Welcome to

Electric Machines & Drives

thomasblairpe.com/EMD

Thomas Blair, P.E.
USF Polytechnic – Engineering
tom@thomasblairpe.com

Session 7: Synchronous Motors & Generators

Fall 2011

Session 7

- **Chapter 16 – Synchronous Generators**
- **Chapter 17 – Synchronous Motors**

Chapter 16 – Synchronous Generators

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

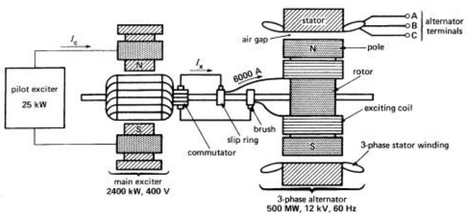
Chapter 16

Stationary Field generator < 5kva
stationary field – rotating armature
slip ring connection to armature
Rotating Field generator (alternator) > 5kva
stationary armature – rotating field
slip ring connection to field

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

DC generator for field generation of Synchronous Generator



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

One complete cycle every time pole pair passed ->
Frequency generated is:
f = p n / 120

f = frequency of the induced voltage (Hz)
p = number of poles on rotor
n = speed of the rotor (rpm)

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Example 16-1

A hydraulic turbine turning at 200 rpm is connected to a synchronous generator. If the induced voltage has a frequency of 60 Hz, how many poles does the rotor have?

Chapter 16

Stator Features: Identical to 3 phase motor
Stacked laminations
Always connected in wye for following reasons:

Voltage per coil 58% line voltage
Third harmonic voltages cancel (same in each phase), in delta they add and cause circulating current.

Max term voltage typically 25kv.

Chapter 16

Rotor Features:
High speed slotted cylindrical forging
Smaller diameter – centrifugal forces
Longer to get air gap area needed for power
Retaining ring – insulated
Low speed typically salient pole
Larger diameter – lower speed – more poles
Shorter due to more air gap area per foot length
Coils in series (mica strip insulation)
Squirrel cage in pole faces (damper winding) for transient dampening

Chapter 16

Field Excitation - typically .5% to 2% machine rating
Two functions

1. maintain ac line voltage
2. provide reactive power to system

Slip ring and Brush exciter

1. provided by DC generator on same shaft
2. Provided by MG set separately driven
3. Provided by separate sourced solid state rectifier

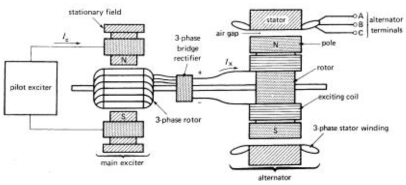
Chapter 16

Brushless exciter

1. Provided by PMG same shaft via separate sourced solid state rectifier to alternator on shaft
2. Provided by external source via solid state rectifier to alternator on shaft.

Chapter 16

Brushless exciter – Less maintenance
Ic controls field current
Frequency > main frequency



Chapter 16

Size of synchronous generators:
Larger size -> higher efficiency
Power per KG greater (more power per $)
Cooling of large machines challenge
Indirectly cooled winding
Gas intercooled winding
Water cooled winding

13

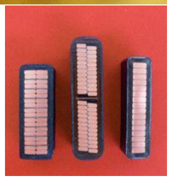
Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Gas intercooled

Water intercooled

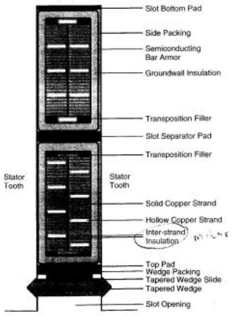
Indirectly Cooled



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Strand insulation – reduce eddy current in conductor



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Robel Transposition – equalize magnetic reactance of each conductor

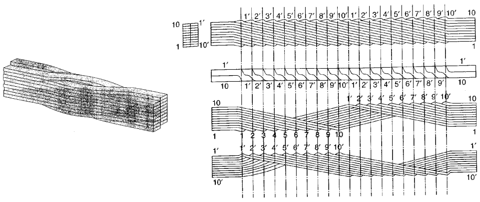
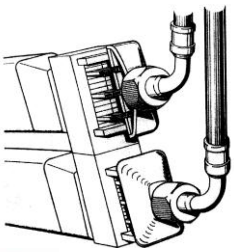


Fig. 2.21 Roebel transposition map. (Courtesy of Alstom Power Inc.).

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

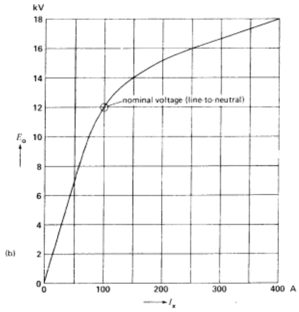
Chapter 16

Connection to liquid cooling system.



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

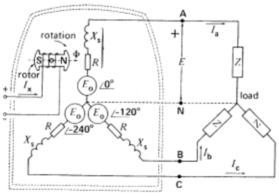
No Load Saturation Curve



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Resistive element & Inductive element
X >> R
Simplify by neglect R

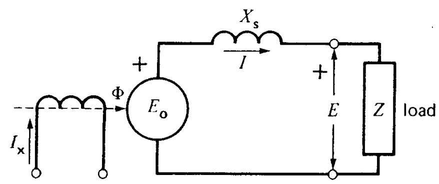


USF UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Simplified SLE circuit for Synchronous Generator



USF UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Synchronous Reactance

Xs = 2 π f L

Xs = Synchronous reactance per phase (Ω)
F = generator frequency (Hz)
L = apparent inductance of stator winding per phase

21

USF UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Measurement of Xs
Open circuit test – rated speed and open terminals, excitation raised to meet rated V (En). This is value of (Ixn)
Short Circuit test – rated speed and shorted terminals, excitation raised back to Ixn, and armature current measured (value of Isc)

22

USF UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Xs = En / Isc

Xs = synchronous reactance pwer phase (Ω)
En = rated open circuit line to neutral voltage (V)

23

USF UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Example 16-2

A 3 phase synchronous generator produces an open circuit line voltage of 6928 V when the dc exciting current is 50A. The ac terminals are then short circuited and the three line currents are found to be 800A. Calculate;

a. The synchronous reactance per phase
b. The terminal voltage if three 12 Ω resistors are connected in wye across the terminals.

24

USF UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Base impedance –
Use rated LINE TO NEUTRAL voltage (Eb) and rated power (S) PER PHASE

$Zb = Eb^2 / Sb$

Zb = base impedance (line to neutral) of the generator (Ω)
Eb = base voltage (line to neutral (V)
Sb = base power per phase (VA)

Example 16-3

A 30 MVA, 15kV, 60 Hz ac generator has a synchronous reactance of 1.2 pu and a resistance of 0.02 pu. Calculate

a. The base voltage, base power and base impedance of the generator
b. The actual value of the synchronous reactance
c. The actual winding resistance, per phase
d. The total full load copper losses

Chapter 16

Short Circuit Ratio (SCR) –
Ratio of Ix1 to Ix2, where Ix1 is field current to produce nominal open circuit voltage and Ix2 is field current to produce nominal armature current on short circuited terminals (steady state)

Xs (pu) = (Ix2 / Ix1) = 1/SCR

Chapter 16

Generator supplying lagging load - Lagging PF,
I leads E,
E(Xs) leads I by 90 degrees,
Eo = E + Ex, therefore Eo > E,
Angle between E and Eo is power angle (δ)

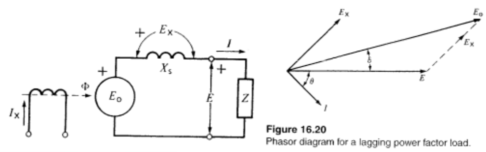


Figure 16.20
Phasor diagram for a lagging power factor load.

Chapter 16

Generator supplying leading load - Leading PF,
I lags E,
E(Xs) leads I by 90 degrees,
Eo = E + Ex, therefore Eo < E,
Angle between E and Eo is power angle (δ)
Note same power angle as before.

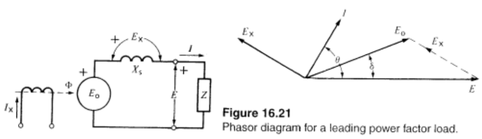


Figure 16.21
Phasor diagram for a leading power factor load.

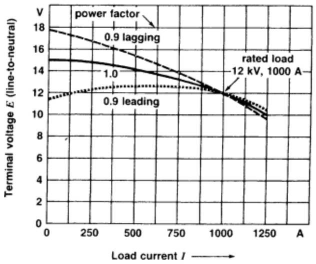
Example 16-4

A 36 MVA, 20.8 kV, 3 phase alternator has a synchronous reactance of 9 Ω and a nominal current of 1 kA. The no load saturation curve giving the relationship between Eo and Ix is given in Fig 16.13b. If the excitation is adjusted so that the terminal voltage remains fixed at 21 kV, calculate the exciting current required and draw the phasor diagram for the following conditions;

a. No load
b. Resistive load of 36 MW
c. Capacitive load of 12 Mvar

Chapter 16

Voltage regulation vs. load PF
Eo Fixed at rated load



Chapter 16

Percent Regulation is defined as:

% regulation = 100% (Enl = Eb) / Eb

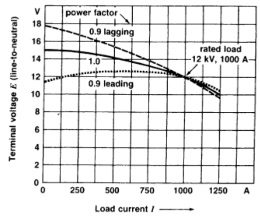
Enl = no load voltage (V)
Eb = rated voltage (V)

Example 16-5

Generator Synchronization:
1. Generator Frequency = System Frequency (preferred slightly faster) WHY?
2. Generator Voltage Magnitude = System Voltage Magnitude (preferred slightly higher) WHY?
3. Generator Voltage Phase Angle = System Voltage Phase Angle (breaker closing time added to calculation)
4. Generator Phase sequence = System Phase Sequence

Chapter 16

Calculate the percent regulation corresponding to the unity power factor curve in figure below.



Chapter 16

Infinite Bus Characteristics:
1.Adjusting excitation adjusts Eo – controls VAR flow.
2.Adjusting mechanical torque adjusts power angle δ – control watts flow.

Chapter 16

Zero current, E in phase with Eo

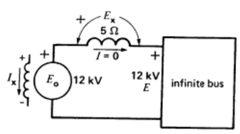
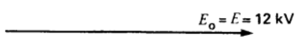


Figure 16.26a
Generator *floating* on an infinite bus.



Chapter 16

Overexcited System looks like Inductive Load – I lags E
Ex in phase with E
E + Ex = Eo
Var transfer to system

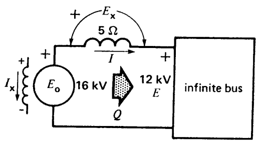
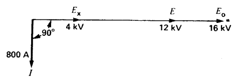


Figure 16.26b
Over-excited generator on an infinite bus



Chapter 16

Under excited System looks like Capacitive Load – I leads E
Ex 180O out of phase with E
E + Ex = Eo
Var transfer to generator

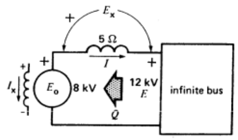
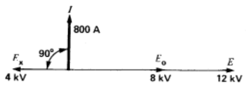
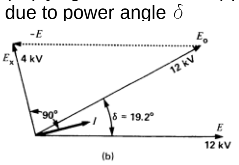


Figure 16.26c
Under-excited generator on an infinite bus.



Chapter 16

Increasing Torque,
Eo advances ahead of E,
increased power angle δ,
NOTE: even though E and Eo have same magnitude (implying no VAR transfer) power is still transferred due to power angle δ



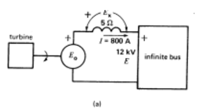
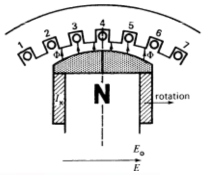
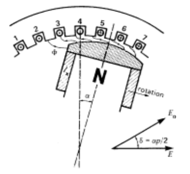


Figure 16.27
a. Turbine driving the generator.
b. Phasor diagram showing the torque angle δ.

Chapter 16

Rotor Position – no load to full load – Torque by prime mover advances rotor position





Chapter 16

Mechanical angle of rotor pole to stator pole related to power angle by: (Note for 2 pole generator, $\alpha = \delta$)

$\delta = \alpha$ (p/2)

δ = torque angle between the terminal voltage E and excitation voltage Eo (electrical degrees)
P = number of poles on generator
α = mechanical angle between the centers of the stator and rotor poles (mechanical degrees)

Example 16-6

The rotor poles of an 8 pole synchronous generator shift by 10 mechanical degrees from no load to full load.

a. Calculate the torque angle between Eo and the terminal voltage E at full load.
b. Which voltage, E or Eo is leading?

Chapter 16

For Proof of equation, see web site;
http://www.thomasblairpe.com/EMD/PPE_PWR_XFER.pdf

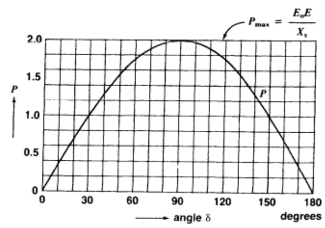
P = [(Eo E) / Xs] sin δ

P = active power per phase (W)
Eo = induced voltage per phase (V)
E = terminal voltage per phase (V)
δ = torque angle between Eo and E (Degrees)

Chapter 16

Rated power typically around 30^{O} – Power angle > 90^{O} cause pole slip and out of synch condition.

Curve different for salient pole machine



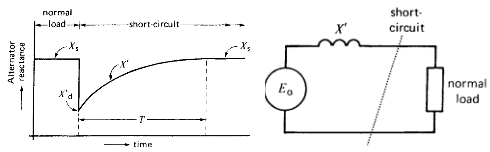
Example 16-7

A 36 MVA, 21kV, 1800 rpm, 3 phase generator connected to a power grid has a synchronous reactance of 9 Ω per phase. If the exciting voltage is 12 kV (lien to neutral) and the system voltage is 17.3 kV (line to line), calculate the following:

a. The active power which the machine delivers when the torque angle δ is 30^{O} (electrical)
b. The peak power that the generator can deliver before it falls out of step.

Chapter 16

Transient reactance vs synchronous reactance 0.15PU typical – breaker interrupt capability – better voltage regulation during transient



Example 16-8

A 250 MVA, 25 kV, 3 phase steam turbine generator has a synchronous reactance of 1.6 pu and a transient reactance X'd of 0.23 pu. It delivers its rated output at a power factor of 100%. A short circuit suddenly occurs on the line, close to the generating station. Calculate

a. The induced voltage Eo prior to the short
b. The initial value of the short circuit current
c. The final value of the short circuit current if the circuit breakers should fail to open.

Chapter 16

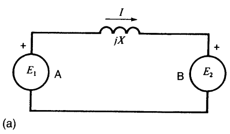
Power flow between 2 machines:
Power flow from leading voltage to lagging voltage (regardless of magnitude)

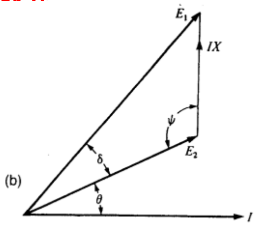
P = [(E1 E2) / X] sin δ

P = active power transmitted (W)
E1 = voltage of source 1 (V)
E2 = voltage of source 2 (V)
δ = torque angle between E1 and E2 (Degrees)

Chapter 16

P = [(E1 E2) / X] sin δ





Chapter 16

Referring to fig. 16.33a, source A generates a voltage E1 = 20 kV /_ 5^{O} and source B generates a voltage E2 = 15 kV /_ 42^{O} and source. The transmission line connecting them has an inductive reactance of 14 Ω. Calculate the active power that flows over the line and specify which source is actually a load.

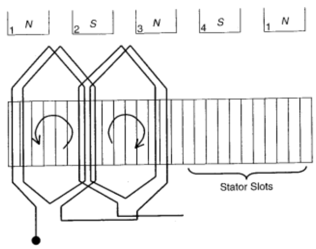
Chapter 16

As machine size increases, efficiency increases
Larger machines produce more power / KG material ($)
Temperature rise challenge – cooling more complex

η = 100% (Po/Pi)

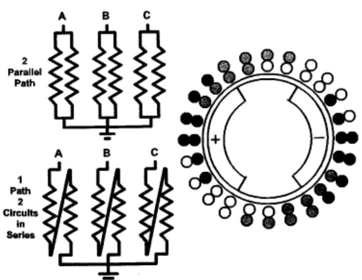
Chapter 16

Coil installation:



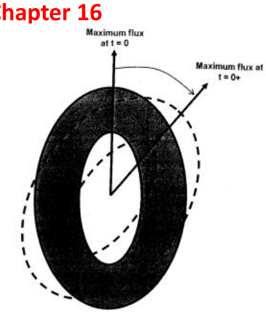
Chapter 16

Coils may be series or parallel



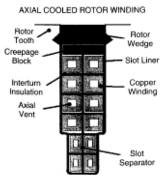
Chapter 16

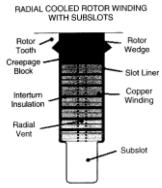
2 pole machines oscillate at 2X line frequency – core mounting absorbs vibration

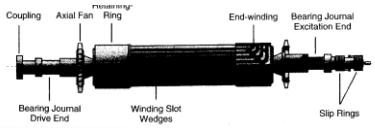


Chapter 16

Cylindrical Rotor Construction





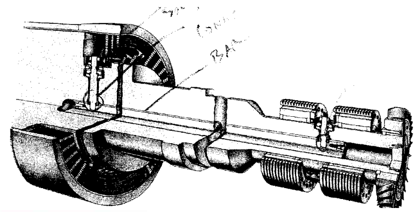


UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Bore Copper and terminal stud connector for DC field circuit

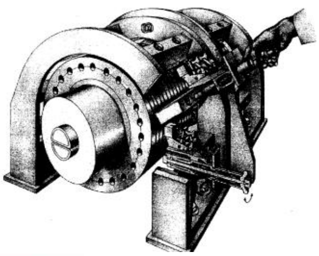


UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Typical Brush gear for DC field circuit

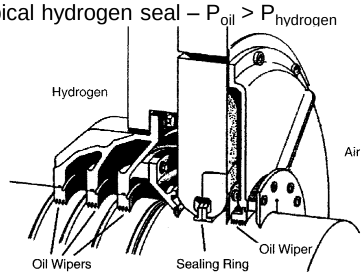


UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

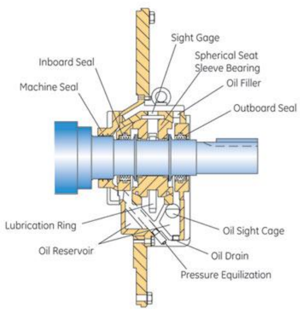
Chapter 16

Typical hydrogen seal – $P_{oil} > P_{hydrogen}$



UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

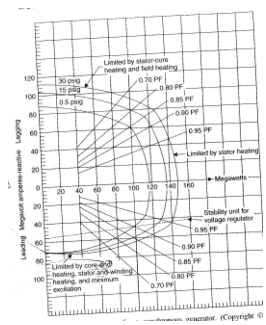


UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

Generator Capability Curve

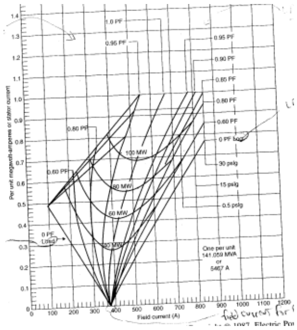


UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 16

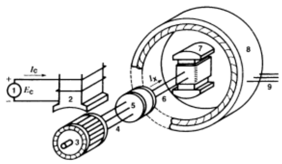
V-Curve – Apparent power to Field current for various power loading



Chapter 17 – Synchronous Motors

Chapter 17

Construction similar to Synchronous Generator
Stator slotted wedges
Rotor Salient Poles – damper winding imbedded in pole face



1 - dc control source
2 - stationary exciter poles
3 - alternator (3-phase exciter)
4 - 3-phase connection
5 - bridge rectifier
6 - dc line
7 - rotor of synchronous motor
8 - stator of synchronous motor
9 - 3-phase input to stator

Example 17-1

Calculate the number of salient poles on the rotor of the synchronous motor rated at 4000 HP (3000 kW), 200 rpm, 6.9 kV, 60 Hz, 80% power factor. The brushless exciter is rated at 50 kW, 250 V.

Chapter 17

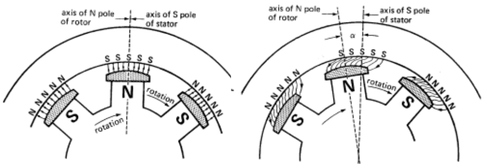
Starting Synchronous motor – amortisseur winding
Short field winding during start - Limit induced voltage on field winding & improve starting torque
Also reduced voltage start or pony motor start
VFD also used for starting very large synchronous motor (and combustion turbine generators)

Chapter 17

Pull in torque – Applying DC to field generates field – pulls rotor into synch with stator field (pull in torque)
Detection of position of rotor pole position important
When in synch, amortisseur winding sees no slip -> no voltage induced in winding

Chapter 17

As Load increase α increases. Pull out torque, value at which poles slip. Value depends on mmf of rotor and stator – depend on field and armature current.



Chapter 17

Motor under load calculations:

Chapter 17

E = Ex + Eo

Note δ still between E and Eo, but Eo now lags E (unlike generator)

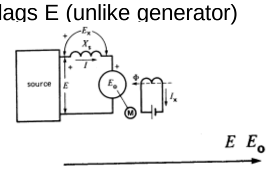


Figure 17.7b
Motor at no-load, with E_o adjusted to equal E.

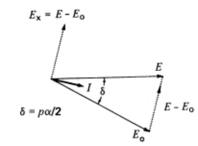


Figure 17.7c
Motor under load E_o has the same value as in Fig. 17.7b, but it lags behind E.

Example 17-2a

A 500 HP, 720 rpm synchronous motor connected to a 3980V, 3 phase line generates an excitation voltage Eo of 1790 V (line to neutral) when the dc exciting current is 25 A. The synchronous reactance is 22 Ω and the torque angle between Eo and E is 30°. Calculate;

a. The value of Ex
b. The ac line current
c. The power factor of the motor
d. The approximate HP developed by the motor
e. The approximate torque developed at the shaft.

Example 17-2b

The motor in example 17-2a has a stator resistance of 0.64 Ω per phase and possesses the following losses:.

I2R loss in rotor	3.2 kW
Stator iron loss	3.3 kW
Windage / friction loss	1.5 kW

Calculate

a. The actual HP developed
b. The actual torque developed at the shaft
c. The efficiency of the motor.

Chapter 16

Power & Torque

P = [(Eo E) / Xs] sin δ

Pmax = (Eo E) / Xs

P = mechanical power of motor per phase (W)
Eo = line to neutral voltage induced by Ix (V)
E = line to neutral voltage of source (V)
Xs = synchronous reactance per phase (Ω)
δ = torque angle between Eo and E (Degrees)

Chapter 16

Power & Torque

$T = 9.55\ P / ns$

T = torque per phase (N m)
P = mechanical power per phase (W)
ns = synchronous speed (rpm)

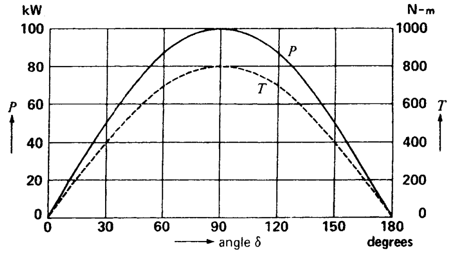
Example 17-3

A 150 kW, 1200 rpm, 460V 3 phase synchronous motor has a synchronous reactance of 0.8 Ω per phase. If the excitation voltage Eo is fixed at 300V per phase, determine the following;

a. The power verses δ curve
b. The torque versus δ curve
c. The pull out torque of the motor

Example 17-3

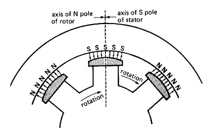
Solution

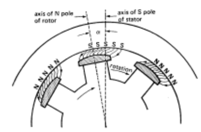


Chapter 17

Relationship between power angle δ and mechanical angle α between stator and rotor pole centers
Same as Generator – also note for 2 pole machine, $\alpha = \delta$

$\delta = \alpha\ (p/2)$



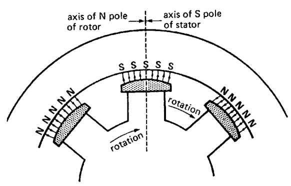


Example 17-4

A 3 phase, 6000 kW, 4kV, 180 rpm, 60 Hz motor has a synchronous reactance of 1.2 Ω. At full load the rotor poles are displaced by a mechanical angle of 1° from their no load position. If the line to neutral excitation Eo – 2.4 kV, calculate the mechanical power developed.

Chapter 17

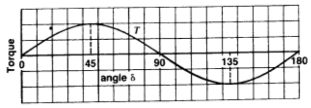
The flux produced by the stator flows across the air gap through the salient poles

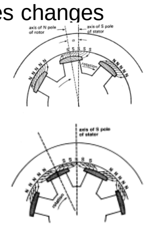


Chapter 17

Reluctance torque for salient pole machine – As power angle d increases, concentration of flux between rotor and stator poles changes

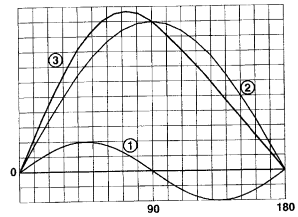
This variation in flux leads to variation in torque (known as reluctance torque)





Chapter 17

Resultant Torque
1 – Reluctance Torque
2 – Cylindrical Torque
3 – Resultant Torque
PEAK – 70^{O}

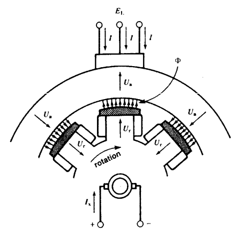


Chapter 17

Large Vs Small Synchronous Motor characteristic
1. δ ranges from 27^{O} to 37^{O}
2. Excitation power (per unit) smaller for larger machine
3. Improved efficiency for larger motor
4. Xs >> Rs – simplified SLE model

Chapter 17

Excitation & Reactive Power
Controlling Ix, controls flux in motor,
If flux < needed, motor absorbs reactive power from line
If flux > needed, motor delivers reactive power to line.



Chapter 17

Power Factor Rating – Motor rated PF allows motor to deliver reactive power without derate of motor active power. Motor larger for lower PF rating

P = Eab Ip

Figure 17.14
Unity power factor synchronous motor and phasor diagram at full-load.

Chapter 17

Motor with 80% power factor
Ip – contributes to active power to load
Iq – contributes to reactive power to system
Ip = 0.8 Is
Iq = 0.6 Is
Q = Eab Iq
= 0.6 Eab Is
P = Eab Ip
= 0.8 Eab Is

Figure 17.15
80 percent power factor synchronous motor and phasor diagram at full-load.

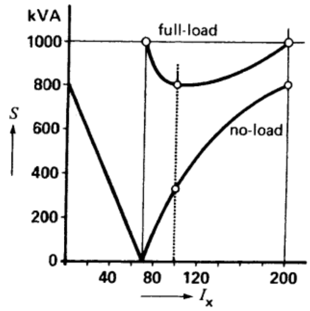
Chapter 17

V-curves:
If we reduce Ix below that needed for unity power, motor draws reactive power
If we increase Ix above that needed for unity power, motor provides reactive power

$S = \sqrt{(P^2 + Q^2)}$

-> S minimum at PF = 1.0, increases for either increasing or decreasing excitation current

Shown on V-Curve



Example 17-5

A 4000 HP (3000 kW), 6600V, 60 Hz, 200 rpm synchronous motor operates at full load at leading power factor of 0.8. If the synchronous reactance is 11 Ω, calculate the following:

a. The apparent power of the motor, per phase
b. The ac line current
c. The value and phase of Eo
d. Draw the phasor diagram
e. Determine the torque angle δ

Chapter 17

Stopping Synchronous Motor –
Following methods:
Coasting (may take time to come to rest)
Break by maintain full DC excitation with Armature short circuit (dynamic braking)
Break by maintain full CD excitation with Armature connected to resistor bank (dynamic braking)
Apply mechanical break

Example 17-6

A 1500 kW, 4600V, 600 rpm, 60 Hz synchronous motor possesses a synchronous reactance of 16 Ω and a stator resistance of 0.2 Ω per phase. The excitation voltage Eo is 2400V and the moment of inertia of the motor and its load is 275 kg m^2. We wish to stop the motor by short circuiting the armature while keeping the dc rotor current fixed.

Example 17-6

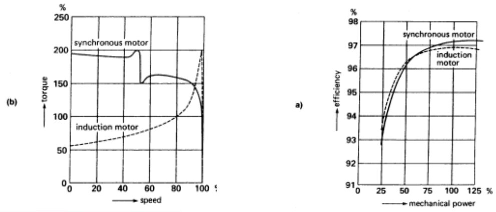
Calculate
a. The power dissipated in the armature at 600 rpm
b. The power dissipated in the armature at 150 rpm
c. The kinetic energy at 600 rpm
d. The kinetic energy at 150 rpm
e. The time required for the speed to fall from 600 rpm to 150 rpm.

Chapter 17

Synchronous motor vs induction motor –
Low Speed – Synchronous machine efficiency higher (near rated load) and PF adjust to 1.0
Can provide reactive power to plant for voltage support
Starting Torque Higher for synchronous motor

Chapter 17

Comparison between the efficiency and starting torque of induction and synchronous motor



Example 17-7

A synchronous capacitor is rated at 160 Mvar, 16 kV, 1200 rpm, 60 Hz. It has a synchronous reactance of 0.8 pu and is connected to a 16 kV line. Calculate the value of Eo so that the machine

a. Absorbs 160 Mvar
b. Delivers 120 Mvar

Chapters 18 and 19 next session

Electric Machines & Drives

thomasblairpe.com/EMD

Thomas Blair, P.E.
USF Polytechnic – Engineering
tom@thomasblairpe.com

End of Session 7: Synchronous Motors & Generators

Spring 2011