Welcome to

Energy Production Systems Engineering

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UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Session 5: Electrical Systems

Spring 2012

Session 5: Electrical Systems

- **Electrical Systems**

Electrical Systems

Electrical Systems

Generator – energy conversion

Synchronous and Induction
Synchronous description

f = n * p / 120

Example 4:

2 pole, 3600 rpm machine ->

f = 3600 * 2 / 120 = 60 hz

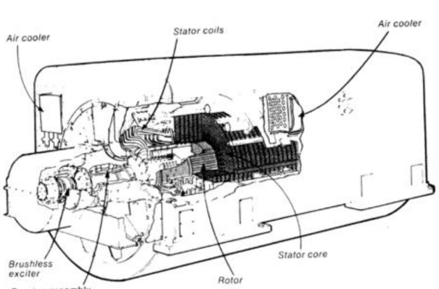
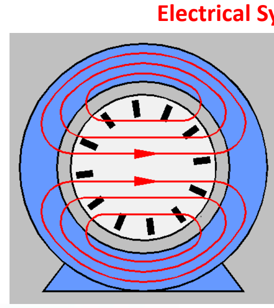


FIGURE 4.1.2 Key elements of an air-cooled ac generator.

Electrical Systems



Synchronous Generator

Electrical Systems

Induction Generator

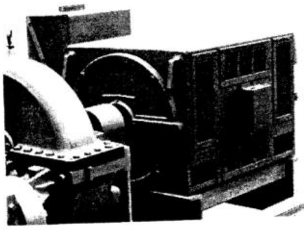


FIGURE 4.1.3 Induction generator.

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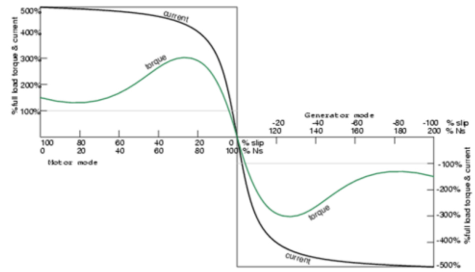

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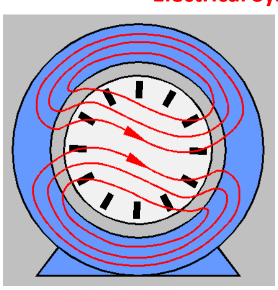

Induction Motor

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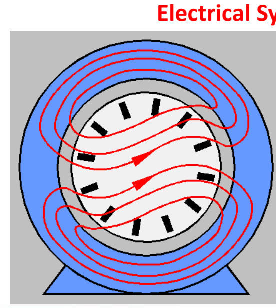

Induction
Generator

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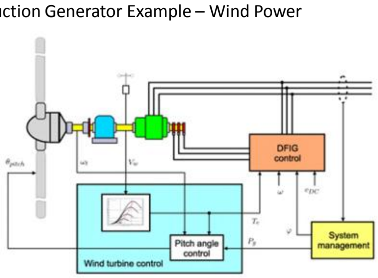
Induction Generator Example – Wind Power



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Electrical Systems

Stator –
Coil wound in stator slots
Indirect cooling
Direct cooling gas & water
H2 pressure effects cooling -> capability
Construction discussion

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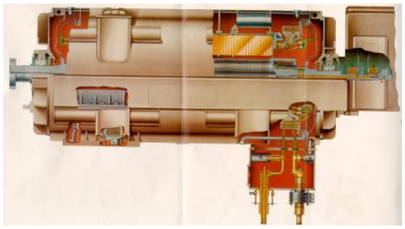
Air Cooled



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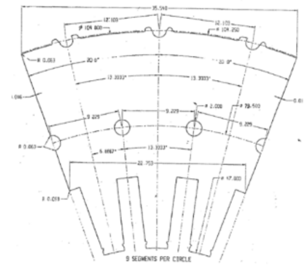

9 seg / cir
3 slots / seg
27 slots per cir
27 coils or
54 half coils

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Electrical Systems

Stator –
Hysteresis loss – change in flux
Eddy current – flow in laminations
Thin lamination construction with teeth for slot

Example 5
9 laminations per disc, each lamination is 15 mil thick, core length is 225 inches (excluding vent fingers), how many laminations?

9 laminations * 225 inches * (1000 mil / 1 inch) / 15 mil

= 135,000 laminations

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Electrical Systems

End Turn Region

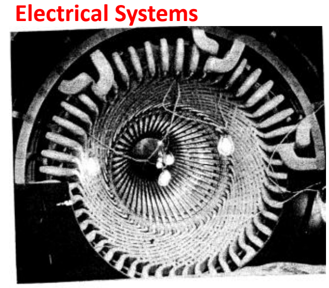

FIGURE 4.1.4 Stator winding.

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End Turn Region

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Electrical Systems

Flux Probe

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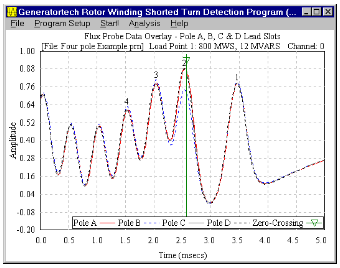
Flux Probe

Electrical Systems



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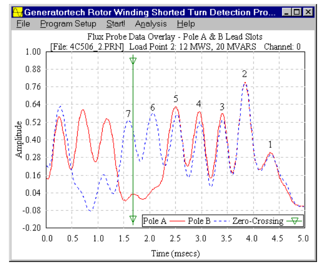
Flux Probe

Electrical Systems



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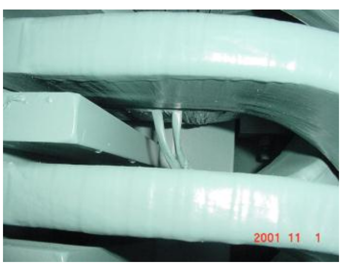
Slot RTD

Electrical Systems



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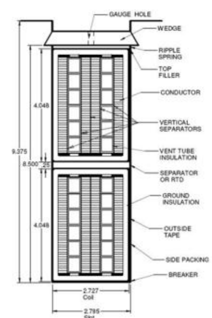

Electrical Systems

Cross section
winding
Intercooled gas
winding
Top coil half /
Bottom coil half

Hydrogen vs. air

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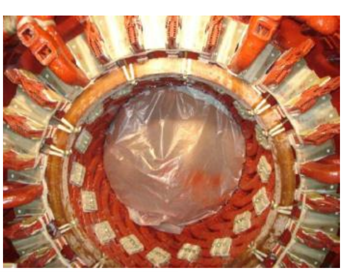
Electrical Systems



Epoxy Resin
coating

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Electrical Systems

Stator Half
Coils

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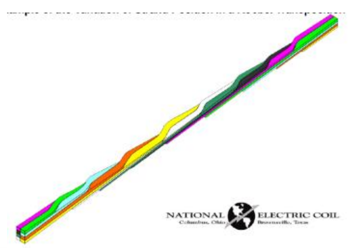
Electrical Systems

Robel Transposition



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Electrical Systems

Slot Construction

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Electrical Systems

Slot cross section

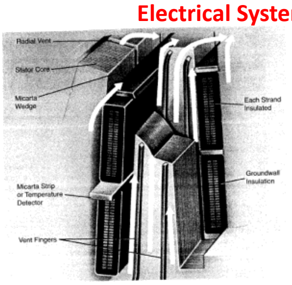

FIGURE 4.1.6 Stator slot cross section.

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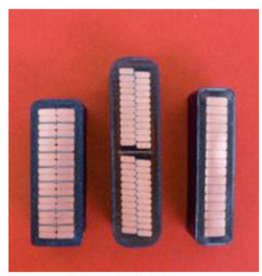
Electrical Systems

Indirect cooling



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Electrical Systems

H2 cooled machine

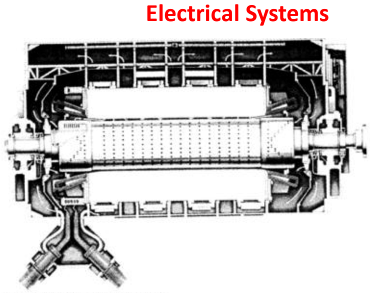

FIGURE 4.1.7 Hydrogen-cooled generator.

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Electrical Systems

Direct Cooled
–
Inter-gas cooled

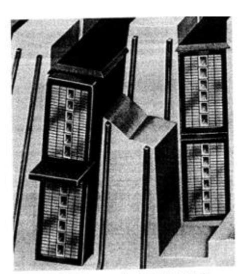

FIGURE 4.1.8 Hydrogen gas directly cooled stator coils.

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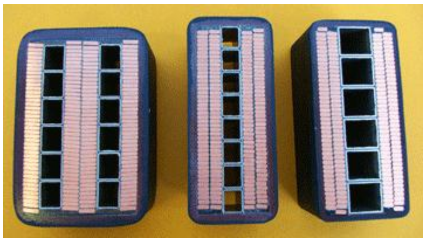
Direct Cooled – Inter-gas cooled



Electrical Systems

Direct cooled – Water intercooled

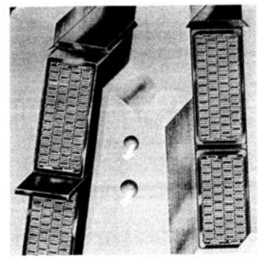


FIGURE 4.1.9 Directly water-cooled stator coils.

Electrical Systems

Direct cooled – Water intercooled

Electrical Systems

Building Bolts

Electrical Systems

Building Bolts

Electrical Systems

Rotors – two basic types
Cylindrical (2 & 4 pole)
Uniform air gap or round rotor
Salient pole
Higher pole count
Non uniform air gap
Higher speed rotor – smaller diameter

Electrical Systems

Ratings –
Turbine nominal, VWO, VWO + 5%
Generator – MVA
    Speed, freq, volt, pf, gas pressure
Generator Capability Curve –
+MVA limited by rotor winding
MW limited by stator winding
-MVA limited by endwinding heating

Electrical Systems

MVA * PF = MW
To get certain MW rating, as you specify lower PF, you get larger MVA generator.
SCR (Short Circuit Ratio) =
I rotor @ FVNL / I rotor @FL for 3 phase fault
Higher SCR – increased stability, reduced efficiency, higher fault current
Reactance – low transient better for stability, higher momentary fault current value
Efficiency – about 98.5% efficient – remove heat

Electrical Systems

Voltage –
Increased V -> lower losses
Reduced bracing system

SCR = If (full voltage, NL)/If (rated stator amps, SC)

Higher SCR = less field current to maintain voltage
 leads to more fault current -> ensure protection work
But look at bracing for faults
 leads to better stability
Higher SCR = larger size, less efficiency
Effects ability to absorb VARs

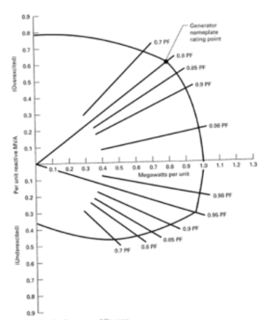
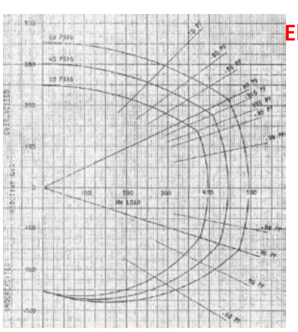


FIGURE 4.1.10 Generator capability curve.

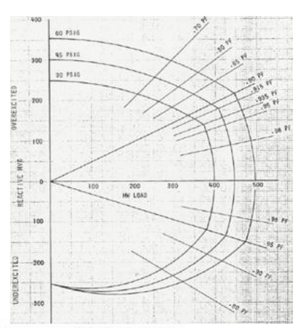
Electrical Systems

Capacity curve



Electrical Systems

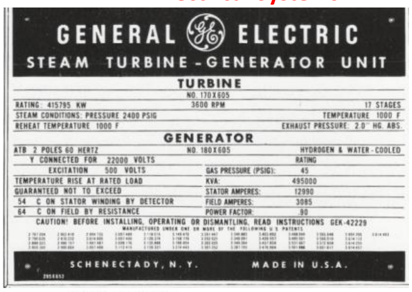
H2 intercooled
495MVA
0.9 PF lead
24KV
3600 RPM
0.58 SCR
60 PSIG H2



Electrical Systems

capability
curve - H2
pressure
dependent

Electrical Systems



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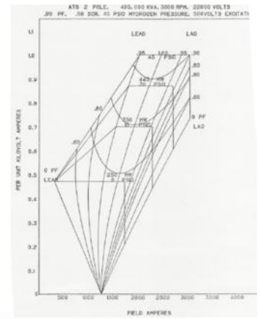
Electrical Systems

V-Curve



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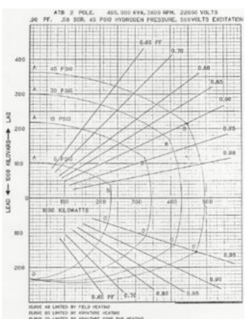

Curve Limitations

Curve AB – Field Heating
Curve BC – Armature Heating
Curve CD – Armature Core End Heating

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Calculation of Field winding Temperature

M = (Rh – Rc)/(Th – Tc)

M = 0.000422 ohm/°C

T2 = [(Rt2 – Rt1)/M] + T1

T2 = [(Rt2 – 0.1094)/0.000422] + 25°C

Field Amperes: 3860 at rated gen. volts and amps at Ø p.f. overexcited.
Field Resistance: .1516 ohms@ 125 C° .1094 ohms@ 25 C°

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Electrical Systems

Calculation of Field winding Temperature

Example 6:
What is Temperature of rotor in °C if resistance measured is 0.1225?

T2 = [(0.1225 – 0.1094)/0.000422] + 25°C

T2 = 56°C

Field Amperes: 3860 at rated gen. volts and amps at Ø p.f. overexcited.
Field Resistance: .1516 ohms@ 125 C° .1094 ohms@ 25 C°

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Electrical Systems

Generator impedance

Calculated Generator Constants - Base: 495,000 KVA

X"d"	1.66	Xo	.125	T'do	4.0	
X'di	.240	Xq	1.60	T"do	.032	
X'dv	.225	X'q	.430	Ta3	.14	
X"di	.185	X1m	.130	T'qo	.5008	
X"dv	.155	R1	.0039	T"qo	.0620	
X2v	.155	R2	.022	Cap. 3Ø	.5456	mfd
				Cap. Ø	.2182	mfd

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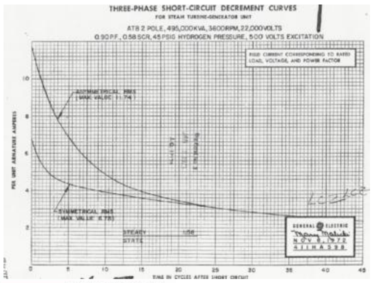
Electrical Systems



3 phase short circuit characteristics

Electrical Systems

Rating based on H2 pressure

ATB- 2 Poles, 495,000 KVA, 3600 RPM, 22,000 Volts
.90 P.F., .58 SCR, 45 psig H_2 Pressure, 60 CPS
Exciter: 1635 KW, 500 Volts, Type- compact alterrex

Hyd. Psig	PU KVA	Generator KVA	Generator KW	Stator Amps	Field Amps Calc.	Field Volts 125°C Calc.
45	1.0	495000	445500	12990	3085	467.6
30	.85	420750	378675	11042	2740	415.4
15	.65	321750	289575	8444	2312	350.5
5	.35	173250	155925	4547	1749	265.1
No Liq.	.285	141075	126967	3702	1642	249.0

Electrical Systems

Metering and instrumentation are essential to satisfactory plant operation.
Voltage, Current, Power (real, reactive, apparent), Energy, etc

Electrical Systems

Instrument transformers
120VAC – 5A (1A) output
PT – CT
Based on application – not device (Draw on board)
PT circuit – parallel connected devices
CT circuit – series connected devices
Shorting terminals used for CT devices
Polarity of PT – CT (Draw on board)

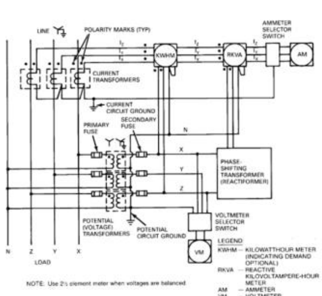


Figure 11-1—Sample metering scheme (3-phase, 4-wire, high current and voltage)

Electrical Systems

KWH meter - To calculate power, count the seconds for a given number of revolutions
of the disk, and then use this formula:

$$\text{power (kilowatts)} = \frac{3.6 \cdot r \cdot K_h \cdot \text{multiplier}}{\text{seconds}}$$

Kh is the meter disk constant in watt-hours per revolution and r is the number of revolutions. Multiplier PTR * CTR

Electrical Systems

Kilowatt-hour meters come in several classes. Below is a listing of the common classes along with the maximum current each can safely monitor

- Class 10 — 10 A
- Class 20 — 20 A
- Class 100 — 100 A
- Class 200 — 200 A
- Class 320 — 320 A

Electrical Systems

KWH metering IT requirements

Table 11-1—Metering and instrument transformer requirements

Service voltage	Stators	CTs	PTs	Assumed load characteristic
1-phase, 2-wire	1	1	1	
1-phase, 3-wire	1	2	1	
1-phase, 3-wire	2	2	2	
1-phase, 3-wire (wye)	2	2	2	
3-phase, 3-wire (delta)	2	2	2	
3-phase, 4-wire (wye)	$2^1/_2$	3	2	balanced conditions
3-phase, 4-wire (wye)	3	3	3	
3-phase, 4-wire (delta)	3	3	3	
3-phase, 4-wire (delta)	2	3	2	balanced mid-tap voltage

Electrical Systems

KVAR Meter - Measures the amount of reactive energy. The internal mechanisms are identical to kilowatt-hour meter. However, the potential applied to this meter is shifted 90 electrical degrees.

Electrical Systems

Q-hour meter - KWH meter with voltages displaced 60 electrical degrees
(lagging) from the standard connection.
Combined with a watt-hour meter can measure power factor between limits of 0.50 lagging and 0.866 leading.

Electrical Systems

Never OC a CT secondary while primary current is flowing (shorting switch).
CTs (and PTs) must have secondary grounded NEC
The accuracy of a CT is usually stated as a percent at rated burden; that is, 0.3 at B = 0.1 means 0.3% accuracy at a maximum burden of 2.5 VA at 5 A.

Electrical Systems

CT Burden information

Table 11-2—Standard current transformer burdens

Type	Maximum VA burden	Maximum external impedance
$B = 0.1$	2.5	0.1 Ω
$B = 0.2$	5.0	0.2 Ω
$B = 0.5$	12.5	0.5 Ω
$B = 1.0$	25.0	1.0 Ω
$B = 2.0$	50.0	2.0 Ω

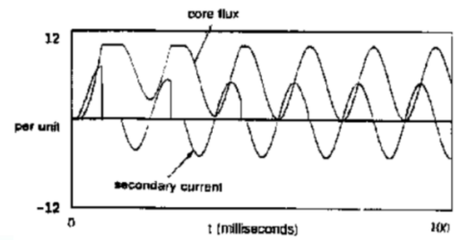
Electrical Systems

Accuracy Class C, K, or T. Based on 10% error at 20 times rated current.
Example, 10C400 XXX:5 CT can develop up to 400V on secondary at 100 amps and maintain 10% accuracy.
Tap CTs Burden vary directly with tap
Example, C400 1000:5 CT , on 500A tap, has new class of C400 * (500/1000) = C200
Conductor lead may be majority of burden

Electrical Systems

CT functions on Rate of Change

$$e = N\frac{d\phi}{dt}$$



Electrical Systems

Excitation systems
Rated MVA, Rated PF, 105% voltage = max amps
Output voltage proportional to field amps
Discuss real and reactive power flow
Transient field forcing – increase current to maintain synchronism
Exciter types –
DC generator commutator exciter (older) –
Direct coupled or motor driven – maintenance makes this less popular

Electrical Systems

Rotating AC exciter – Rotating field and stationary armature to feed stationary solid state rectifier – DC fed back to main field via brushes
Brushless exciter, similar except DC output sent to stationary field and rotating armature on shaft induced current – diode wheel rectified to main field.
Also employs PMG for voltage regulator circuit.
Potential source static exciter – stationary source (generator or stations service) – field flashing circuit. – uses brushes and slip rings.
Compound source static exciter – both PT and CT – for short circuit low voltage conditions

Electrical Systems

Static Exciter

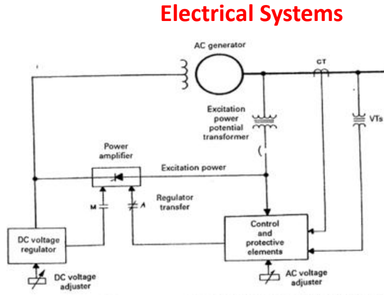


FIGURE 4.1.13 Block diagram arrangement of a typical potential source static excitation system.

Electrical Systems

Voltage regulator –
Manual vs. automatic
Negative feedback loop
Reactive current compensation – parallel generators (not normally used if each generator has GSU)

Aux control functions –
Excitation System Stabilizer – reduction of gain for VR during transients – prevent oscillation
Power System Stabilizer – add additional feedback (i.e. freq, speed, or power) to dampen oscillations

Electrical Systems

Under exciter limiter (UEL) – uses real / reactive power to ensure operation in capability curve
Over excitation limiter and protection (OEL) –
Limits time at high field amps (possibly during field forcing) to protect field winding
Volts-per-hertz limiter and protection –
Reduce field current, reduce stator volts to limit V/F
Protection of core iron in generator / GSU
Off line excitation limiter – acts at VFnL to prevent greater than 105% output voltage.

Electrical Systems

Excitation performance
Brushless system independent of output voltage –
Static excitation system dependence on output voltage – may require higher ceiling voltage and quicker response

Electrical Systems

Generator Synchronizing –
Match magnitude, frequency, phase rotation, and phase angle of voltage (actually frequency a little faster so generator does not motor (about 0.05 hz)
Two types of relays – synch check & synchronizing
Synch check verifies above parameters
Synchronizing has output to control field amps and generator governor to control speed / voltage magnitude.
Synch scope – clockwise rotation = generator freq > system freq
Counter clockwise rotation = generator freq < system freq

Electrical Systems

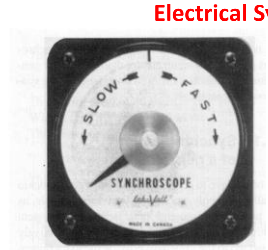


Figure 16.24
Synchroscope.
(Courtesy of Lab-Volt)

Electrical Systems

IEEE defined protection numbers
21 = distance relay
25 = synchronism / synch check relay
27 = under voltage relay
32 = directional power relay
40 = loss of field relay
46 = current unbalance / reverse phase relay
47 = phase sequence – voltage relay
49 = thermal relay
50 = instantaneous overcurrent relay
50N = Neutral instantaneous overcurrent relay
50G = Ground instantaneous overcurrent relay

Electrical Systems

IEEE defined protection numbers
51 = time delay overcurrent relay
51N = Neutral time delay overcurrent relay
51G = Ground time delay overcurrent relay
52 = breaker
59 = Overvoltage relay
67 = directional overcurrent relay
67V = voltage restrained directional overcurrent relay
81U = under frequency relay
81O = over frequency relay
86 = lockout relay (mechanically latching)
87 = differential current relay

Electrical Systems

Generator protection – two functions
Security of power system (primary)
Protection of generator from transients (secondary)
(IPP may have different priority)

Types of protection relays –
Differential current protection – sense internal faults and trip quickly – slope = operate current / restraint current.

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Electrical Systems

Brushless Exciter

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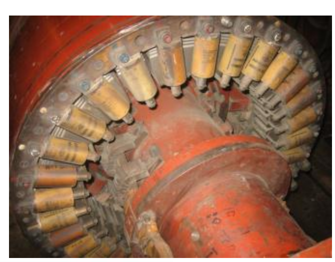

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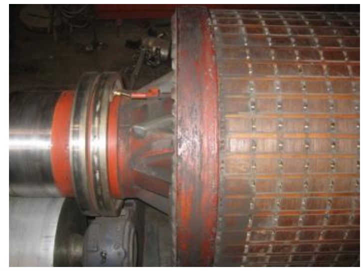

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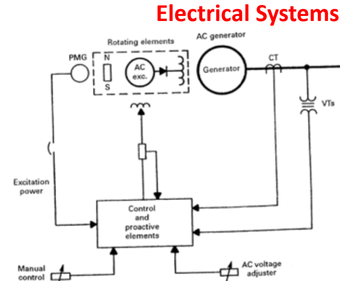

FIGURE 4.1.12 Block diagram arrangement of a typical brushless excitation system.

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relaying

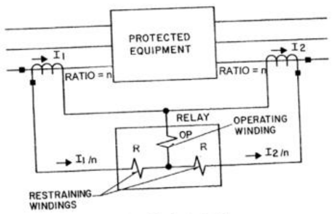

FIGURE 4.1.14 Basic differential relaying circuit.

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Stator OC protection;
Not typical, alternately, monitor stator temperature

Negative Sequence Current protection – protect rotor

Stator GF protection –
Neutral impedance via distribution xfmr – OV relay on secondary to detect GF – can not detect gnd near neutral –
Third harmonic UV detect ground near neutral

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Field Ground Protection –
Apply voltage to gnd on field to detect current
Resistance across field to detect shift
Brushless – momentary connect gnd detection circuit via slip rings

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gnd detection

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Loss of excitation –
Loss of field, protect rotor heading during induction operation
Detect MW & MVAR to detect absorbed MVAR

Motor protection – Detect reverse power to protect Turbine from overheat.

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Electrical Systems

Rotor –
Cylindrical rotor (uniform air gap or round rotor)
2 & 4 pole machines
Salient pole machines
6 pole and more
DC excitation of field winding
Ventilation channels for gas flow
Construction discussion

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Electrical Systems

Rotor in Balance Pit

Electrical Systems

Components

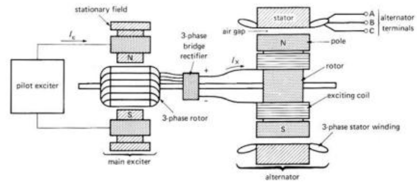

Figure 16.8
Typical brushless exciter system.

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Size Factors –

Small machines: lower efficiencies
Big machines: better efficiencies
1000MW generator: almost 99%!!!
Think again of magnetics and scale rules
Therefore rather one big machine than more smaller machines
1% efficiency = thousands of $ per day in power plant!!!

Electrical Systems

Modeling a synchronous generator

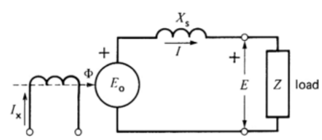

Figure 16.17
Equivalent circuit of a 3-phase generator, showing only one phase.

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Power delivered function of power angle.

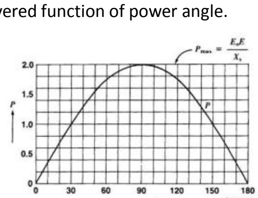

Figure 16.29
Graph showing the relationship between the active power delivered by a synchronous generator and the torque angle.

Electrical Systems

Real Power controlled by power angle
Reactive power controlled by voltage magnitude

Electrical Systems

Transient Reactance -

Sudden load changes give much lower synchronous reactance
Steady state has the usual reactance
Large machines need up to 10 secs to reach normal Xs after transients!
Good for voltage regulation at transients
Bad for circuit breakage: high current

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Electrical Systems

To be continued …

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End of Session 5: Electrical Systems

Spring 2012