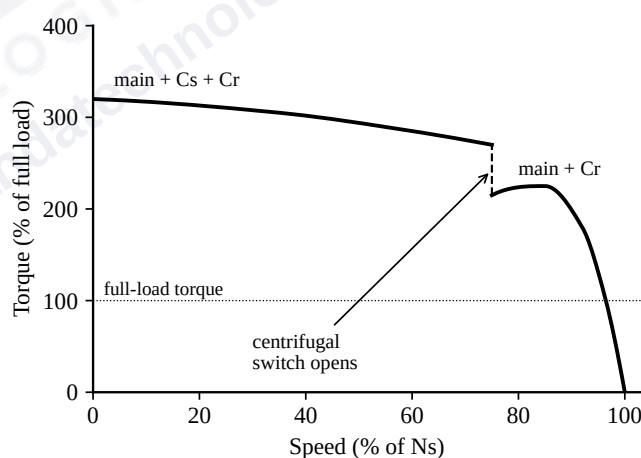
Capacitor-start capacitor-run (two-value capacitor) motor

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° → **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)

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

d) Resistance split-phase vs capacitor start motor

4 M

Point	Resistance split-phase	Capacitor start induction run
Phase splitting by	High resistance of auxiliary winding	Capacitor in series with auxiliary winding

Phase difference α	Small (about 25–30°)	Large (about 80–90°)
Starting torque	Moderate (150–200 % of FL)	High (300–400 % of FL)
Starting current	High	Comparatively low
Cost	Cheaper	Costlier (capacitor)
Applications	Washing machines, fans, grinders, small pumps	Compressors, refrigerators, conveyors, pumps

(Any four points, 1 M each)

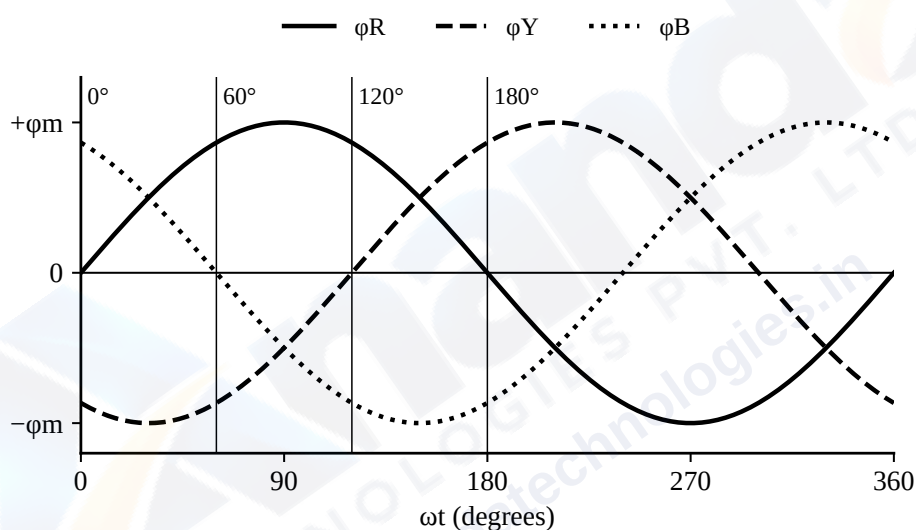
Q.4 Attempt any THREE of the following: (12 M)

a) Production of RMF of constant magnitude

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:

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

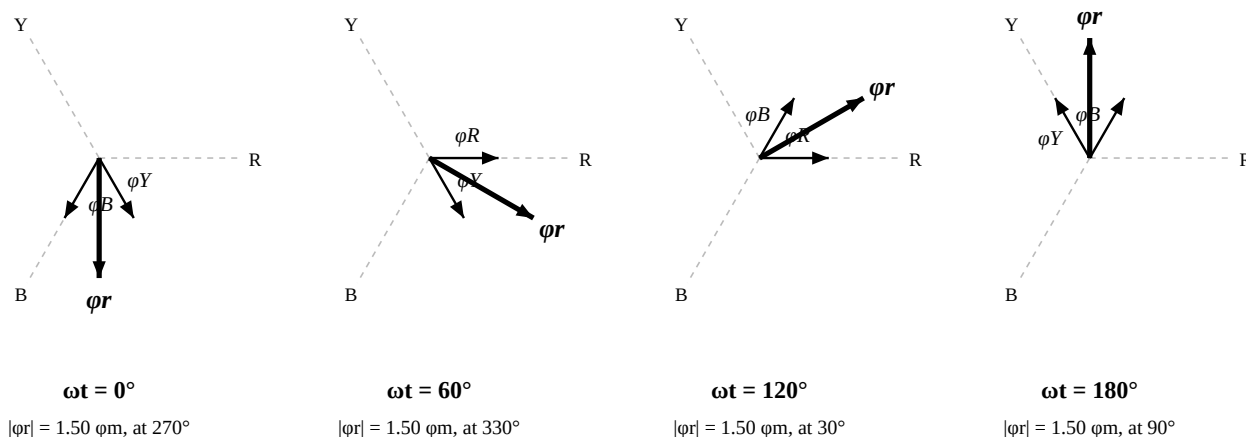


Three-phase fluxes ϕ_R , ϕ_Y , ϕ_B (120° apart) and the instants considered

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

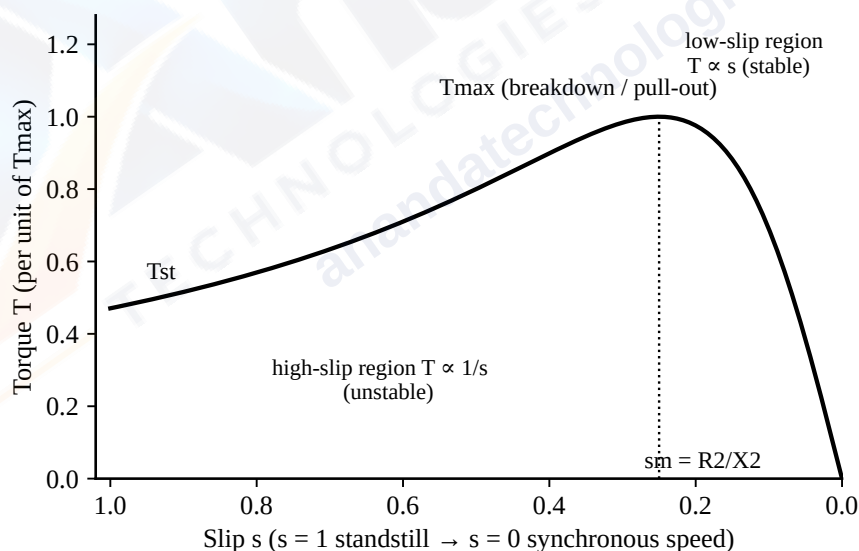
- At every instant the resultant flux has the same magnitude **1.5 ϕ_m** .
- From $\omega t = 0^\circ$ to 180° the resultant has turned through 180° in space; i.e. it turns by the same angle as ωt .
- Hence a **rotating magnetic field of constant magnitude 1.5 ϕ_m** is produced, rotating at synchronous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

(Diagrams 2 M, explanation 2 M)

b) T-s characteristics with effect of rotor resistance

4 M

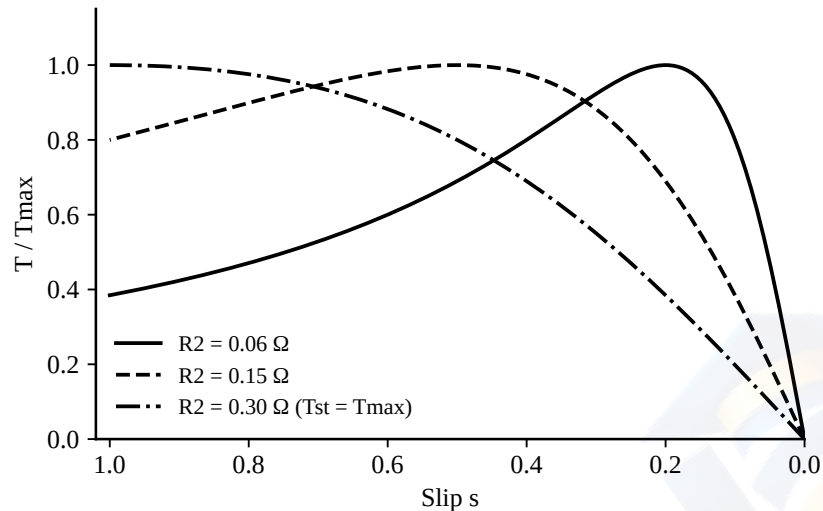
Torque under running condition: $T = k s E^2 R_2 / (R_2^2 + s^2 X_2^2)$.



Torque-slip characteristic of 3- ϕ induction motor

- **Low-slip region** (normal running, $s \approx 0$ to s_m): $sX_2 \ll R_2$, so $T \propto s$ — the curve is almost a straight line. Speed falls slightly as load increases; operation is **stable**.
- **Maximum torque** T_{max} occurs at $s_m = R_2/X_2$; $T_{max} = k E^2/(2X_2)$. T_{max} does not depend on R_2 , but the slip at which it occurs does.

- **High-slip region** ($s > s_m$): $sX_2 \gg R_2$, so $T \propto 1/s$ — a rectangular hyperbola. If load exceeds T_{max} the motor slows down further and stops: **unstable** region.
- **Starting torque** T_{st} is the torque at $s = 1$. Adding rotor resistance (slip-ring motor) raises T_{st} ; $T_{st} = T_{max}$ when $R_2 = X_2$.
- At $s = 0$ ($N = N_s$) torque is zero.



Effect of rotor resistance: T_{max} unchanged, s_m increases, T_{st} increases

Increasing rotor resistance shifts the maximum-torque point towards $s = 1$ without changing T_{max} ; when $R_2 = X_2$ the maximum torque occurs at starting.

(Characteristic 2 M, explanation 2 M)

c) VR stepper numerical

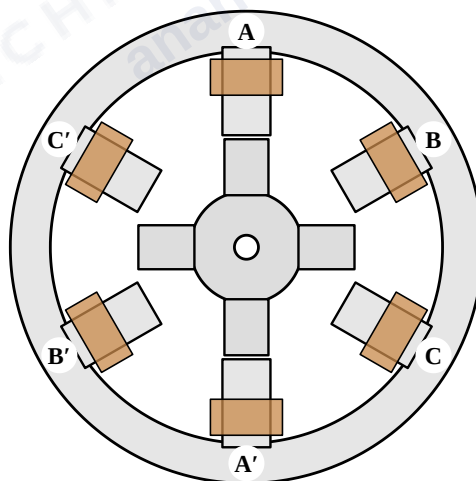
4 M

Given: $N_s = 6$ stator teeth, $N_r = 4$ rotor teeth, $f = 250$ pulses/s

Step angle $\beta = (N_s - N_r)/(N_s \times N_r) \times 360^\circ = (6 - 4)/(6 \times 4) \times 360^\circ = 30.00^\circ$

Steps per revolution = $360^\circ/\beta = 360/30.00 = 12$

Speed $n = \beta \times f / 360^\circ$ (rps) = $30.00 \times 250 / 360 = 20.833$ rps = **1,250.0 rpm**



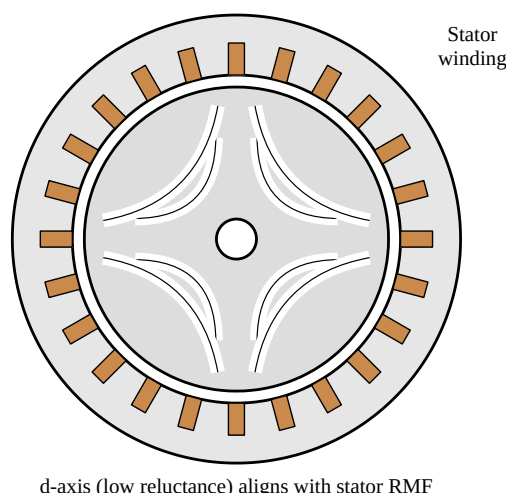
Variable reluctance stepper motor (6 stator poles = 3 phases, 4 rotor teeth)

Answer: $\beta = 30^\circ$; 12 steps/rev ; $N = 1,250$ rpm

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

d) Synchronous reluctance motor

4 M



Synchronous reluctance motor: 3- ϕ stator + rotor with flux barriers (salient reluctance rotor)

- **Stator:** same as a 3- ϕ induction motor — laminated core with a distributed 3- ϕ winding that produces a rotating magnetic field.
- **Rotor:** no field winding and no permanent magnet. It is built with different reluctance along two axes — salient-pole cut-outs or internal **flux barriers** (axially / transversely laminated) — giving a low-reluctance d-axis and a high-reluctance q-axis.
- A squirrel-cage winding may be added for line starting (or the motor is started by a VFD).
- **Working:** the rotor tries to align its low-reluctance axis with the RMF (minimum reluctance position) and produces **reluctance torque**; it runs at **synchronous speed**.
- Advantages: simple, rugged, no rotor copper loss, cooler rotor. Applications: timers, recorders, textile fibre spinning, pumps and fans with VFDs.

(Sketch 2 M, construction and working 2 M)

e) Methods of slip measurement — tachometer and stroboscopic

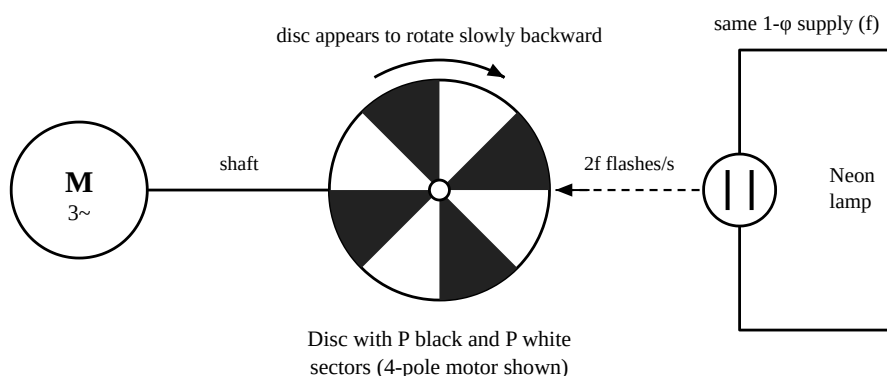
4 M

1. Actual rotor speed measurement (tachometer method)
2. Stroboscopic method
3. Galvanometer method (rotor frequency measurement, slip-ring motor)
4. Search-coil / millivoltmeter method (cage motor)

Actual speed (tachometer) method: Measure rotor speed N with a tachometer (mechanical, digital or non-contact optical). Calculate $N_s = 120f/P$ and $s = (N_s - N)/N_s$. It is simple but not accurate for small slip because a small error in N gives a large error in $(N_s - N)$.

Stroboscopic method:

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 N_s , it would move by exactly one pair of sectors between two flashes and would appear **stationary**.
4. Since $N < N_s$, 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 $N_s - N = n / P$ rpm, and $s = (n / P) / N_s$ (or count apparent backward revolutions n' per minute: $s = n' / N_s$).

(List 1 M, tachometer 1 M, stroboscopic 2 M)

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

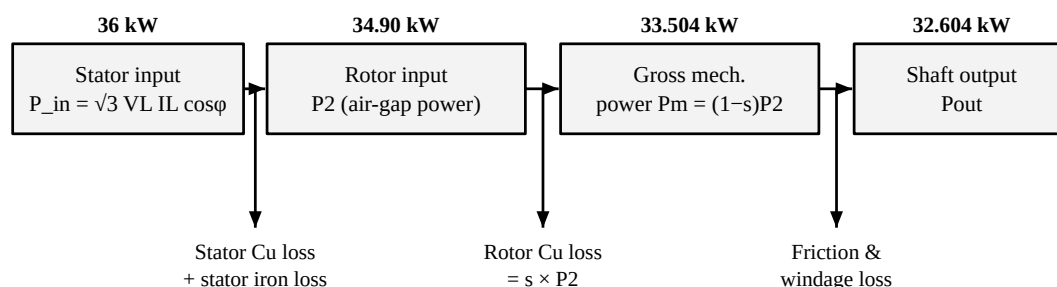
a) Power stages numerical

6 M

Given: $P = 8$, $f = 50$ Hz, $N = 720$ rpm, Stator input = 36 kW, Stator losses = 1.1 kW, Friction & windage loss = 0.9 kW

- 1) **Synchronous speed:** $N_s = 120f / P = 120 \times 50 / 8 = 750$ rpm
 - 2) **Slip:** $s = (N_s - N) / N_s = (750 - 720) / 750 = 0.0400 = 4.00 \%$
 - 3) **Rotor input (air-gap power):** $P_2 = \text{Stator input} - \text{Stator losses} = 36 - 1.1 = 34.90$ kW
 - 4) **Rotor copper loss:** $P_{cu2} = s \times P_2 = 0.0400 \times 34.90 = 1.396$ kW
 - 5) **Gross mechanical power (rotor output):** $P_m = P_2 - P_{cu2} = (1 - s) P_2 = 33.504$ kW
 - 6) **Shaft output:** $P_{out} = P_m - \text{F\&W loss} = 33.504 - 0.9 = 32.604$ kW
 - 7) **Efficiency:** $\eta = P_{out} / P_{in} \times 100 = 32.604 / 36 \times 100 = 90.57 \%$
- Rotor frequency:** $f_r = s f = 0.04 \times 50 = 2.0$ Hz

$$P_2 : \text{Rotor Cu loss} : P_m = 1 : s : (1 - s)$$



$$\text{Efficiency } \eta = P_{out} / P_{in}$$

Power flow for this motor

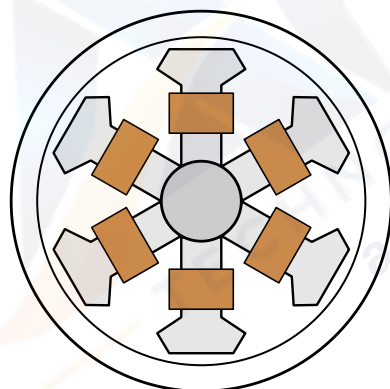
Answer: $s = 0.04$; $f_r = 2.0 \text{ Hz}$; rotor Cu loss = 1.396 kW ; output = 32.604 kW ; $\eta = 90.57 \%$

(Slip 1 M, fr 1 M, Cu loss 1 M, output 1½ M, η 1½ M)

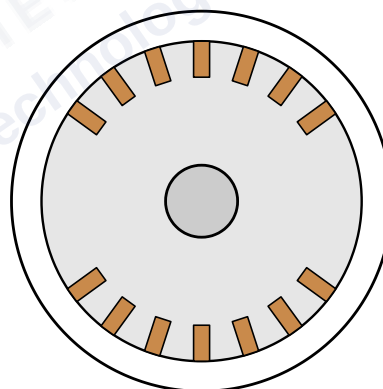
b) Construction of alternator; salient vs cylindrical

6 M

- **Stator (armature):** laminated silicon-steel core with slots carrying a 3- ϕ distributed, star-connected winding; frame of cast iron / fabricated steel.
- **Rotor (field):** carries the field winding excited by DC through two slip rings (or brushless exciter). Two types: salient pole and cylindrical (non-salient).
- **Why rotating field:** only two slip rings are needed for low-voltage DC; the high-voltage armature is stationary — easy insulation, better cooling, more space for conductors, lighter rotor, high-voltage output taken directly without sliding contacts.
- **Excitation systems:** DC exciter (shaft-mounted DC generator), AC exciter with rotating rectifier (brushless), static exciter (thyristor rectifier fed from the generator terminals).



Salient pole rotor (large dia., short length)



Cylindrical rotor (small dia., long length)

Rotor types: salient pole (hydro) and cylindrical / non-salient (turbo)

Point	Turbo alternator (cylindrical rotor)	Hydro alternator (salient pole)
Prime mover	Steam / gas turbine	Water turbine
Speed	High: 1500 / 3000 rpm	Low: 100–1000 rpm
Poles	2 or 4	Large number (e.g. 12 to 60)
Rotor diameter / length	Small diameter, long axial length	Large diameter, short axial length
Air gap	Uniform	Non-uniform

Damper winding	Not needed	Provided
Mounting	Horizontal	Usually vertical
Windage loss, noise	Less (smooth surface)	More

(Construction 3 M, comparison 3 M)

c) Torque numerical and extra rotor resistance

6 M

Given: $P = 6$, $f = 50$ Hz, $R_2 = 0.04 \Omega/\text{ph}$, $X_2 = 0.24 \Omega/\text{ph}$, $E_2 = 80$ V/ph (standstill), $N = 960$ rpm

$N_s = 120f/P = 120 \times 50/6 = 1,000$ rpm; $n_s = 1,000/60 = 16.6667$ rps

Full-load slip $s = (N_s - N)/N_s = (1,000 - 960)/1,000 = \mathbf{0.0400}$

Torque equation (3- ϕ): $T = (3 / 2\pi n_s) \times s E_2^2 R_2 / (R_2^2 + (s X_2)^2)$ N·m; $3/(2\pi n_s) = 0.02865$

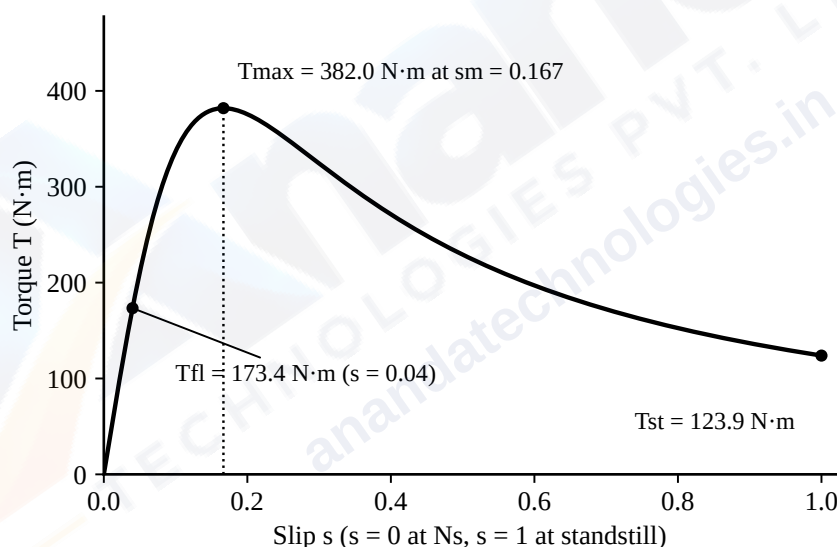
i) Starting torque ($s = 1$): $T_{st} = 0.02865 \times 80^2 \times 0.04 / (0.04^2 + 0.24^2) = \mathbf{123.88 \text{ N}\cdot\text{m}}$

ii) Full-load torque ($s = 0.0400$): $T_{fl} = 0.02865 \times 0.0400 \times 80^2 \times 0.04 / (0.04^2 + (0.0400 \times 0.24)^2) = \mathbf{173.36 \text{ N}\cdot\text{m}}$

iii) Maximum torque: occurs at $s_m = R_2/X_2 = 0.04/0.24 = 0.167$; $T_{max} = (3 / 2\pi n_s) \times E_2^2 / (2 X_2) = 0.02865 \times 80^2 / (2 \times 0.24) = \mathbf{381.97 \text{ N}\cdot\text{m}}$

Speed at maximum torque: $N = N_s (1 - s_m) = 1,000 \times (1 - 0.167) = \mathbf{833.3 \text{ rpm}}$

iv) Extra resistance for T_{max} at starting: T_{max} occurs at $s = 1$ when $(R_2 + r) = X_2 \Rightarrow r = X_2 - R_2 = 0.24 - 0.04 = \mathbf{0.20 \Omega \text{ per phase}}$



Computed torque-slip curve for this motor

Answer: $T_{st} = 123.88 \text{ N}\cdot\text{m}$; $T_{fl} = 173.36 \text{ N}\cdot\text{m}$; $T_{max} = 381.97 \text{ N}\cdot\text{m}$; extra $R = 0.20 \Omega/\text{ph}$

(1½ M each part)

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

a) Voltage regulation with given R_a and X_s

6 M

Given: 1200 kVA, 6600 V, star, $R_a = 0.25 \Omega/\text{ph}$, $X_s = 5 \Omega/\text{ph}$, load $P = 960$ kW

The load current depends on p.f.: $I = P / (\sqrt{3} V_L \cos \phi)$.

Phase voltage $V = 6600/\sqrt{3} = \mathbf{3,810.51 \text{ V}}$

At 0.8 p.f. lagging: $I = P / (\sqrt{3} VL \cos\phi) = 960 \times 10^3 / (\sqrt{3} \times 6600 \times 0.8) = \mathbf{104.97 \text{ A}}$

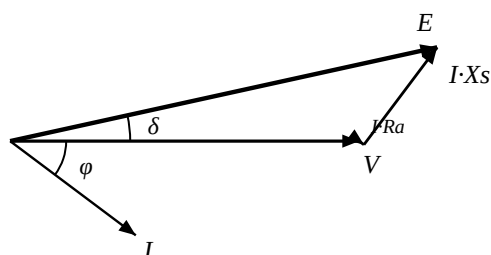
$E = \sqrt{[(V \cos\phi + IR_a)^2 + (V \sin\phi + IX_s)^2]} = \sqrt{[(3,048.41 + 26.24)^2 + (2,286.31 + 524.86)^2]} = \mathbf{4,166.07 \text{ V}}$

% Regulation = $(E - V)/V \times 100 = (4,166.07 - 3,810.51)/3,810.51 \times 100 = \mathbf{9.33 \%}$

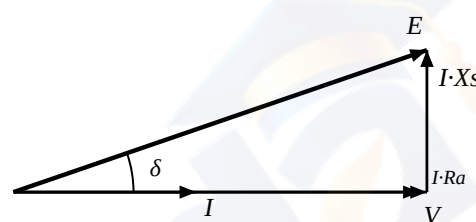
At unity p.f.: $I = P / (\sqrt{3} VL \cos\phi) = 960 \times 10^3 / (\sqrt{3} \times 6600 \times 1.0) = \mathbf{83.98 \text{ A}}$

$E = \sqrt{[(V + IR_a)^2 + (IX_s)^2]} = \sqrt{[(3,810.51 + 20.99)^2 + (419.89)^2]} = \mathbf{3,854.45 \text{ V}}$

% Regulation = $(E - V)/V \times 100 = (3,854.45 - 3,810.51)/3,810.51 \times 100 = \mathbf{1.15 \%}$



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



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

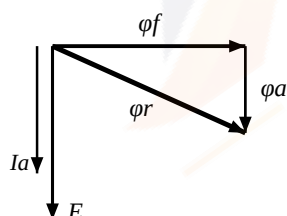
Answer: 0.8 lag: $I = 104.97 \text{ A}$, regulation = 9.33 % ; unity: $I = 83.98 \text{ A}$, regulation = 1.15 %

(3 M each case)

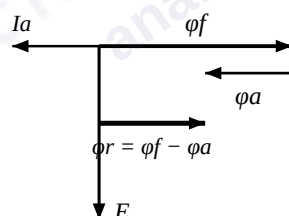
b) Armature reaction with phasors and waveforms

6 M

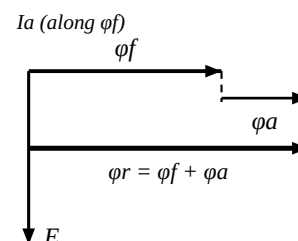
Armature reaction: the effect of the armature (stator) flux, produced by the load current, on the main field flux of the alternator. Its nature depends on the power factor of the load.



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



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

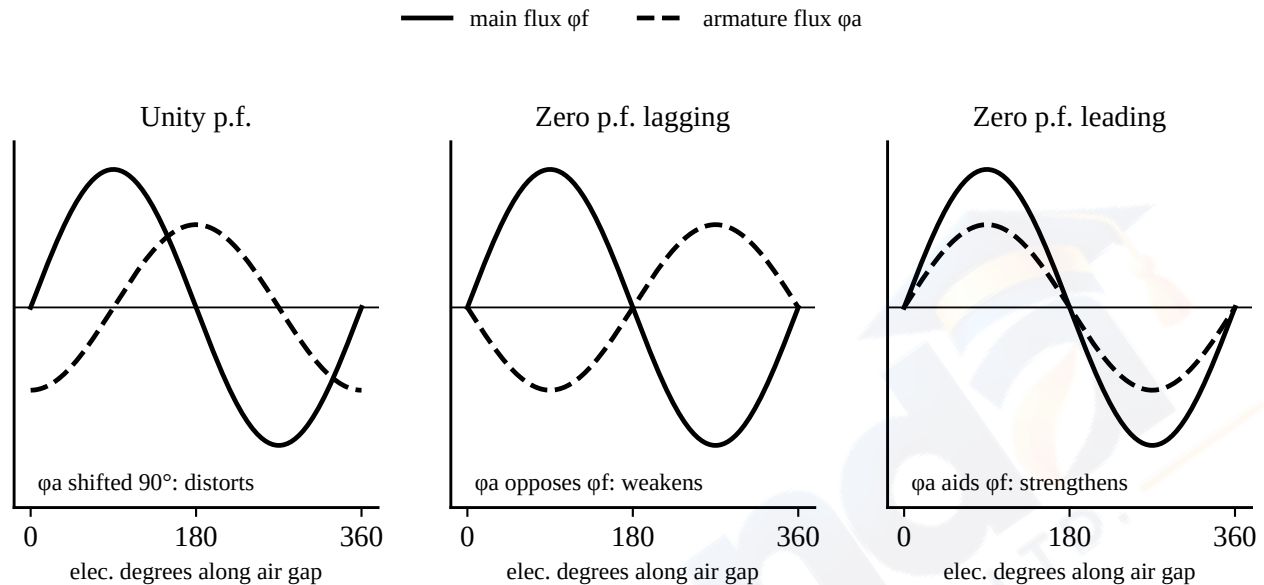


Zero p.f. leading
magnetising
 I_a leads E by 90°

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

- 1. 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.

2. **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.
3. **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.
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.



(Definition 1 M, three cases with phasors and waveforms 5 M)

c) K_p , K_d and e.m.f. numerical

6 M

(i)

Pitch factor (coil span factor) K_p : 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) K_d : 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.

(ii) Full pitch = $90/10 = 9$ slots; coil span 8 slots $\Rightarrow$ short by 1 slot.

Given: $P = 10$, slots = 90, $\Phi = 0.08$ Wb, $N = 600$ rpm, 4 conductors/slot, coil short-pitched by 1 slot(s)

Frequency $f = PN/120 = 10 \times 600/120 = 50$ Hz

Slots per pole = $90/10 = 9$; slot angle $\beta = 180^\circ/9 = 20.00^\circ$

Slots per pole per phase $m = 90/(10 \times 3) = 3$

Pitch factor: coil short by 1 slot $\Rightarrow \alpha = 1 \times 20.00 = 20.00^\circ$; $K_p = \cos(\alpha/2) = \cos(10.00^\circ) = 0.9848$

Distribution factor: $K_d = \sin(m\beta/2) / (m \sin(\beta/2)) = \sin(30.00^\circ) / (3 \times \sin(10.00^\circ)) = 0.9598$

Total conductors $Z = 90 \times 4 = 360$; $Z_{ph} = 360/3 = 120$; turns/phase $T = Z_{ph}/2 = 60$

EMF per phase: $E_{ph} = 4.44 f \Phi T K_p K_d = 4.44 \times 50 \times 0.08 \times 60 \times 0.9848 \times 0.9598 = 1,007.2 \text{ V}$

Line voltage (star): $E_L = \sqrt{3} \times E_{ph} = \sqrt{3} \times 1,007.2 = 1,744.6 \text{ V}$

Answer: $f = 50 \text{ Hz}$; $K_p = 0.9848$; $K_d = 0.9598$; $E_{ph} = 1,007.2 \text{ V}$; $E_L = 1,744.6 \text{ V}$

(Definitions 2 M, numerical 4 M)

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