Lesson 17: Synchronous Machines

ET 332b

Ac Motors, Generators and Power Systems

Learning Objectives

After this presentation you will be able to:

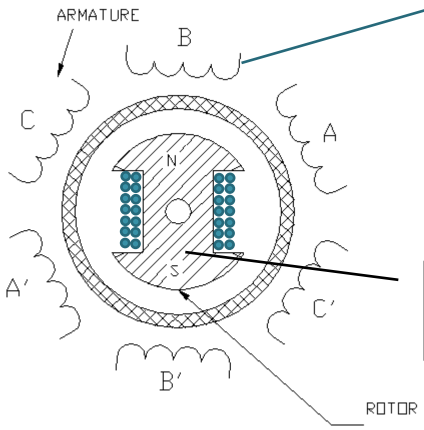
- Explain how synchronous machines operate.
- Draw the per phase circuit model of a synchronous machine.
- Write and utilize the power equations for synchronous machines.
- Use machine equations to determine a machines operation point and power
- Compute motor torques

Synchronous Machines

Synchronous Motors – Convert electrical power into mechanical power. They operate at a constant speed

Synchronous generator (Alternator) - Convert mechanical power into electrical power (3-phase). Constant speed of mechanical drive gives constant frequency ac

Basic Construction of Synchronous Machines



Stationary part of machine called the armature. Similar to induction motor stator

Rotating part of machine is electromagnet energized by a dc source and called the field

Operational Theory for Synchronous Machines

Motor Operation

1.) Armature is connected to 3-phase source - rotating magnetic field formed in armature windings

2.) Rotor (field) is energized by dc source. Creates a magnetic dipole

3.) Motor has no starting torque, must be started as induction motor. Damper windings engaged (induction motor action). Motor accelerates to almost synchronous speed.

4.) Damper winding disengaged, motor stays locked to rotating magnetic field and produces torque

Synchronous motors operate at constant speed regardless of load applied

Operational Theory for Synchronous Machines

Alternator Operation

1.) Prime mover attached to machine shaft.

2.) Dc supply applied to rotor to make magnetic dipole

3.) Prime mover accelerates machine to operating speed. Speed and number of poles determine frequency

4.) Armature (stationary winding) generate 3-phase voltages

Note: mechanical power input determines electrical power output exciter voltage level determines alternator terminal voltage

Synchronous Motor Operation

Motor speed constant at synchronous speed, n_s

$$n_s = \frac{120 \cdot f}{P}$$

Where f = power system frequency (Hz)
P = number of motor poles

Speed can only be changed by changing system f or number of poles in machine

Motor Reaction to Application Load Application

1.) Motor rotor is in phase with rotating armature (stator) field

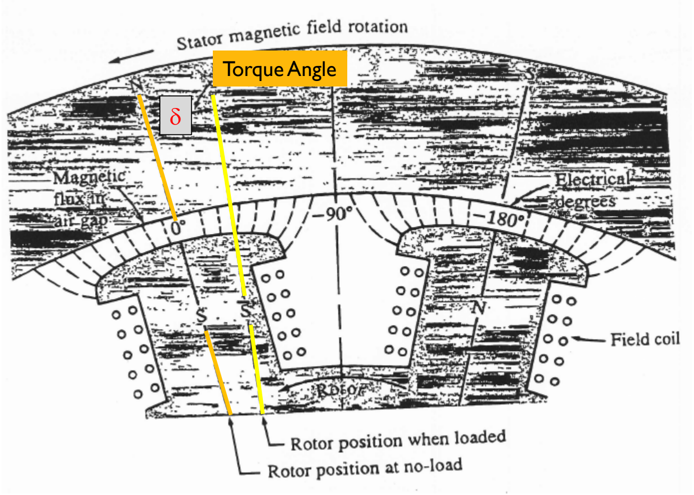
2.) Mechanical load is applied, rotor slows instantaneously then returns to n_s.

3.) Instantaneous speed reduction causes rotor to lag rotating field by an angle (phase shift) Angular shift called power angle (δ).

5.) Torque and power developed is related to angular shift

High values of δ will cause rotor to slip out of synchronization with rotating magnetic field. Condition called out-of-step operation or pole slipping (Causes current pulses in armature windings)

Synchronous Motor Operation

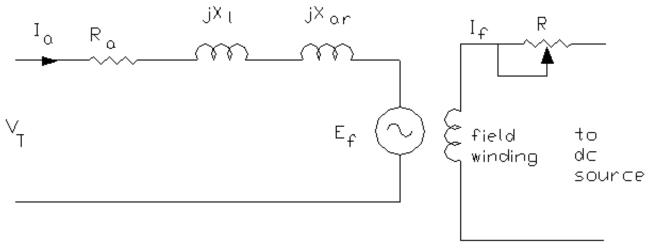


Counter-EMF Components in Synchronous Machines

Field flux induces voltage into armature (stator) due to rotation (E_f). E_f depends on I_f (dc field current) and n_s The parameter E_f , called excitation voltage.

Rotating magnetic field in armature (stator) induces voltage in armature called armature reaction voltage. (E_{ar}) This voltage depends on the speed of the rotating magnetic field produced by the applied voltage

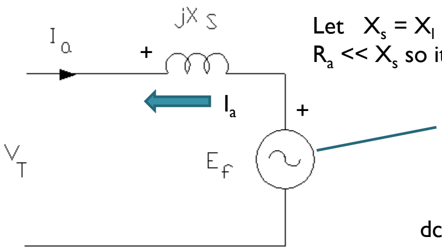
Per Phase Circuit Model



Motor Operation $\overline{V}_T = \overline{I}_a[R_a + j(X_l + X_{ar})] + \overline{E}_f$

Where: V_T = applied V /phase (phasor)
I_a = armature current (phasor)
X_l = armature leakage reactance ohms/phase
X_{ar} = armature-reaction reactance ohms/phase
R_a = armature resistance ohms/phase

Simplified Synchronous Machine Model



Let $X_s = X_l + X_{ar}$ = synchronous reactance
$R_a << X_s$ so it is usually ignored

E_f also called voltage behind synchronous reactance.

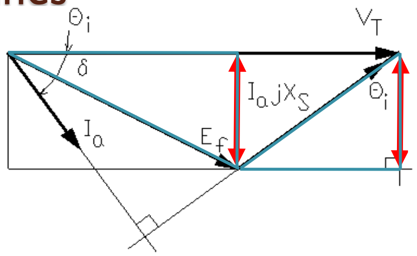
dc field is implied in this drawing

For alternator operation, reverse the direction of I_a

$\overline{V}_T = \overline{E}_f + \overline{I}_a \cdot jX_s$

Where V_T = per phase terminal voltage (phasor)
E_f = voltage behind synchronous reactance
I_a = armature current (phasor)
X_s = synchronous reactance

Power Transfer in Synchronous Machines



δ

E_f

$\left.\right\} E_f \sin(\delta)$

$I_a \cdot X$

θ_i

$\underbrace{\qquad\qquad}_{I_a \cdot X_s \cos(\theta_i)}$

From phasor diagram above $E_f \sin(\delta) = I_a \cdot X_s \cos(\theta_i)$

Power Transfer In Synchronous Machines

Multiplying the equation from the phasor diagram by V_T and dividing both sides by X_s gives power/phase.

$$\frac{|V_T| \cdot |E_f|}{|X_s|} \sin(\delta) = V_T \cdot I_a \cos(\theta_i)$$

Where: θ_i = machine power factor.

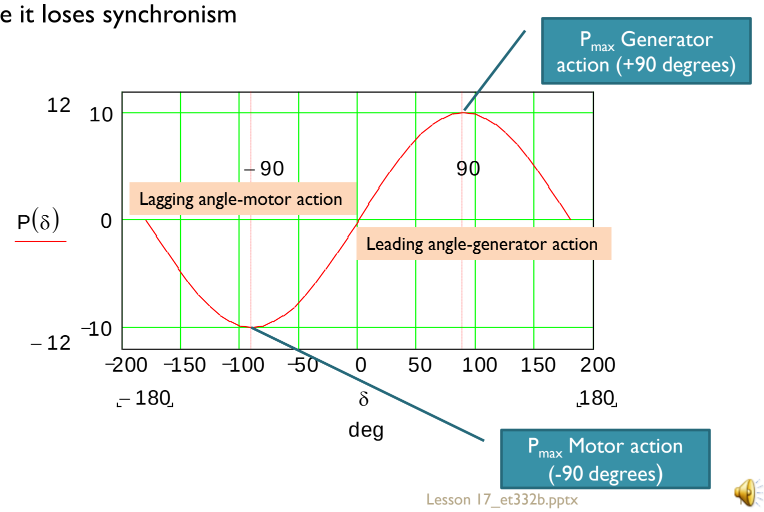
Total 3-phase power is

$$P_{in} = \frac{-3|V_T| \cdot |E_f|}{|X_s|} \sin(\delta)$$ In terms of machine quantities

$$P_{in} = -3V_T \cdot I_a \cos(\theta_i)$$ In terms of input quantities

Maximum Power Transfer in Synchronous Machines

There is a maximum power that a synchronous machine can develop before it loses synchronism



P_{max} Generator action (+90 degrees)

Lagging angle-motor action

Leading angle-generator action

P_{max} Motor action (-90 degrees)

Example 17-1: A 100 hp 460 volt 60 Hz 4-pole synchronous motor is operating at rated conditions and a power factor of 80% leading. The motor efficiency is 96% and the synchronous reactance is 2.72 ohms/phase. Find:

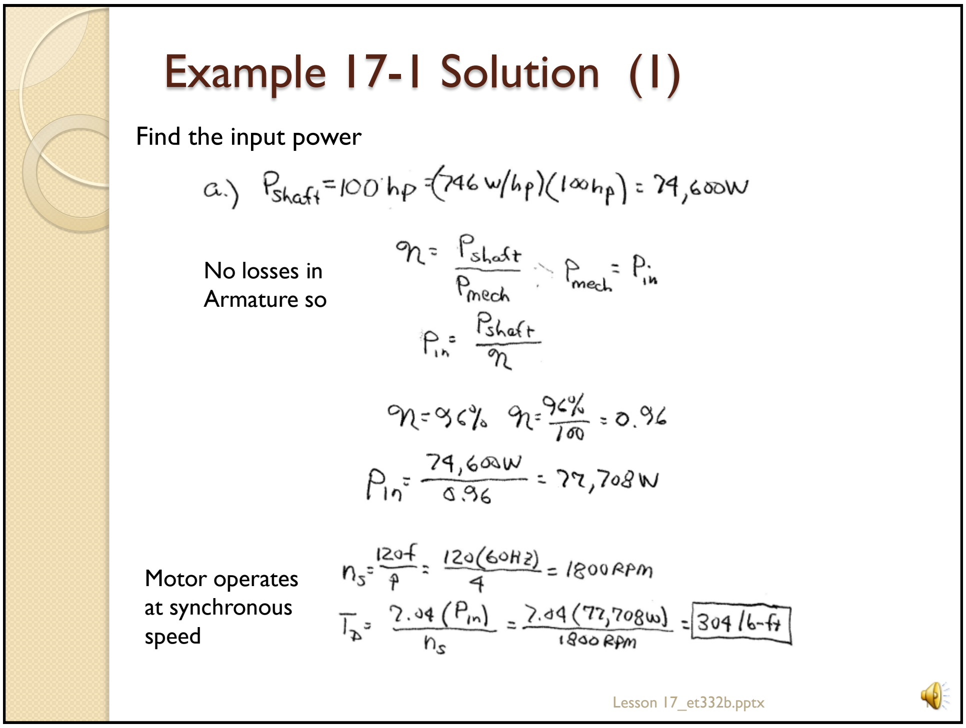
a.) developed torque;

b.) armature current;

c.) excitation voltage (E_f);

d.) power angle;

e.) the maximum torque the motor can develop without loss of synchronization. (pull-out torque).



Example 17-1 Solution (1)

Find the input power

$$a.)\quad P_{shaft} = 100\,hp = (746\,W/hp)(100\,hp) = 74{,}600\,W$$

No losses in Armature so

$$\eta = \frac{P_{shaft}}{P_{mech}} \quad \therefore \quad P_{mech} = P_{in}$$

$$P_{in} = \frac{P_{shaft}}{\eta}$$

$$\eta = 96\% \quad \eta = \frac{96\%}{100} = 0.96$$

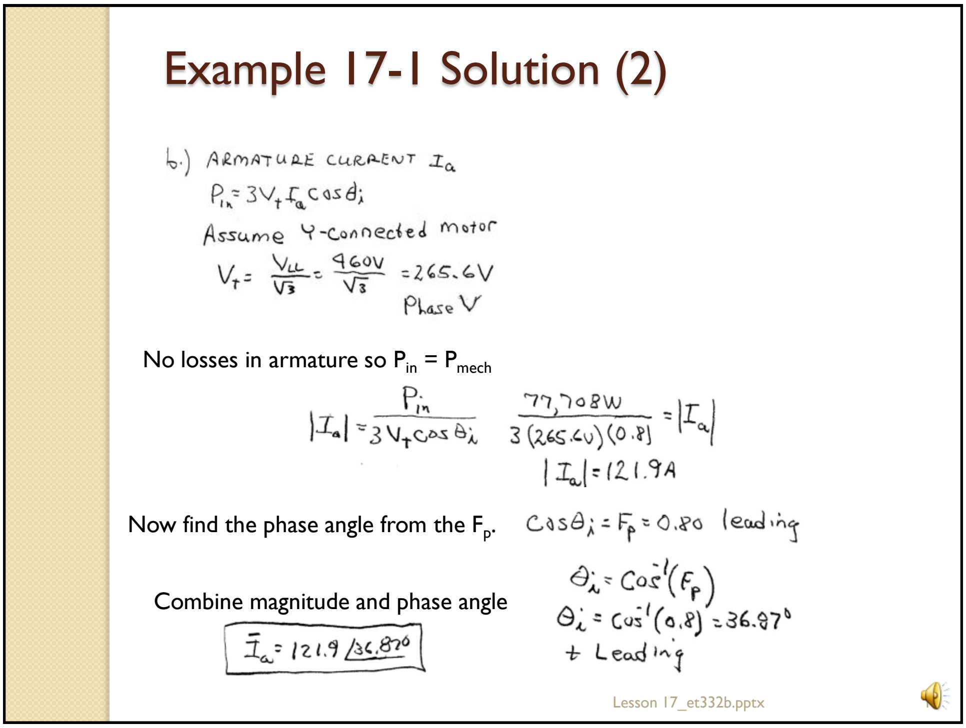
$$P_{in} = \frac{74{,}600\,W}{0.96} = 77{,}708\,W$$

Motor operates at synchronous speed

$$n_s = \frac{120f}{P} = \frac{120(60\,Hz)}{4} = 1800\,RPM$$

$$T_D = \frac{7.04\,(P_{in})}{n_s} = \frac{7.04\,(77{,}708\,W)}{1800\,RPM} = \boxed{304\ lb\text{-}ft}$$

Lesson 17_et332b.pptx



Example 17-1 Solution (2)

b.) ARMATURE CURRENT I_a

$$P_{in} = 3 V_T I_a \cos\theta_i$$

Assume Y-connected motor

$$V_T = \frac{V_{LL}}{\sqrt{3}} = \frac{460V}{\sqrt{3}} = 265.6V$$

Phase V

No losses in armature so $P_{in} = P_{mech}$

$$|I_a| = \frac{P_{in}}{3 V_T \cos\theta_i} \qquad \frac{77{,}708W}{3(265.6V)(0.8)} = |I_a|$$

$$|I_a| = 121.9A$$

Now find the phase angle from the F_p. $\cos\theta_i = F_p = 0.80$ leading

$$\theta_i = \cos^{-1}(F_p)$$

$$\theta_i = \cos^{-1}(0.8) = 36.87^\circ$$

+ Leading

Combine magnitude and phase angle

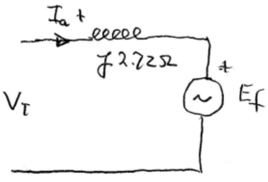
$$\boxed{\bar{I}_a = 121.9\angle 36.87^\circ}$$

Lesson 17_et332b.pptx

Example 17-1 Solution (3)

Find voltage behind synchronous reactance

c.)



$$\bar{E}_f = \bar{V}_T - \bar{I}_a X_s j$$

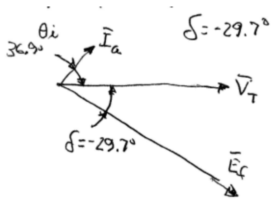
Assume that V_T is the reference phasor

$$\bar{E}_f = 265.6\angle 0^\circ - 121.9\angle 36.87^\circ\,(2.72\angle 90^\circ)$$

$$\bar{E}_f = 265.6\angle 0^\circ - 331.568\angle 126.9^\circ$$

$$\bar{E}_f = 534.9\angle -29.7^\circ$$

d.) Torque angle is the same as the angle on E_f



Example 17-1 Solution (4)

Now find the pullout torque

e.) Pullout or max Torque
occurs at P_{max} P_{max} OCCURS
at $\delta = -90^\circ$ (MOTOR ACTION)

$$P_{max} = \frac{-3|\bar{V}_T||\bar{E}_f|}{|X_s|}\sin\delta \qquad \sin(-90) = -1$$

$$P_{max} = \frac{-3(265.6)(534.9)}{2.72}(-1)$$

$$P_{max} = 156,694\text{ W}$$

Compute the torque from P_{max} and synchronous speed

$$T_{max} = \frac{7.04\,(P_{max})}{n_s} \qquad T_{max} = \frac{7.04\,(156,694\text{W})}{1800\text{ RPM}} = \boxed{613\text{ lb-ft}}$$

ET 332b
Ac Motors, Generators and Power Systems

END LESSON 17