Electrical Machines

Short notes for B.Tech EE · EEE · GATE EE

Uncodemy Handwritten Notes · free for students

1. Basics of Energy Conversion

- Electrical machine = converts energy between electrical and mechanical form using a **magnetic field**.
- **Generator action**: conductor moves in a field → EMF ($e = B\,l\,v$). Fleming's **right-hand** rule.
- **Motor action**: current-carrying conductor in a field → force ($F = B\,I\,l$). Fleming's **left-hand** rule.
- Every machine has both actions at the same time: a motor produces back EMF, a generator feels a back torque.
- **Transformer** is a static machine (no moving part); its frequency stays the same.

REMEMBER Field energy and co-energy are equal only in a linear (unsaturated) magnetic system.

2. DC Generators

- Parts: yoke, poles, field winding, armature core, armature winding, commutator and brushes.
- Commutator works as a mechanical rectifier: AC inside the armature, DC at the terminals.
- **Lap winding**: $A = P$ (parallel paths = poles), for high current, low voltage.
- **Wave winding**: $A = 2$, for high voltage, low current.

FORMULA EMF equation: $E = P\,\Phi\,Z\,N / (60\,A)$. P = poles, Φ = flux per pole (Wb), Z = total conductors, N = rpm.

EXAMPLE 4-pole lap-wound generator, Z = 500, Φ = 0.02 Wb, N = 1200 rpm. A = 4. E = 4 x 0.02 x 500 x 1200 / (60 x 4) = 48000 / 240 = 200 V. If wave-wound (A = 2), E = 400 V.

➤ Types and equations

Type	Field connection	Key equation
Separately excited	Field from separate source	Eg = V + Ia Ra
Shunt	Field across armature	Ia = IL + Ish
Series	Field in series with load	Ia = IL = Ise
Compound	Both shunt and series fields	Cumulative or differential

- **Self-excitation conditions**: residual magnetism must exist, field winding connected to aid it, field resistance less than critical field resistance, speed above critical speed.
- **Armature reaction**: armature flux distorts and weakens main flux; shifts the magnetic neutral axis. Fix: interpoles, compensating winding.
- **Commutation**: reversal of current in a coil while it is shorted by the brush. Sparking is reduced by interpoles (voltage commutation).

3. DC Motors

FORMULA Back EMF Eb = V - Ia Ra = P Φ Z N / (60 A). So N ∝ Eb / Φ. Torque T ∝ Φ Ia, T = 0.159 P Φ Z Ia / A (N·m).

Motor	Torque vs Ia	Speed	Use
Shunt	T ∝ Ia	Nearly constant	Lathe, fans, pumps
Series	T ∝ Ia^2 (before saturation)	Varies a lot with load	Traction, cranes, hoists
Cumulative compound	Between the two	Drops with load	Rolling mills, presses

EXAM POINT A DC series motor must not be started at no load; Φ is very small, so speed can rise to a dangerous value.

Speed control

- **Flux (field) control**: speed above base speed (weaken field). Constant power region.
- **Armature voltage / resistance control**: speed below base speed. Constant torque region.
- Ward-Leonard system: very smooth, wide range of speed control (old method).

Starters

- At start Eb = 0, so Ia = V / Ra is very high. A starter adds resistance at start.
- **3-point starter**: for shunt motors, has no-volt release and overload release. Problem: field control can drop the hold-on coil current.
- **4-point starter**: hold-on coil connected across supply, so field control does not affect it.

Losses and tests

- Constant losses: iron + friction + windage (+ shunt field copper). Variable loss: armature copper loss.
- Maximum efficiency when variable loss = constant loss.
- **Swinburne's test**: no-load test, finds constant losses (not for series motors). **Hopkinson's test**: back-to-back test on two identical machines.

EXAMPLE Shunt motor, 220 V, Ra = 0.5 Ω, takes Ia = 20 A at 1000 rpm. Eb1 = 220 - 10 = 210 V. Load raises Ia to 40 A (flux same): Eb2 = 220 - 20 = 200 V. N2 = 1000 x 200/210 = 952 rpm.

4. Single-Phase Transformer

FORMULA E1 = 4.44 f N1 Φm, E2 = 4.44 f N2 Φm. K = N2/N1 = E2/E1 = I1/I2.

- **Ideal transformer**: no losses, no leakage flux, infinite permeability.
- No-load current I0 is small (a few % of rated). It has two parts: Iw (core loss) and Iμ (magnetising). No-load pf is very low.
- Referring impedance from secondary to primary: Z' = Z / K^2.

Tests

Test	Done on	Other side	Gives
Open-circuit (OC)	LV side	HV open	Core loss, R0, X0
Short-circuit (SC)	HV side	LV shorted	Full-load copper loss, Req, Xeq

- In OC test the wattmeter reads iron loss (copper loss negligible). In SC test it reads copper loss (flux small, iron loss negligible).

Voltage regulation

FORMULA % Regulation = (E2 - V2) / V2 x 100 ≈ (I R cos ϕ ± I X sin ϕ) / V x 100. Use + for lagging pf, - for leading pf.

- Regulation can be **negative** at leading pf. Zero regulation occurs at a leading pf where tan ϕ = R / X.

Efficiency

FORMULA η = x S cos ϕ / (x S cos ϕ + Pi + x^2 Pcu), where x = fraction of full load. Max η at x = sqrt(Pi / Pcu,FL).

EXAMPLE 20 kVA transformer, iron loss 200 W, full-load copper loss 500 W, pf 0.8. Full-load η = 16000 / (16000 + 700) = 95.8%. Max η at x = sqrt(200/500) = 0.632, i.e. at 12.65 kVA. Then output = 10.12 kW, losses = 400 W, η = 10120/10520 = 96.2%.

- **All-day efficiency** = energy output in 24 h / energy input in 24 h. Important for distribution transformers (energised all day, lightly loaded), so they are designed with low iron loss.

5. Three-Phase Transformers and Autotransformer

- Connections: Y-y, D-d, Y-d, D-y. Vector group shows phase shift, e.g. Dyn11 (secondary leads by 30°), Yd1 (lags by 30°).

- **Dy** is common for distribution (neutral on LV side). **Yd** is common for step-down at the generating / transmission end.
- **Open delta (V-V)**: two transformers supply a 3-phase load. Capacity = 57.7% of the D-D bank (1/√3).
- **Scott connection**: 3-phase to 2-phase conversion.

➤ Parallel operation conditions

1. Same voltage ratio (else circulating current).
2. Same polarity.
3. Same per-unit impedance (for load sharing in kVA ratio).
4. Same X/R ratio (for same pf).
5. For 3-phase: same phase sequence and same phase shift (same vector group).

➤ Autotransformer

- Single winding, part common to primary and secondary.
- Copper saving = K x (copper of two-winding transformer), where K = V2/V1 (step-down).
- Cheaper and more efficient, but no electrical isolation. Used for motor starting and for interconnecting nearby voltages.

6. Three-Phase Induction Motor

- Stator supply creates a **rotating magnetic field** at Ns = 120 f / P.
- **Squirrel cage** rotor: bars shorted by end rings, rugged, cheap. **Slip ring** (wound) rotor: external resistance can be added.

FORMULA Slip s = (Ns - N)/Ns. Rotor frequency f2 = s f. Rotor EMF at slip s = s E2.

FORMULA Power flow: Pg (air-gap) : Pcu2 (rotor copper) : Pm (mechanical) = 1 : s : (1 - s).

EXAMPLE 4-pole, 50 Hz motor, slip 4%. Ns = 1500 rpm, N = 1440 rpm, f2 = 0.04 x 50 = 2 Hz. If Pg = 10 kW: rotor copper loss = 400 W, gross mechanical power = 9.6 kW.

Torque-slip

- $T \propto s\ E2^2\ R2 / (R2^2 + (s\ X2)^2)$.
- **Max torque** at $s = R2 / X2$. $T_{max} \propto E2^2 / (2\ X2)$, independent of R2.
- Max torque at start ($s = 1$) when $R2 = X2$ (slip ring motor with added resistance).
- Low slip: $T \propto s$ (linear). High slip: $T \propto 1/s$.
- $T \propto V^2$, so a 10% voltage drop reduces torque by about 19%.

Starting methods

Method	Starting current	Starting torque	Note
DOL	5–7 x rated	Full	Small motors
Star-delta	1/3 of DOL	1/3 of DOL	Motor must be delta in run
Autotransformer (tap x)	x^2 of DOL	x^2 of DOL	Large motors
Rotor resistance	Low	High	Slip ring motors only

- **Tests**: no-load (core + friction losses), blocked-rotor (copper loss, equivalent impedance). Circle diagram drawn from these.
- **Cogging**: motor fails to start (stator and rotor slots lock). **Crawling**: runs at about 1/7 of Ns due to 7th harmonic. Fix: skewed rotor slots.
- Speed control: V/f control (most used now with VFD), pole changing, rotor resistance, slip power recovery.

7. Single-Phase Induction Motors

- Single winding gives a pulsating field, not a rotating one → not self-starting.
- **Double revolving field theory**: pulsating field = two equal fields rotating in opposite directions. At start the two torques cancel.

Type	Starting torque	Use
Split phase	Low–moderate	Fans, blowers, washing machines
Capacitor start	High	Compressors, pumps
Capacitor start-capacitor run	High, quiet running	Refrigerators, ACs
Permanent split capacitor	Low	Ceiling fans
Shaded pole	Very low	Table fans, small loads

8. Synchronous Generator (Alternator)

- Field on rotor (DC), armature on stator. Runs at exactly $N_s = 120 f / P$.
- **Salient pole**: many poles, low speed, large diameter (hydro). **Cylindrical (non-salient)**: 2 or 4 poles, high speed, long rotor (steam / gas turbines).

FORMULA EMF per phase $E = 4.44 f \Phi T K_p K_d$. $K_p = \cos(\alpha/2)$ (pitch factor), $K_d = \sin(m\beta/2) / (m \sin(\beta/2))$ (distribution factor).

- **Voltage regulation** methods: synchronous impedance (EMF, pessimistic), MMF (optimistic), ZPF (Potier), ASA.
- **Short circuit ratio (SCR)** = 1 / Xs (per unit). High SCR → better stability, better regulation, bigger and costlier machine.
- Output power: $P = (E V / X_s) \sin \delta$. Maximum at $\delta = 90°$ (cylindrical rotor).
- **Synchronisation conditions** (parallel with grid): same voltage, same frequency, same phase sequence, in phase. Checked by synchroscope or lamp method.

9. Synchronous Motor

- Not self-starting: rotor cannot follow the field instantly. Started with damper windings (as an induction motor) or a pony motor.
- Runs only at synchronous speed. Stops if load torque exceeds the pull-out torque.
- **V-curves**: armature current vs field current at constant load. Under-excited → lagging pf, over-excited → leading pf.
- **Synchronous condenser**: over-excited motor at no load, used to improve pf / control voltage.
- **Hunting**: oscillation of rotor about its steady position after sudden load change. Damper winding reduces it.

Point	Induction motor	Synchronous motor
Speed	Less than Ns	Exactly Ns
Self-starting	Yes	No
Power factor	Always lagging	Can be lagging, unity or leading
Excitation	Not needed	DC excitation needed

10. Most Asked Questions (practice)

1. Derive the EMF equation of a DC generator and solve a numerical.
2. Explain armature reaction and commutation. How are they reduced?
3. Compare speed control methods of DC shunt motors. Why is a starter needed?
4. Derive the EMF equation of a transformer. Draw its equivalent circuit and phasor diagram.
5. Explain OC and SC tests. Find regulation and efficiency from test data.
6. Condition for maximum efficiency of a transformer. What is all-day efficiency?
7. Derive the torque equation of an induction motor and the condition for maximum torque.
8. Explain star-delta starting. Why is a single-phase induction motor not self-starting?
9. Explain the synchronous impedance method of finding alternator regulation.
10. What are V-curves? Explain the synchronous condenser and hunting.

TIP In GATE EE, machines numericals come mostly from transformer efficiency/regulation, induction motor slip and power flow, DC motor speed and alternator P-δ. Practise the per-unit and ratio method for quick answers.