Synchronous Machines

1. Synchronous Generators

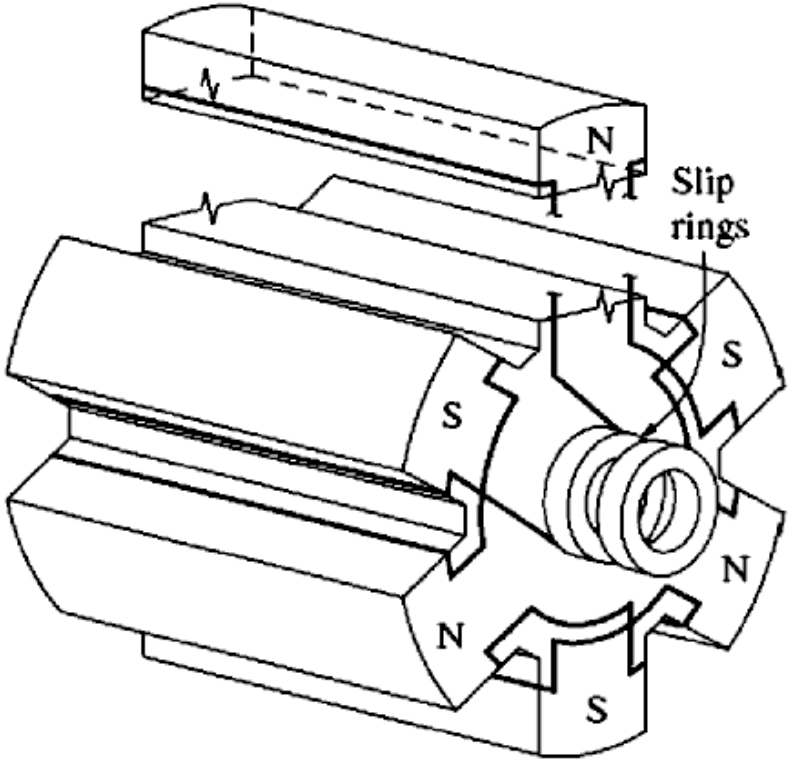
- Principle of Operation
- Phasor Diagram and Equivalent Circuit
- Power and Torque
- Synchronous Generator Characteristics & Tests
- Generator Modes of Operation
- Generator Stability
- Generator Rating
- Practical Generator

Synchronous Machines

1. Synchronous Generators

Synchronous Machines

Salient Pole Machine

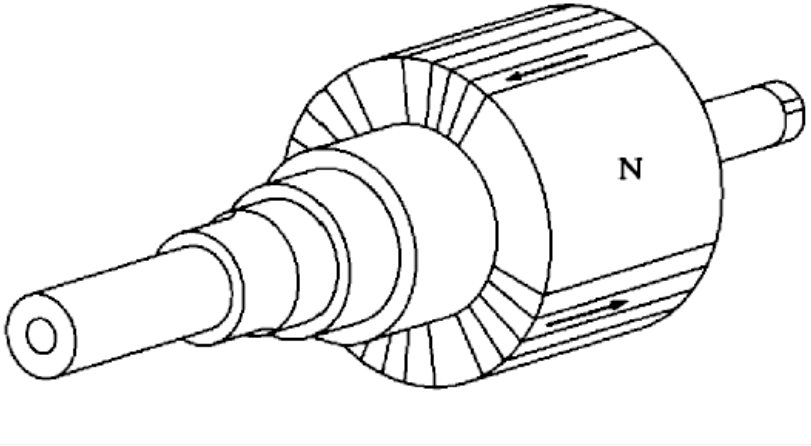


Synchronous Machines

Hydro-Turbines

Synchronous Machines

Cylindrical (Turbo) Machine



Synchronous Machines

Steam-turbines

Synchronous Machines

Salient Poles

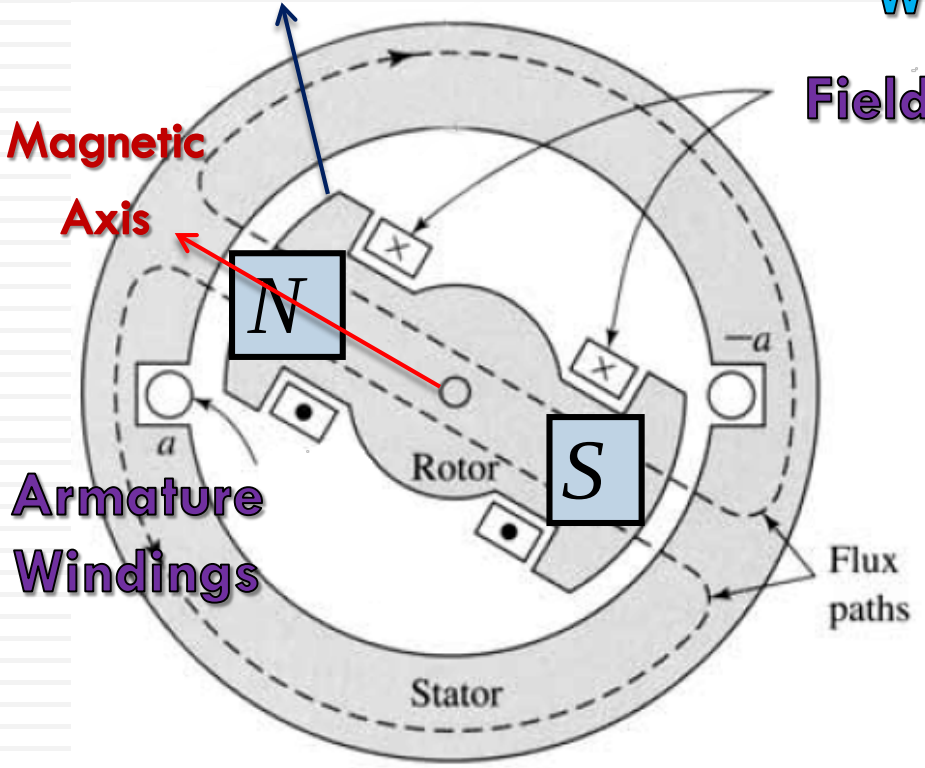
Concentrated Windings

Field Windings

Pole Arc

Magnetic Axis

Two Magnetic Poles

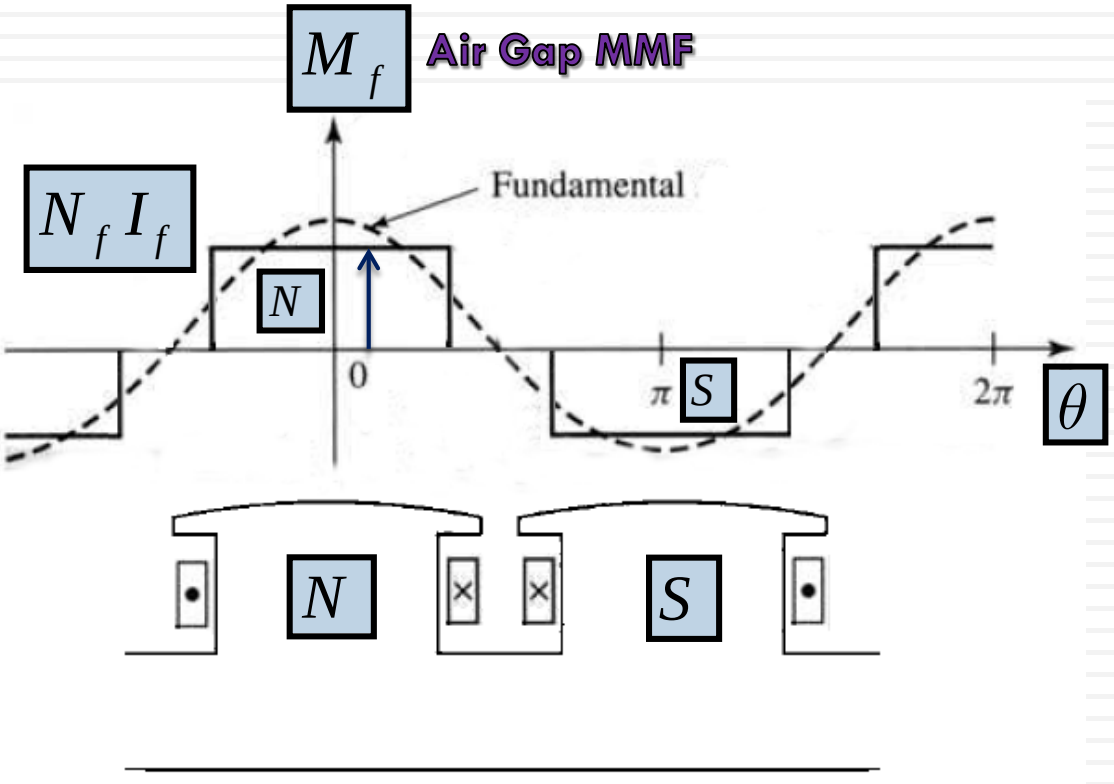


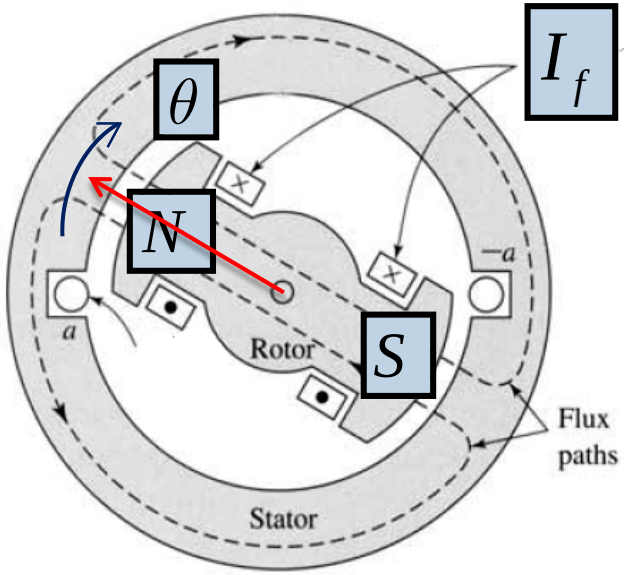
Armature Windings

Salient Poles

Synchronous Machines: Field Distribution

Salient Poles

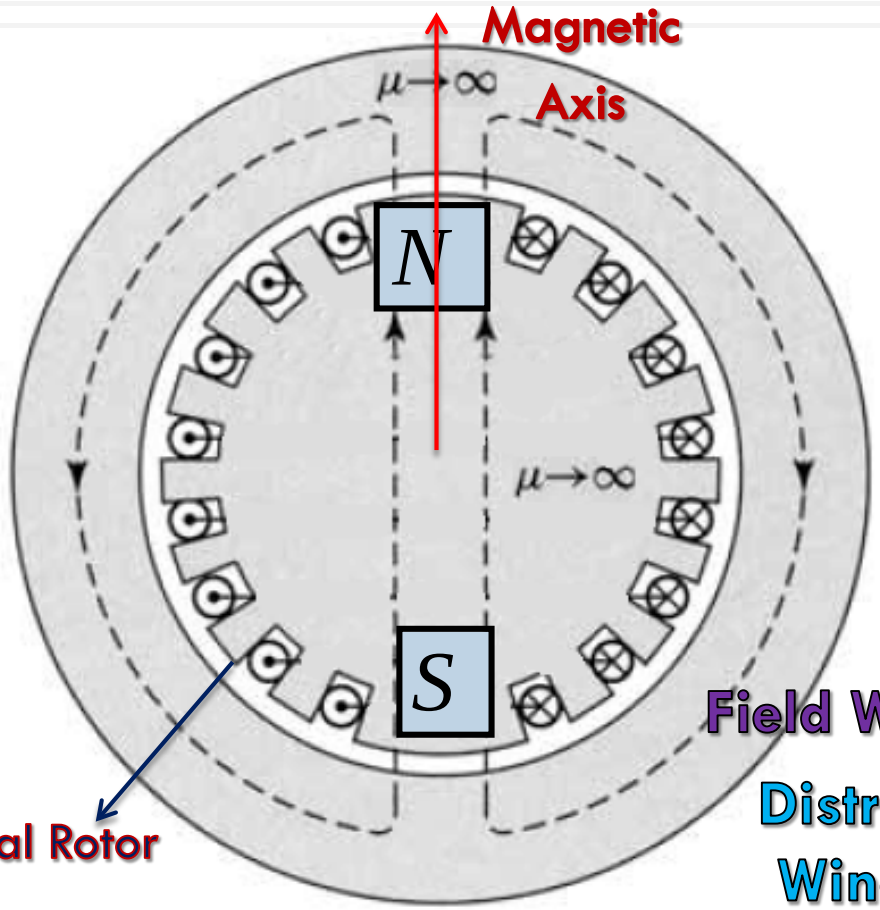




I_f **DC Current** → M_f **Stationary Field**

Synchronous Machines

Non-salient poles



Two Magnetic Poles

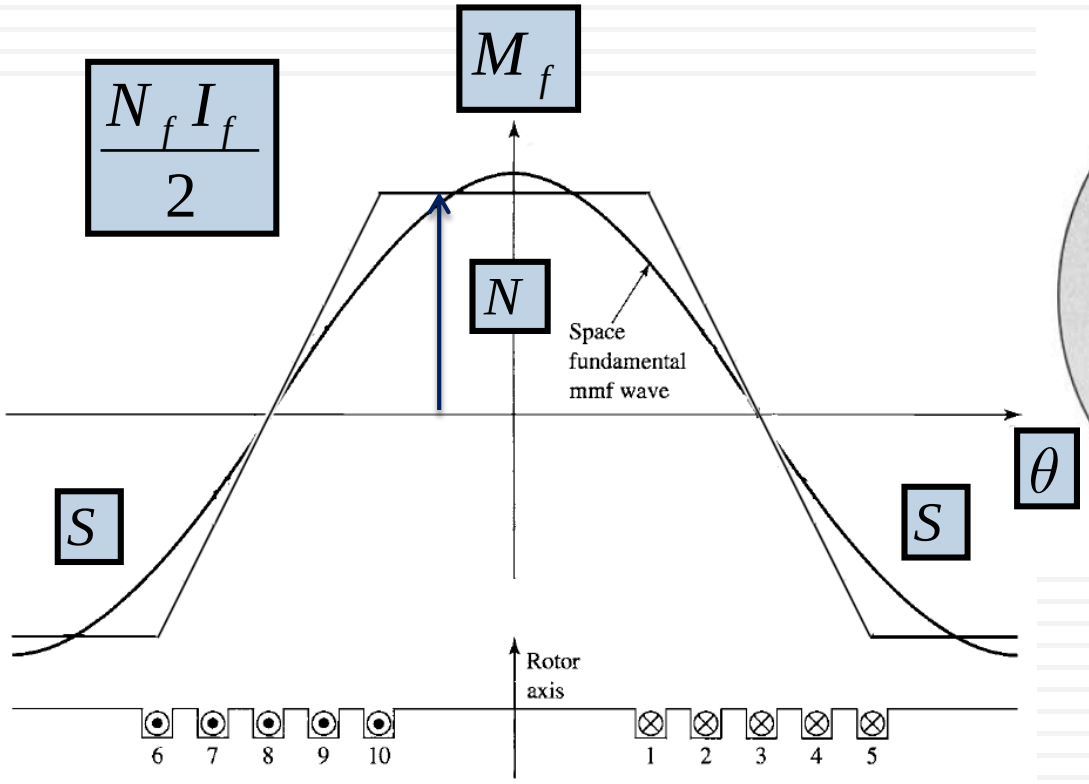
Non-Salient Poles

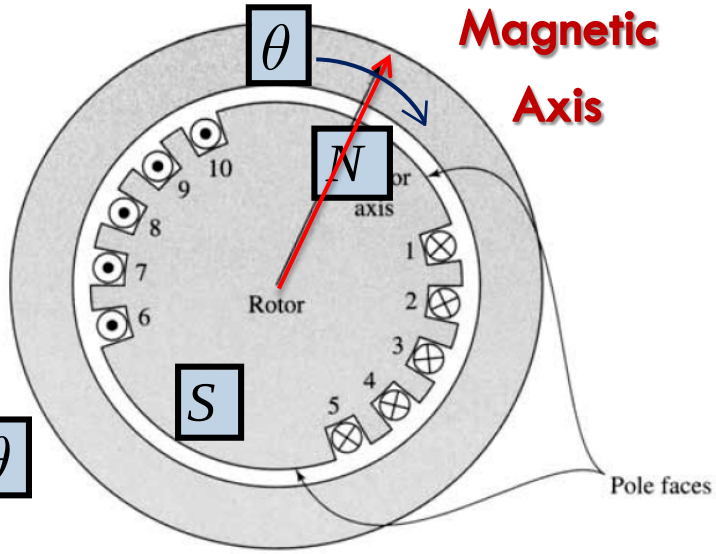
Field Windings

Distributed Windings

Synchronous Machines: Field Distribution

Non-salient poles





Synchronous Machines: Generated EMF

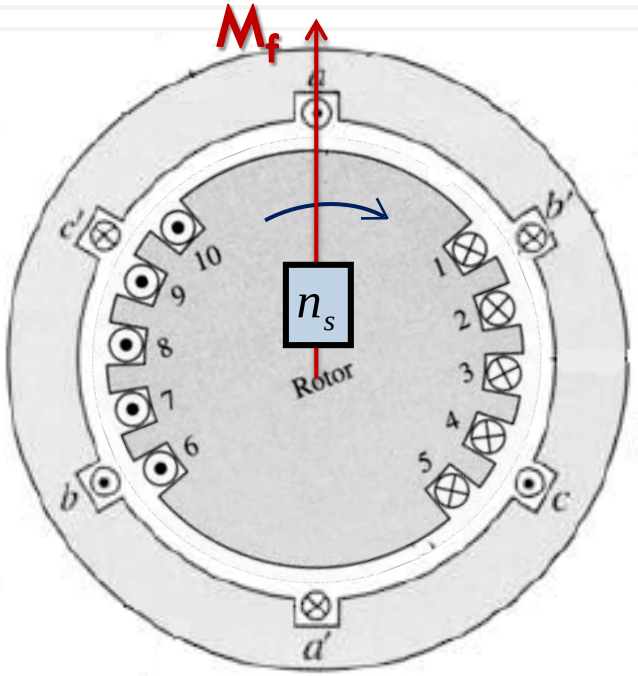
For the fundamental:

$$E_{1phase} = 4.44 f \, \phi_1 N_{ph} \frac{k_{w1}}{m}$$

For Space Harmonics:

$$\frac{E_h}{E_1} = \frac{B_h k_{wh}}{B_1 k_{w1}}$$

$$E_{phase} = \sqrt{E_1^2 + E_3^2 + E_5^2 + \ldots}$$



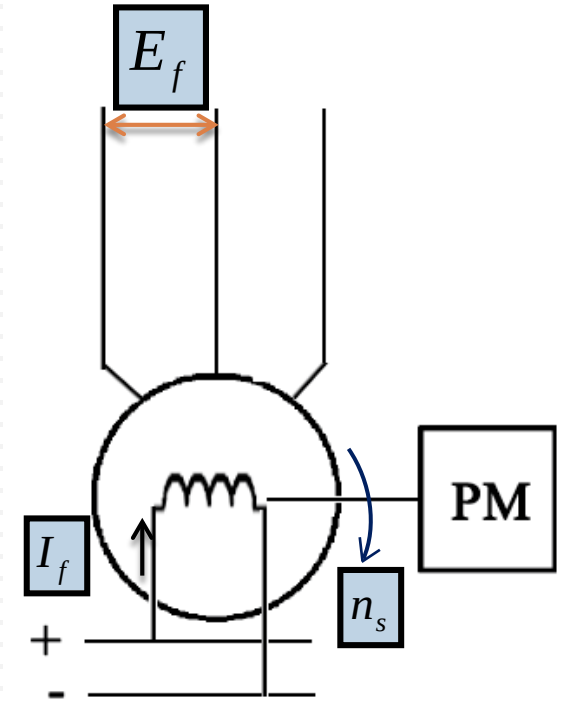
$$f = \frac{pn_s}{60}$$

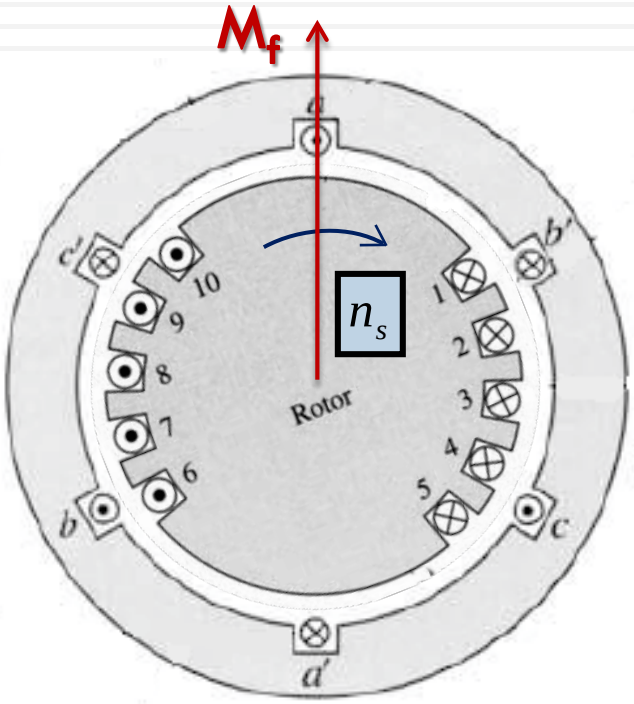
Synchronous Generator: Phasor Diagram

Open Circuit Condition

$$E_f = 4.44 f \phi_1 N_{ph} \frac{k_{w1}}{m}$$

Open Circuit Voltage

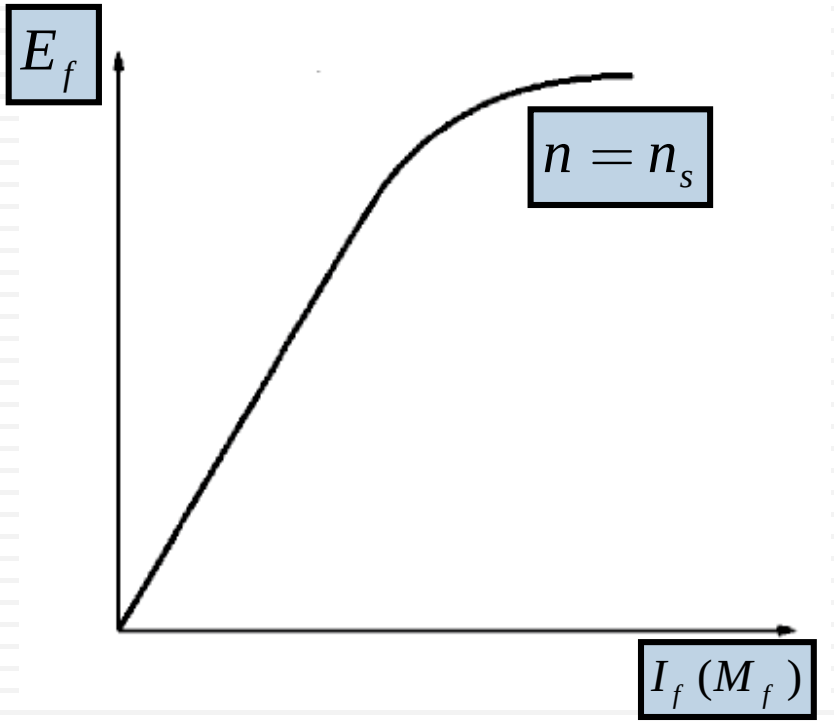


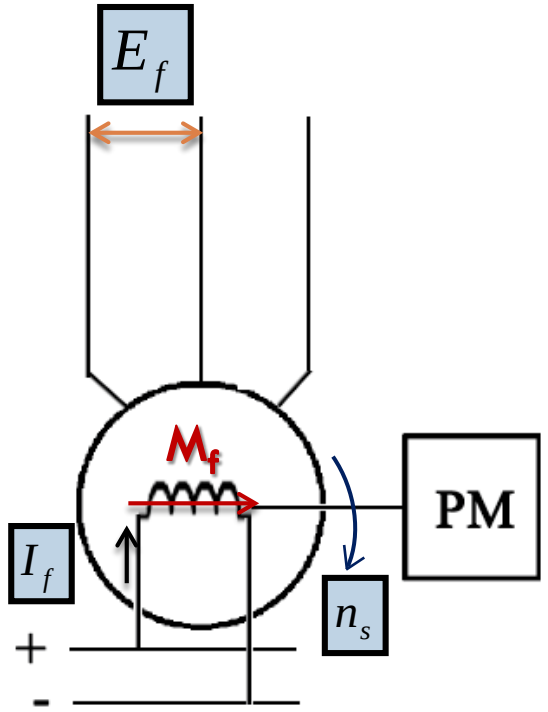


Synchronous Generator: Phasor Diagram

Open Circuit Condition

$$E_f = 4.44 f \phi_1 N_{ph} \frac{k_{w1}}{m}$$



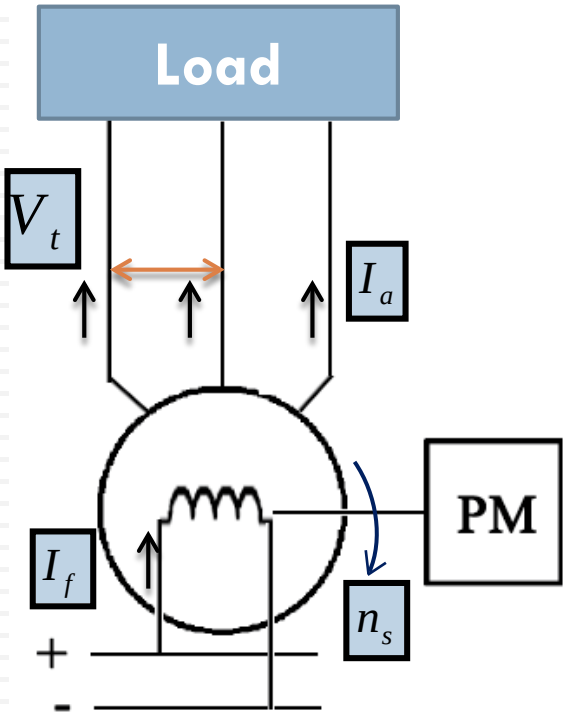


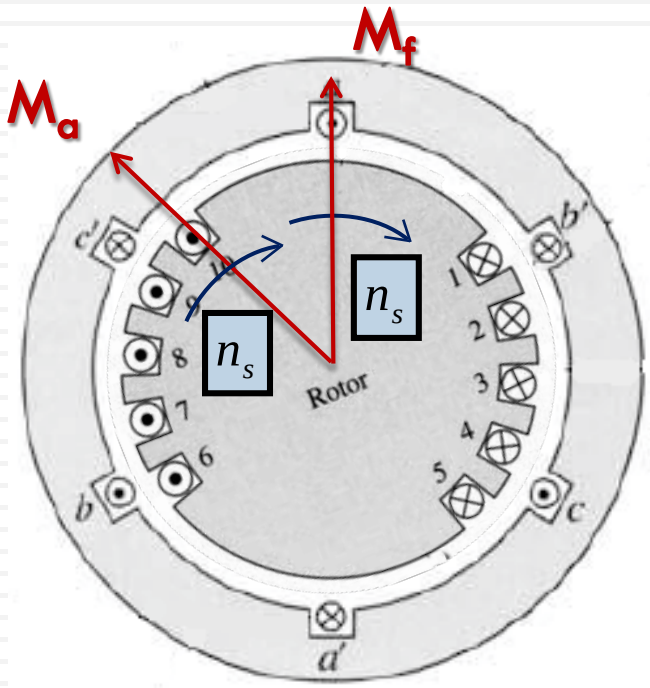
$M_f \rightarrow E_f$

Synchronous Generator: Phasor Diagram

Loading Conditions

M_a = armature reaction



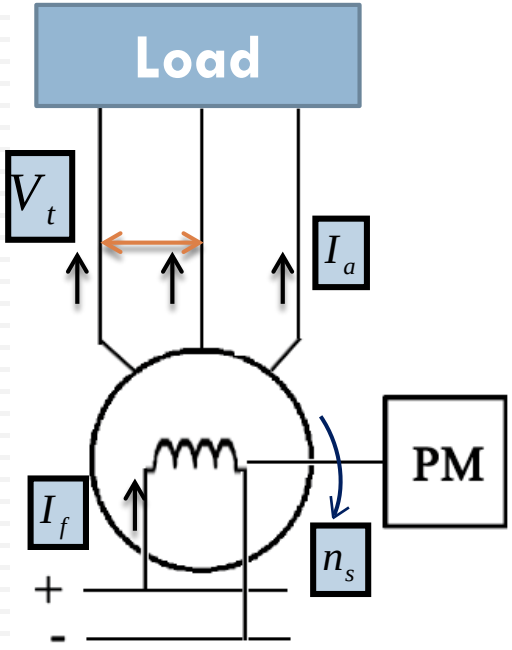


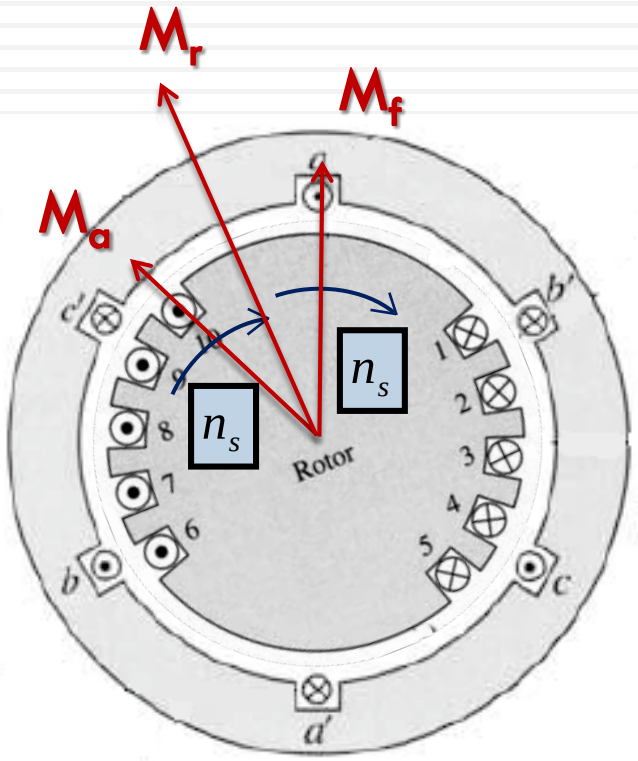
$$M_a = \frac{3}{2}\frac{4}{\pi}\frac{N_{ph}k_w}{2p} I_m \cos(\omega_e t - \theta)$$

$$M_a = 1.35cqI_{rms}k_w \cos(\omega_e t - \theta)$$

Synchronous Generator: Phasor Diagram

Loading Conditions





$$V_{t\phi} = E_r - I_a(R_a + jX_l)$$

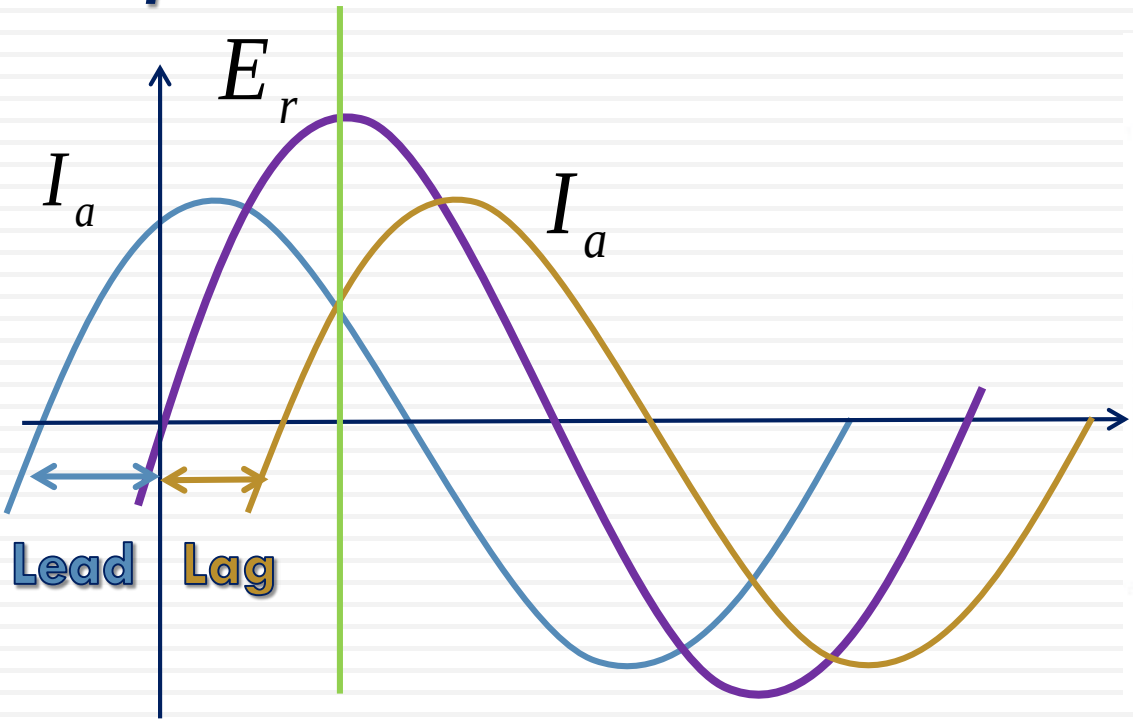
Terminal Voltage

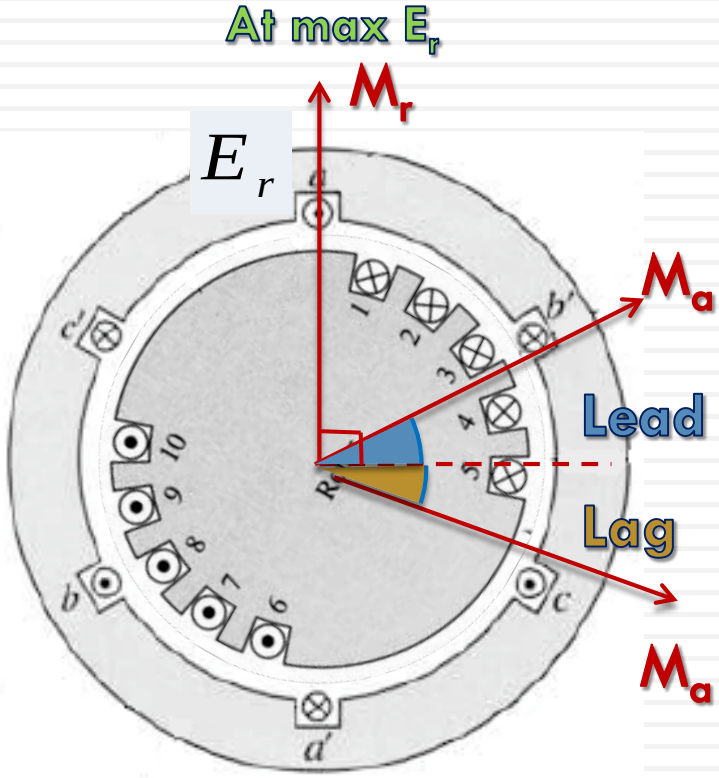
$$M_r = M_f + M_a$$

Resultant Field

Synchronous Generator: Phasor Diagram

Space and Time Phasors





$$V_{t\phi} = E_r - I_a(R_a + jX_l)$$

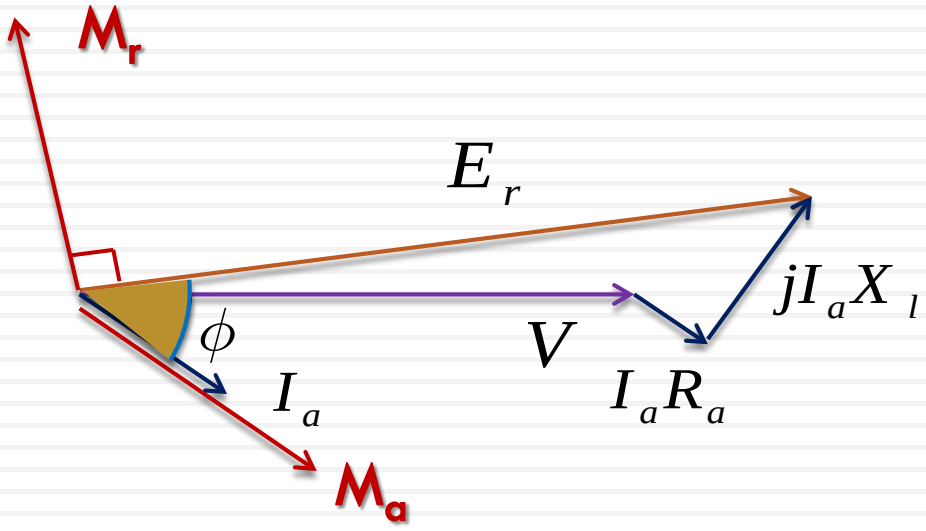
Time Phasor

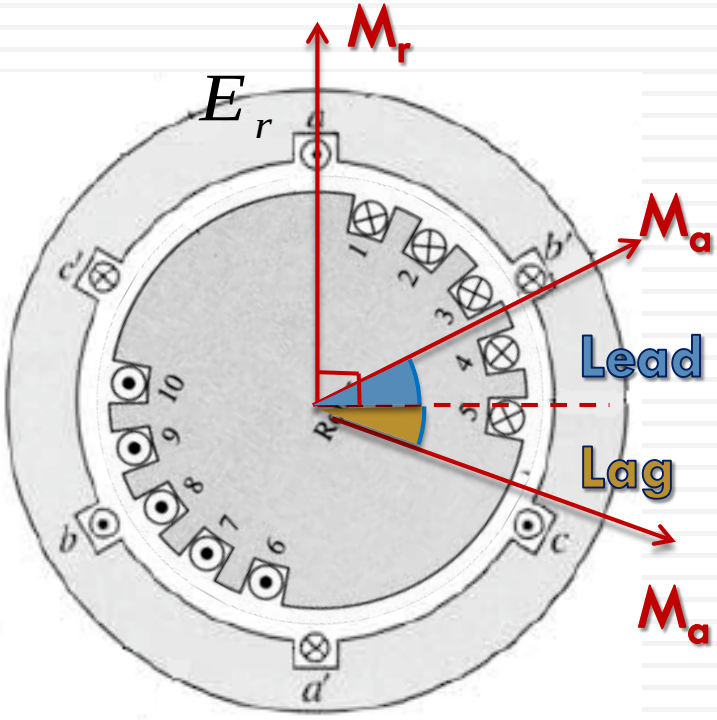
$$M_r = M_f + M_a$$

Space Phasor

Synchronous Generator: Phasor Diagram

Space and Time Phasors





$$V_{t\phi} = E_r - I_a(R_a + jX_l)$$

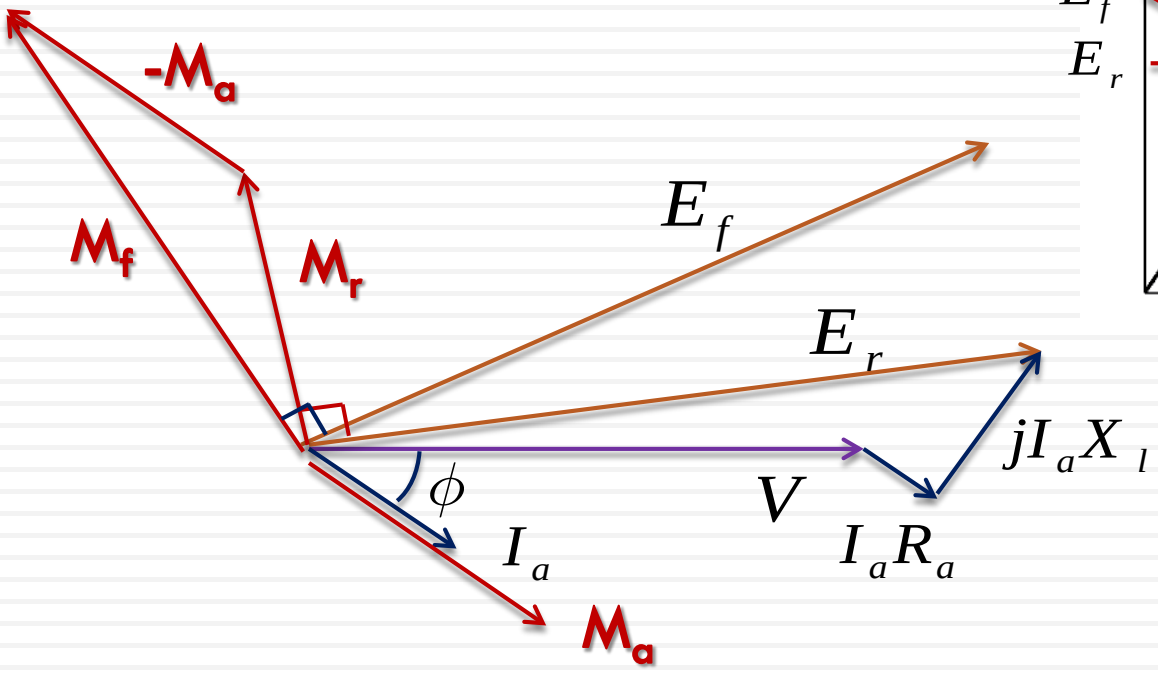
Time Phasor

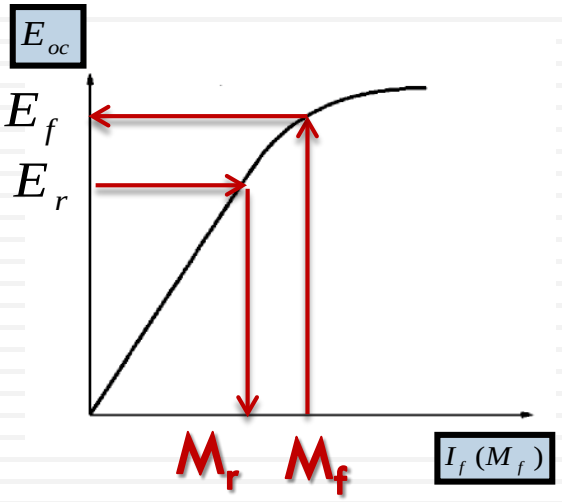
$$M_r = M_f + M_a$$

Space Phasor

Synchronous Generator: Phasor Diagram

Exact Phasor Diagram





$$V_{t\phi} = E_r - I_a(R_a + jX_l)$$

Time Phasor

$$M_r = M_f + M_a$$

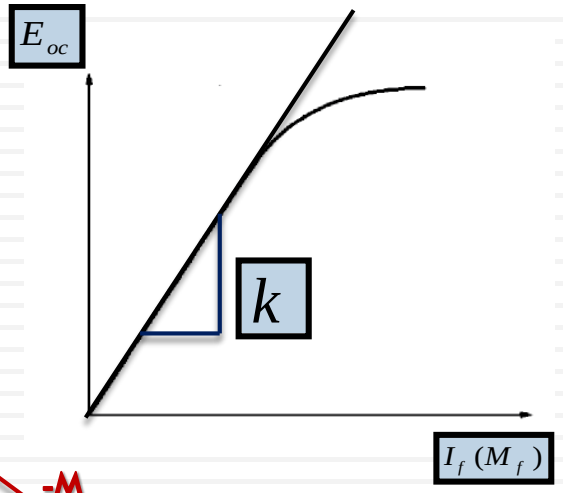
Space Phasor

Synchronous Generator: Equivalent Circuit

Synchronous Reactance

$$V_{t\phi} = E_r - I_a(R_a + jX_l) \quad (1)$$

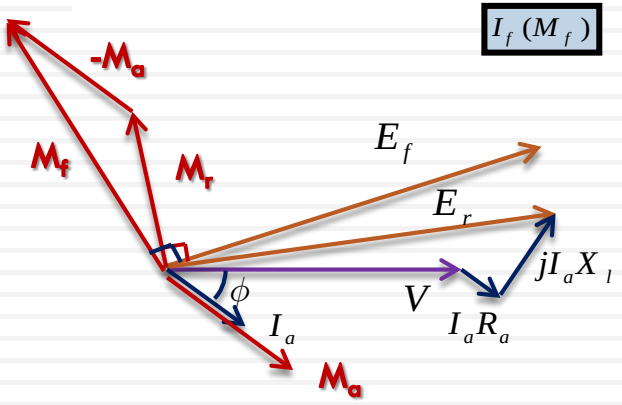
$$M_r = M_f + M_a \quad (2)$$



Assuming linear magnetic characteristics

$$E_f \propto M_f \qquad E_r \propto M_r$$

$$E_f = -jkM_f \qquad E_r = -jkM_r \qquad M_a = k_1 I_a$$



From (2)

$$E_r = E_f - jkM_a$$

$$E_r = E_f + E_{ar}$$

Synchronous Generator: Equivalent Circuit

Synchronous Reactance

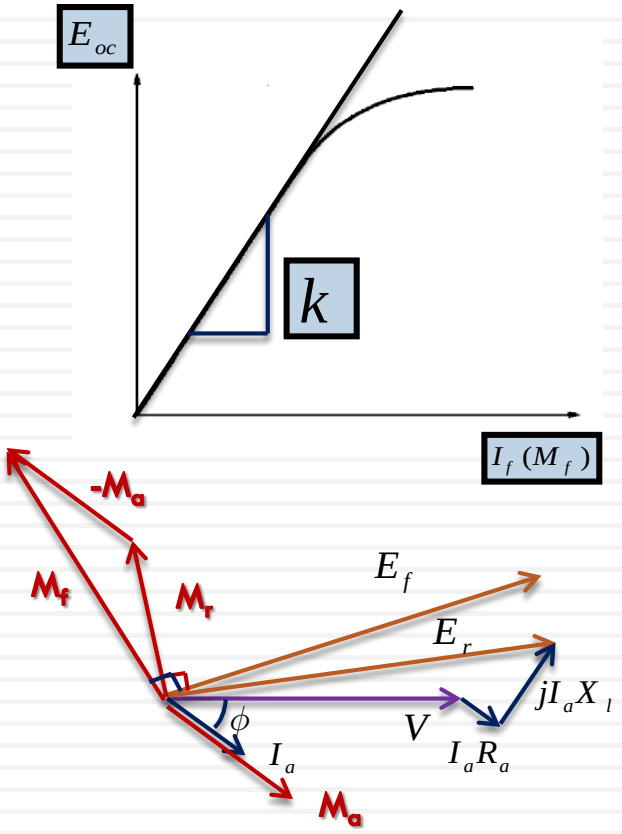
Substituting in (1)

$$V_{t\phi} = E_f - jkk_1 I_a - I_a(R_a + jX_l)$$

$$V_{t\phi} = E_f - I_a[R_a + j(kk_1 + X_l)]$$

$$V_{t\phi} = E_f - I_a[R_a + j(X_{ar} + X_l)]$$

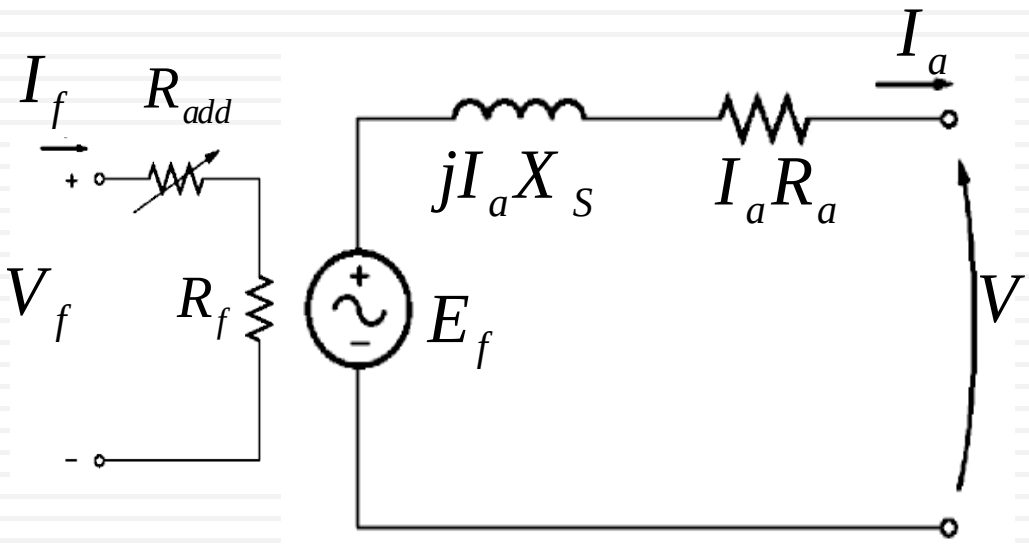
$$V_{t\phi} = E_f - I_a[R_a + jX_S]$$

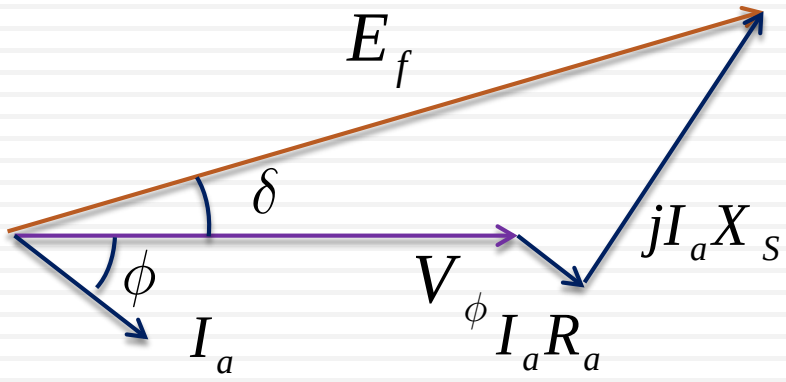


X_S = synchronous reactance

Synchronous Generator: Equivalent Circuit

Approximate Equivalent Circuit





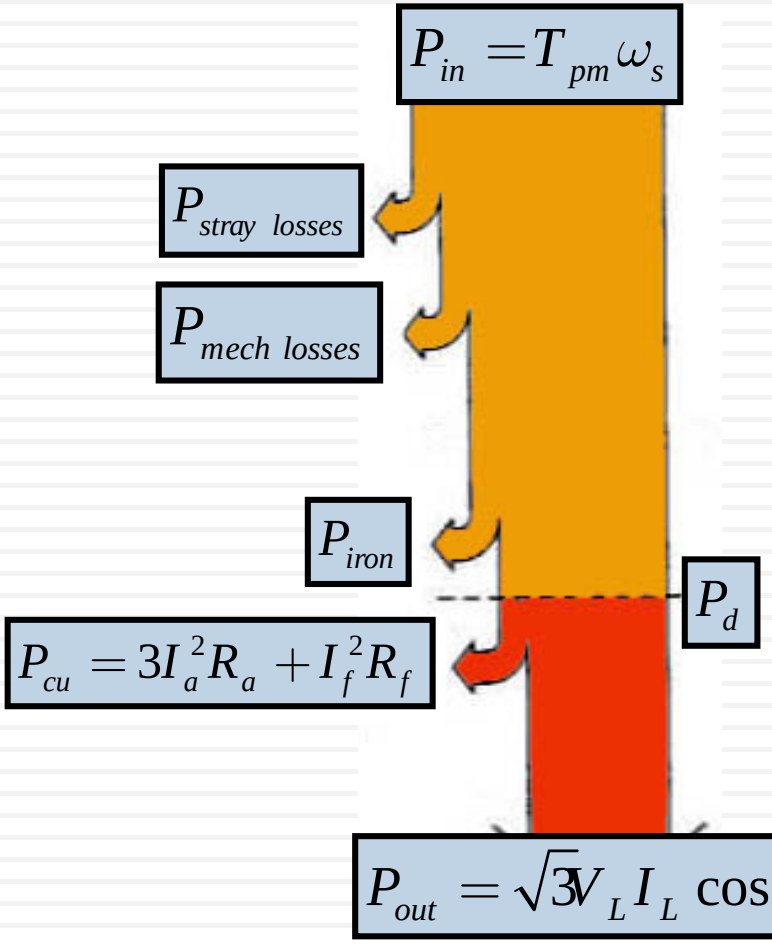
$$V_\phi = E_f - I_a[R_a + jX_S]$$

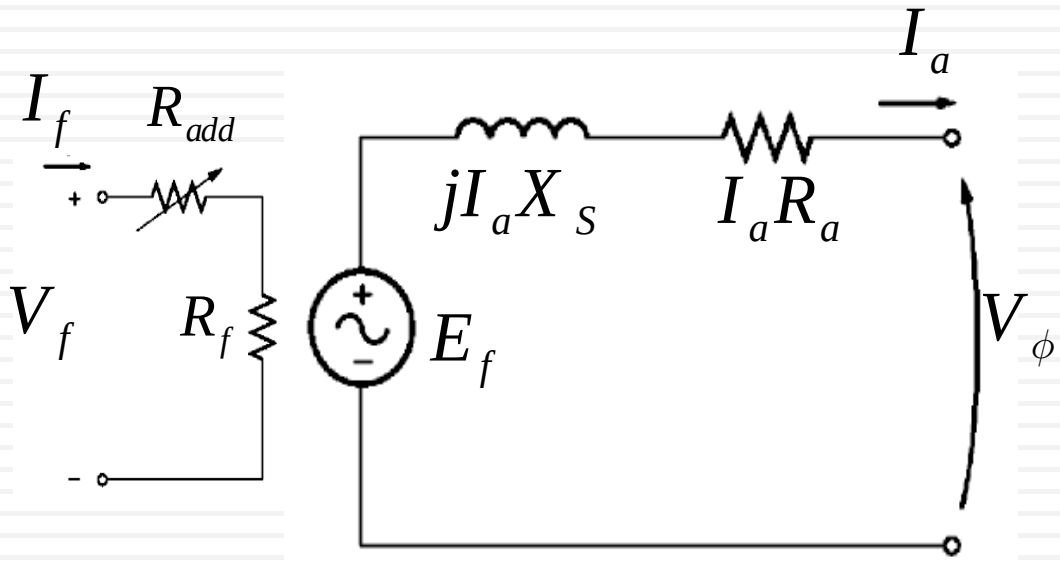
$$V_\phi = E_f - jI_aX_S$$

Neglecting R_a

Synchronous Generator: Power & Torque

Power Flow





$P_d = T_d \omega_s$

Synchronous Generator: Power & Torque

$$V_\phi = E_f - I_a[R_a + jX_S]$$

$$V_\phi = E_f - jI_aX_S$$

Neglecting R_a

$$P_{out} = \sqrt{3}V_L I_L \cos\phi$$

$$P_{out} = 3V_\phi I_a \cos\phi$$

$$Q_{out} = \sqrt{3}V_L I_L \sin\phi$$

$$Q_{out} = 3V_\phi I_a \sin\phi$$

$$P = \frac{3V_\phi E_f \sin\delta}{X_S}$$

δ = Power Angle

$$T_d = \frac{3V_\phi E_f \sin\delta}{\omega_s X_S}$$