ELG2336
Introduction to Electric Machines

Magnetic Circuits

DC Machine

–Shunt: Speed control

–Series: High torque

–Permanent magnet: Efficient

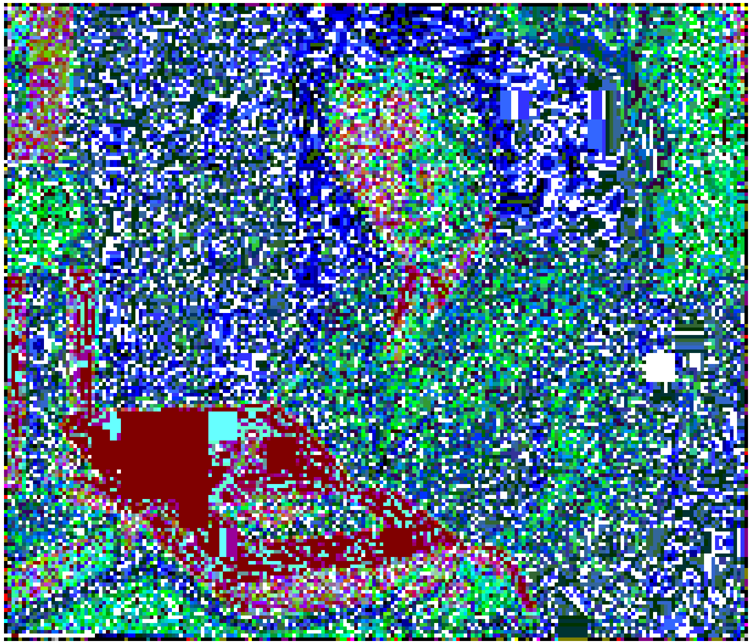
AC Machine

–Synchronous: Constant speed

–Induction machine: Cheap and light weight

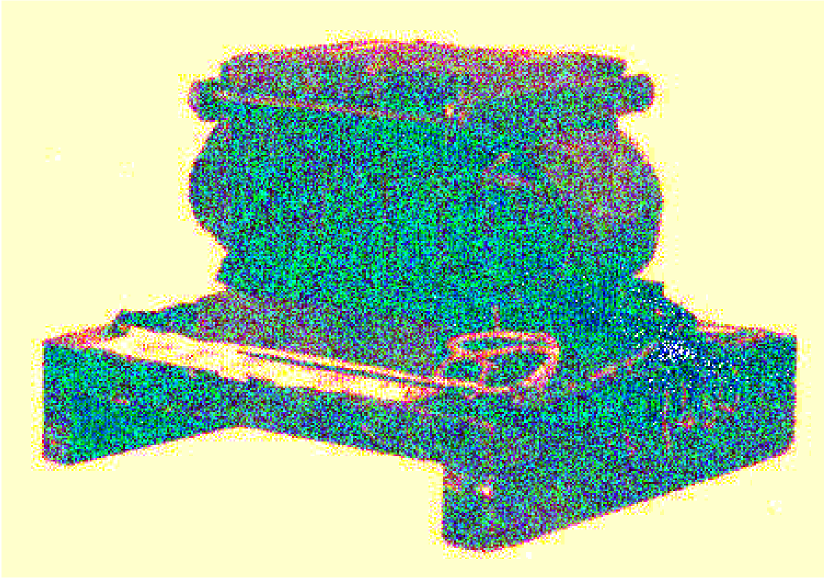
History of DC Electric Machines

1884 **Frank J. Sprague produces DC motor for Edison systems**



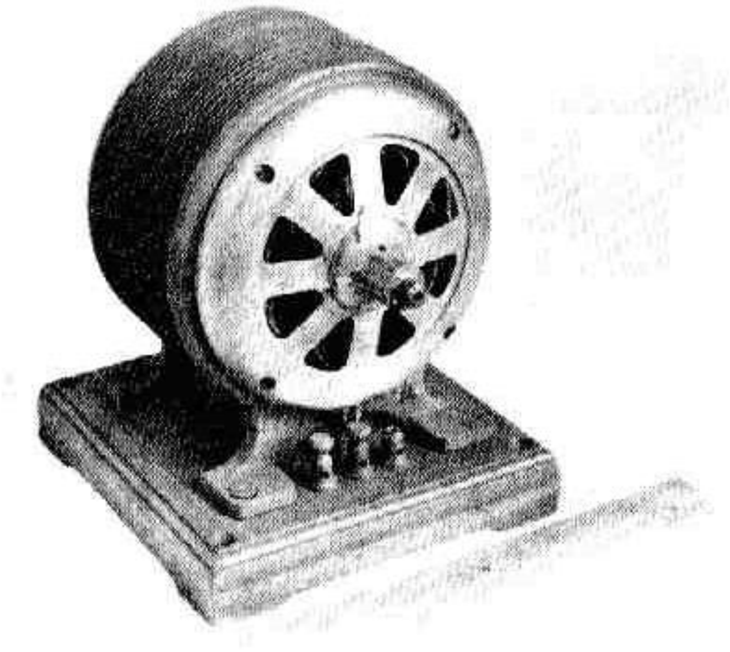
History of Magnetic Application

1885 **William Stanley develops commercially practical transformer**



Chapman: Electric Machinery

History of Electric Synchronous Machines



The TESLA AC Motor—1888.

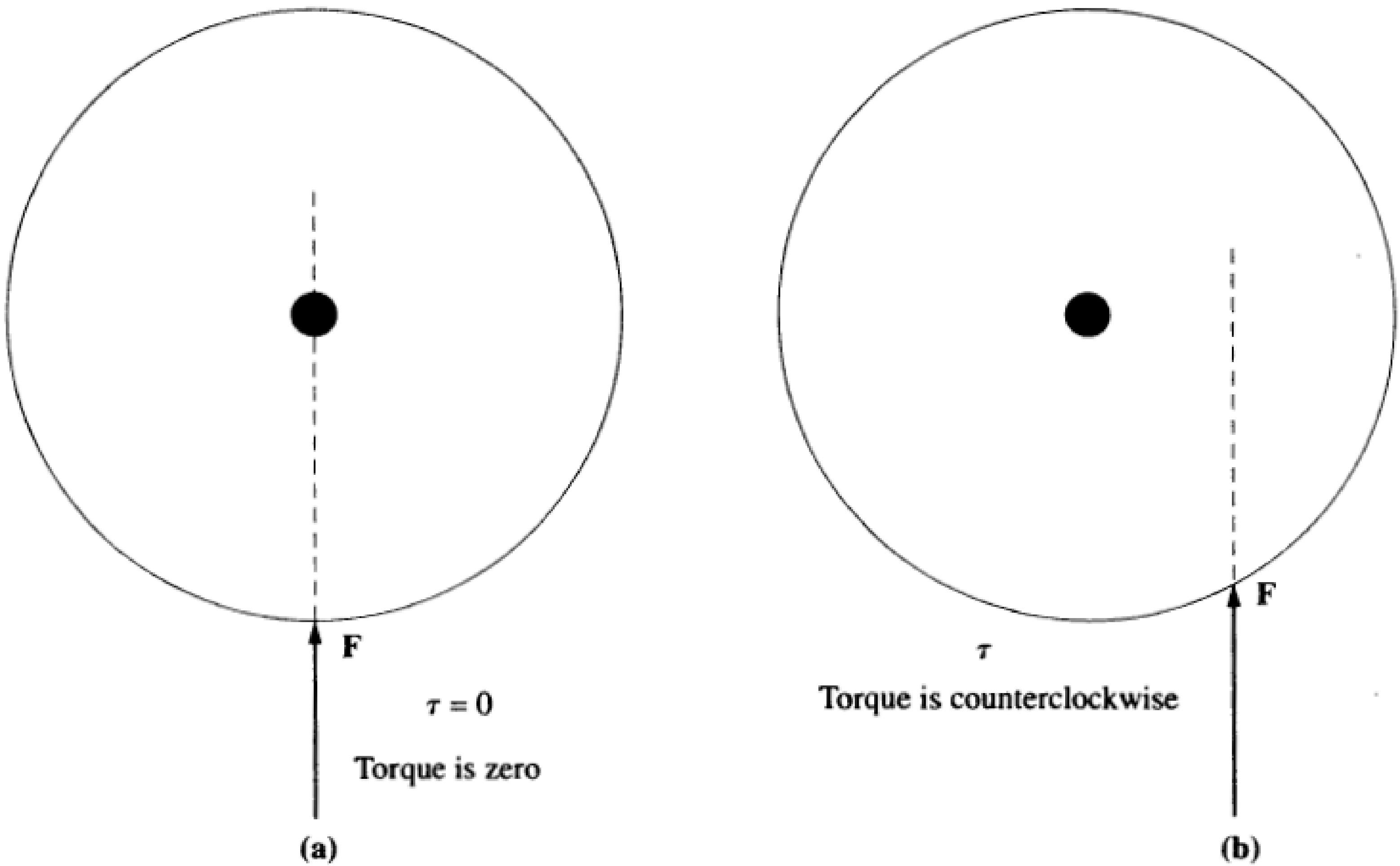
1888

Nikola Tesla presents paper on two-phase ac induction and synchronous motors

Machinery Principles

1. Rotation motion, Newton's law and power relationships
2. The magnetic field
3. Faraday's law
4. Produce an induced force on a wire
5. Produce an induced voltage on a conductor
6. Linear dc machine examples
7. Real, reactive and apparatus power in AC circuits

Torque



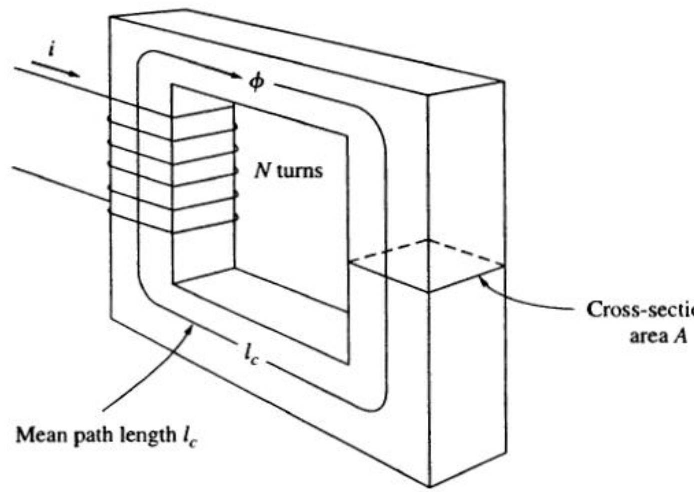
Magnetic Field: Ampere's Law

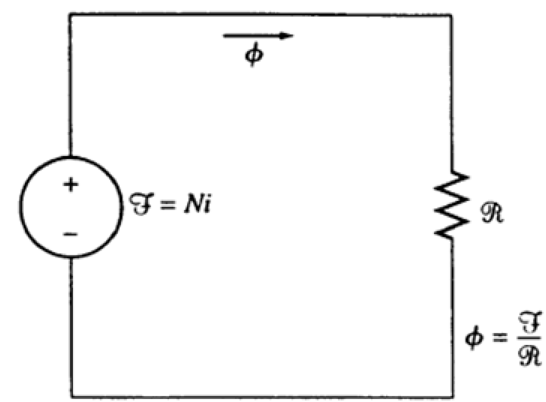
1. The magnetic field is produced by ampere's law
2. The core is a ferromagnetic material

$$\oint \mathbf{H} \cdot d\mathbf{l} = I_{net}$$

$$Hl_c = Ni$$

$$H = \frac{Ni}{l_c}$$

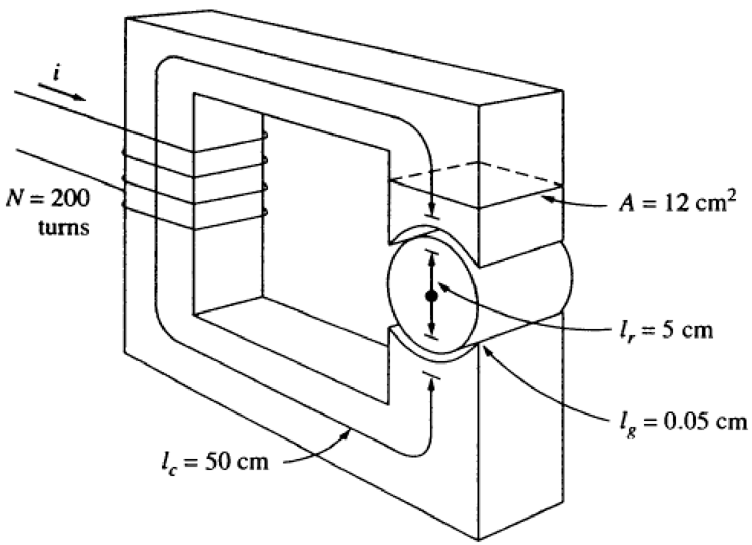


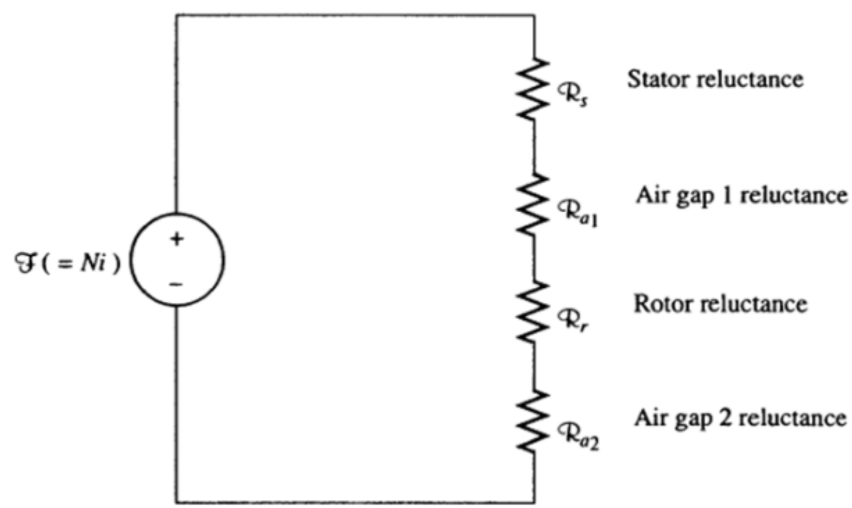


Chapman: Electric Machinery

Example

Figure shows a simplified rotor and stator for a dc motor. The mean path length of the stator is 50 cm, and its cross-sectional area is 12 cm². The mean path length of the rotor is 5 cm, and its cross-sectional area also may be assumed to be 12 cm². Each air gap between the rotor and the stator is 0.05 cm wide, and the cross-sectional area of each air gap (including fringing) is 14 cm². The iron of the core has a relative permeability of 2000, and there are 200 turns of wire on the core. If the current in the wire is adjusted to be 1 A, what will the resulting flux density in the air gaps be?





Chapman: Electric Machinery

Solution

To determine the flux density in the air gap, it is necessary to first calculate the magnetomotive force applied to the core and the total reluctance of the flux path. With this information, the total flux in the core can be found. Finally, knowing the cross-sectional area of the air gaps enables the flux density to be calculated.

The reluctance of the stator is

$$\mathcal{R}_s = \frac{l_s}{\mu_r \mu_0 A_s}$$

$$= \frac{0.5 \text{ m}}{(2000)(4\pi \times 10^{-7})(0.0012 \text{ m}^2)}$$

$$= 166{,}000 \text{ A} \bullet \text{turns/Wb}$$

The reluctance of the rotor is

$$\mathcal{R}_r = \frac{l_r}{\mu_r \mu_0 A_r}$$

$$= \frac{0.05 \text{ m}}{(2000)(4\pi \times 10^{-7})(0.0012 \text{ m}^2)}$$

$$= 16{,}600 \text{ A} \bullet \text{turns/Wb}$$

The reluctance of the air gaps is

$$\mathcal{R}_a = \frac{l_a}{\mu_r \mu_0 A_a}$$

$$= \frac{0.0005 \text{ m}}{(1)(4\pi \times 10^{-7})(0.0014 \text{ m}^2)}$$

$$= 284{,}000 \text{ A} \cdot \text{turns/Wb}$$

The magnetic circuit corresponding to this machine is shown in Figure 1–9b. The total reluctance of the flux path is thus

$$\mathcal{R}_{eq} = \mathcal{R}_s + \mathcal{R}_{a1} + \mathcal{R}_r + \mathcal{R}_{a2}$$

$$= 166{,}000 + 284{,}000 + 16{,}600 + 284{,}000 \text{ A} \cdot \text{turns/Wb}$$

$$= 751{,}000 \text{ A} \cdot \text{turns/Wb}$$

The net magnetomotive force applied to the core is

$$\mathcal{F} = Ni = (200 \text{ turns})(1.0 \text{ A}) = 200 \text{ A} \cdot \text{turns}$$

Therefore, the total flux in the core is

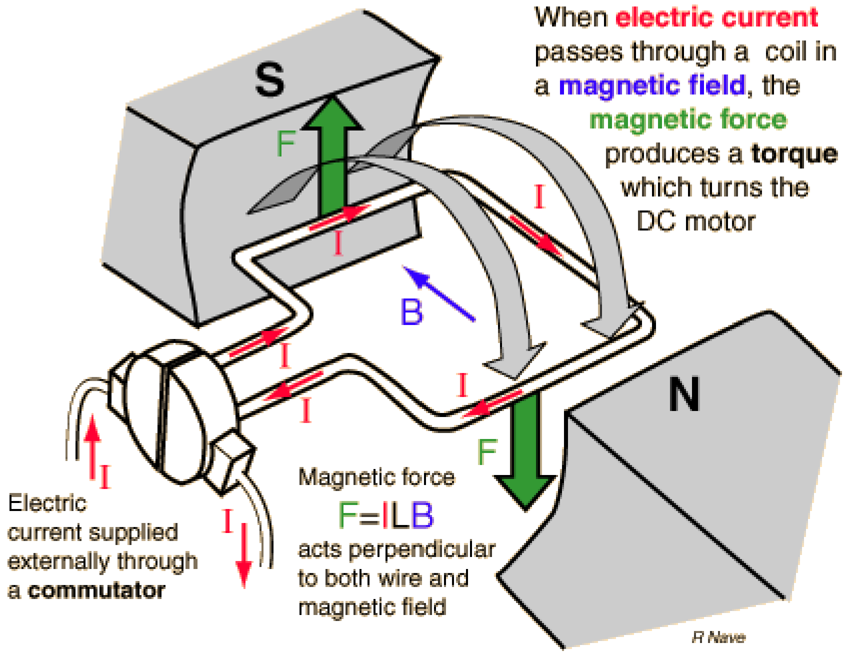
$$\phi = \frac{\mathcal{F}}{\mathcal{R}} = \frac{200 \text{ A} \cdot \text{turns}}{751{,}000 \text{ A} \cdot \text{turns/ Wb}}$$

$$= 0.00266 \text{ Wb}$$

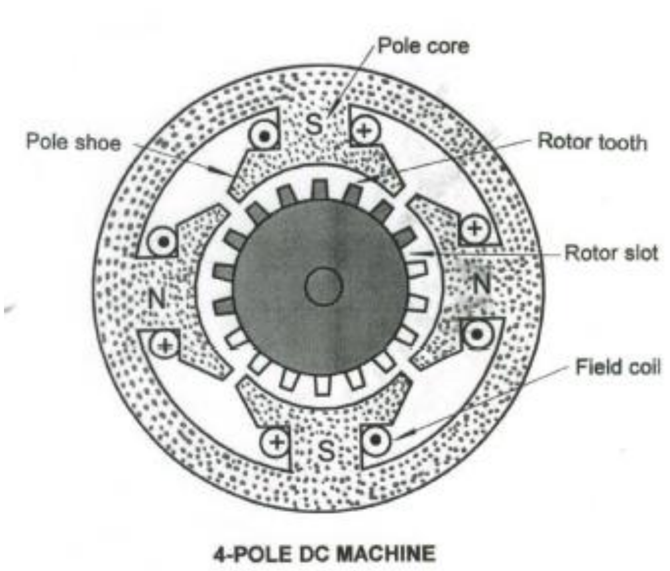
Finally, the magnetic flux density in the motor's air gap is

$$B = \frac{\phi}{A} = \frac{0.000266 \text{ Wb}}{0.0014 \text{ m}^2} = 0.19 \text{ T}$$

DC Machines



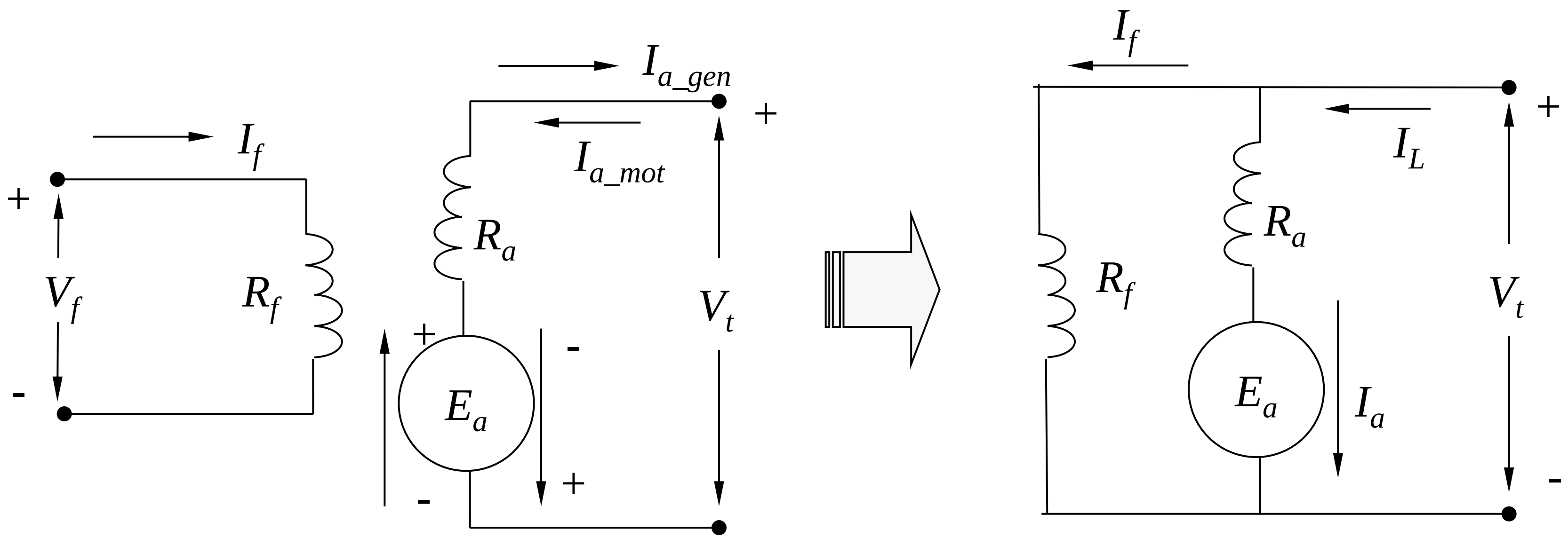
S
N
F
F
B
I
When electric current passes through a coil in a magnetic field, the magnetic force produces a torque which turns the DC motor
Electric current supplied externally through a commutator
Magnetic force
F=ILB
acts perpendicular to both wire and magnetic field
R Nave



Pole core
Pole shoe
Rotor tooth
Rotor slot
Field coil
S
N
N
S
4-POLE DC MACHINE

Equivalent Circuit of a DC Machine

Left: Separately Excited; Right: Self-Excited Shunt



$$V_f = I_f R_f$$

$$V_t = E_a \pm I_a R_a$$

Generated *emf* and Electromagnetic Torque

$$V_f = I_f R_f$$

$$V_t = E_a \pm I_a R_a$$

Motor: $V_t > E_a$
Generator: $V_t > E_a$

Voltage generated in the armature circuit due the flux of the stator field current

$$E_a = K_a \phi_d \omega_m$$

K_a: design constant

Electromagnetic torque

$$T_e = K_a \phi_d I_a$$

$$P_{em} = E_a I_a = T_e \omega_m$$

Efficiency

$$\eta = \frac{\textit{Power Output}}{\textit{Power Input}}$$

$$= \frac{\textit{Power Input} - \textit{Losses}}{\textit{Power Input}}$$

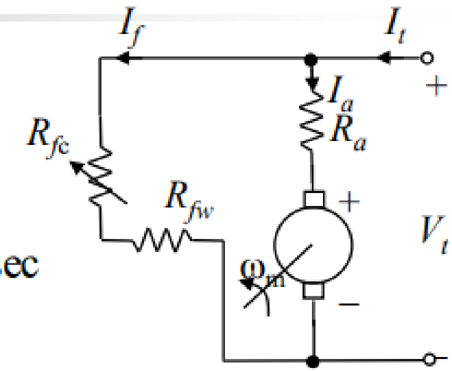
$$= 1 - \frac{\textit{Losses}}{\textit{Power Input}}$$

The losses are made up of rotational losses (3-15%), armature circuit copper losses (3-6%), and shunt field copper loss (1-5%). The voltage drop between the brush and commutator is 2V and the brush contact loss is therefore calculated as $2I_a$.

Example

A 250V shunt motor has an armature resistance of 0.25Ω and a field resistance of 125Ω. At no-load the motor takes a line current of 5.0A while running at 1200 rpm. If the line current at full-load is 52.0A, what is the full-load speed?

Solution



At no-load:

$$I_t = 5A$$

$$n_m = 1200 \ rpm \ \Rightarrow \omega_m = \frac{1200 \times 2\pi}{60} = 125.66 \ rad/\sec$$

$$I_f = \frac{V_t}{R_f} = \frac{250}{125} = 2A, I_{a\_NL} = I_{t\_NL} - I_f = 5 - 2 = 3A$$

$$E_{a\_NL} = V_t - I_{a\_NL} R_a = 250 - 3 \times 0.25 = 249.25V$$

$$K_a \phi = \frac{E_{a\_NL}}{\omega_{m\_NL}} = \frac{249.25}{125.66} = 1.984 \text{ V.sec/rad}$$

Solution

$$I_L = 52A \Rightarrow I_{a\_FL} = I_{t\_FL} - I_f = 52 - 2 = 50A$$

$$E_{a-FL} = V_t - I_{a-FL} R_a = 250 - 50 \times 0.25 = 237.5V$$

$$E_{a\_FL} = K_a \phi \omega_{m\_FL}$$

$$\Rightarrow \omega_{m\_FL} = \frac{E_{a\_FL}}{K_a \phi} = \frac{237.5}{1.984} = 119.71 \text{ rad/sec}$$

$$n_{m\_FL} = \frac{\omega_m \times 60}{2\pi} = 1142.4 \text{ rpm}$$

Reactive Power Q and Apparatus Power S

1. Reactive power Q (VAR) is defined from instantaneous power

$$Q = VI \sin \theta$$

2. Apparatus power S (VA) is defined to represent the product of voltage and current magnitudes

$$S = VI$$

Complex Power

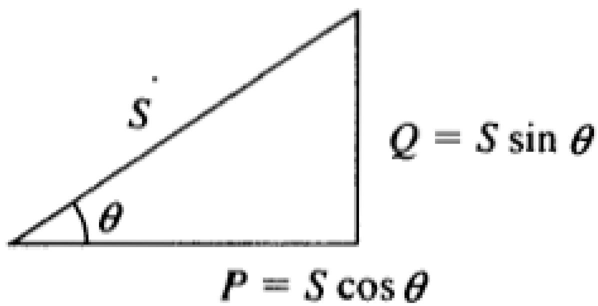
To understand this equation, let's suppose that the voltage applied to a load is $\mathbf{V} = V \angle \alpha$ and the current through the load is $\mathbf{I} = I \angle \beta$. Then the complex power supplied to the load is

$$\begin{aligned} \mathbf{S} = \mathbf{VI}^* &= (V\angle\alpha)(I\angle-\beta) = VI \angle(\alpha - \beta) \\ &= VI\cos(\alpha - \beta) + jVI\sin(\alpha - \beta) \end{aligned}$$

The impedance angle θ is the difference between the angle of the voltage and the angle of the current ($\theta = \alpha - \beta$), so this equation reduces to

$$\begin{aligned} \mathbf{S} &= VI\cos\theta + jVI\sin\theta \\ &= P + jQ \end{aligned}$$

Power Factor



$$\cos\theta = \frac{P}{S}$$

$$\sin\theta = \frac{Q}{S}$$

$$\tan\theta = \frac{Q}{P}$$

The quantity cos θ is usually known as the *power factor* of a load. The power factor is defined as the fraction of the apparent power S that is actually supplying real power to a load. Thus,

$$\text{PF} = \cos\theta \qquad (1\text{–}71)$$

where θ is the impedance angle of the load.

Synchronous Machines

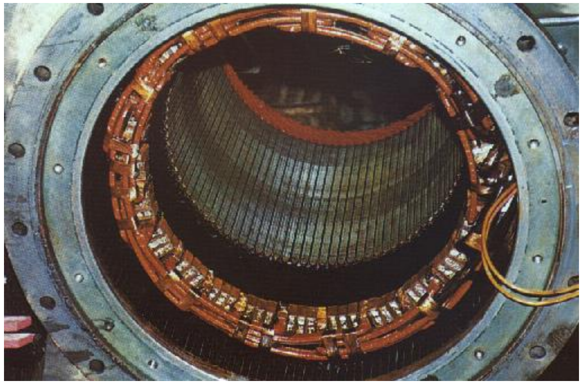
Synchronous machines are AC machines that have a field circuit supplied by an external DC source.

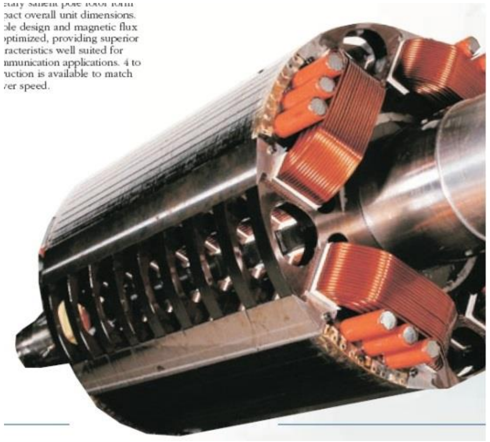
In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then turned by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.

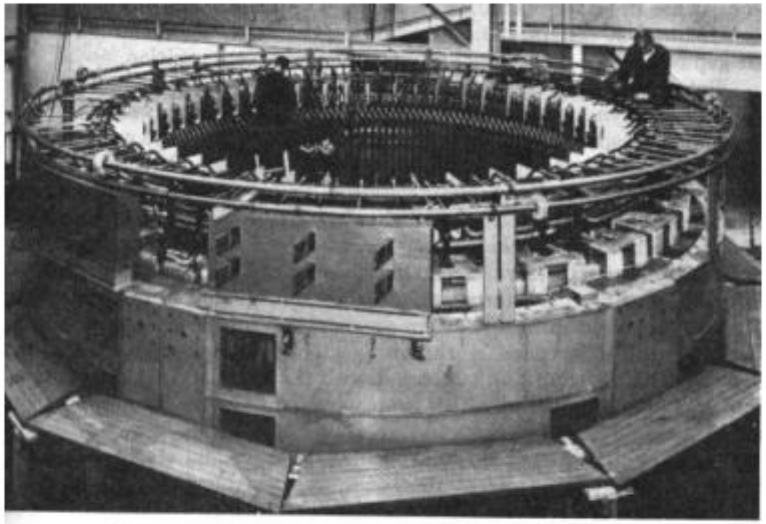
In a synchronous motor, a 3-phase set of stator currents produces a rotating magnetic field causing the rotor magnetic field to align with it. The rotor magnetic field is produced by a DC current applied to the rotor winding.

Field windings are the windings producing the main magnetic field (rotor windings for synchronous machines); armature windings are the windings where the main voltage is induced (stator windings for synchronous machines).

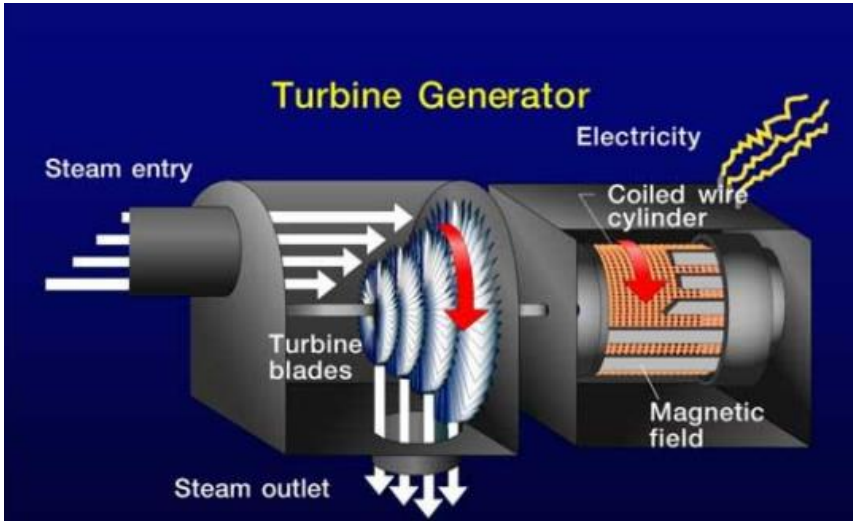
Construction of Synchronous Machines







Stator of a 190-MVA three-phase 12-kV 375-r/min hydroelectric generator. The conductors have hollow passages through which cooling water is circulated. (*Brown Boveri Corporation.*)



Voltage Regulation

A convenient way to compare the voltage behaviour of two generators is by their *voltage regulation* (*VR*). The *VR* of a synchronous generator at a given load, power factor, and at rated speed is defined as

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\%$$

Where V_{fl} is the full-load terminal voltage, and V_{nl} (equal to E_f) is the no-load terminal voltage (internal voltage) at rated speed when the load is removed without changing the field current. For lagging power factor (PF), *VR* is fairly positive, for unity *PF*, *VR* is small positive and for leading *PF*, *VR* is negative.

Example

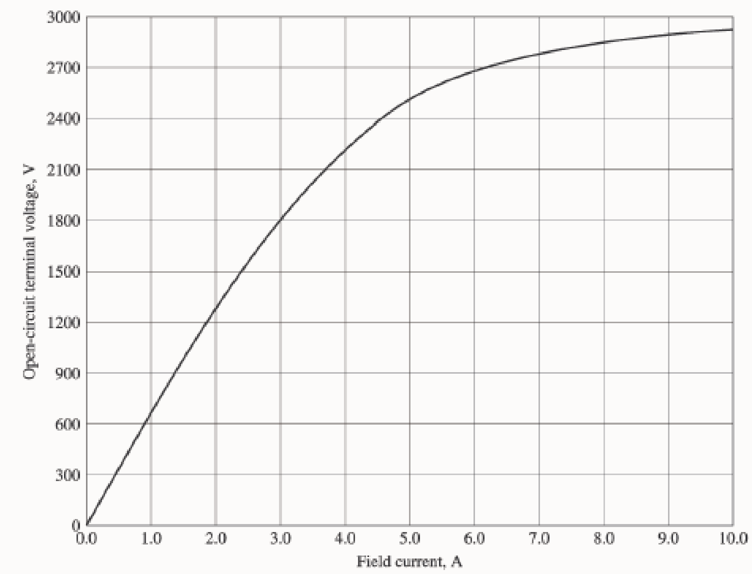
5-2. A 2300-V 1000-kVA 0.8-PF-lagging 60-Hz two-pole Y-connected synchronous generator has a synchronous reactance of 1.1 Ω and an armature resistance of 0.15 Ω. At 60 Hz, its friction and windage losses are 24 kW, and its core losses are 18 kW. The field circuit has a dc voltage of 200 V, and the maximum I_F is 10 A. The resistance of the field circuit is adjustable over the range from 20 to 200 Ω. The OCC of this generator is shown in Figure P5-1.

(a) How much field current is required to make V_T equal to 2300 V when the generator is running at no load?

(b) What is the internal generated voltage of this machine at rated conditions?

(c) How much field current is required to make V_T equal to 2300 V when the generator is running at rated conditions?

(d) How much power and torque must the generator's prime mover be capable of supplying?



Solution

(a) If the no-load terminal voltage is 2300 V, the required field current can be read directly from the open-circuit characteristic. It is 4.25 A.

(b) This generator is Y-connected, so $I_L = I_A$. At rated conditions, the line and phase current in this generator is

$$I_A = I_L = \frac{P}{\sqrt{3}\ V_L} = \frac{1000\ \text{kVA}}{\sqrt{3}(2300\ \text{V})} = 251\ \text{A} \ \text{ at an angle of } -36.87°$$

The phase voltage of this machine is $V_\phi = V_T / \sqrt{3} = 1328\ \text{V}$. The internal generated voltage of the machine is

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A \mathbf{I}_A + jX_S \mathbf{I}_A$$

$$\mathbf{E}_A = 1328\angle 0° + (0.15\ \Omega)(251\angle -36.87°\ \text{A}) + j(1.1\ \Omega)(251\angle -36.87°\ \text{A})$$

$$\mathbf{E}_A = 1537\angle 7.4°\ \text{V}$$

(c) The equivalent open-circuit terminal voltage corresponding to an E_A of 1537 volts is

$$V_{T,oc} = \sqrt{3}(1527\ \text{V}) = 2662\ \text{V}$$

From the OCC, the required field current is 5.9 A.

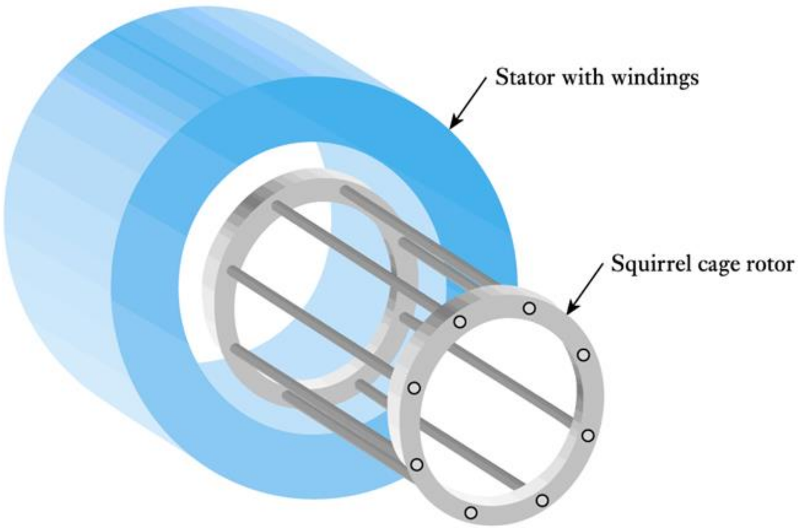
(d) The input power to this generator is equal to the output power plus losses. The rated output power is

$$P_{\text{OUT}} = (1000\ \text{kVA})(0.8) = 800\ \text{kW}$$

$$P_{\text{CU}} = 3 I_A^2 R_A = 3(251\ \text{A})^2 (0.15\ \Omega) = 28.4\ \text{kW}$$

$$P_{\text{F\&W}} = 24\ \text{kW}$$

Induction Motor



Induction Motor Speed

The induction motor will always run at a speed lower than the synchronous speed

The difference between the motor speed and the synchronous speed is called the *Slip*

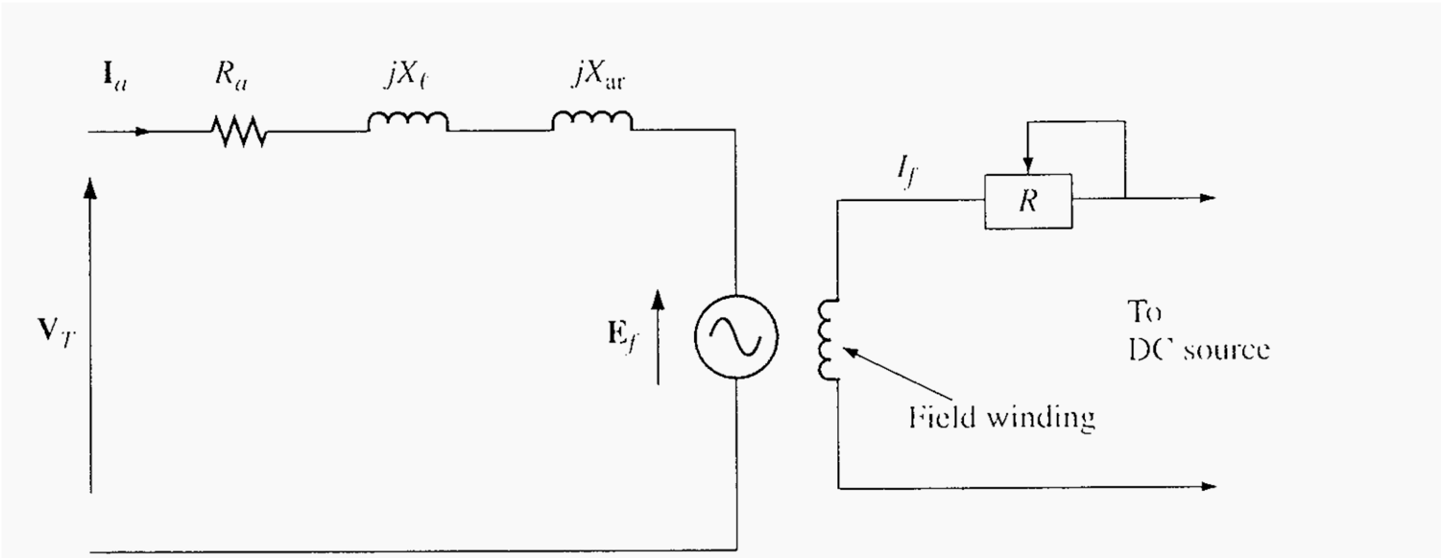
$$n_{slip} = n_{sync} - n_m$$

Where n_{slip} = slip speed

n_{sync} = speed of the magnetic field

n_m = mechanical shaft speed of the motor

Equivalent Circuit of a Synchronous Motor



$$V_T = I_a R_a + I_a jX_l + I_a X_{ar} + E_f$$

$$X_s = X_l + X_{ar}$$

$$V_T = E_f + I_a (R_a + jX_s)$$

$$V_T = E_f + I_a Z_s$$

Rotation Speed of Synchronous Machine

Synchronous generators produce electricity whose frequency is synchronized with the mechanical rotational speed.

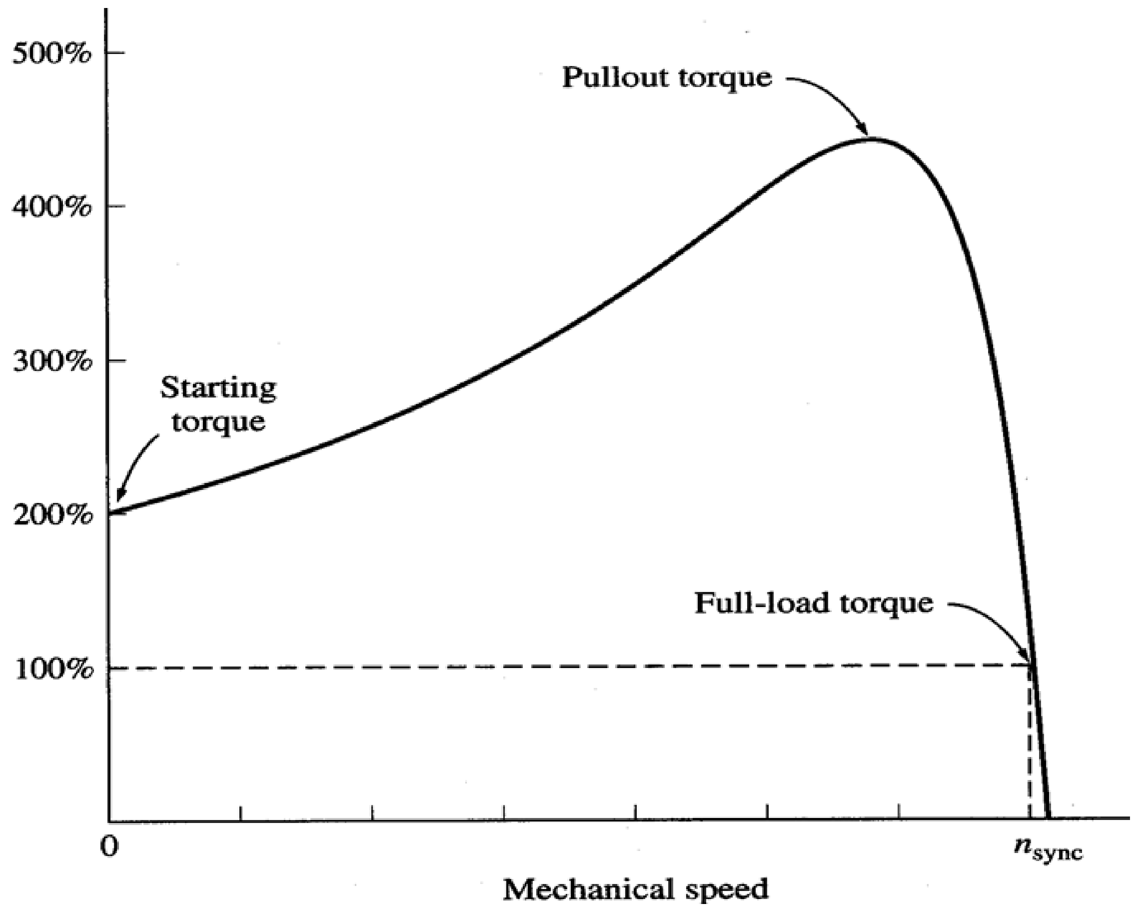
$$f_e = \frac{n_m P}{120}$$

Where f_e is the electrical frequency, Hz;
n_m is mechanical speed of magnetic field (rotor speed for synchronous machine), rpm;
P is the number of poles.

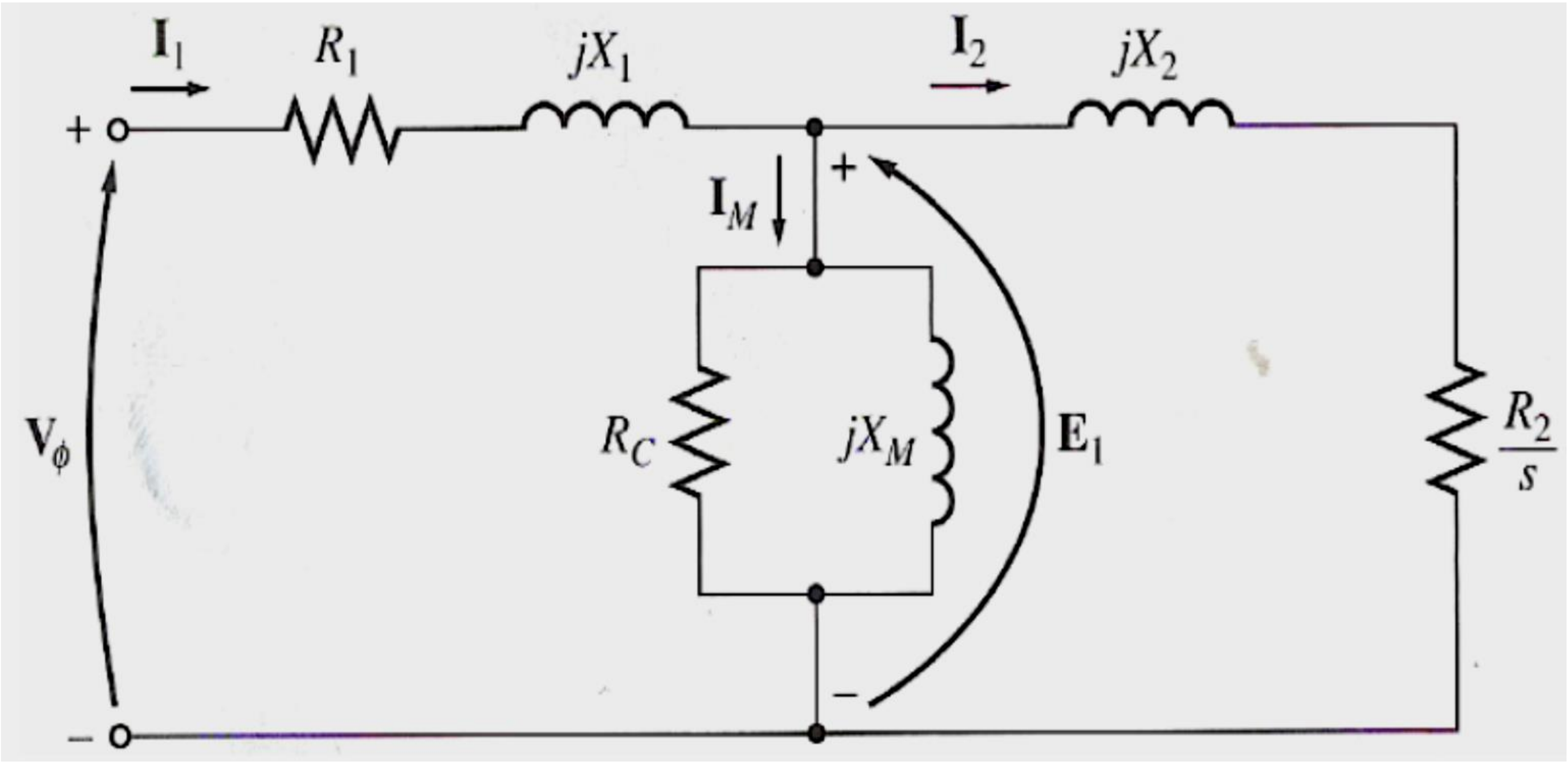
Steam turbines are most efficient when rotating at high speed; therefore, to generate 60 Hz, they are usually rotating at 3600 rpm and turn 2-pole generators. Water turbines are most efficient when rotating at low speeds (200-300 rpm); therefore, they usually turn generators with many poles.

Selection of Induction Motors

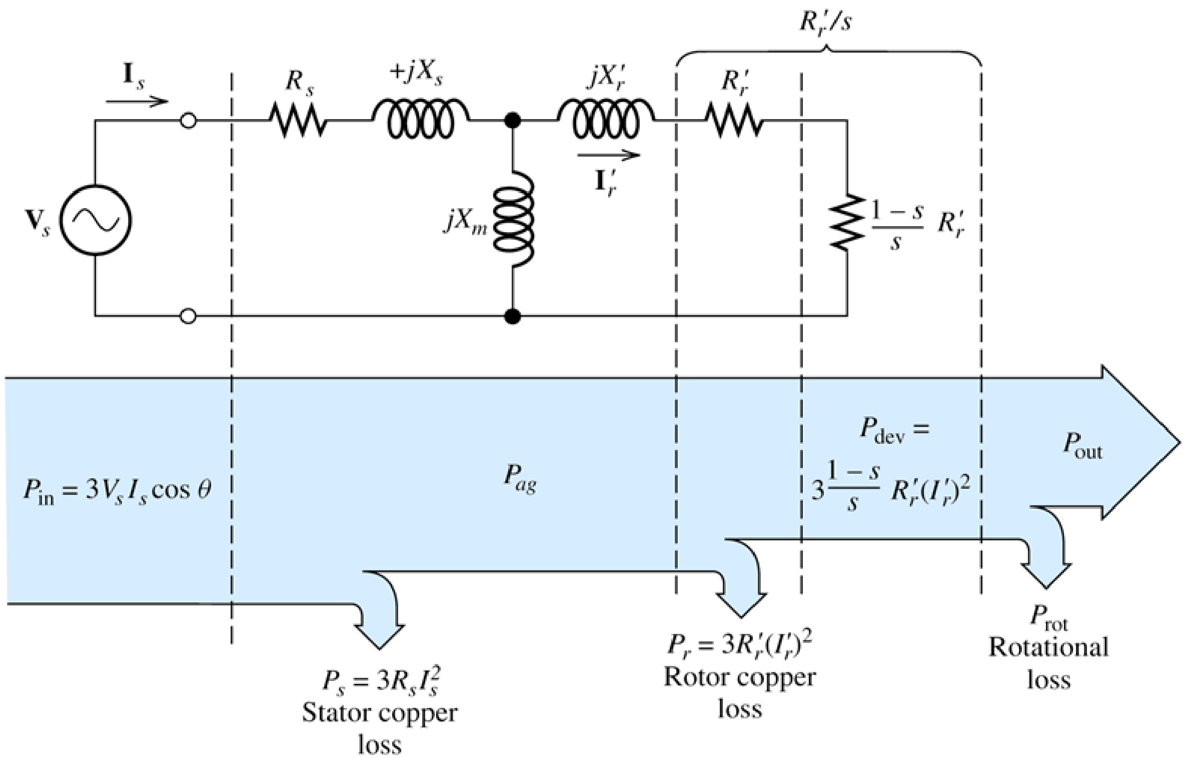
Efficiency
Starting torque
Pull-out torque
Power factor
Starting current



The Equivalent Circuit



Power Flow



$$P_{in} = 3I_sV_s\cos(\theta)$$

$$P_{out} = P_{dev} - P_{rot}$$

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$T_{dev} = \frac{P_{dev}}{\omega_m}$$

Example 1

A 480-V, 60 Hz, 50-hp, three phase induction motor is drawing 60A at 0.85 PF lagging. The stator copper losses are 2 kW, and the rotor copper losses are 700 W. The friction and windage losses are 600 W, the core losses are 1800 W, and the stray losses are negligible. Find the following quantities:

1. The air-gap power $P_{AG.}$
2. The power converted P_{conv}.
3. The output power P_{out}.
4. The efficiency of the motor.

Solution

$$P_{in} = \sqrt{3} V_L I_L \cos\theta$$

1.

$$= \sqrt{3} \times 480 \times 60 \times 0.85 = 42.4 \text{ kW}$$

$$P_{AG} = P_{in} - P_{SCL} - P_{core}$$

$$= 42.4 - 2 - 1.8 = 38.6 \text{ kW}$$

$$P_{conv} = P_{AG} - P_{RCL}$$

2.

$$= 38.6 - \frac{700}{1000} = 37.9 \text{ kW}$$

$$P_{out} = P_{conv} - P_{F\&W}$$

3.

$$= 37.9 - \frac{600}{1000} = 37.3 \text{ kW}$$

$$P_{out} = \frac{37.3}{0.746} = 50 \text{ hp}$$

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$= \frac{37.3}{42.4} \times 100 = 88\%$$

Example 2

A 460-V, 25-hp, 60 Hz, four-pole, Y-connected induction motor has the following impedances in ohms per phase referred to the stator circuit:

$R_s = 0.641\Omega$ $R_r = 0.332\Omega$

$X_s = 1.106\ \Omega$ $X_r = 0.464\ \Omega$ $X_m = 26.3\ \Omega$

The total rotational losses are 1100 W and are assumed to be constant. The core loss is lumped in with the rotational losses. For a rotor slip of 2.2 percent at the rated voltage and rated frequency, find the motor's

1. Speed
2. Stator current
3. Power factor
4. P_{conv} and P_{out}
5. τ_{ind} and τ_{load}
6. Efficiency

Solution

1.
$$n_{sync} = \frac{120 f_e}{P} = \frac{120 \times 60}{4} = 1800 \text{ rpm}$$
$$n_m = (1-s)n_{sync} = (1-0.022) \times 1800 = 1760 \text{ rpm}$$

2.
$$Z_2 = \frac{R_2}{s} + jX_2 = \frac{0.332}{0.022} + j0.464$$
$$= 15.09 + j0.464 = 15.1\angle 1.76^\circ \ \Omega$$

$$Z_f = \frac{1}{1/jX_M + 1/Z_2} = \frac{1}{-j0.038 + 0.0662\angle -1.76^\circ}$$
$$= \frac{1}{0.0773\angle -31.1^\circ} = 12.94\angle 31.1^\circ \ \Omega$$

Solution

$$Z_{tot} = Z_{stat} + Z_f$$

$$= 0.641 + j1.106 + 12.94\angle 31.1^\circ \ \Omega$$

$$= 11.72 + j7.79 = 14.07\angle 33.6^\circ \ \Omega$$

$$I_1 = \frac{V_\phi}{Z_{tot}} = \frac{\frac{460\angle 0^\circ}{\sqrt{3}}}{14.07\angle 33.6^\circ} = 18.88\angle -33.6^\circ \ \text{A}$$

$$PF = \cos 33.6^\circ = 0.833 \quad \text{lagging}$$

3.

$$P_{in} = \sqrt{3} V_L I_L \cos\theta = \sqrt{3} \times 460 \times 18.88 \times 0.833 = 12530 \ \text{W}$$

4.

$$P_{SCL} = 3I_1^2 R_1 = 3(18.88)^2 \times 0.641 = 685 \ \text{W}$$

$$P_{AG} = P_{in} - P_{SCL} = 12530 - 685 = 11845 \ \text{W}$$

Solution

$$P_{conv} = (1-s)P_{AG} = (1-0.022)(11845) = 11585 \text{ W}$$

$$P_{out} = P_{conv} - P_{F\&W} = 11585 - 1100 = 10485 \text{ W}$$

$$= \frac{10485}{746} = 14.1 \text{ hp}$$

5. $$\tau_{ind} = \frac{P_{AG}}{\omega_{sync}} = \frac{11845}{2\pi \times 1800/60} = 62.8 \text{ N.m}$$

$$\tau_{load} = \frac{P_{out}}{\omega_m} = \frac{10485}{2\pi \times 1760/60} = 56.9 \text{ N.m}$$

6. $$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{10485}{12530} \times 100 = 83.7\%$$

Solve this Example

A 460 V, 25-hp, 60Hz, four pole, Y-connected induction motor has the following impedances in ohms per phase referred to the stator circuit:

$R_s = 0.641\Omega$ $\quad R_r = 0.332\Omega$

$X_s = 1.106\Omega$ $\quad X_r = 0.464\Omega$ $\quad X_m = 26.3\Omega$

The total rotational losses = 110 W, rotor slip = 2.2% at rated voltage and frequency.

Find the motor's

i) Speed, ii) Stator Current, iii) Power factor, iv) Pconv,

v) Pout vi) τ_{ind}, vii) τ_{load} and viii) Efficiency

Ideas for the Course Project

https://howtomechatronics.com/tutorials/arduino/arduino-dc-motor-control-tutorial-l298n-pwm-h-bridge/

http://www.instructables.com/id/Control-DC-and-stepper-motors-with-L298N-Dual-Moto/

https://dronebotworkshop.com/dc-motors-l298n-h-bridge/

https://howchoo.com/g/mjg5ytzmnjh/controlling-dc-motors-using-your-raspberry-pi

https://javatutorial.net/raspberry-pi-control-dc-motor-speed-and-direction-java