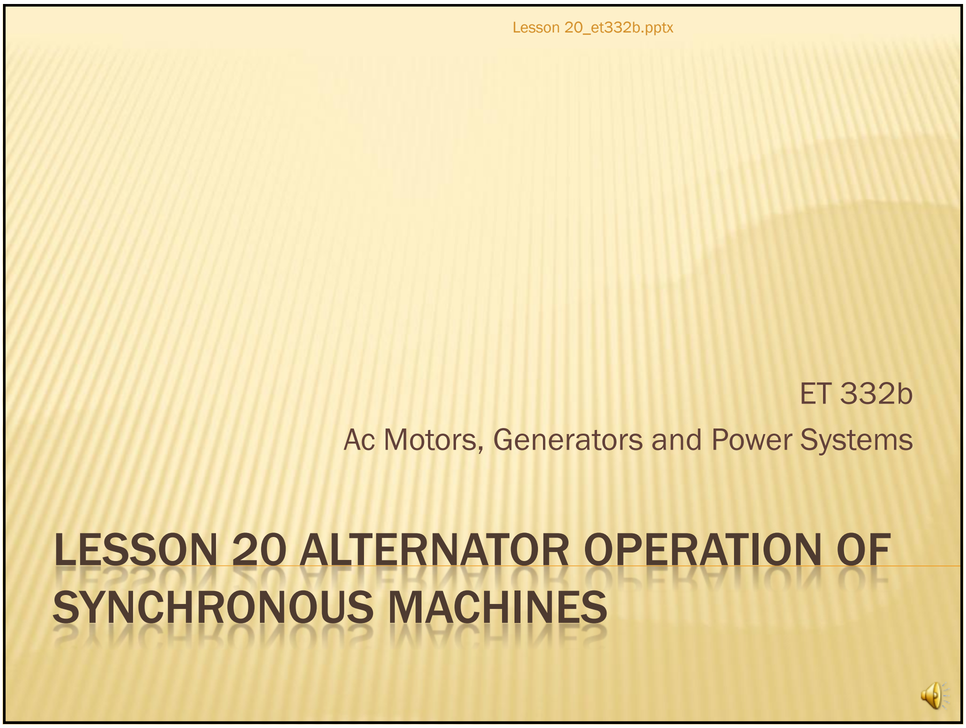
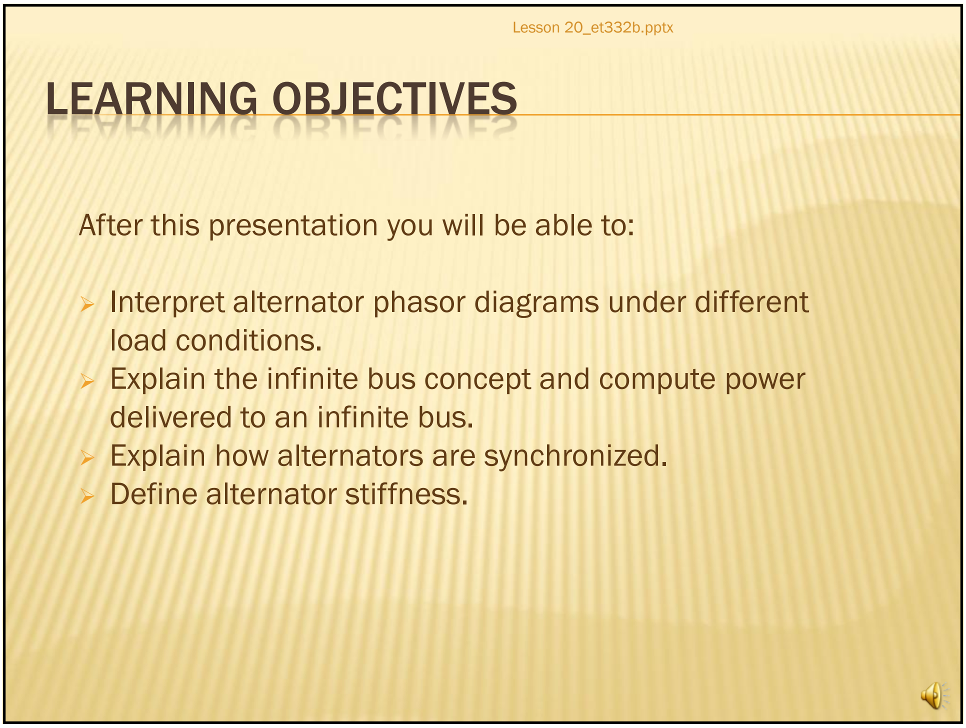


ET 332b
Ac Motors, Generators and Power Systems

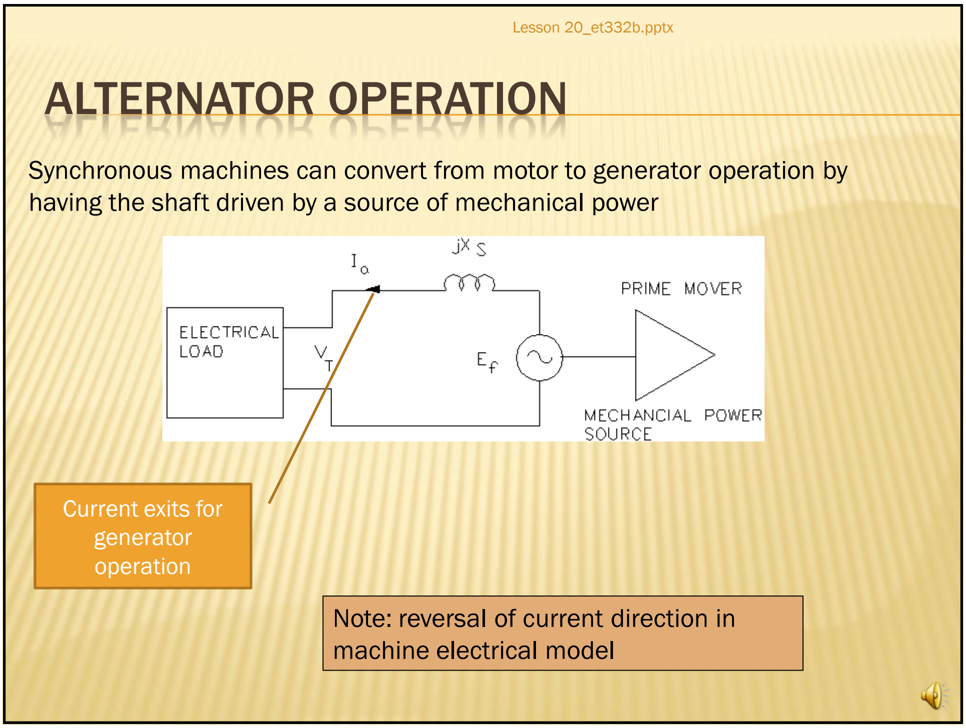
# LESSON 20 ALTERNATOR OPERATION OF SYNCHRONOUS MACHINES



## LEARNING OBJECTIVES

After this presentation you will be able to:

- Interpret alternator phasor diagrams under different load conditions.
- Explain the infinite bus concept and compute power delivered to an infinite bus.
- Explain how alternators are synchronized.
- Define alternator stiffness.



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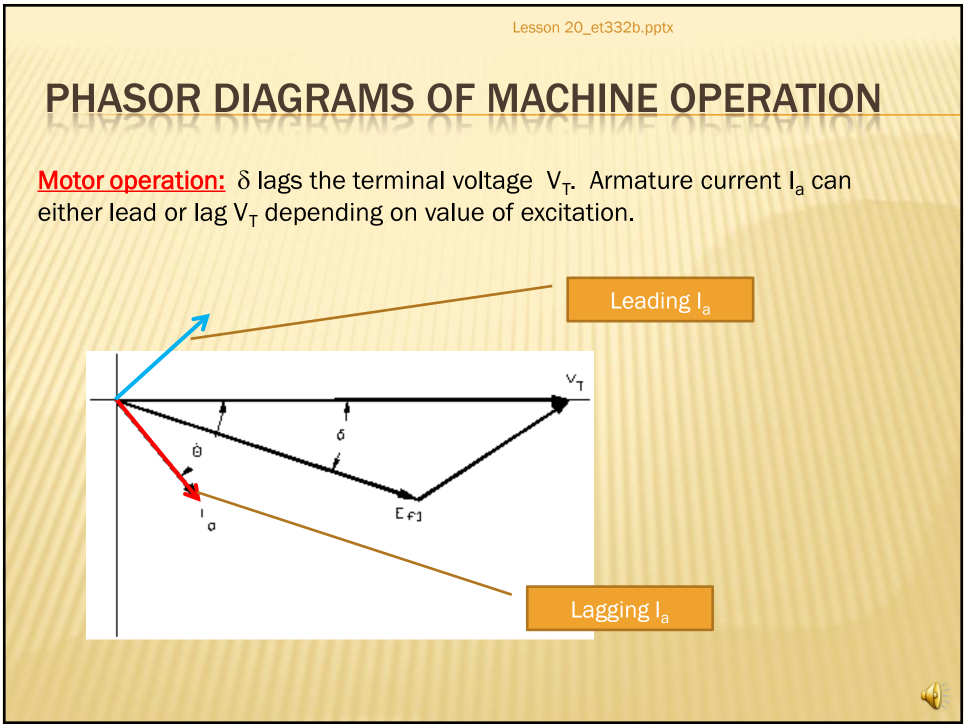
## ALTERNATOR OPERATION

Synchronous machines can convert from motor to generator operation by having the shaft driven by a source of mechanical power

Current exits for generator operation

Note: reversal of current direction in machine electrical model



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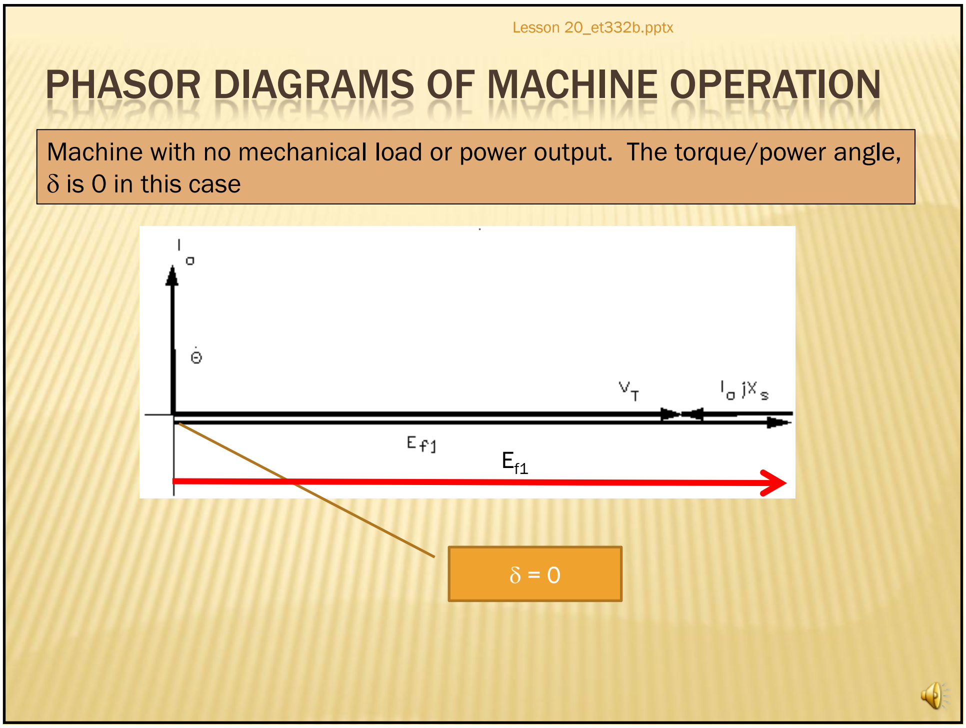
## PHASOR DIAGRAMS OF MACHINE OPERATION

**Motor operation:** $\delta$ lags the terminal voltage $V_T$. Armature current $I_a$ can either lead or lag $V_T$ depending on value of excitation.

Leading $I_a$

Lagging $I_a$



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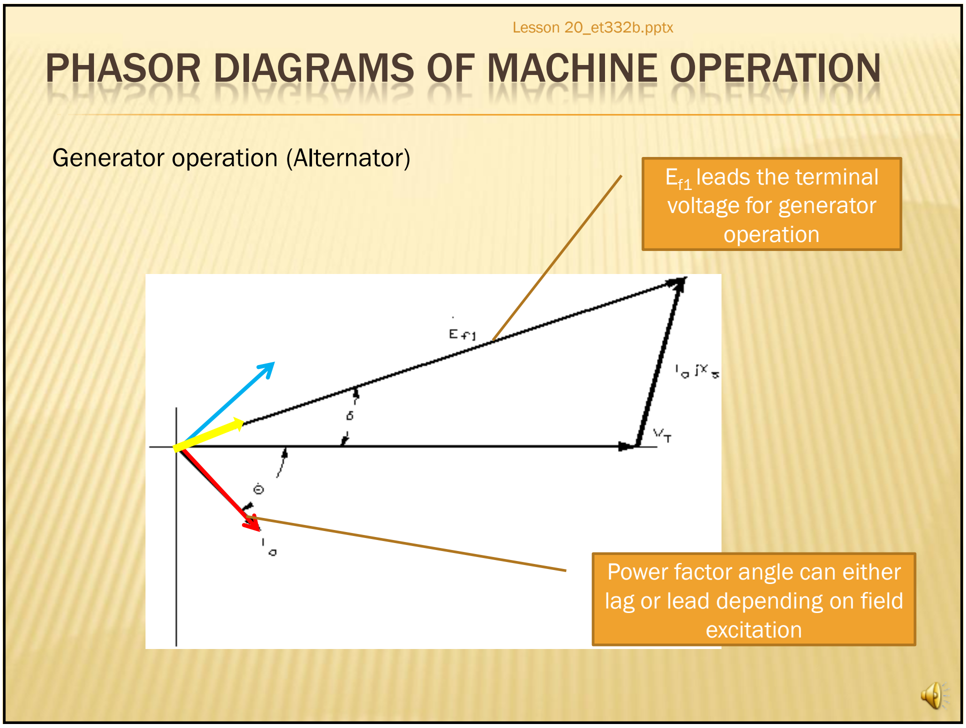
## PHASOR DIAGRAMS OF MACHINE OPERATION

Machine with no mechanical load or power output. The torque/power angle, δ is 0 in this case

δ = 0



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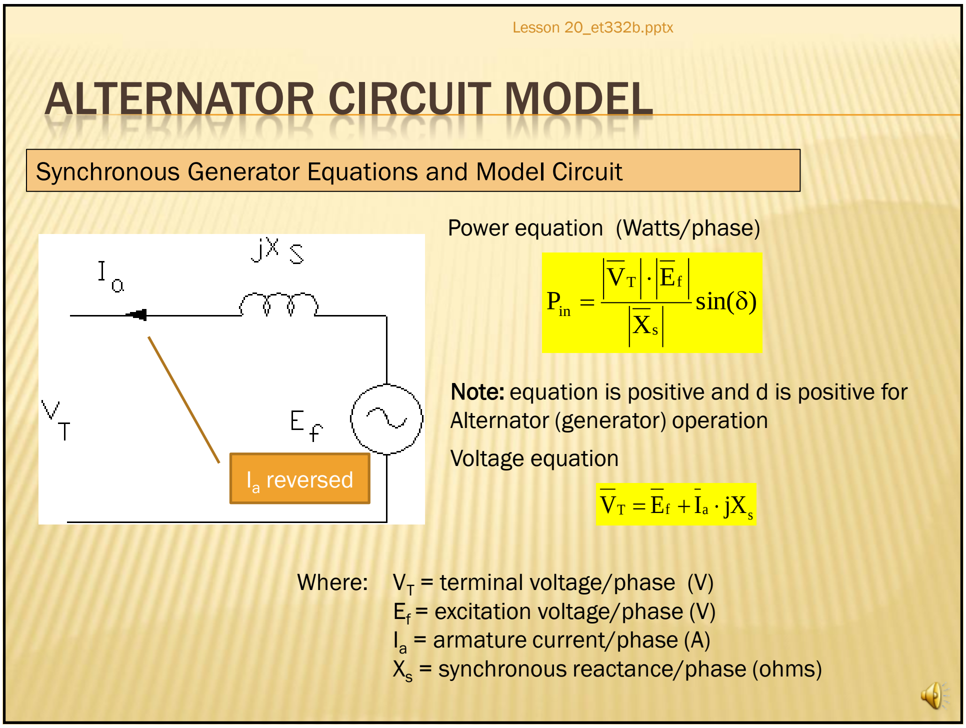
## PHASOR DIAGRAMS OF MACHINE OPERATION

Generator operation (Alternator)

$E_{f1}$ leads the terminal voltage for generator operation

Power factor angle can either lag or lead depending on field excitation



# ALTERNATOR CIRCUIT MODEL

Synchronous Generator Equations and Model Circuit

$I_a$ reversed

Power equation (Watts/phase)

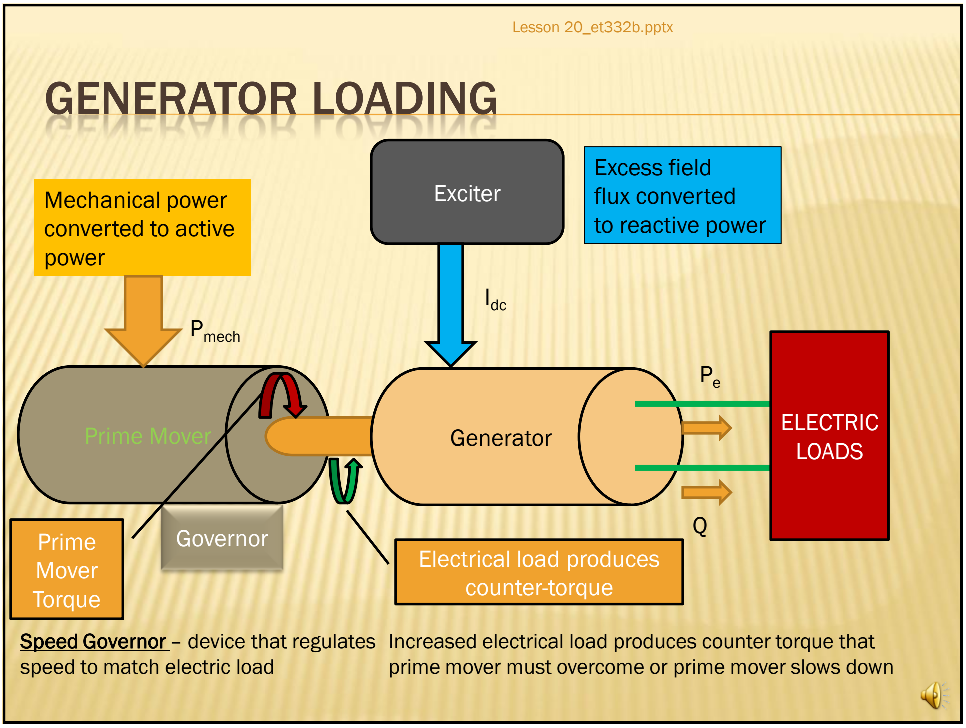
$$P_{in} = \frac{|\overline{V}_T|\cdot|\overline{E}_f|}{|\overline{X}_s|}\sin(\delta)$$

**Note:** equation is positive and d is positive for Alternator (generator) operation

Voltage equation

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

Where: $V_T$ = terminal voltage/phase (V)
$E_f$ = excitation voltage/phase (V)
$I_a$ = armature current/phase (A)
$X_s$ = synchronous reactance/phase (ohms)



# GENERATOR LOADING

Mechanical power converted to active power

Excess field flux converted to reactive power

Prime Mover Torque

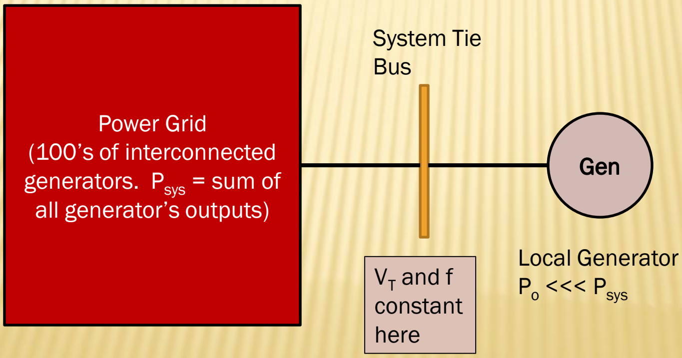
Electrical load produces counter-torque

**Speed Governor** – device that regulates speed to match electric load

Increased electrical load produces counter torque that prime mover must overcome or prime mover slows down

# INFINITE BUS CONCEPT

In large power systems, $V_T$ and system frequency are assumed constant. Individual generators added to large system can not change $V_T$ and f. Good approximation when generator small with respect to all other generation connected



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# INFINITE BUS EXAMPLE

**Example 20-1:** 3-phase, 460 V, 2-pole, 60 Hz, wye-connected, synchronous alternator. $X_s$ = 1.26 ohm/phase. Connected to an infinite bus and supplies 117 kW with a power angle of 25 degrees. Neglect losses and find:

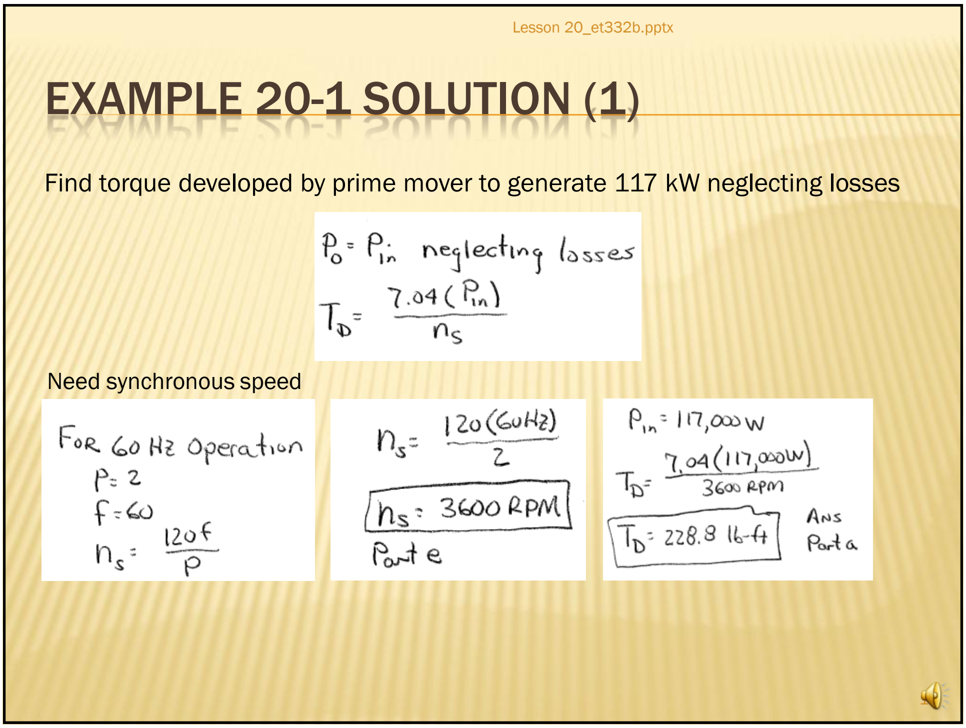
a.) turbine torque supplied to alternator;

b.) excitation voltage;

c.) active, reactive power and machine power factor;

d.) neglecting saturation effects of the field, the excitation voltage if the field current is reduced to 85% of its original value in part a;

e.) the turbine speed for 60 Hz operation



# EXAMPLE 20-1 SOLUTION (1)

Find torque developed by prime mover to generate 117 kW neglecting losses

$P_o = P_{in}$ neglecting losses

$$T_D = \frac{7.04(P_{in})}{n_s}$$

Need synchronous speed

For 60 Hz operation

$P = 2$

$f = 60$

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

$$n_s = \frac{120(60\text{ Hz})}{2}$$

$$\boxed{n_s = 3600\text{ RPM}}$$

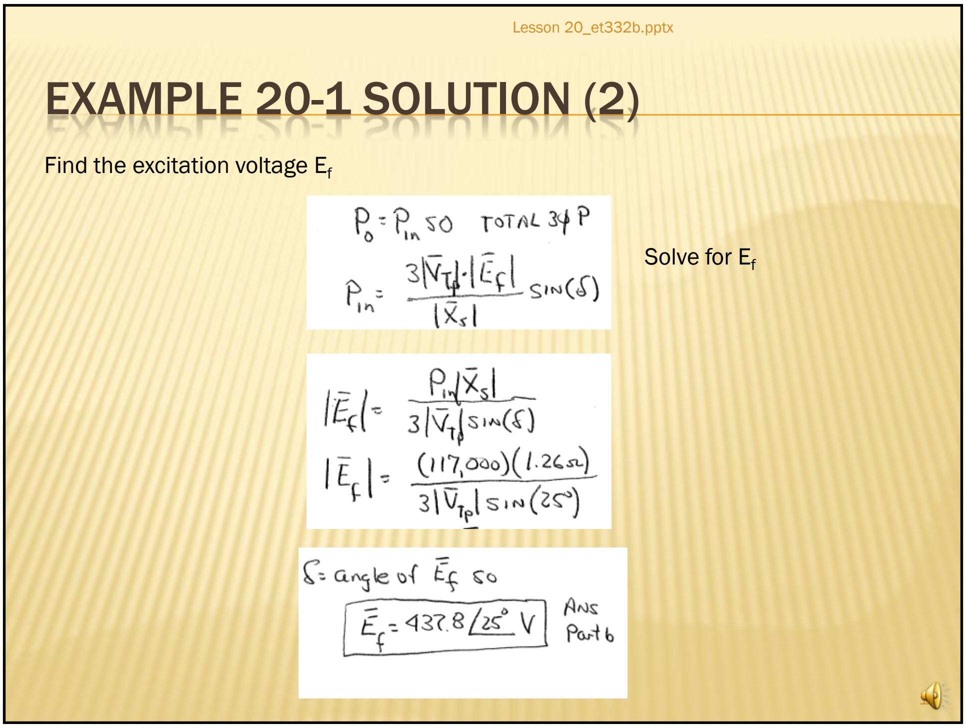
Part e

$P_{in} = 117{,}000\text{ W}$

$$T_D = \frac{7.04(117{,}000\text{ W})}{3600\text{ RPM}}$$

$$\boxed{T_D = 228.8\text{ lb-ft}}$$

ANS Part a



# EXAMPLE 20-1 SOLUTION (2)

Find the excitation voltage $E_f$

$P_o = P_{in}$ so TOTAL 3φ P

$$P_{in} = \frac{3|\bar{V}_{T\phi}|\cdot|\bar{E}_f|}{|\bar{X}_s|}\sin(\delta)$$

Solve for $E_f$

$$|\bar{E}_f| = \frac{P_{in}|\bar{X}_s|}{3|\bar{V}_{T\phi}|\sin(\delta)}$$

$$|\bar{E}_f| = \frac{(117{,}000)(1.26\,\Omega)}{3|\bar{V}_{T\phi}|\sin(25^\circ)}$$

$\delta$ = angle of $\bar{E}_f$ so

$$\boxed{\bar{E}_f = 437.8\angle 25^\circ\text{ V}}$$

ANS Part b

# EXAMPLE 20-1 SOLUTION (3)

Part c.) Find $S_{out}$ $P_{out}$ and $Q_{out}$ of generator. Need armature current

$\bar{S}_\phi = \bar{V}_{Tp}\bar{I}_a^*$

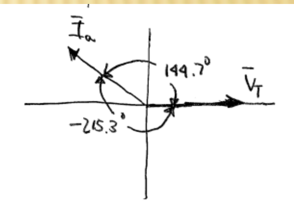
$\bar{V}_{Tp} = \bar{E}_f + \bar{I}_a jX_s$

Solve for $\bar{I}_a$

$$\frac{\bar{V}_{Tp} - \bar{E}_f}{jX_s} = \bar{I}_a$$

$jX_s = j1.26\ \Omega/\text{phase}$ $\bar{V}_{Tp} = 265.6\angle 0^\circ$

$$\bar{I}_a = \frac{\bar{V}_{Tp} - \bar{E}_f}{jX_s} = \frac{265.6\angle 0^\circ - 437.8\angle 25^\circ\ V}{j1.26\ \Omega} = \frac{226.83\angle -125.3}{1.26\angle 90^\circ}$$



$\bar{I}_a = 180\angle -215.3^\circ = 180\angle 144.7^\circ A$

$360 - 215.3^\circ = 144.7^\circ$

# EXAMPLE 20-1 SOLUTION (4)

Find the power phasor using the following formulas

$\bar{S}_\phi = \bar{V}_{Tp}\bar{I}_a^*$ PER PHASE

TOTAL POWER

$\bar{S}_T = 3\bar{V}_{Tp}\bar{I}_a^*$

$\bar{S}_T = 3(265.6\angle 0)(180\angle 144.7)^*$

$\bar{S}_T = 3(265.6\angle 0)(180\angle -144.7)$

$\bar{S}_T = 143,424\angle -144.7^\circ\ VA$

CONVERT TO RECTANGULAR

$\bar{S}_T = -117,000W - j82,971VAR$

$P = -117,000\ W$ Generator Delivery to System $Q = -82,971\ VAR$ NEG VARS DELIVERED TO SYSTEM

# EXAMPLE 20-1 SOLUTION (5)

Find the power factor and the change in excitation voltage

$$F_p = \frac{P_o}{|S_T|} = \frac{117{,}000\ W}{143{,}424\ VA}$$

$F_p = 0.816$ Leading

Part d $E_f$ for $I_f$ reduced to 85% of rated

Ignoring saturation $E_f \propto I_f$

$E_{f_2} = 0.85 E_{f_1}$ $|\bar{E}_{f_1}| = 432.8V$ Part B

$E_{f_2} = 0.85(432.8V) = \boxed{372.13V}$ Ans Part d

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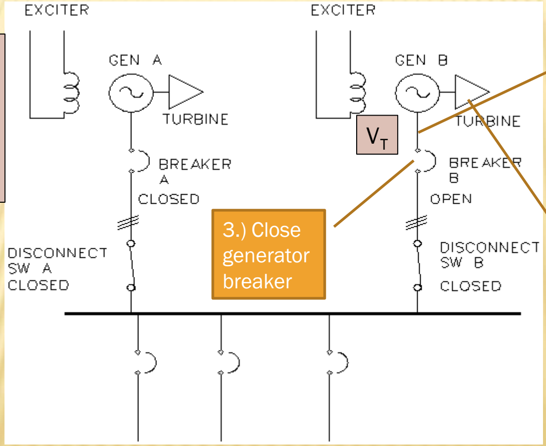
# PARALLELING SYNCHRONOUS GENERATORS

:**Required initial conditions** : Machines must have same phase sequence (order of voltages) (ABC) or (BAC). Incorrect phase sequence causes short circuit.



Turbine speed should be a fraction of Hz faster than system to prevent motoring of generator

1.) Adjust voltage of incoming machine to match system voltage

2.) Adjust frequency of incoming generator to match system f (Synchronize to system)

3.) Close generator breaker

# MEASURING SYSTEM/MACHINE FREQUENCY

**Synchroscope** - instrument to determine if machine frequency is the same as system frequency. Instrument indicates fast-slow operation by comparing the frequencies of the two voltages (system-generator)

Mathematically, phase shift is integral of frequency change

$$\phi = \int_0^t \left[ f_s \pm f_g(t) \right] dt$$

Where: $\phi$ = phase shift
$f_s$ = system frequency
$f_g(t)$ = generator frequency

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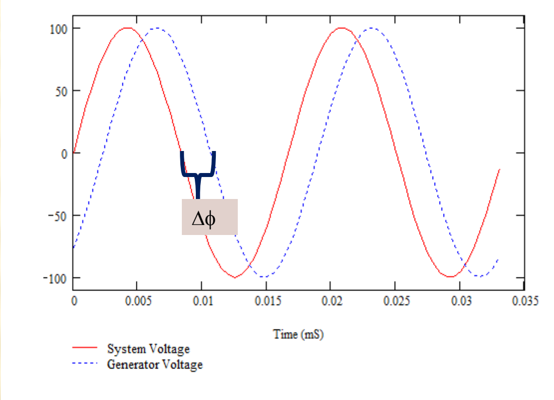
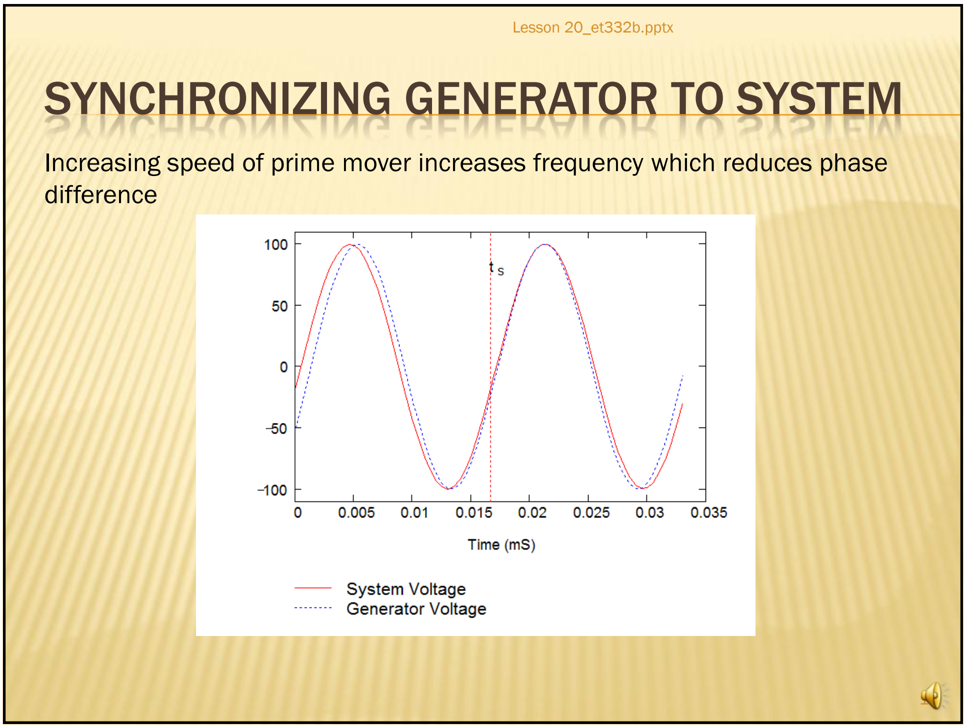
# SYNCH EXAMPLE

Generator voltage lagging system voltage - crosses zero later in time

Also cause rotor oscillations which cause the generator to be unstable



Closing Generator breaker with phase shifts of greater than 10 degrees causes high armature currents and will trip the generator off line



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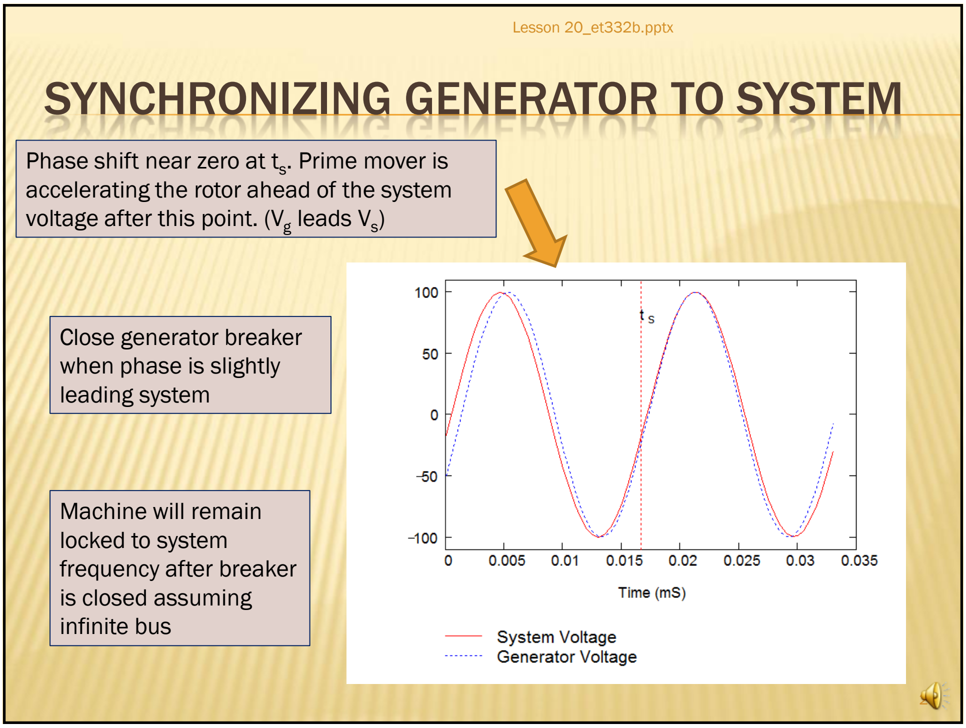
# SYNCHRONIZING GENERATOR TO SYSTEM

Increasing speed of prime mover increases frequency which reduces phase difference



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# SYNCHRONIZING GENERATOR TO SYSTEM

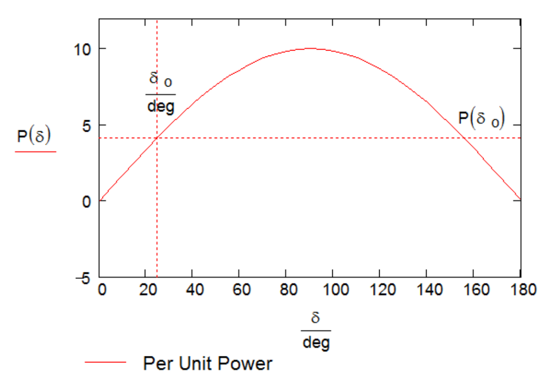
Phase shift near zero at $t_s$. Prime mover is accelerating the rotor ahead of the system voltage after this point. ($V_g$ leads $V_s$)

Close generator breaker when phase is slightly leading system

Machine will remain locked to system frequency after breaker is closed assuming infinite bus

# STIFFNESS OF SYNCHRONOUS MACHINES

**Stiffness** -Ability of a synchronous machine to resist forces that pull it out of synchronism. Slope of the power-angle curve around a given operating point



Operating point in graph above is at $\delta_o$

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# STIFFNESS OF SYNCHRONOUS MACHINES

Remember power equation

$$P = \frac{3 \cdot |\overline{V}_T| \cdot |\overline{E}_f|}{|\overline{X}_s|} \sin(\delta)$$

To find slope, take derivative of P with respect to δ. This is defined as the stiffness

$$P_s = \frac{\Delta P}{\Delta \delta} = \frac{dP}{d\delta} = \frac{3 \cdot |\overline{V}_T| \cdot |\overline{E}_f|}{|\overline{X}_s|} \cos(\delta)$$

Units of $P_s$ are watts/radian (or degree)

# STIFFNESS OF SYNCHRONOUS MACHINES

**Example 20-2:** A 3-phase 13.2 kV 60 Hz, 50 MVA wye-connected cylindrical rotor synchronous generator has $X_s$ = 2.49 ohms/phase and an internally generated voltage at the operating point of 15,767 $V_{LL}$ with a power angle of 11.1 degrees. The machine has 8 poles. Determine:

a.) the synchronizing power in MW/rad and MW/ mechanical degree
b.) synchronizing torque in N-n/radian

# EXAMPLE 20-2 SOLUTION (1)

Find the per phase quantities of $V_T$ and $E_f$ from the line-to-line values

$$V_{LL} = 13200 \cdot V$$

$$V_T = \frac{13200 \cdot V}{\sqrt{3}}$$

$$V_T = 7621\,V$$

$$E_{fL} = 15877 \cdot V$$

$$E_f = \frac{15767 \cdot V}{\sqrt{3}}$$

$$E_f = 9103$$

$$X_s = 2.49 \cdot \text{ohm}$$

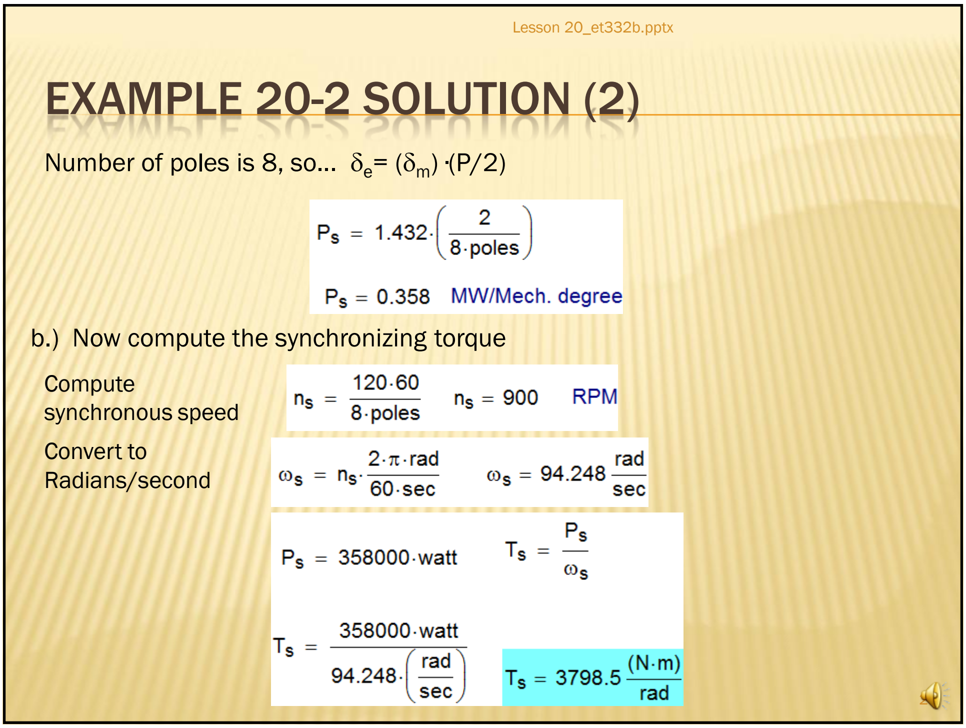
$$\delta = 11.1 \cdot \text{deg}$$

$$P_s = \left[\frac{[3 \cdot (7621 \cdot V)(9103 \cdot V)]}{2.49 \cdot \text{ohm}}\right] \cdot \cos(11.1 \cdot \text{deg})$$ Watts

$$P_s = 82.019 \frac{MW}{rad}$$ scaled to MW

Convert to degrees

$$82.02 \cdot \frac{\pi}{180} = 1.432$$ MW/elec. degree



# EXAMPLE 20-2 SOLUTION (2)

Number of poles is 8, so… $\delta_e = (\delta_m) \cdot (P/2)$

$$P_s = 1.432 \cdot \left( \frac{2}{8 \cdot \text{poles}} \right)$$

$$P_s = 0.358 \quad \text{MW/Mech. degree}$$

b.) Now compute the synchronizing torque

Compute synchronous speed

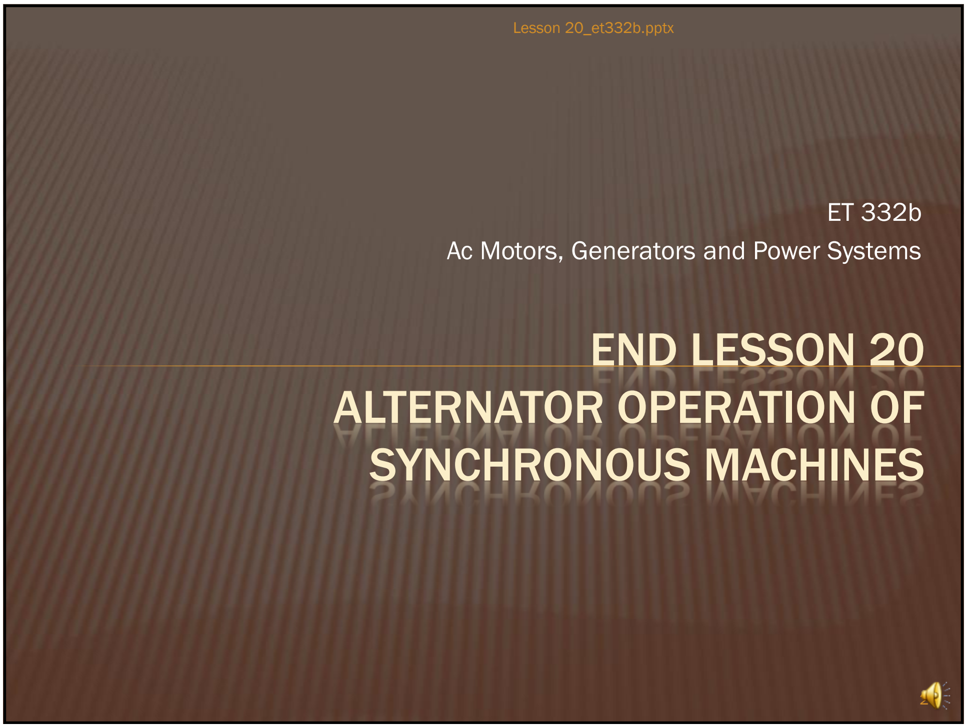
$$n_s = \frac{120 \cdot 60}{8 \cdot \text{poles}} \qquad n_s = 900 \quad \text{RPM}$$

Convert to Radians/second

$$\omega_s = n_s \cdot \frac{2 \cdot \pi \cdot \text{rad}}{60 \cdot \text{sec}} \qquad \omega_s = 94.248 \frac{\text{rad}}{\text{sec}}$$

$$P_s = 358000 \cdot \text{watt} \qquad T_s = \frac{P_s}{\omega_s}$$

$$T_s = \frac{358000 \cdot \text{watt}}{94.248 \cdot \left( \frac{\text{rad}}{\text{sec}} \right)} \qquad T_s = 3798.5 \frac{(\text{N} \cdot \text{m})}{\text{rad}}$$



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# END LESSON 20
# ALTERNATOR OPERATION OF SYNCHRONOUS MACHINES