What Are Electrical Machines? Definition, Classification, and Their Role in the Power System

1 What is an Electrical Machine?

An electrical machine is a device that converts energy between electrical and non-electrical domains, or between different electrical forms. In practice:

- Motors: electrical $\rightarrow$ mechanical
- Generators: mechanical $\rightarrow$ electrical
- Transformers: electrical (AC) $\rightarrow$ electrical (AC), different voltage/current levels

2 Fundamental Laws

Electrical machines rely on Faraday's law of induction and electromagnetic force/torque relations:

$$e = -N\frac{d\phi}{dt}, \tag{1}$$

$$E_{\mathrm{rms}} = 4.44 f N \phi, \tag{2}$$

$$P = T\omega. \tag{3}$$

3 Classification

3.1 By Energy Conversion

- Motors: induction, synchronous, DC, BLDC/PMSM
- Generators: synchronous, induction
- Transformers: power, instrument, special (auto-, phase-shifting, etc.)

3.2 By Construction

- Rotating machines (motors/generators)
- Static machines (transformers)

3.3 By Excitation / Commutation

- DC machines (commutator/brush)
- AC machines: synchronous, induction

4 Power System Placement

4.1 Generation

Synchronous generators dominate large power plants. Step-up transformers raise voltage for transmission.

4.2 Transmission

Power transformers in substations. Synchronous condensers may appear for VAR support.

4.3 Distribution

Distribution transformers, tap-changing regulation equipment.

4.4 Loads

Induction motors are the bulk of industrial loads. Synchronous motors and PMSMs appear where power factor or efficiency is critical.

4.5 Renewables and Storage

DFIGs and full-converter PM machines in wind; synchronous machines in hydro and pumped storage.

5 Key Ratings and Performance Metrics

Rated apparent power S_{rated}, voltage/current, frequency f, poles p, efficiency η, power factor $\cos\phi$, temperature rise and insulation class, short-circuit impedance.

6 Modeling Snippets

$$n_s = \frac{120f}{p} \quad \text{(r/min)}, \tag{4}$$

$$s = \frac{n_s - n_r}{n_s}, \tag{5}$$

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}, \tag{6}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{loss}}}. \tag{7}$$

7 Worked Problems

7.1 Beginner

A 3-phase induction motor delivers $P_{\text{out}} = 18\,\text{kW}$ at $\eta = 0.9$ and $\cos\phi = 0.85$. Find S_{in}.

Solution.

$$P_{\text{in}} = \frac{18}{0.9} = 20\,\text{kW}, \tag{8}$$

$$S_{\text{in}} = \frac{20}{0.85} \approx 23.53\,\text{kVA}. \tag{9}$$

7.2 Intermediate

A 4-pole, 60 Hz induction motor runs at $1750\,\text{r/min}$. Find n_s, slip s, and rotor frequency f_r.

Solution.

$$n_s = \frac{120 \times 60}{4} = 1800\,\text{r/min}, \tag{10}$$

$$s = \frac{1800 - 1750}{1800} \approx 0.0278, \tag{11}$$

$$f_r = sf \approx 1.67 \text{ Hz}. \tag{12}$$

7.3 Advanced

A 50 Hz synchronous generator delivers $S = 50\,\text{MVA}$ at $\cos\phi = 0.9$ (lag). Losses are 2% of P_{out}. Speed $n = 3000\,\text{r/min}$. Compute mechanical input power and torque.

Solution.

$$P_{\text{out}} = 50 \times 0.9 = 45\,\text{MW}, \tag{13}$$

$$P_{\text{loss}} = 0.02 \times 45 = 0.9\,\text{MW}, \tag{14}$$

$$P_{\text{in, mech}} = 45 + 0.9 = 45.9\,\text{MW}, \tag{15}$$

$$\omega = \frac{2\pi n}{60} = 314.159\,\text{rad/s}, \tag{16}$$

$$T = \frac{45.9 \times 10^6}{314.159} \approx 1.461 \times 10^5\,\text{N} \cdot \text{m}. \tag{17}$$

8 Glossary

f: frequency, p: poles, n_s: synchronous speed, n_r: rotor speed, s: slip, S, P, Q: apparent/real/reactive power, η: efficiency, $\cos\phi$: power factor, ω: angular speed, T: torque, ϕ: flux.

9 Common Mistakes

Ignoring power factor, confusing induction vs synchronous, forgetting rotor frequency $f_r = sf$, treating transformers as lossless in regulation/short-circuit studies.