1. Manufacturing of Large Electrical Machines

1.1 History and significance of electric machinery

1.2 State-of-the art of medium and high power machines

1.3 Trends in large generators and high power drives

Source: Andritz Hydro, Austria
1. Manufacturing of Large Electrical Machines

1.2.1 Manufacturing of a big hydro generator

Source: Andritz Hydro, Austria
1. Manufacturing of Large Electrical Machines

Manufacturing the stator of a hydro generator with vertical shaft
Welded stator housing of synchronous hydro generator

Source: Andritz Hydro, Austria
Stacking of stator iron sheets of synchronous hydro generator

Source: Andritz Hydro, Austria
Pressing of laminated stator iron core with hydraulic cylinders

Source: Andritz Hydro, Austria
Insulation of high voltage stator winding (one turn = stator bar) with insulation robot

Big generators:
Only one turn per coil.
Coil is split into 2 halves = 2 bars.

Here visible: Insulating one bar for a 2-pole turbine generator with glass-fibre band with mica layer for high voltage insulation.

Source:
Andritz Hydro, Austria
Insulation of high voltage stator winding (one turn = stator bar) with insulation robot

Source: Andritz Hydro, Austria
Resin impregnated coils are heated in the oven to dry and harden the insulation

Source: Andritz Hydro, Austria
High voltage form wound stator coil with several turns $N_c$ for two-layer winding

Winding overhang

coil side, inserted in slot

coil terminals

Source:
Andritz Hydro, Austria
Inserting of impregnated form wound coils in the stator slots of a synchronous hydro generator with high pole count

Ventilation duct
Tooth
Slot
Massive iron clamping finger
Pressing plate
1\textsuperscript{st} layer
2\textsuperscript{nd} layer
winding overhang

Source: Andritz Hydro, Austria
High voltage stator winding of synchronous hydro generator - Pressing of winding bars in the slots

Source: Andritz Hydro, Austria
Vertically mounted salient pole “big hydro” generator

**Shi San Ling / China**

- 222 MVA
- 2p = 12
- 13.8 kV Y, 50 Hz
- 9288 A per phase
- \( \cos \phi = 0.9 \) over-excited
- 500/min rated speed
- over-speed 725/min
- inertia 605 000 kg·m²

**Source:**
VATech Hydro, Austria (now Andritz Hydro)

---

Prof. A. Binder : Large Generators & High Power Drives

Institut für Elektrische Energiewandlung • FB 18
Upper spider for the bracket of a vertically mounted salient pole hydro generator

Skewed spider to equalize better the thermal expansion

Source: Alstom power (former BBC, Switzerland)
Skewed spider for the bracket of a vertically mounted salient pole hydro generator

Skewed spider to equalize better the thermal expansion

Due to skewed spider arms the centre of the shaft keeps better aligned also under thermal expansion

Source:
Alstom power (former BBC, Switzerland)
1. Manufacturing of Large Electrical Machines

Manufacturing of the segmented sleeve bearings
Segment sleeve bearing for vertical load

Bolts for bearing segments

Oil supply for lubrication and cooling

Source: VATech Hydro, Austria (now Andritz Hydro)
Segment sleeve bearing for vertical load

Bearing segments for vertical load

Oil outlet for lubrication

Source:
VATech Hydro, Austria (now Andritz Hydro)
Mounting of sleeve bearing segments for vertical load

Bolts for segments

Source: VATech Hydro, Austria (now Andritz Hydro)
Detailed view of bearing segments for vertical load

Source:
VATech Hydro, Austria
(now Andritz Hydro)
1. Manufacturing of Large Electrical Machines

Manufacturing of the salient rotor
Fixation of rotor poles for high centrifugal forces (e.g. pump storage plants)

Source: VATech Hydro, Austria (now Andritz Hydro)
Manufacturing of field winding for salient pole machines

Non-insulated flat copper winding provides good heat transfer to cooling air at front sides

Inter-turn insulation

“Cooling fins” by increased copper width

Source: VATech Hydro, Austria (now Andritz Hydro)
Completed salient pole before mounting

Pump storage hydro power plant Vianden/Belgium

Refurbishment

Three-fold hammer head fixation

“Cooling fins” by increased copper width

Damper ring segments

Source:
VA Tech Hydro, Austria (now Andritz Hydro)
Completed “big hydro” salient pole synchronous rotor for high centrifugal force at over-speed, 14 poles

- Dove tail fixation of rotor poles
- “Cooling fins” by increased copper width
- Damper ring
- Damper retaining bolts
- Rotor back iron
- Rotor spider
- Generator shaft

Source: VATech Hydro, Austria (now Andritz Hydro)
Balancing & over-speed test of salient 4 pole rotor in test tunnel

4 pole rotor
Exciter generator 3-phase winding
Rotating diode rectifier
Balancing bearing (Schenck Company, Darmstadt)

Source: VATech Hydro, Austria (now Andritz Hydro)
1. Manufacturing of Large Electrical Machines

Manufacturing of the salient rotor of bulb type generator
Ring synchronous generator with high pole count for river hydro power plant (bulb type generators)

Rotor with spider, rotor poles with field winding and damper cage

At plant site Freudenau/Vienna, Austria

River Danube

Mounting of rotor to turbine shaft

32 MVA, 50 Hz
92 poles
rotor diameter 7.45 m
rated speed 65.2/min
over-speed 219/min

circumference velocity at over-speed:
\[ v_{u,max} = 85 \text{ m/s} \]
centrifugal acceleration at over-speed: \[ a/g = 200 \]

Source:
VATech Hydro, Austria
(now Andritz Hydro)
Rotor spider during milling before mounting of rotor yoke

Manufacturing of bulb type hydro generator for Freudenau power plant

Source:
VATech Hydro, Austria (now Andritz Hydro)
Manufacturing of poles for high pole count low speed ring generator

Pole shoes, built as **laminated iron stack** to suppress eddy currents, which are induced by **slot ripple magnetic air gap field** due to stator slot openings.

Slots for damper bars

Source: VATech Hydro, Austria (now Andritz Hydro)
Massive rotor pole shaft welded to laminated pole shoes

Source:
VATech Hydro, Austria
(now Andritz Hydro)
Drilling holes into massive pole shaft to fix them to rotor yoke ring with screws

Source: VATech Hydro, Austria (now Andritz Hydro)
1. Manufacturing of Large Electrical Machines

1.2.1 Manufacturing of big turbine generators

Source: Siemens AG, Mülheim/Ruhr, Germany
Stator iron stack

Stator winding insertion

ROEBEL bar manufacturing

Source: Alstom Power Generation, Mannheim
Source: Alstom Power Generation, Mannheim

Stator into housing

Rotor into stator

Ready for shipping

Prof. A. Binder: Large Generators & High Power Drives

1/35
Fixation of coil overhang of stator winding

Source: Siemens AG, Mülheim/Ruhr, Germany
Stator end zone of an air-cooled turbine generator: press plates, winding overhangs, stepped end packets

Source: Siemens AG, Mülheim/Ruhr, Germany
Stator manufacturing

- Stator core assembly with bonded stator core packs
- Stator coil winding insulation system in the resin oven
- Support system of stator winding overhang

Source:
Siemens AG, Mülheim/Ruhr, Germany
Completed stator with three-phase winding and coil connections

Source: Siemens AG, Mülheim/Ruhr, Germany
Manufacturing of air-cooled stator
Manufacturing of stator housing

Source: Alstom Power Generation, Mannheim
Manufacturing of Gas-cooled Two-pole Rotor

Source: Alstom Power Generation, Mannheim
Two-pole Rotor Excitation Winding

Source: Alstom Power Generation, Mannheim
Rotor End Winding Retaining Cap

Stainless steel end caps for retaining of the rotor end winding - Before the shrink-fit mounting on the rotor (stress: 680 MPa at $n = 0$, 800 MPa at operation for e. g. 600 MW generator)

**Material:**

*Older types:* Cold worked nonmagnetic austenitic manganese steel, sensible to stress corrosion cracking in moisture or aggressive halogen atmosphere

*New types:* Fe-18Mn-18Cr-0.05C-07N steel (“18:18 steel”), more resistant to stress corrosion cracking due to Cr content

Source: Electra, April 2012

Air Cooled Two Pole Turbine Generator: End cap failure due to stress corrosion cracking during the 1970s
Fitting of the Two-pole rotor into the stator of an air-cooled generator for a gas turbine power plant

Source:
Alstom Power Generation, Mannheim
Source: Alstom Power Generation, Birr, Switzerland (former BBC)
Testing of a turbine generator in the manufacturers test rig

Source: Alstom Power Generation, Mannheim
Transportation of a turbine generator stator via the road

Source: Siemens AG, Mülheim/Ruhr, Germany
Fully assembled turbine generator for easy installation on-site

Railway transportation  Car transportation

Source:
Siemens AG, Mülheim/Ruhr, Germany
Completed steam-turbine and two-pole generator group in the nuclear power plant *Leibstadt, Switzerland*, 1230 MVA, 3000/min, 50 Hz

Source: Alstom, Switzerland (former BBC)
Summary:

State-of-the-art of medium and high power machines
- Largest E-machines in the world are synchronous generators
- Maximum power of 2-pole turbine generators surpasses 1 GW
- Biggest power per generator 2 GW for four-pole turbine generators
- Salient-pole generators with up to 900 MW built
- Expensive direct water or hydrogen cooling systems needed
- Cheap air-cooling possible up to 400 MW rated power
- Each generator project has unique data = special design and manufacturing
1. Manufacturing of Large Electrical Machines

1.1 History and significance of electric machinery

1.2 State-of-the art of medium and high power machines

1.3 Trends in large generators and high power drives

Source: Andritz Hydro, Austria
1.3 Trends in large generators and high power drives

- Increasing the size of hydro and turbine generators

1960 – 2010: Peak power ratings
2000 MVA for turbine generators - 850 MVA for hydro generators

Source: G. Neidhöfer, Birr, Switzerland
### 1.3 Trends in large generators and high power drives

#### Trends in manufacturing turbine generators

Raising power limit by **improved cooling**

<table>
<thead>
<tr>
<th>Year</th>
<th>1950</th>
<th>1995…2000</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air gap flux density</td>
<td>0.85</td>
<td>1.1</td>
<td>130 %</td>
</tr>
<tr>
<td>Current loading</td>
<td>700</td>
<td>3200</td>
<td>460 %</td>
</tr>
<tr>
<td>Esson’s number</td>
<td>7.5</td>
<td>45</td>
<td>600 %</td>
</tr>
</tbody>
</table>

Raising power limit of **air-cooled** turbine generators

<table>
<thead>
<tr>
<th>Year</th>
<th>1960</th>
<th>2000</th>
<th>Increase to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated apparent power</td>
<td>50</td>
<td>450 TOP AIR</td>
<td>900 %</td>
</tr>
</tbody>
</table>
1.3 Trends in large generators and high power drives

One of the world’s largest 4-pole turbine generator

„Marriage“:
Insertion of the rotor into the stator

- Four-pole turbine-generator for ca. 2000 MVA, 50 Hz, 1500/min

Source:
Alstom Power, Birr, Switzerland
1.3 Trends in large generators and high power drives

One of the world’s largest hydro generator

**Three-gorges hydro power plant at the river Yangtsekiang, China**

Vertical shaft salient pole synchronous generators
40 MVA, 700 MW, 50 HZ, 80-polig

26 generators:
18.2 GW

World’s largest hydro power plant

Source:
Alstom Power, Birr, Switzerland
1.3 Trends in large generators and high power drives

Increase of power ratings for air-cooled 2-pole turbine generators

- Power ratings fits to the rising power rating of the gas turbines
- Cheap and robust cooling system = air!
- Cooling capability increased by segmented chamber cooling

Source: G. Neidhöfer, Birr, Schweiz
1.3 Trends in large generators and high power drives

One of the world’s largest air-cooled 2-pole turbine generators ("TOPAIR")

Source: ABB (now Alstom Power), Birr, Switzerland

400 MVA
3000/min
50 Hz
1.3 Trends in large generators and high power drives

Above 400 MVA: Big 2-pole water/hydrogen cooled turbine generators

Rated data: $S_N = 950$ MVA, Thermal Class F ($155^\circ$C), utilized acc. to Class B ($130^\circ$C), 700 MW, 50 Hz, 30000/min, coal power plant *Manjung*

*Source: Alstom, Switzerland*
1.3 Trends in large generators and high power drives

Big four-pole turbine generator for nuclear power plant

Rated data: $S_N = 1722$ MVA, 1500 MW, nuclear power plant Oskarshamn, Sweden

Source: Alstom, Belfort

Low pressure stage of steam turbine

Combined hydrogen and water cooling
1.3 Trends in large generators and high power drives

Big four-pole turbine generators for nuclear power plant

Stator: water, Rotor: hydrogen gas cooling

Source: Alstom, Switzerland
1.3 Trends in large generators and high power drives

HV terminal box with bushings and winding main leads

Source: Alstom, Switzerland
1.3 Trends in large generators and high power drives

Wedges tightened to the flexible connection

Source: Alstom, Switzerland
1.3 Trends in large generators and high power drives

Calculated displacements of the flexible connections due to thermal load

Source: Alstom, Switzerland
1.3 Trends in large generators and high power drives

World’s largest electrical machine is an AC generator

- World’s biggest turbine generator 2000 MW for nuclear power plant
- Recent developments in large turbine generators

*Olkiluoto 3* 2 GW turbo generator with brushless exciter at the conclusion of the type test

*Source:* Siemens, Germany

*Olkiluoto 3* 2 GW turbo generator with brushless exciter at the conclusion of the type test
1.3 Trends in large generators and high power drives

**World´s biggest turbine generators 2000 MW**

**Rated data:** \( S_N = 2222 \text{ MVA}, \) Thermal Class F (155°C), utilized acc. To Class B (130°C) 
\[ \cos \varphi_N = 0.9 \text{ over-excited}, \] 27 kV, Y, 50 Hz, 1500/min, four-pole machine 
\[ I_{sN} = 47.5 \text{ kA (l)}, \] and 50 kA at 95% reduced voltage

**Olkiluoto 3 2 GW turbo generator**

Source: Siemens, Germany
1.3 Trends in large generators and high power drives

50 kA, 27 kV: 12 flexible connections per phase from main lead to the HV bushing: Current sharing only +/- 5% deviation!

12 flexible connectors per phase between main leads and bushings

Source: Siemens, Germany
1.3 Trends in large generators and high power drives

Maintenance work at generator stand still:
Inspection of the winding wedges in the stator bore with a robot

Camera air-gap inspection in an air-cooled turbine generator. Due to the rather small air gap the camera robot is entering the air gap only from one side.

Camera air-gap inspection in a hydrogen cooled turbine generator.

Source: Alstom Power GmbH, Mannheim, Germany
1.3 Trends in large generators and high power drives

Speed-variable slip-ring induction machine as doubly-fed Motor-Generator for pump storage

**Example:** Goldisthal, Germany
2 doubly-fed induction Motor-Generators:
340 MVA, 300 ... 346/min, 18-polig, 50 Hz

A Thyristor-controlled cyclo-converter feeds the rotor six-phase winding with 0 ... 5 Hz & ca. 35 MVA power at the slip rings

**Advantage:** Much better fitting of the storable energy to the fluctuating grid excess power!

Source: VA Tech Hydro (now Andritz Hydro), Austria
1.3 Trends in large generators and high power drives

Use of high energy rare-earth permanent magnets (NdFeB) in speed-variable synchronous machines with MW-rating

Prototype of a 32-pole PM rotor for a synchronous motor as a propeller drive for ship propulsion

Source: Siemens AG, Nuremberg, Germany
1.3 Trends in large generators and high power drives

Use of High-temperature Superconductors (HTSC) for the DC rotor winding of large synchronous machines

Prototype testing

2-pole synchronous generator for large ships

4 MW, 3600/min, 60 Hz

HTSC-rotor winding operated at ca. -245°C

Overall generator efficiency (incl. cooling power): ca. 98.5%

Source: Siemens AG, Nuremberg, Germany
1.3 Trends in large generators and high power drives

**Downscaling of motor size:** HTSC-Synchronous motor for ship propulsion

**Conventional motor with rotor copper winding:**
- 21 MW, 4 kV, 150/min, 183 tons

**Motor with HTSC-rotor winding:**
- 36.5 MW, 6.6 kV, 120/min, 75 tons

Source: American Superconductor, USA
Large Generators and High Power Drives

Summary:

Trends in large generators and high power drives
- Further increase of rated power of gas turbines gives need for bigger air-cooled generators above 400 MW
- Variable speed motor-generators for pump storage needed
- Variable speed large induction and synchronous machines needed
- Synchronous motors in the MW-range with high temperature superconductor rotor field winding (e.g. for ship propulsion)
- Increase of size PM synchronous machines for low speed (wind turbines) up to 10 MW