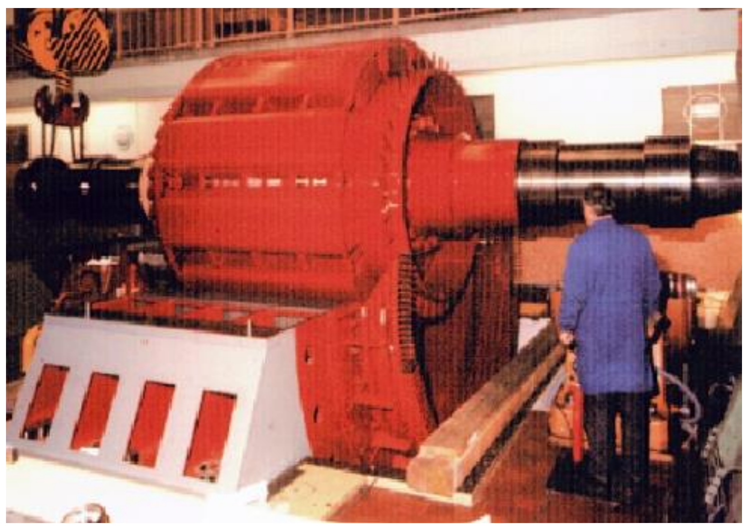
Large Generators and High Power Drives

Contents of lectures

Source:

Siemens AG, Germany

5. Design of large synchronous machines



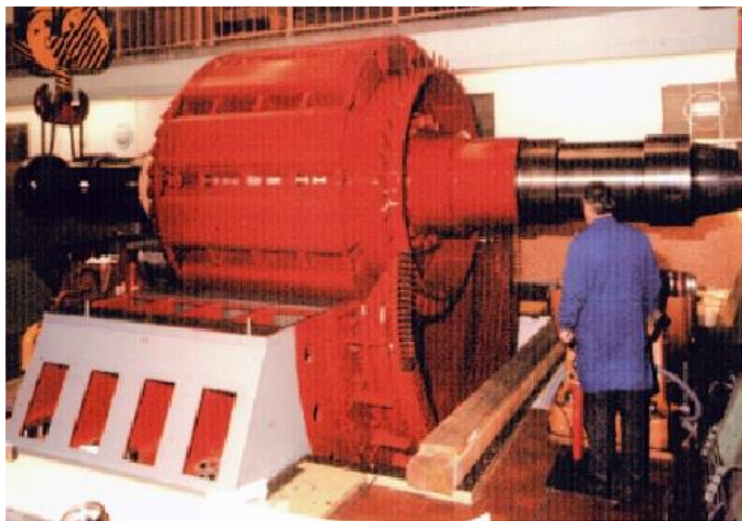
Source: Andritz Hydro, Austria

5. Design of large synchronous machines

5.1 Main features of big synchronous machines

- Basic features of poly-phase synchronous machines

- Types of power plants and related synchronous generators

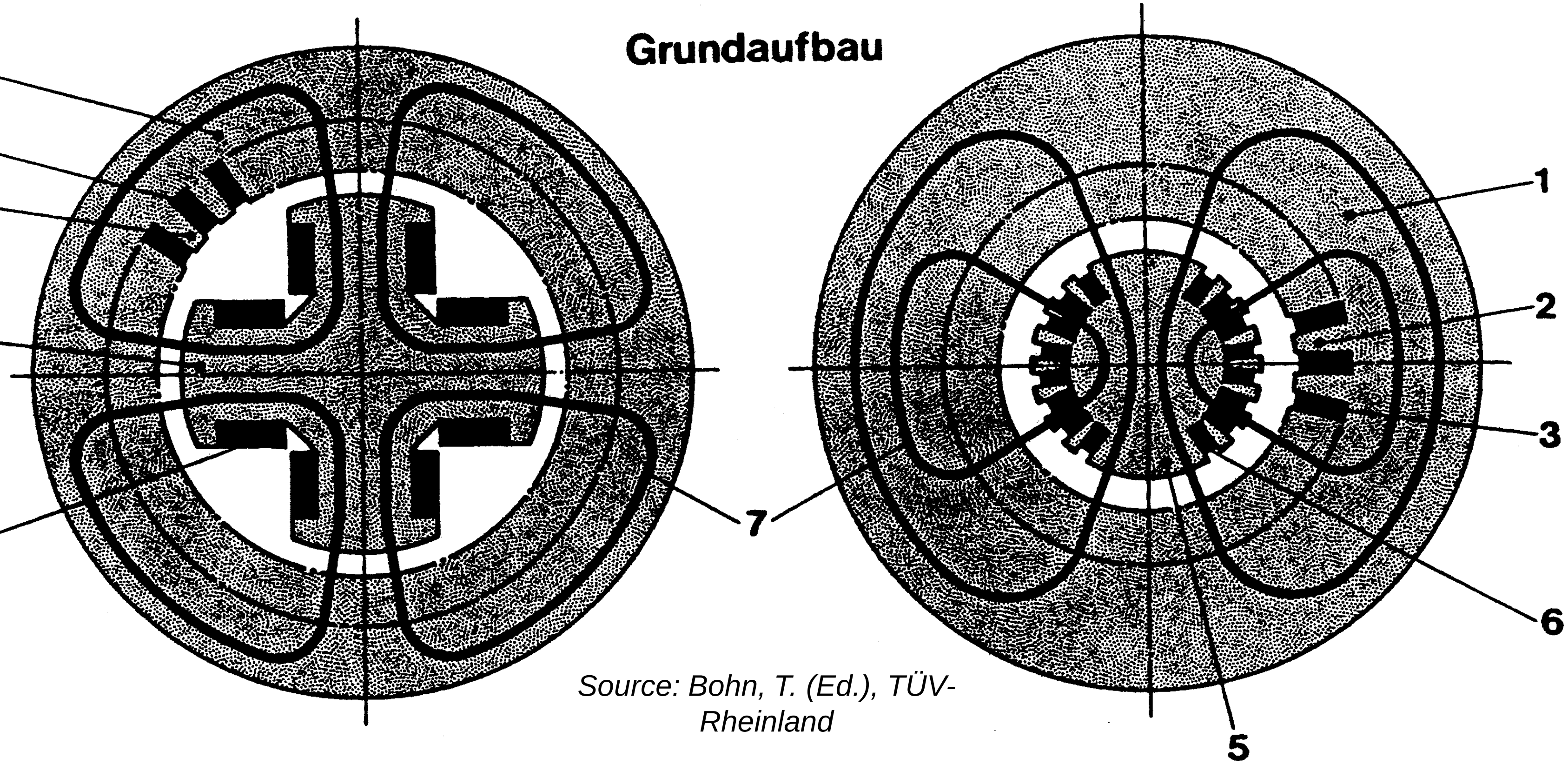


Source: Andritz Hydro, Austria

5. Design of large synchronous machines

Basic features of polyphase synchronous machines

Salient pole machine (2p = 4) | **Cylindrical rotor machine (2p = 2)**



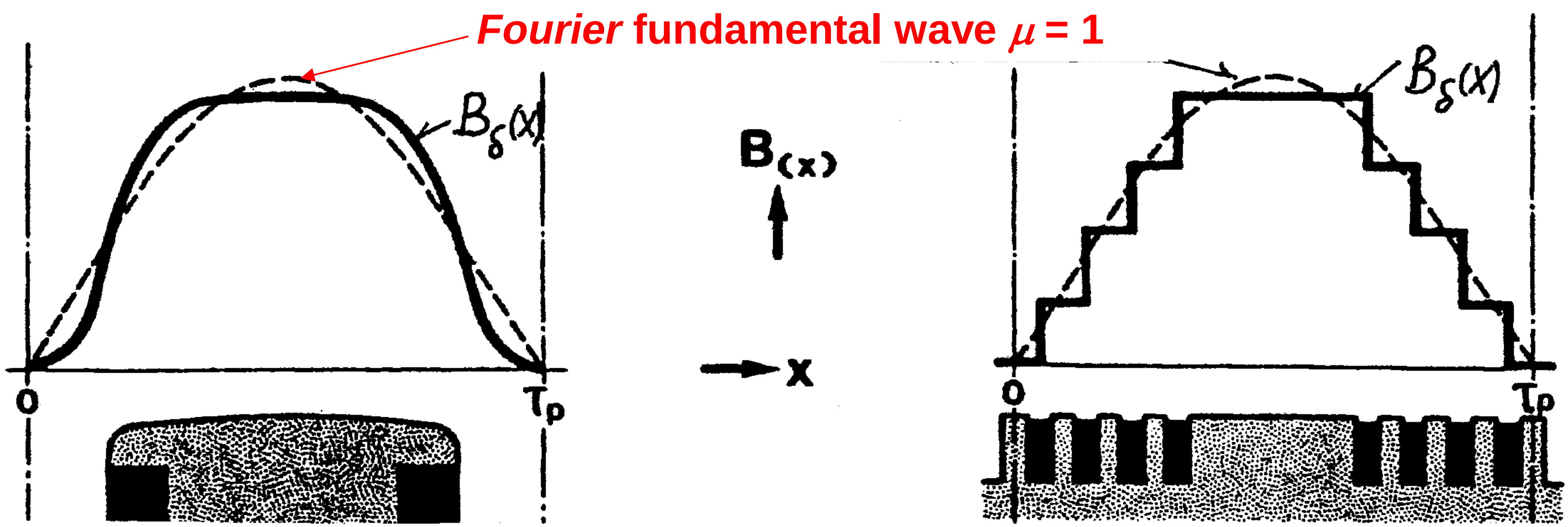
Source: Bohn, T. (Ed.), TÜV-Rheinland

1: Stator yoke | 2: Stator teeth | 3:Stator slots with 3-phase AC winding

4: Rotor pole shoe | 5: Rotor pole | 6: Rotor DC excitation winding

5. Design of large synchronous machines

Rotor DC magnetic field in air gap $B_\delta(x)$



Salient pole machine **Cylindrical rotor machine**

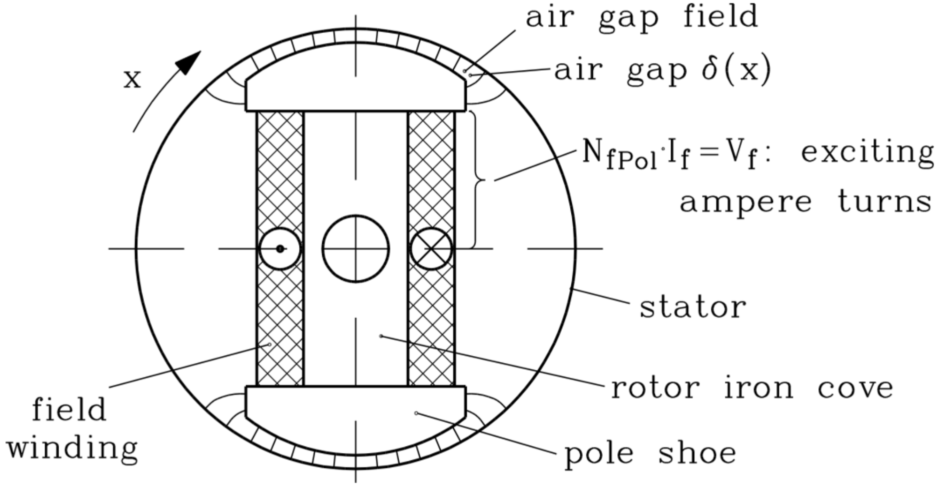
Source: Bohn, T. (Ed.), TÜV-Rheinland

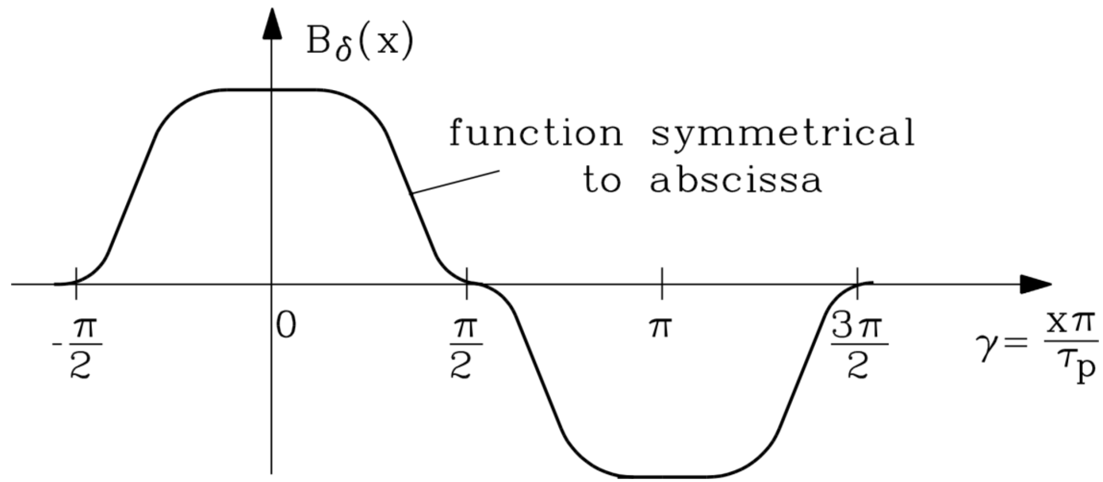
Variable air gap $\delta(x)$ and constant m.m.f. $V_f = N_f \cdot I_f/(2p)$ lead to bell-shaped air gap flux density

Constant air gap δ and step-like m.m.f. $V_f(x)$ due to field winding, distributed in slots, leads to step-like shaped air gap flux density

5. Design of large synchronous machines

Rotor field and back EMF of salient pole synchronous machine





- **Bell shaped rotor air gap field curve $B_\delta(x)$:** A constant m.m.f. V_f excites with a variable air gap $\delta(x)$ a bell shaped field curve. Fundamental of this "bell-shape" ($\mu = 1$):

$$B_\delta(x) = \mu_0 \frac{V_f}{\delta(x)} \quad \rightarrow \quad \text{FOURIER-fundamental wave: Amplitude } \hat{B}_p \text{ proportional to } I_f$$

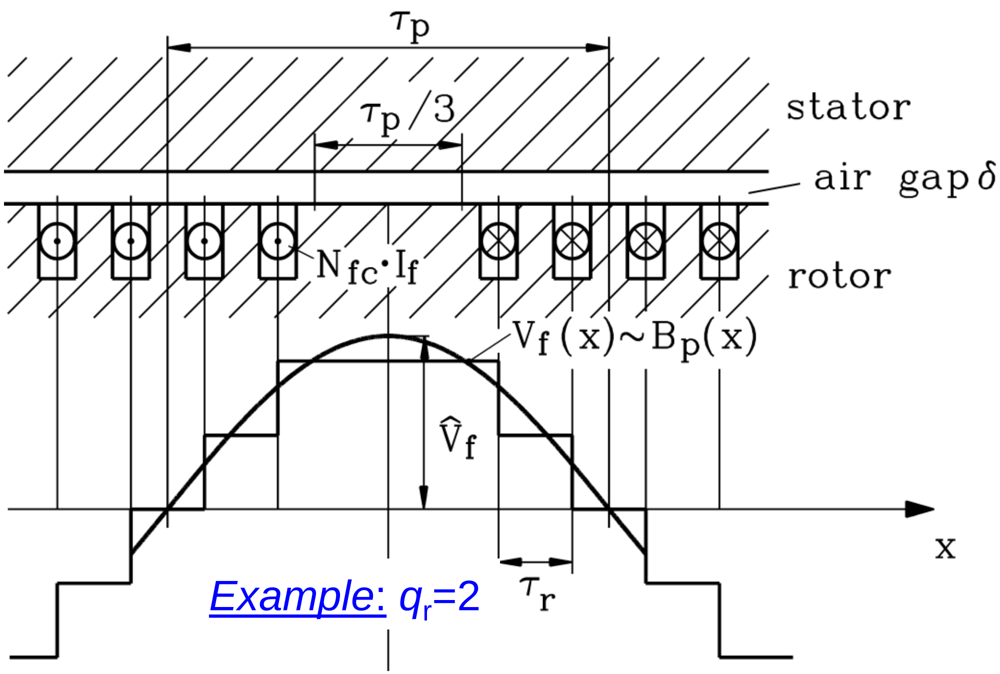
- **Back EMF U_p:** Sinusoidal rotor field fundamental wave B_p induces **in three-phase stator winding** at speed n a three-phase voltage system U_p

$$U_p = \omega \cdot \Psi_p / \sqrt{2} = \omega \cdot N_s k_{w,s} \cdot \Phi_p / \sqrt{2} = \sqrt{2}\pi f \cdot N_s k_{w,s} \cdot \frac{2}{\pi} l \tau_p \hat{B}_p$$

with **frequency** $f = n \cdot p \Rightarrow$ Stator current I_s is flowing in stator winding.

5. Design of large synchronous machines

Rotor air gap field and stator back EMF of round rotor synchronous machine



- **Rotor m.m.f. and air gap field distribution have steps due to slots and contain fundamental** ($\mu = 1$):

$$\hat{V}_f = \frac{2}{\pi} \cdot \frac{N_f}{p} \cdot (k_{p,f} k_{d,f}) \cdot I_f$$

$$\hat{B}_p = \mu_0 \frac{\hat{V}_f}{\delta}, \quad N_f = 2p \cdot q_r \cdot N_{fc}$$

$$k_{p,f} = \sin\left(\frac{W}{\tau_p} \cdot \frac{\pi}{2}\right) = \sin(\pi/3) = \frac{\sqrt{3}}{2}$$

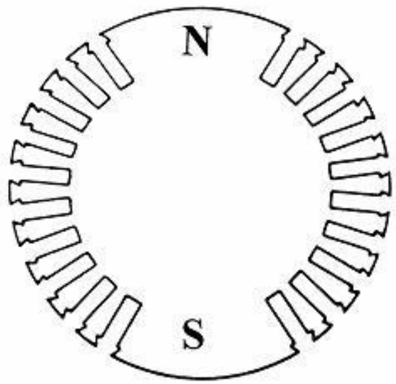
$$k_{d,f} = \frac{\sin(\pi/6)}{q_r \sin(\pi/(6q_r))}, \quad k_{wf} = k_{pf} k_{df}$$

- **Back EMF U_p (synchronously induced stator voltage):** Rotor field fundamental B_p induces **in 3-phase stator winding** at speed n a 3-phase voltage system U_p:

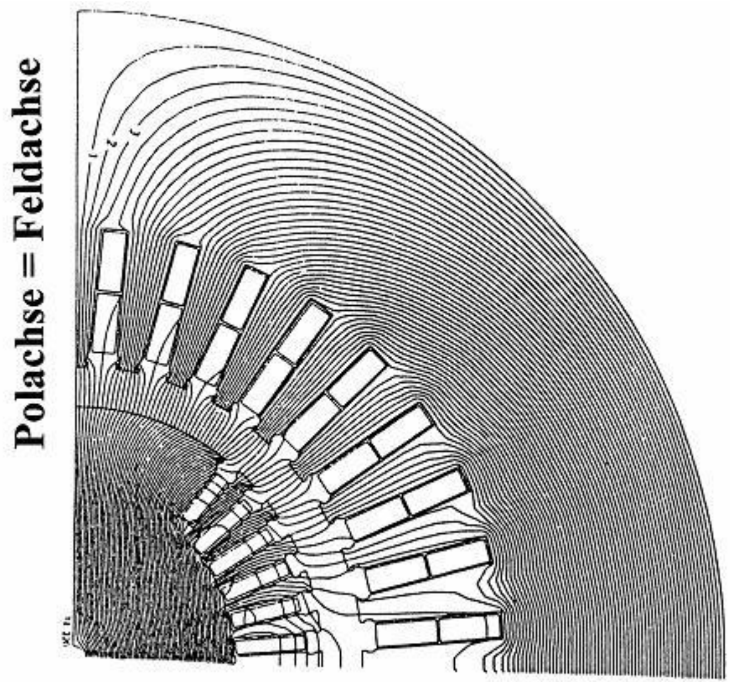
$$U_p = \omega \cdot \Psi_p / \sqrt{2} = \omega \cdot N_s k_{w,s} \cdot \Phi_p / \sqrt{2} = \sqrt{2}\pi f \cdot N_s k_{w,s} \cdot \frac{2}{\pi} l \tau_p \hat{B}_p$$

with **frequency** $f_s = n \cdot p \Rightarrow$ Current I_s will flow in stator winding.

Round rotor synchronous machine: Magnetic field at no-load



Source: Kleinrath, H.; Grundlagen el. Maschinen, Akad. Verlagsgesellschaft

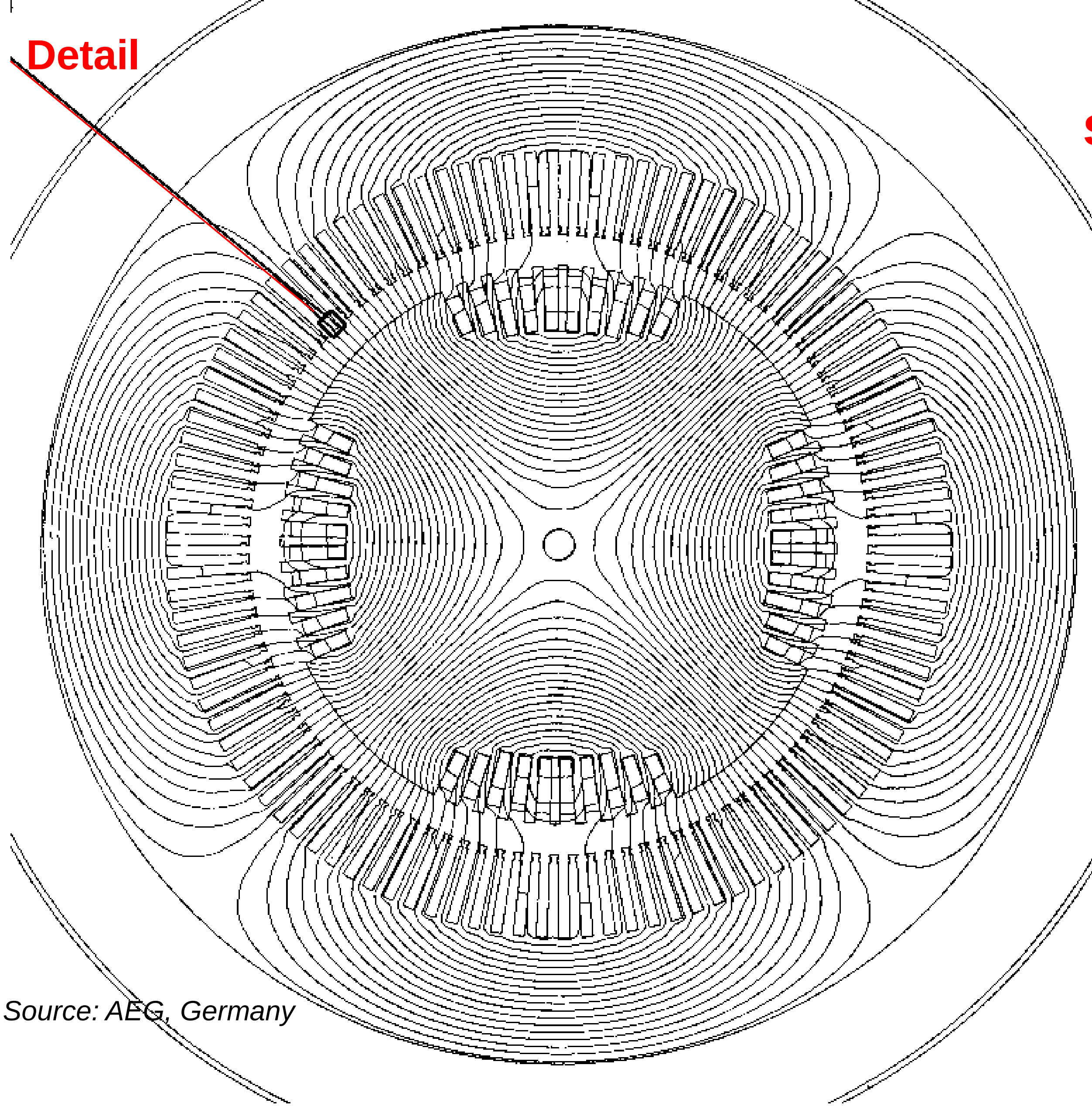


Source: Fuchs, E.; Siemens AG

Rotor cross section without field winding:
- Slots per pole $2q_r = 10$, 2-pole rotor
- Rotor may be constructed of massive iron, as rotor contains only **static magnetic field !**

Magnetic field at no-load ($I_s = 0$, $I_f > 0$):
- Field winding excited by I_f
- Stator winding without current **(no-load)**
- Field lines in air gap in radial direction = no tangential magnetic pull = **torque is zero !**

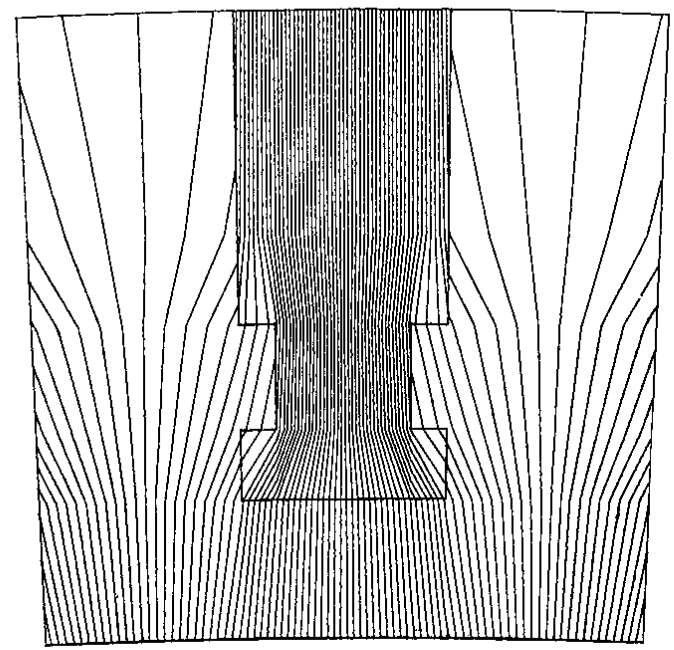
(*Example:* $2p = 2$, $q_s = 6$, $q_r = 6$)



5. Design of large synchronous machines

Numerically calculated no-load field at rated voltage: 4-pole turbine generator, *Biblis, Germany*, 1500 MVA, 1500/min, 50 Hz, 27 stator slots per pole

Detail: Stator tooth-tip



5. Design of large synchronous machines

Synchronous speed $f = p \cdot n$

Pole count $2p$

Example: Synchronous speed at $f = 50$ Hz

$2p$	2	4	6	8	10	20	80	100
n / s^{-1}	50	25	16 2/3	12 1/2	10	5	1 1/4	1
n / min^{-1}	3000	1500	1000	750	600	300	75	60

At $f = 60$ Hz speed values are higher by 20 %.

Type of synchronous machine for grid operation:

a) low pole count, high speed: **cylindrical rotor machine, e.g. thermal power plant**

b) high pole count, low speed: **salient pole machine, e.g. hydro power plant**

Summary:

Basic features of poly-phase synchronous machines

- Cylindrical rotor synchronous machine:
    - Low pole count, high speed
    - Constant air gap
    - Step-like shaped air gap flux density
    - Rotor may be constructed of one piece of massive iron

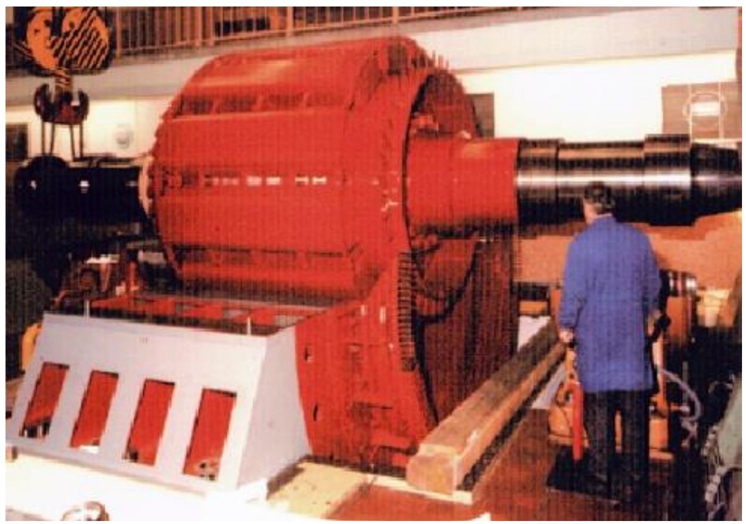
- Salient pole synchronous machine:
    - High pole count, low speed
    - Variable air gap
    - Bell-shaped air gap flux density

5. Design of large synchronous machines

5.1 Main features of big synchronous machines

- Basic features of poly-phase synchronous machines

- Types of power plants and related synchronous generators



Source: Andritz Hydro, Austria

Hydro power plants

5. Design of large synchronous machines

Hydraulic design of hydro power plant

Potential energy of barraged water: $W_{pot} = m \cdot g \cdot H = \rho_{H_2O} V \cdot g \cdot H$

Power: $P_{in} = W_{pot} / t = \rho_{H_2O} \cdot (V / t) \cdot g \cdot H = \rho_{H_2O} \cdot \dot{V} \cdot g \cdot H$

$\dot{V}$: Water flow rate, H: Head, $\rho_{H_2O} = 1000 \text{kg/m}^3$

Efficiency chain:

Hydraulic efficiency: 0.95
Turbine efficiency: 0.9
Generator efficiency: 0.98
Power plant energy consumption: 0.97

Resulting efficiency of power plant: $\eta_{KW} = 0.95 \cdot 0.9 \cdot 0.98 \cdot 0.97 = 0.81$

Electrical power: $P_{out} = P_e = \eta_{KW} \cdot P_{in} = 0.81 \cdot 9.81 \cdot 1000 \cdot \dot{V} \cdot H$

"Rule of thumb": $\boxed{P_e = 8000 \cdot \dot{V} \cdot H}$, $[P_e] = W, [\dot{V}] = m^3 / s, [H] = m$

5. Design of large synchronous machines

Classification of hydro power plants

- High head, low flow rate

- Medium head, medium flow rate

- Low head, high flow rate

Low head	Medium head	High head	High head
High flow rate	Medium flow rate	Low flow rate	Low flow rate
River plant	River barrage plant	Pump storage plant	Storage plant
Wallsee/Austria	*3 Gorges*/ China	*Kaprun*/Austria	*Bieudron*/Switzerland
H = 9.1 m	H = 183 m	H = 780 m	H = 1883 m **)
$\dot{V}$ = 2880 m³/s	$\dot{V}$ = 12295 m³/s	$\dot{V}$ = 32 m³/s	$\dot{V}$ = 86 m³/s
P_e = 210 MW	P_e = 18000 MW	P_e = 200 MW	P_e = 1295 MW
Kaplan-Turbines	*Francis*-Turbines	*Pelton*-Turbines	*Pelton*-Turbines
6 Generators, each 35 MW	26 Generators, each 692 MW	4 Generators, each 2x55 MW, 2x45 MW	3 Generators, each 432 MW

5. Design of large synchronous machines

Classification of hydro generator operation

• Mainly **fixed speed operation** directly at the grid, usually no inverter !

• "Small hydro": Cage induction generators with gear, permanent magnet synchronous generators, or electrically excited synchronous generators to allow over-excited power generation

Unit power: several 100 kW ... Several MW

• "Big hydro": Electrically excited synchronous generators, allowing over-excited power generation, gearless = directly coupled to turbine

Unit power: Several MW ... Several 100 MW

• Typical speed: Synchronous generators: $n = f_s/p$

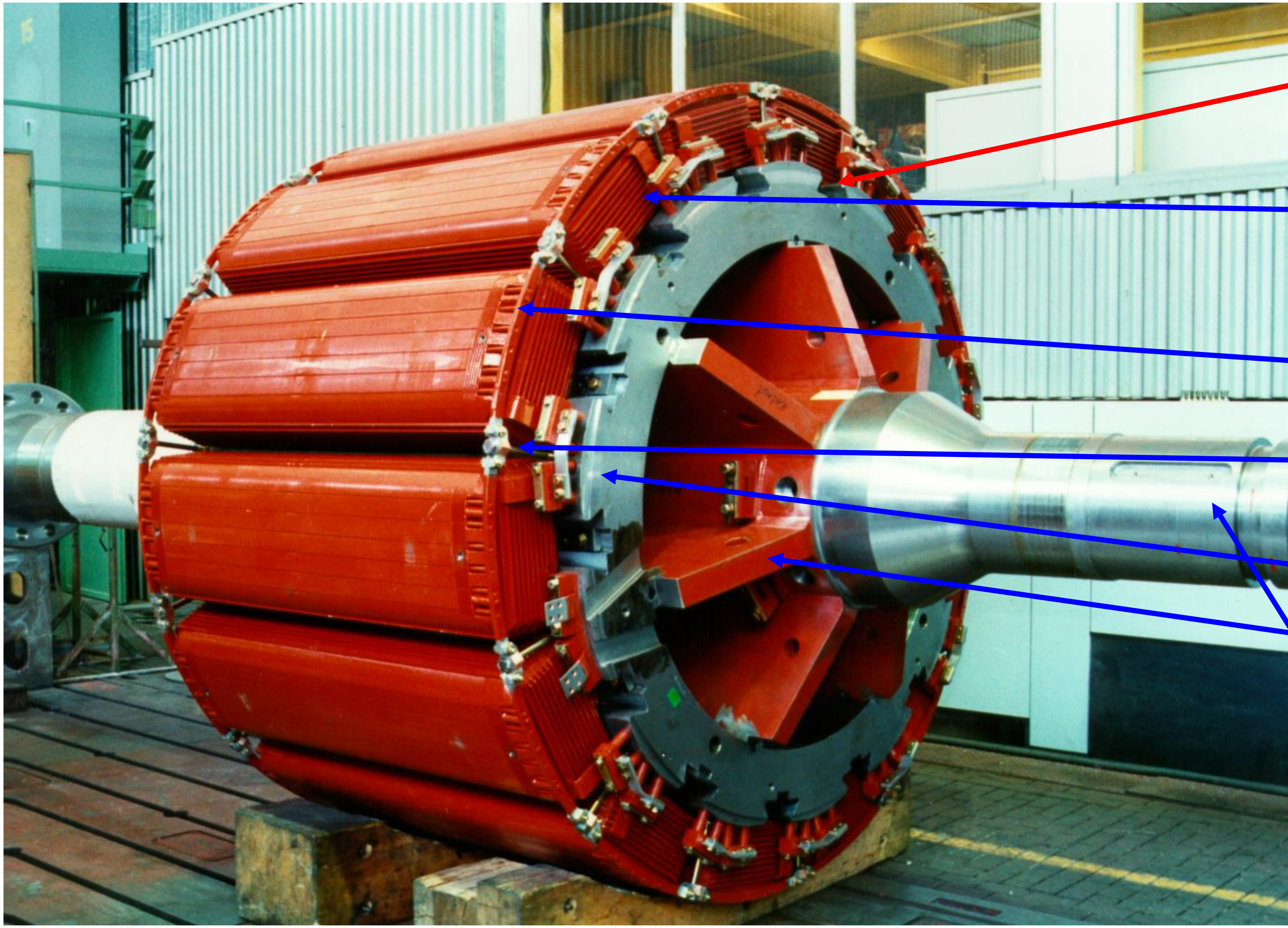
- High head, low flow rate: high speed 750 ... 1000 ... 1500/min

- Medium head, medium flow rate: medium speed 200 ... 500 /min

- Low head, high flow rate: low speed 80 ... 200 /min

5. Design of large synchronous machines

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:

Andritz Hydro, Austria

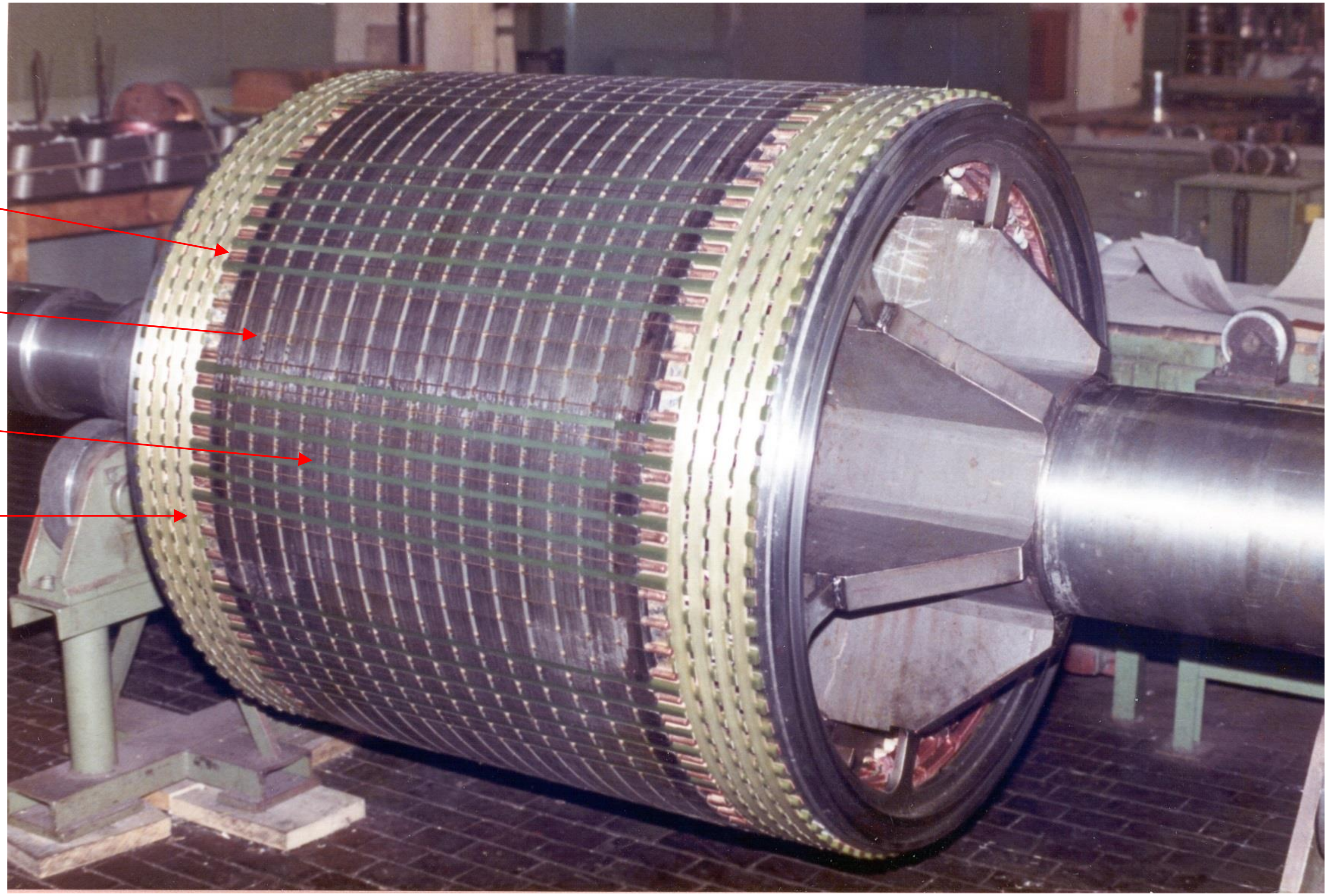
Round rotor of synchronous machine, 8 poles, 2 MVA, 50 Hz, 750/min

Three field coils per pole: $q_r = 3$

Damper cage with 9 bars per pole

Radial ventilation ducts

Glass fibre bandage for fixing rotor coil overhang

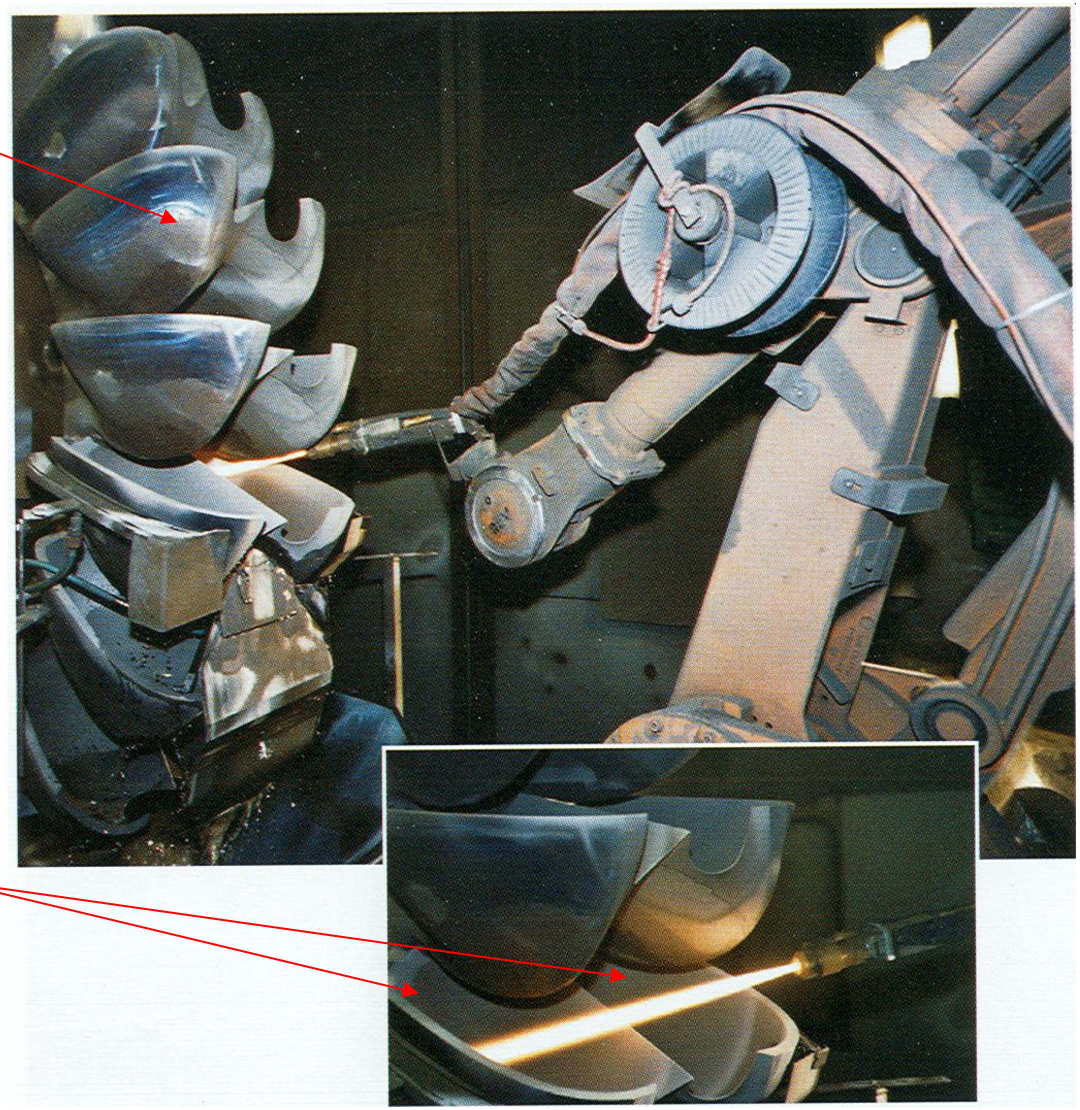


Source:

Andritz Hydro, Bhopal, India

5. Design of large synchronous machines

Fixed blades



Two symmetrical blade shells

Surface finishing of *Pelton* turbine

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines

“Small hydro” power plant with *Pelton* turbines

Power range several MVA

Electrically excited synchronous generator

Housing for flywheel to increase rotor inertia for limiting acceleration at load drop

DC exciter machine

Water inlet

Sleeve bearing

Source:

ABB, Switzerland

5. Design of large synchronous machines

Pelton turbine data – Over-speed at load drop

Example: Simple estimate:

- Power plant *Bieudron*/Wallis, Switzerland:
- Speed of water jet: v_1 = 600 km/h = 166.6 m/s.
- Circumference speed of turbine runner:

theoretically $v_u = v_1/2$ = 83.3 m/s

in reality due to losses: v_u = 103.5 m/s = $d\pi n$.

- With a runner diameter of d = 4.65 m we get a rated speed of n = 428.6 /min.

- At load dropping: Water jet speed = circumference speed:

Over speed: 166.6/103.5 = 1.61; in reality: 1.86-fold: n_{max} = 800/min

Generator data:

Salient pole electrically excited synchronous machine:

432 MW, 465 MVA ($\cos\varphi$ = 0.93), Generator mass 800 t

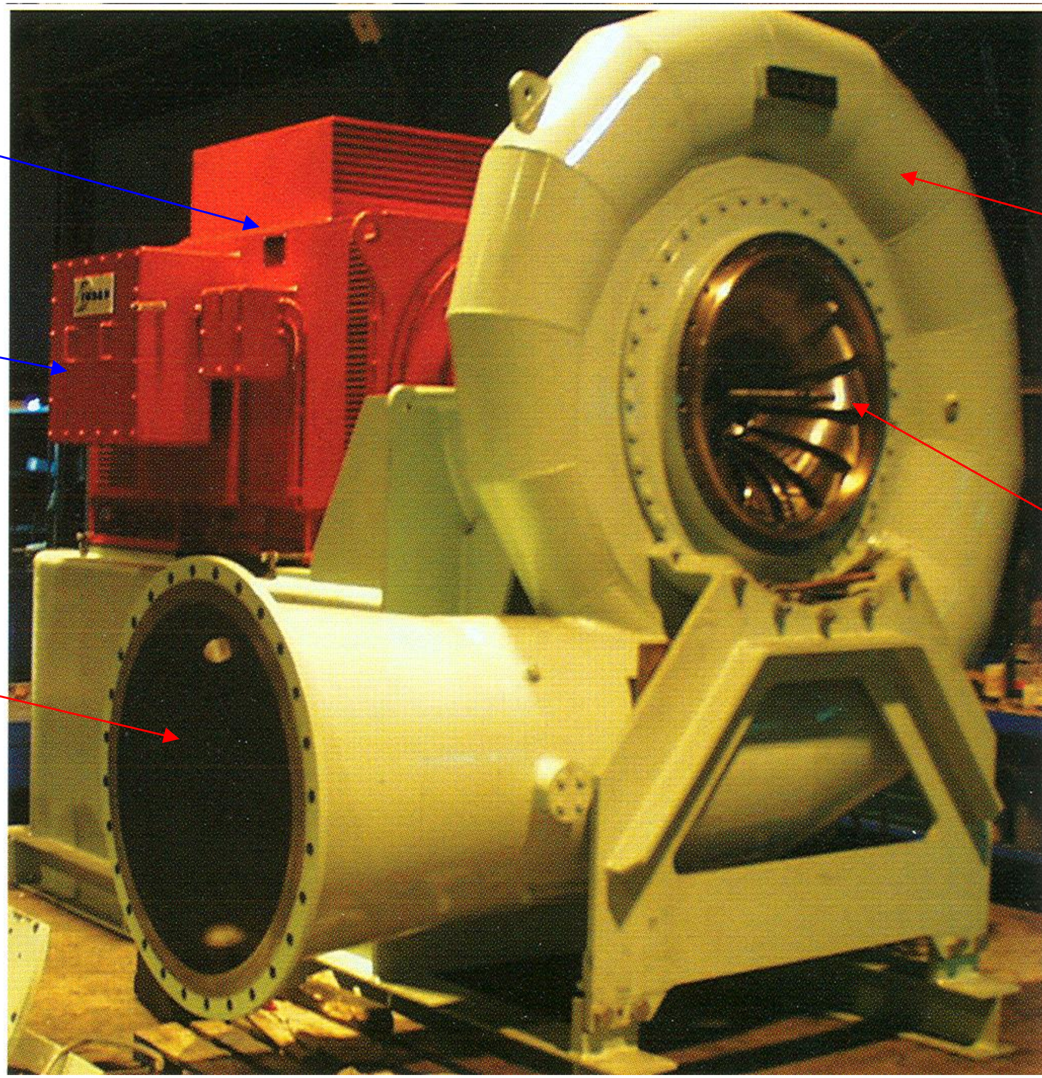
$2p$ = 14, 50 Hz, 428.6 /min, 21 kV, 12.78 kA

5. Design of large synchronous machines

Electrically excited synchronous generator

Terminal box

Water inlet



Small hydro *Francis* turbine in spiral casing

Spiral housing distributes water flow evenly on turbine

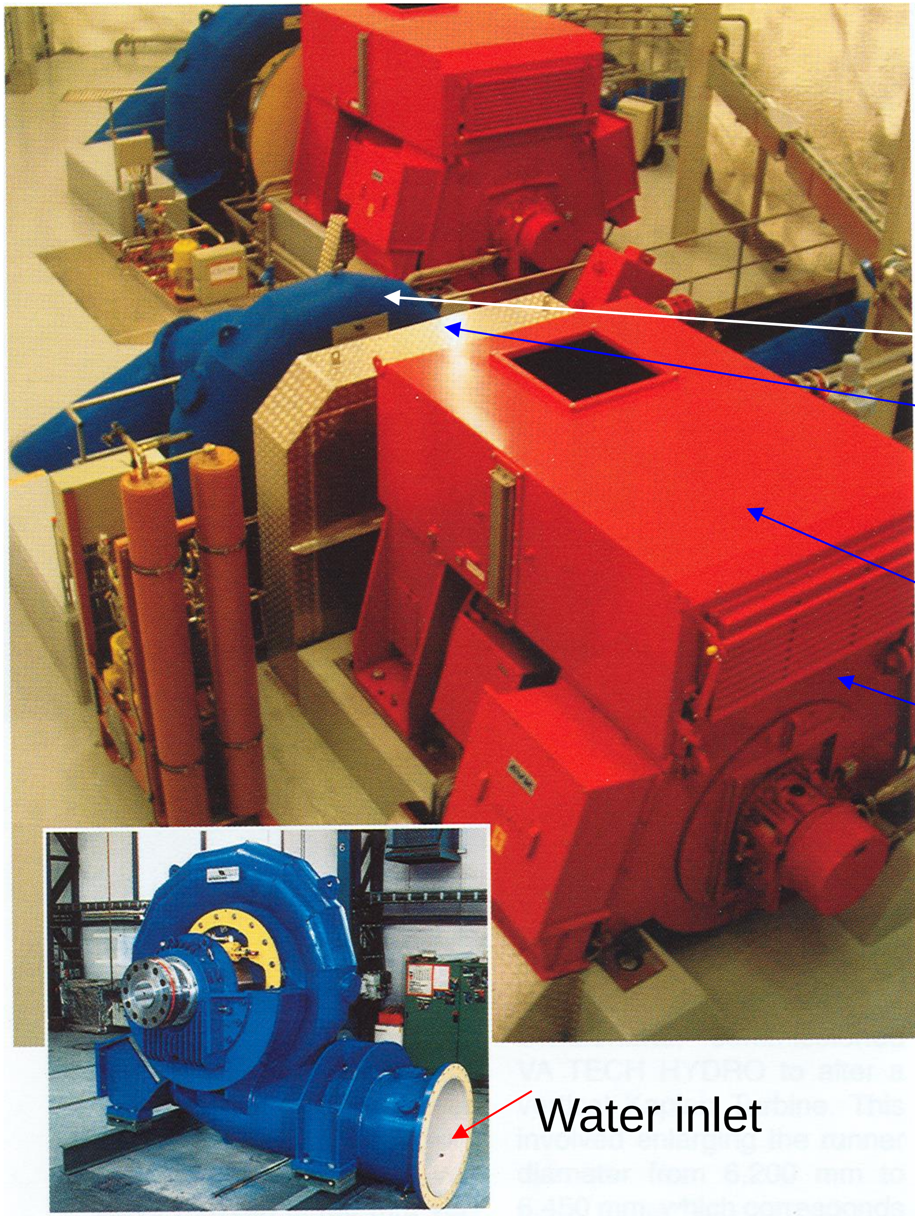
Francis turbine runner,

fixed curved blades

Source:

Andritz Hydro, Austria

“Small hydro” power plant with Francis turbines



Francis turbine spiral housing

Flywheel for increase of inertia to reduce acceleration in case of dropping electrical load

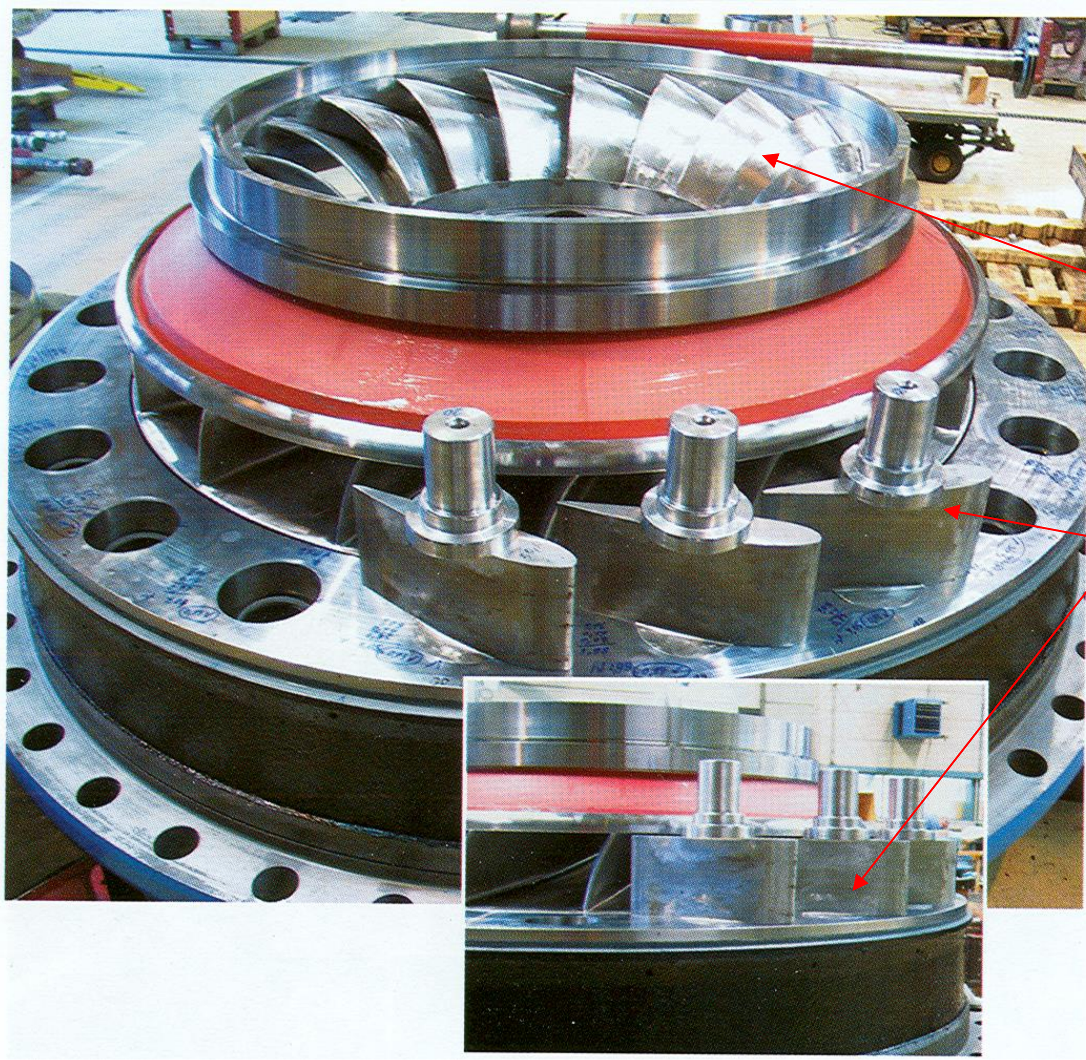
Heat exchanger

Electrically excited synchronous generator

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines



Francis turbine with guiding blades visible

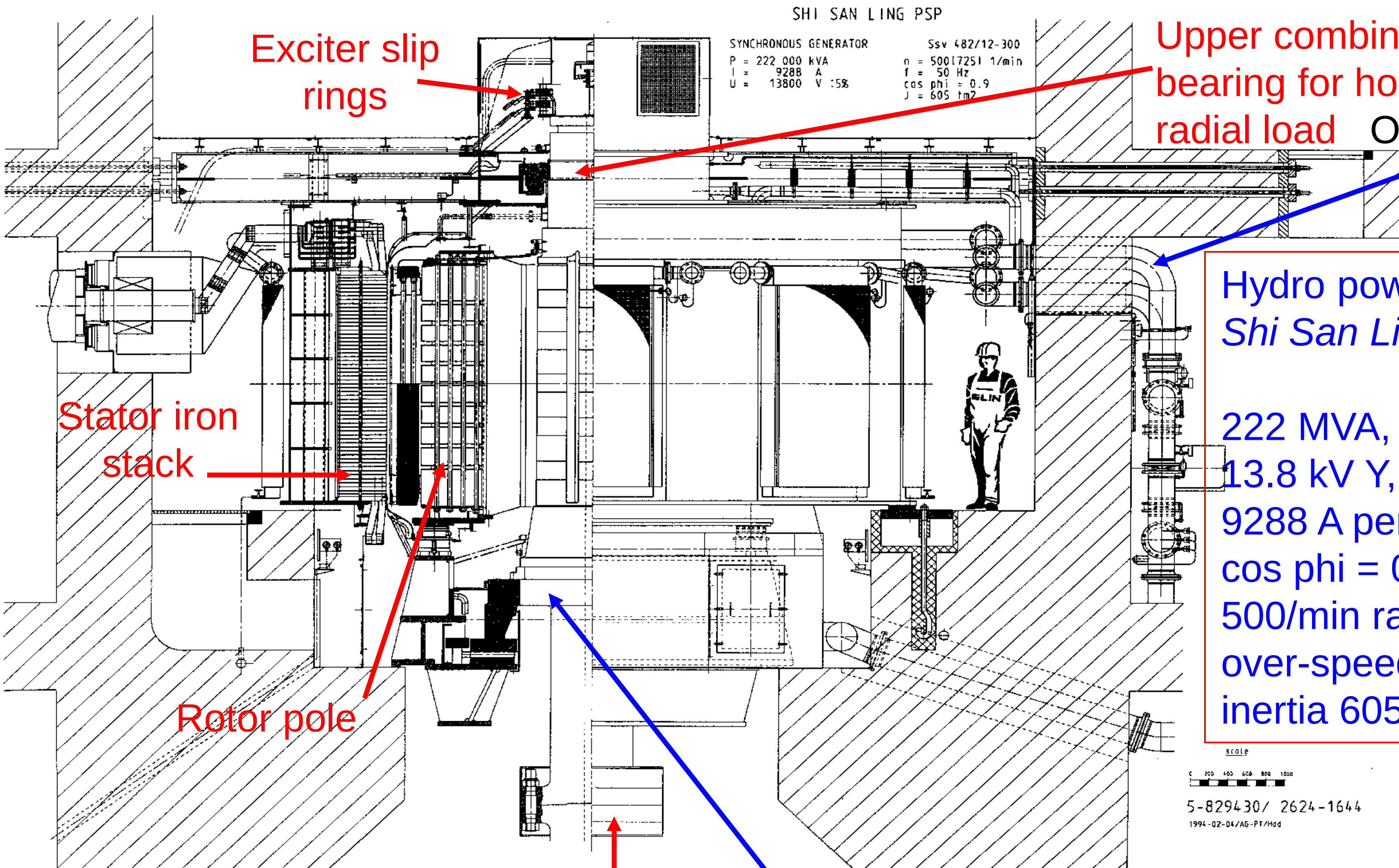
Turbine runner with fixed blades

Turning guiding blades for guiding water in-flow to the turbine runner

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines



Hydro power plant
Shi San Ling / China

222 MVA, 2*p* =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·m^2

Source:

VATech Hydro (now Andritz Hydro), Austria

5. Design of large synchronous machines

Mounting of *Kaplan* turbine runner into turbine housing

Turbine housing

Turbine runner with 5 moveable blades

(propeller turbine)

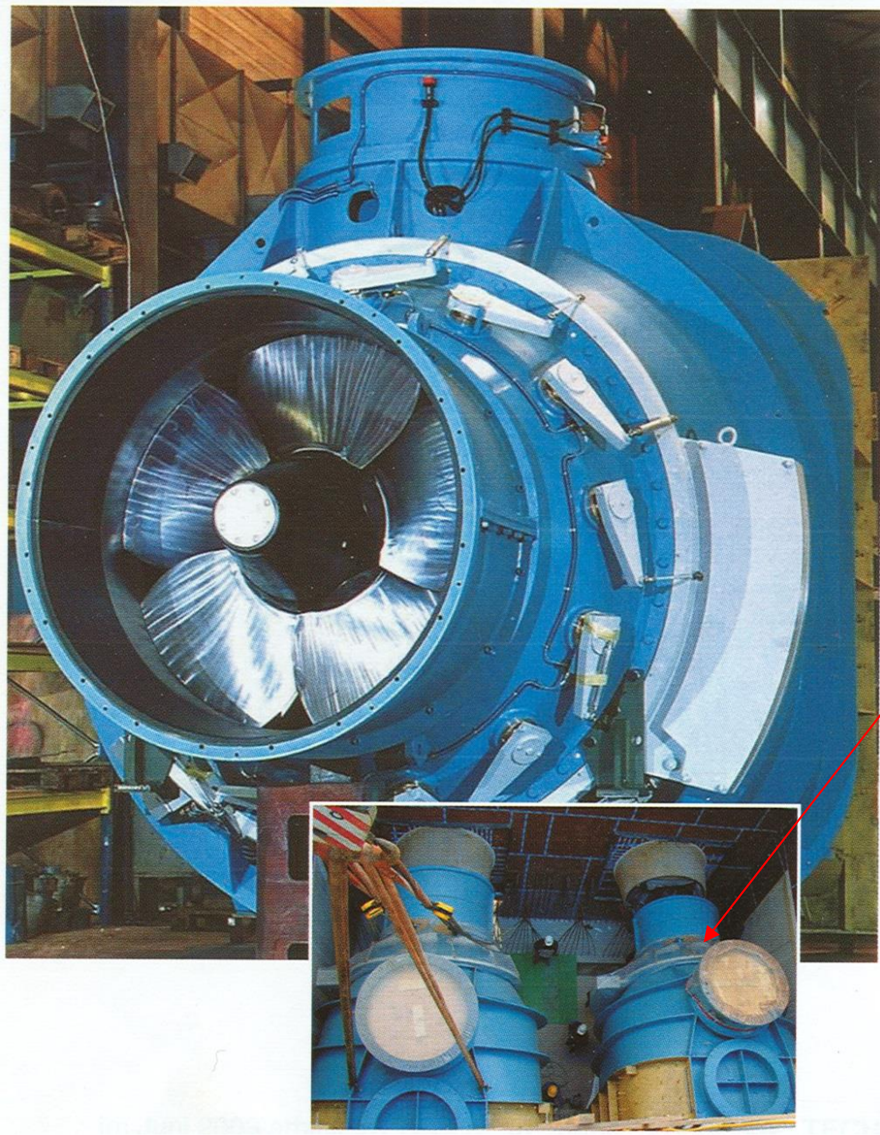
Lever ring to move all guiding blades synchronously

Levers for adjusting the guiding blades, correcting the angle of water inflow at variable flow rate

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines



Kaplan turbine already mounted

View on two parallel turbine housings, lying horizontally in the plant

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines

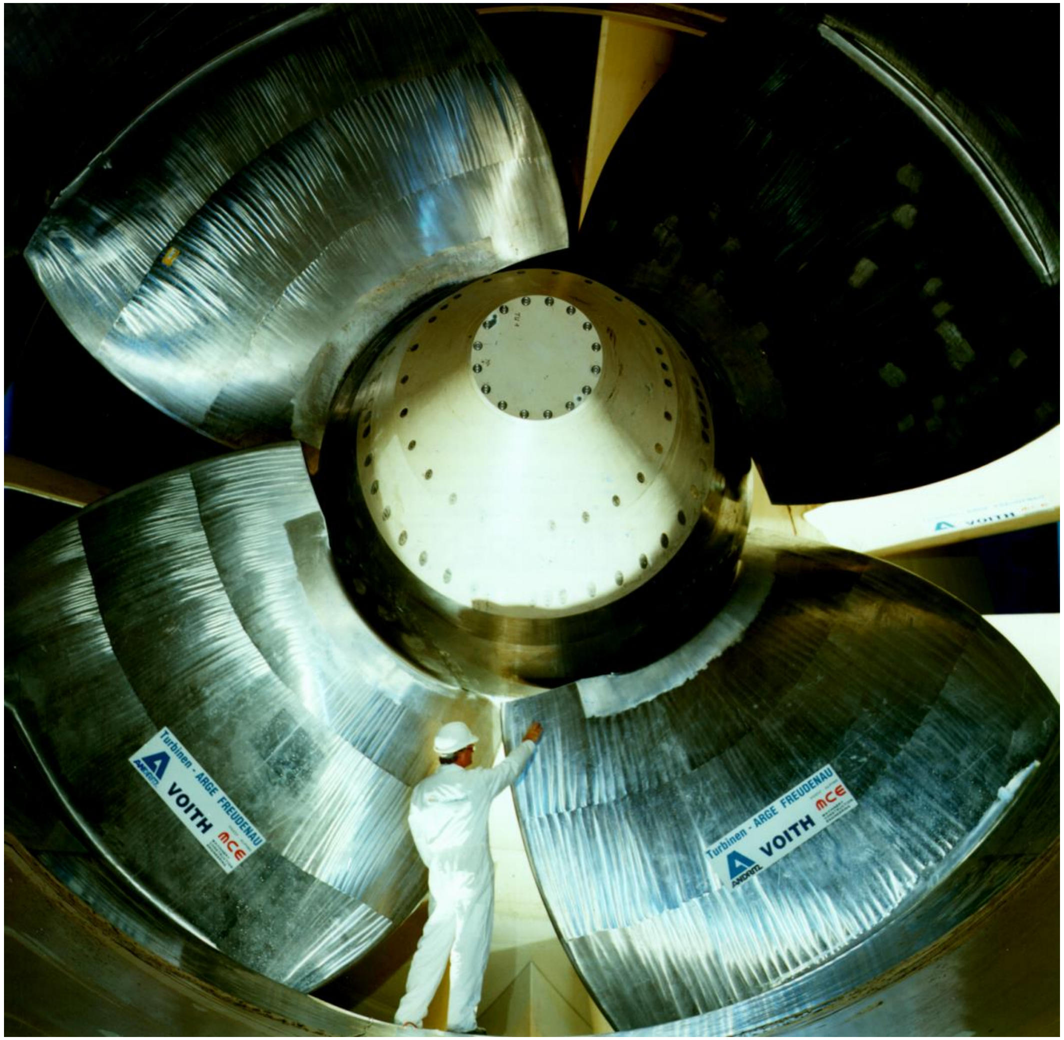
Mounting of *Kaplan* unit into river bed for bulb turbine power plant

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines

Kaplan turbine for bulb turbine generators



- Four blade runner
- Each blade milled in optimum stream-line profile
- Fixed speed operation
- Pitch control: Blade angle adjusted by hydraulic actuators to ensure optimum torque at variable water flow

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines

Ring synchronous generator (high pole count) for bulb river hydro power plant

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:
$\boldsymbol{v_{u,max}}$ **= 85 m/s**

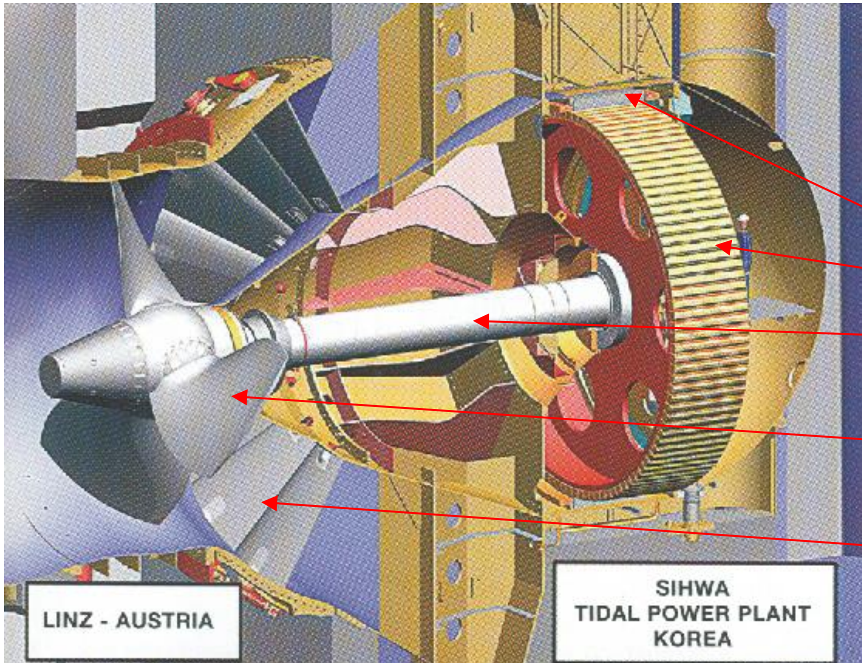
centrifugal acceleration at over-speed: a/g = 200

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines

Bulb type ring synchronous generator with *Kaplan* turbine and horizontal shaft



Generator
Stator
Rotor
Shaft

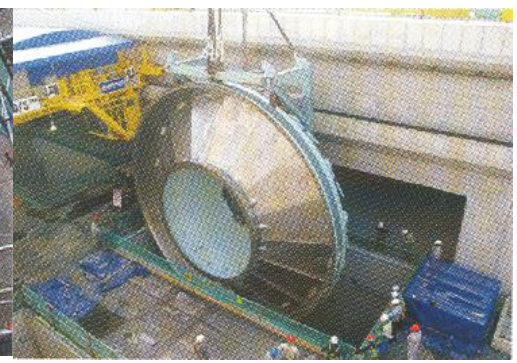
Turbine runner

Guide vane system

Shiwa tidal power plant, *South-Corea*:
26.76 MVA, 60 Hz, 10.2 kV,
112 poles
stator outer diameter 8.2 m,
stator mass: 127 tons
Turbine runner outer diameter 7.5 m
Head 5.82 m

Kaplan turbine runner

Generator rotor 110 t



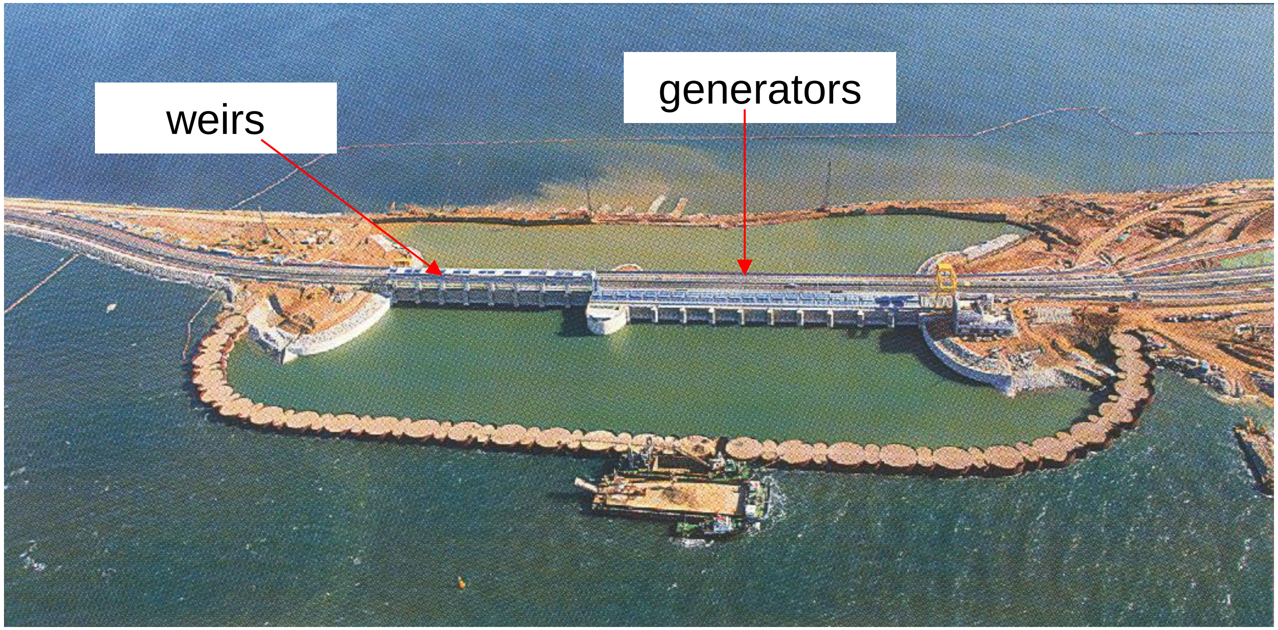
Guide vane system 104 t

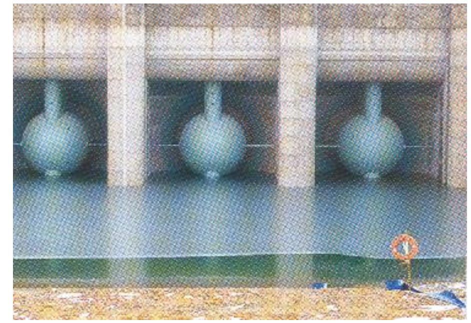
Source:

Andritz Hydro, Austria

5. Design of large synchronous machines

Shiwa tidal power plant, *S-Corea*, 10 x 25.4 MVA





Front view of 3 bulb generators before flooding

Coffer dam for power plant construction (2011):

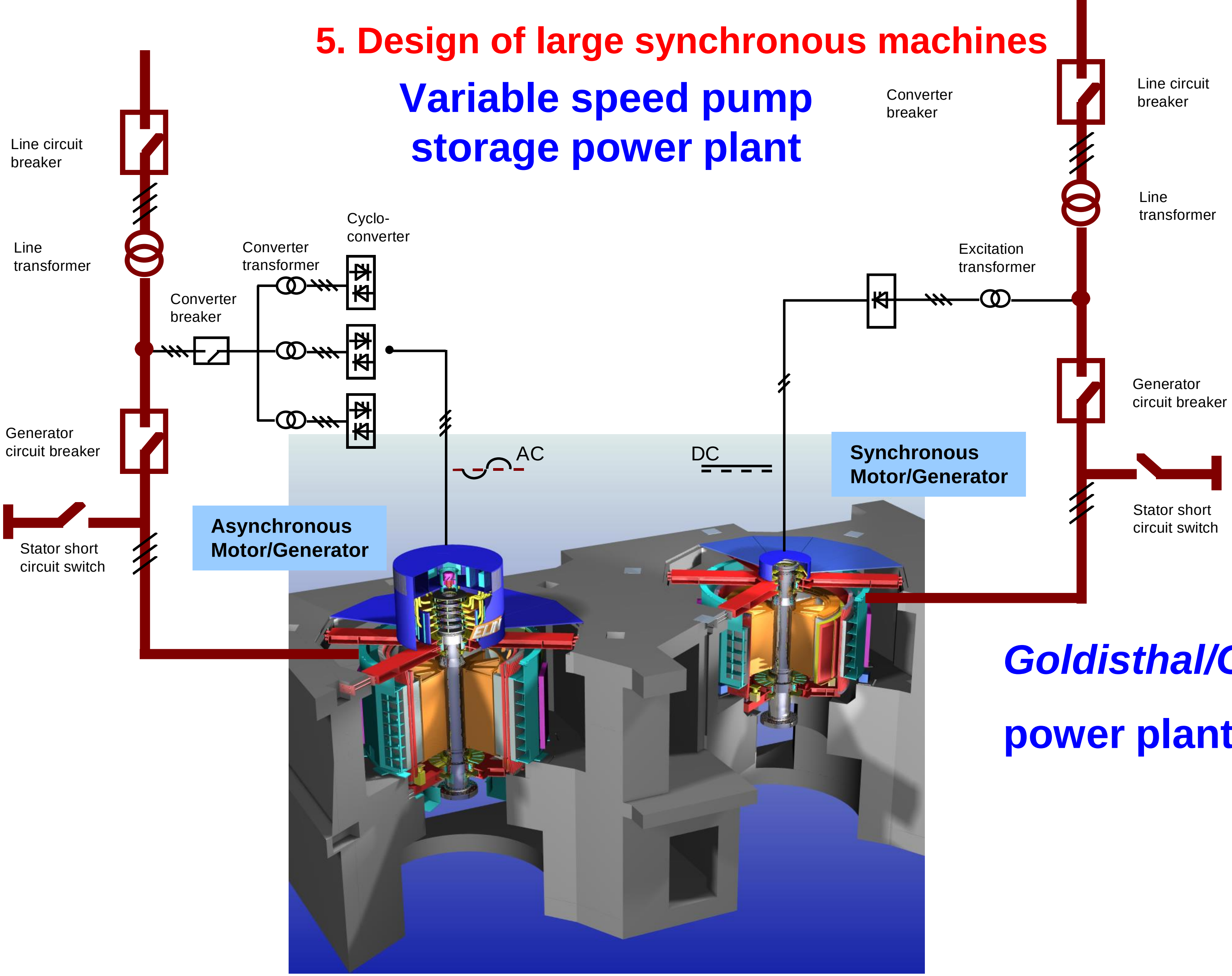
bottom: Artificial lake *Shiwa* 56 km^2

top: sea-side

Source: Andritz Hydro, Austria

Shiwa tidal power plant, *South-Corea*:
<u>During flow tide:</u> Water flow from sea to lake via reverse rotating turbines and
<u>During ebb tide:</u> Water flows from the lake via the operating turbines back to the sea
Hence: Operational time is only a few hours per day!

Variable speed pump storage power plant



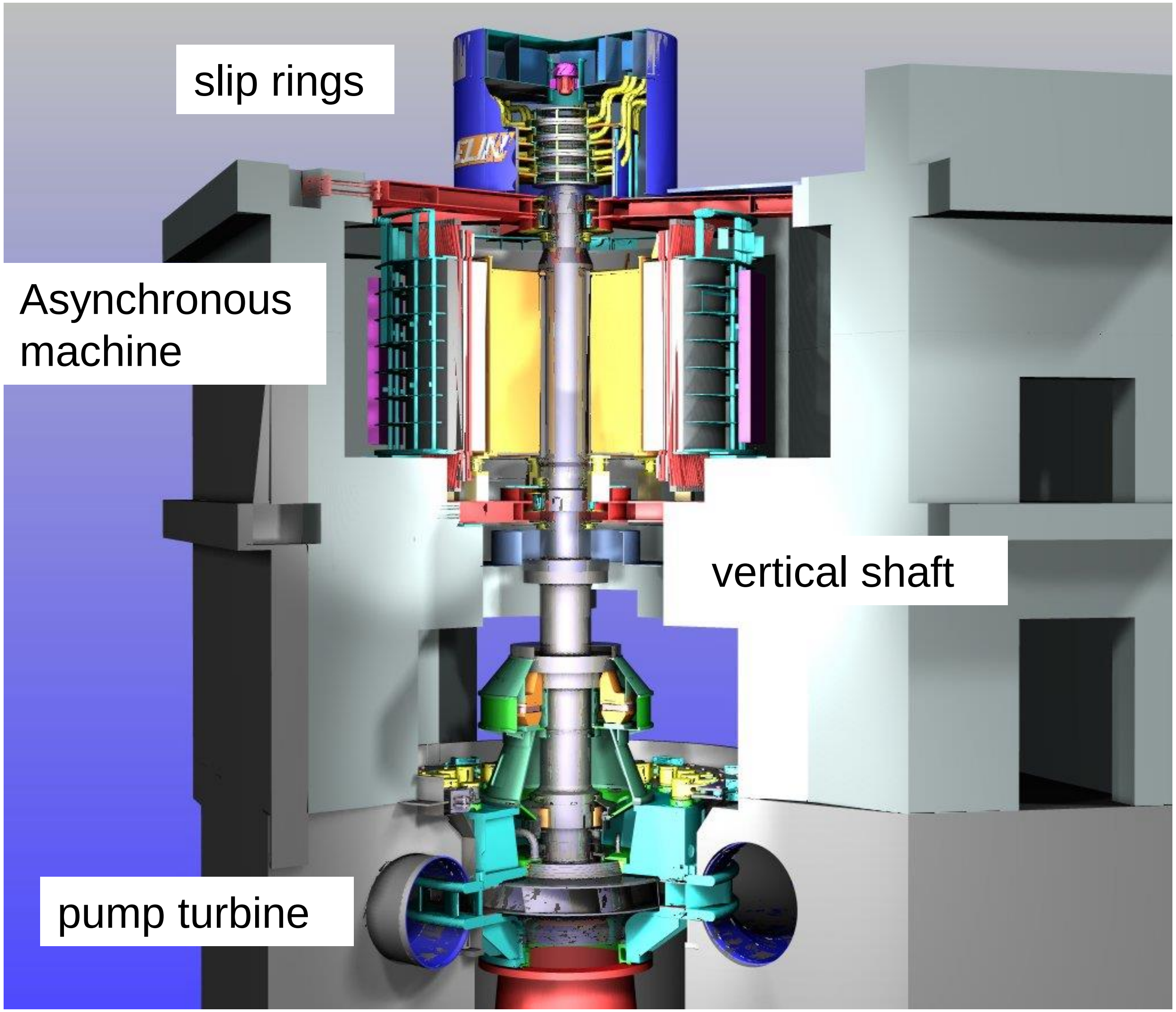
Goldisthal/Germany

power plant

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines



Asynchronous doubly-fed motor/generator

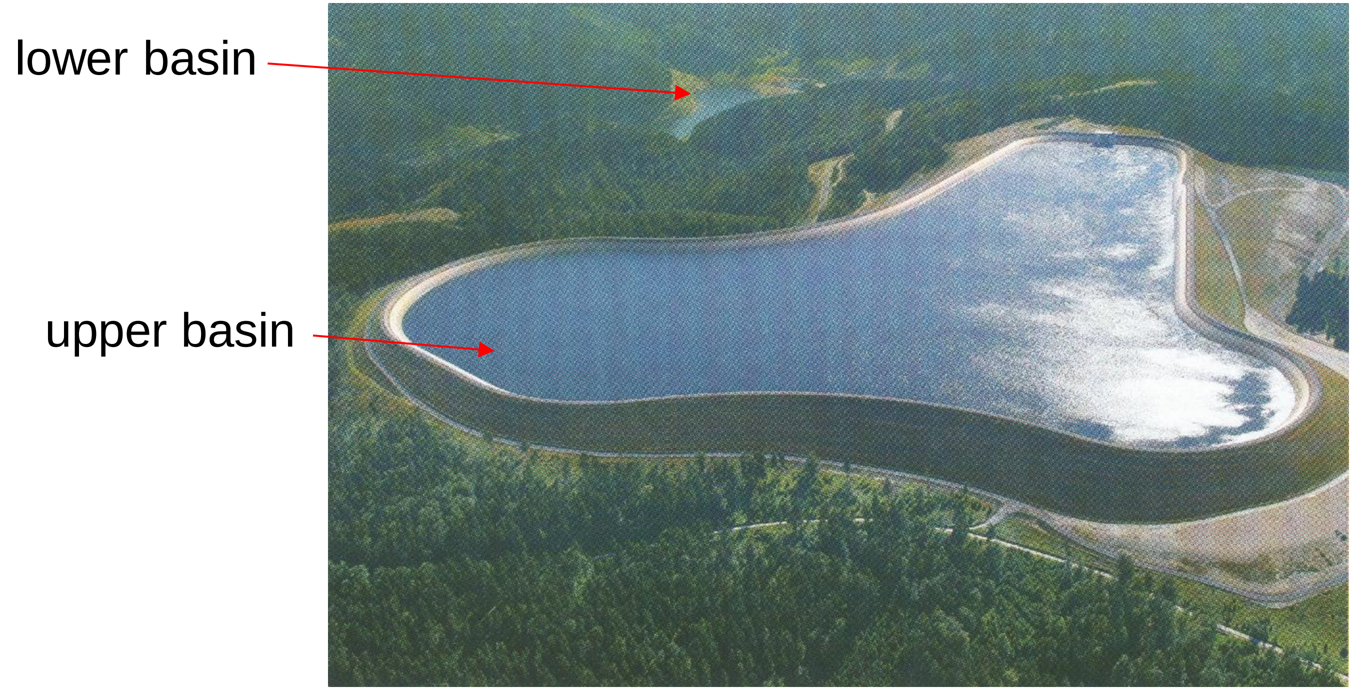
pump storage plant
Goldisthal/Thüringen

Source:

Andritz Hydro, Austria

5. Design of large synchronous machines

Pump storage plant *Goldisthal/Thuringia, Germany,* 4 x 265 MW



Total pump power: 1060 MW,
Energy storage: 8480 MWh
Full power for 8 h to empty/fill the upper basin

Source:
BWK Vo. 63/5, p. 55, 2011

5. Design of large synchronous machines

Pump unit for pump storage plant

Pump shaft

Pump runner

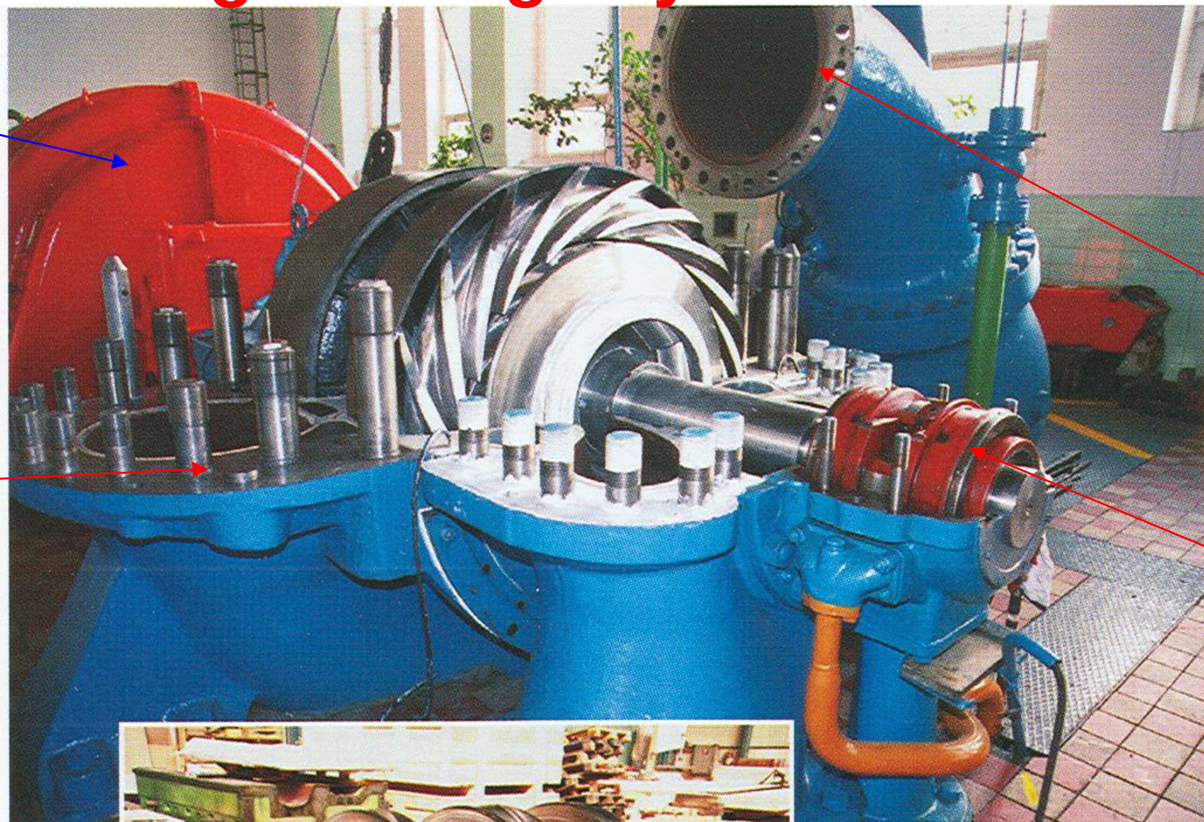
Source:

Andritz Hydro, Austria

5. Design of large synchronous machines

Electrically excited synchronous motor-generator

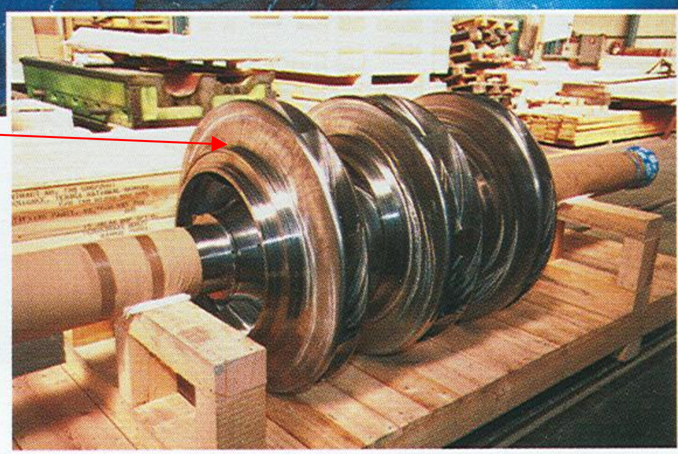
Three-stage pump for pump storage plant



Water outlet

Pump housing

Sleeve bearing



Pump runner

Source:

Andritz Hydro, Austria

Summary:

Types of power plants and related synchronous generators

Hydro power plants

- Hydraulic power depends on: Water flow rate, head
- Classification of power plants, turbine types:
  - River plant (low head, high flow rate), *Kaplan*-Turbine
  - River barrage plant (medium head, medium flow rate), *Francis*-Turbine
  - (Pump) storage plant (high head, low flow rate), *Pelton*-Turbine
- Classification of operation, generator types:
  - Small hydro (several 100 kW … several MW), cage induction gen. with gear, PM synchronous gen., or electrically excited synchronous gen.
  - Big hydro (several MW … several 100 MW), gearless, electrically excited synchronous gen., doubly-fed induction generator

Thermal power plants

Carnot cycle efficiency

Thermal power plants: Electrical energy from thermal energy

- Black/Brown coal burning → Water → Steam → electrical power
- Nuclear fission → Water → Steam → electrical power
- Natural gas burning → exhaust gas → electrical power

Thermal input power P_{in}

Hot steam temperature T_{in}

Electrical output power P_{out}

Condensed water temperature T_{out}

Waste heat in the cooling system P_d

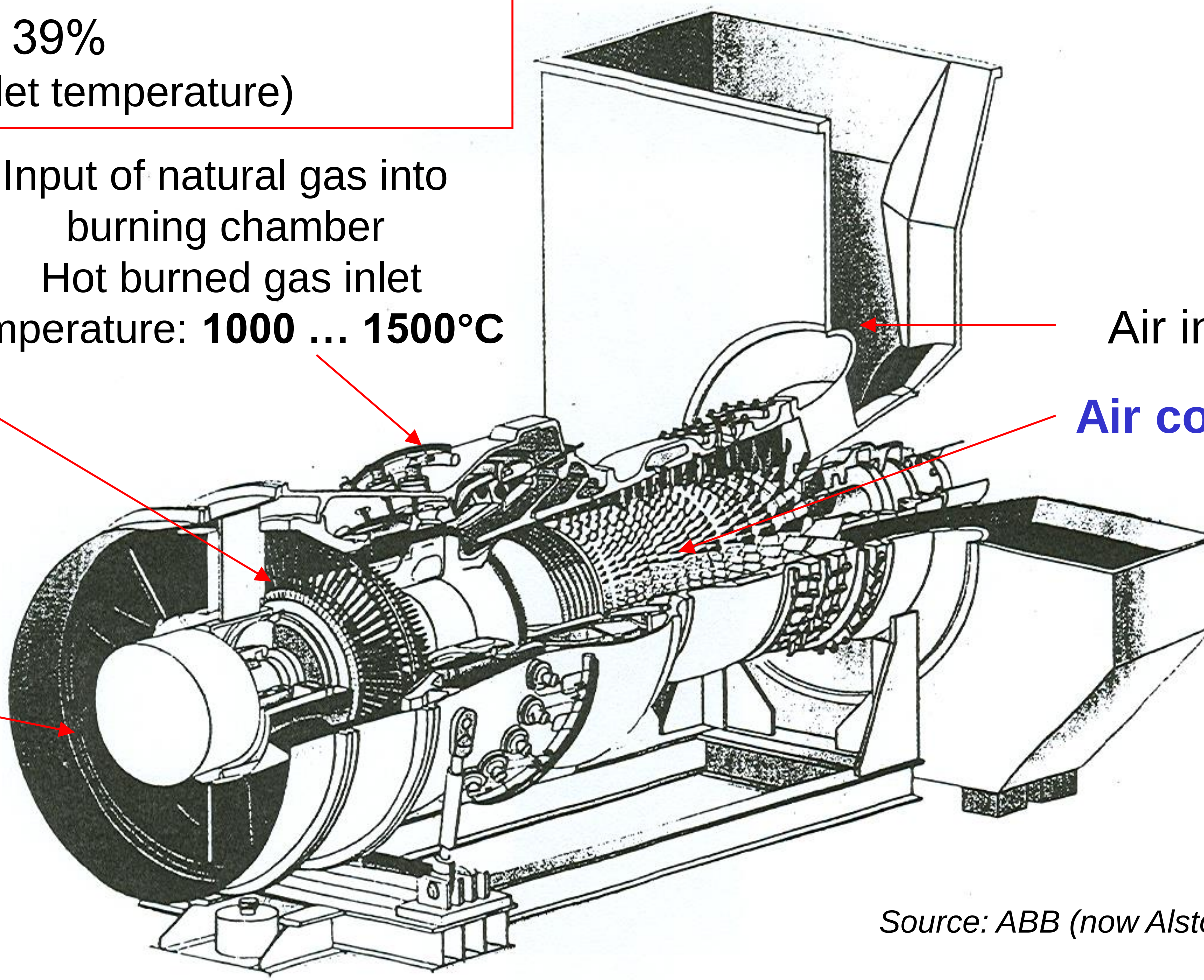
Best possible cycle efficiency is given by *Carnot* cycle:

$$\eta_{Carnot} = P_{out} / P_{in} = 1 - T_{out} / T_{in}$$

Source: BWK, VDI-Verlag

Gas turbines

- Max. power per unit: ca. 350 … 400 MW
- efficiency ca. 35 … 39%
  (Limited by hot gas inlet temperature)



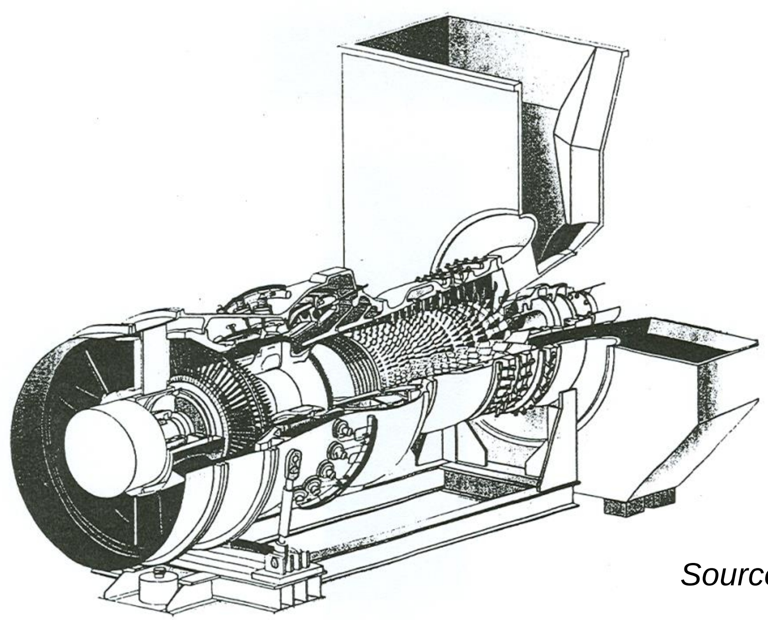
Source: ABB (now Alstom), Germany

Gas turbine efficiency

Example: Gas turbine: P_{ab} = 340 MW electrical power

Inlet-/Outlet temperature of smoke gas ($CO_2 + H_20$): 1100 °C / 550 °C
1373 K / 823 K

$\eta_{GP} = 1 - T_{out}/T_{in} = 1 - 823 / 1373 = 0.4 =$ **40% … 340 MW electrical power**



Source: ABB (now Alstom), Germany

Combined cycle - Gas- and steam power plant (CC, GuD)

Heat exchanger: Hot exhaust gas: Inlet-/Outlet temperature: 550 °C / 100 °C
823 K / 393 K

$\eta_{HE} = 1 - T_{out}/T_{in} = 1 - 393/823 = 52\%$

Steam generated via heat exchanger: Turbine In-/Outlet: 515 °C / 20 °C
788 K / 293 K

$\eta_{ST} = 1 - T_{out}/T_{in} = 1 - 293/788 = 63\%$

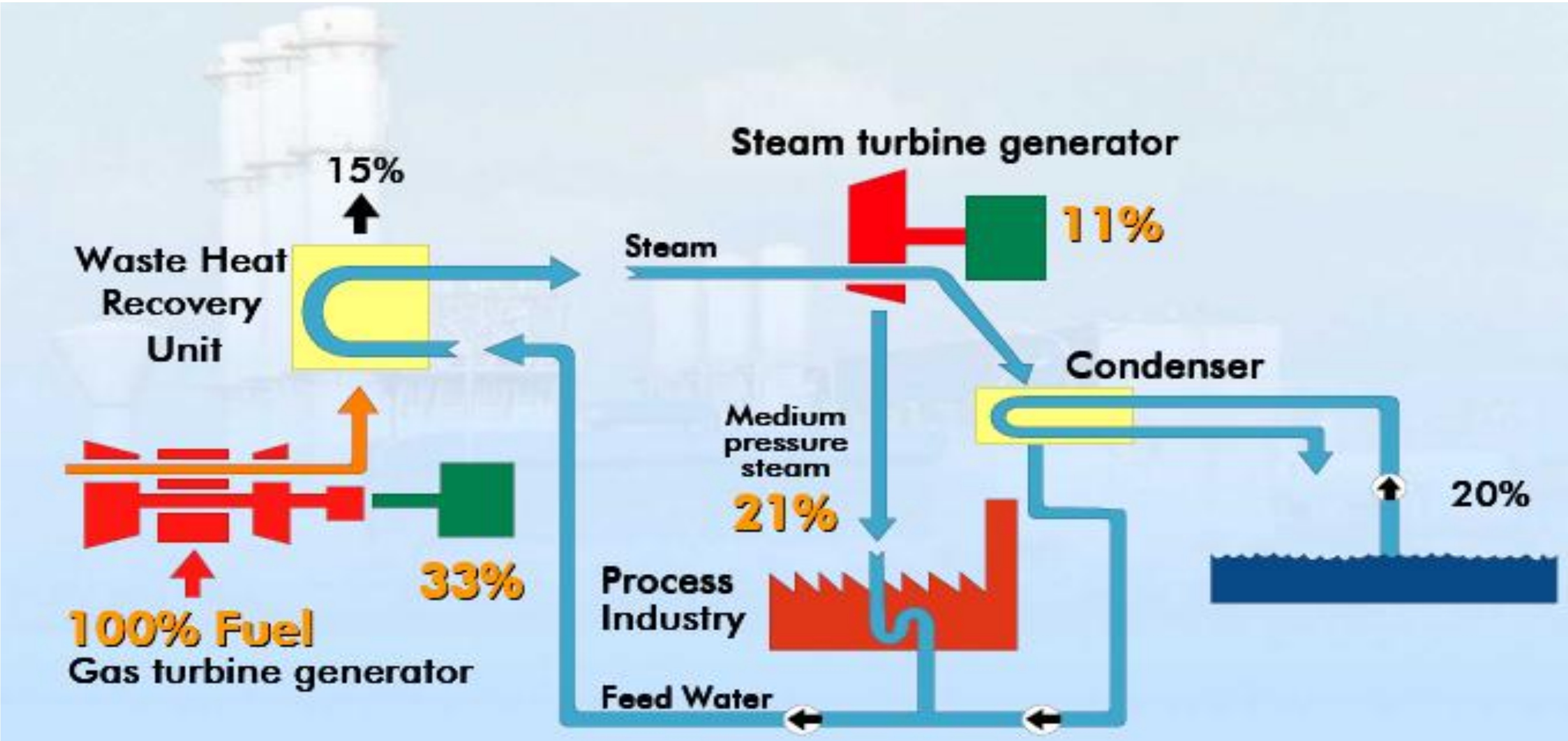
$(1 - 0.4) \cdot 0.52 \cdot 0.63 = 0.2 =$ **20 % … 170 MW additional electrical power**

Theoretical electrical efficiency: 0.4 + 0.2 = 0.6 = 60%

Total electrical power: 340 + 170 = 510 MW

Necessary thermal power (burning natural gas): 510/0.6 = 900 MW

Industrial combined cycle with use of thermal waste energy



Electrical efficiency: 33 + 11 = 44%

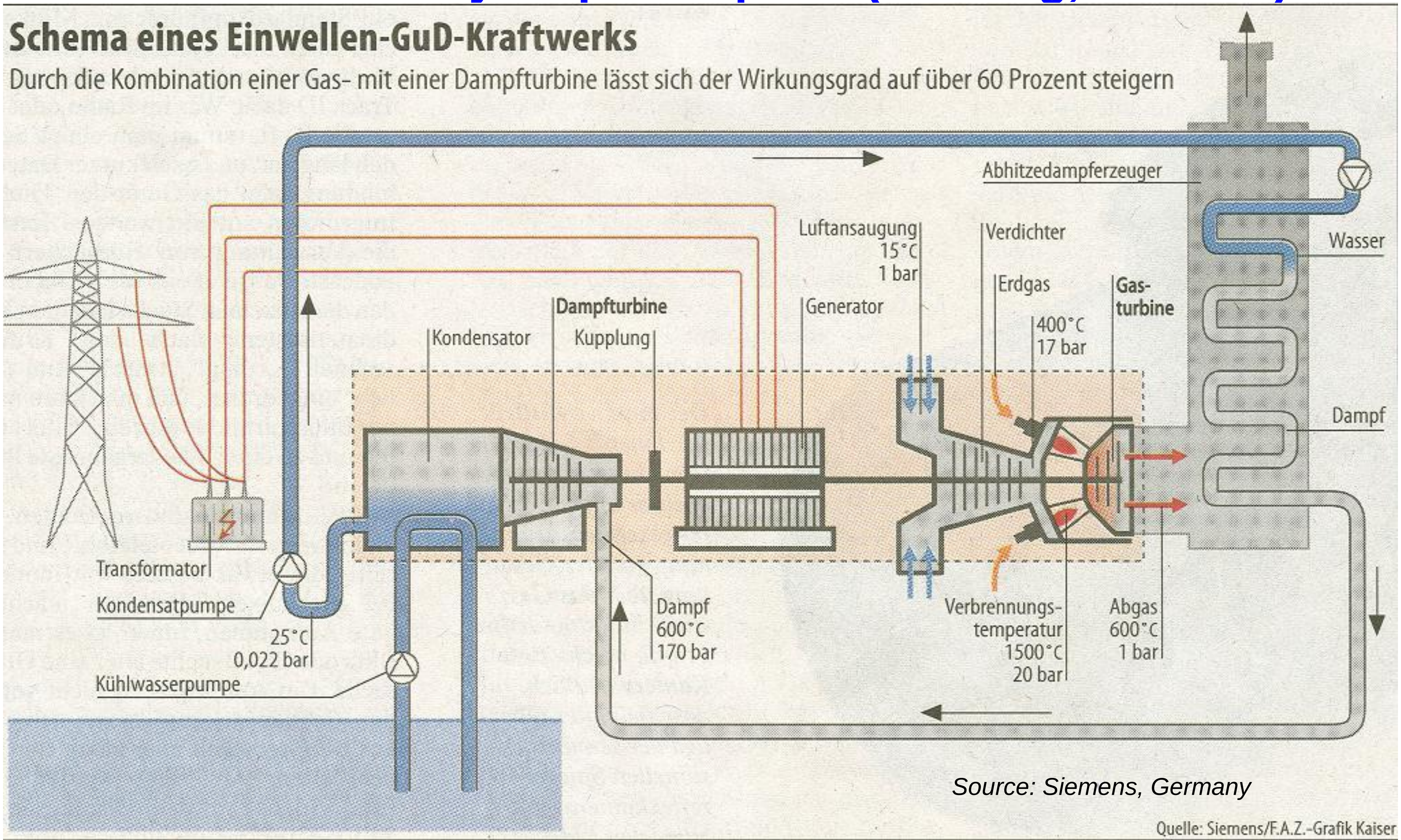
Thermal efficiency: 44 + 21 = 65%

Use of waste heat for the industrial process, e.g. paper manufacturing

Source: Alstom, Germany

5. Design of large synchronous machines

Combined cycle power plant (*Irsching, Bavaria*)



Combined cycle: Increase of efficiency

Combined cycle power plant *Irsching/Bavaria* (e.on):

530 MW electrical power, efficiency: **60%**
(World-wide highest value in unit power and efficiency)

- 40 000 tons CO_2 p. a. via increase of efficiency

Actual average CC efficiencies world-wide: ca. **45 %**

Source:

Siemens AG, Germany

Numerical hot gas flow simulation for optimization of blade profiles in a gas turbine

5. Design of large synchronous machines

Combined cycle (CC) power plant *Irsching/Bavaria (e.on)*

CC *Irsching, Bavaria*

4500 h operating hours p.a.
200 quick starts p.a.

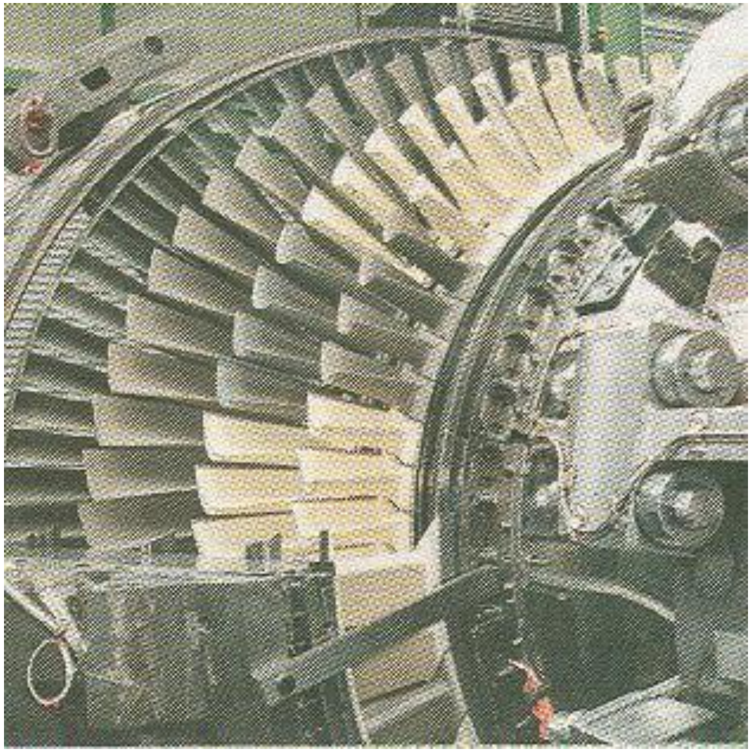
Source: Siemens AG, Germany

Gas turbine *Irsching* during manufacturing
(340 MW, 444 tons)

Volume flow: 600 m^3/s air + 25 m^3/s natural gas
Air compressed to 17 bar

5. Design of large synchronous machines

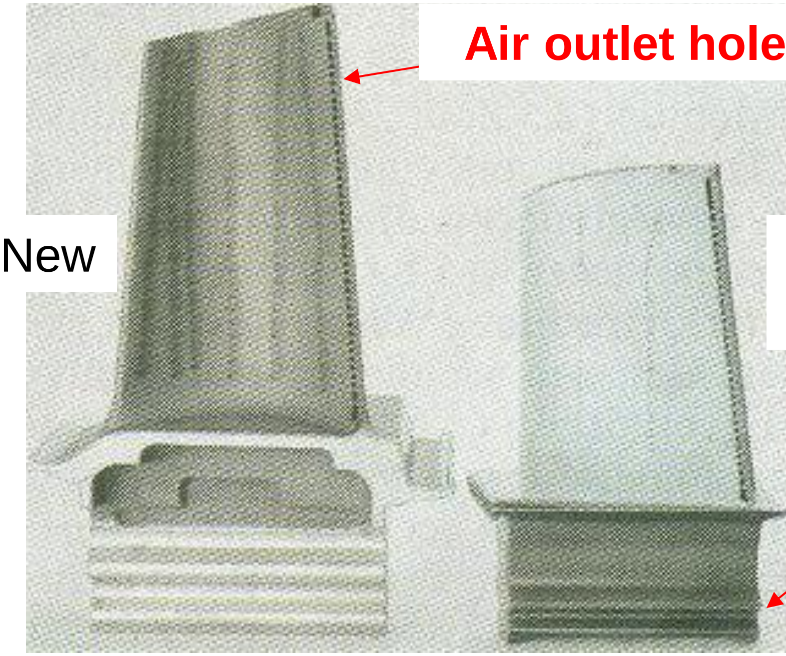
Gas turbine 340 MW, CC power plant *Irsching/Bavaria (e.on)*



Turbine blade stages

Hot exhaust gas inlet temperature: **1500°C**

Source: Siemens AG, Germany

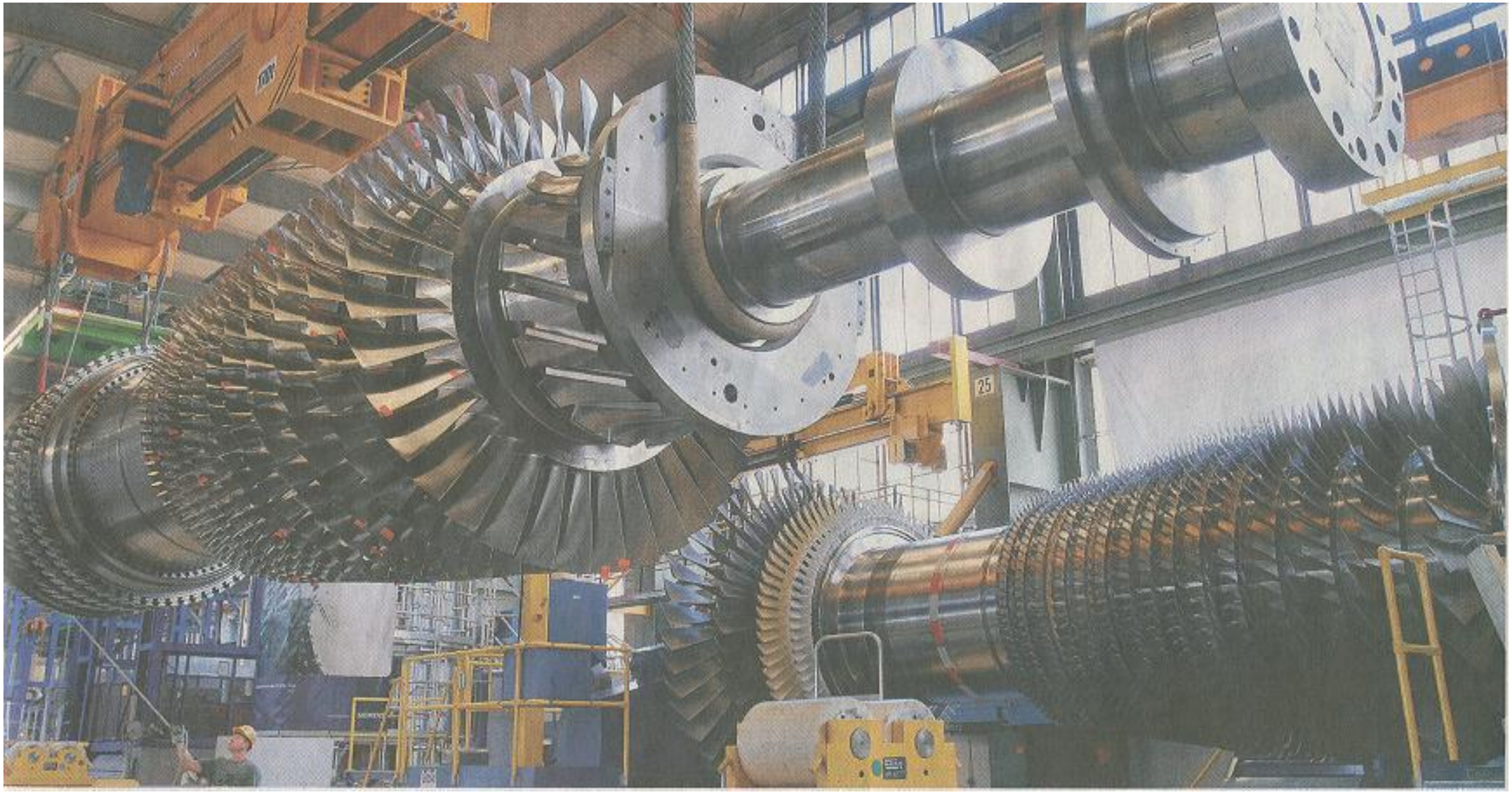


Turbine blades:

Surface temperature of blades: 950°C to limit damage!
Blade from super-crystalline Ni-alloy with 0.3 mm metallic layer bears a ceramic coating to protect against high temperatures,
Cooling air (400°C) as a thin film around the blade surface!

5. Design of large synchronous machines

Rotor of the 340 MW-gas turbine *Irsching/Bavaria*



Source: Siemens AG, Germany

Coal power plants – increasing efficiency

- **Black coal power plant *Moorburg* (Vattenfall):**

2 x 820 MW electrical power, efficiency: 46.5%

Steam: Inlet temperature: 600°C, 276 bar pressure
Outlet: 26 mbar (Steam at ca. 20°C)

Actual average efficiencies in *Germany*: ca. 38%
world-wide: ca. 30%

Decrease of CO_2-production via increase of efficiency: From 850 to 700 grams/kWh

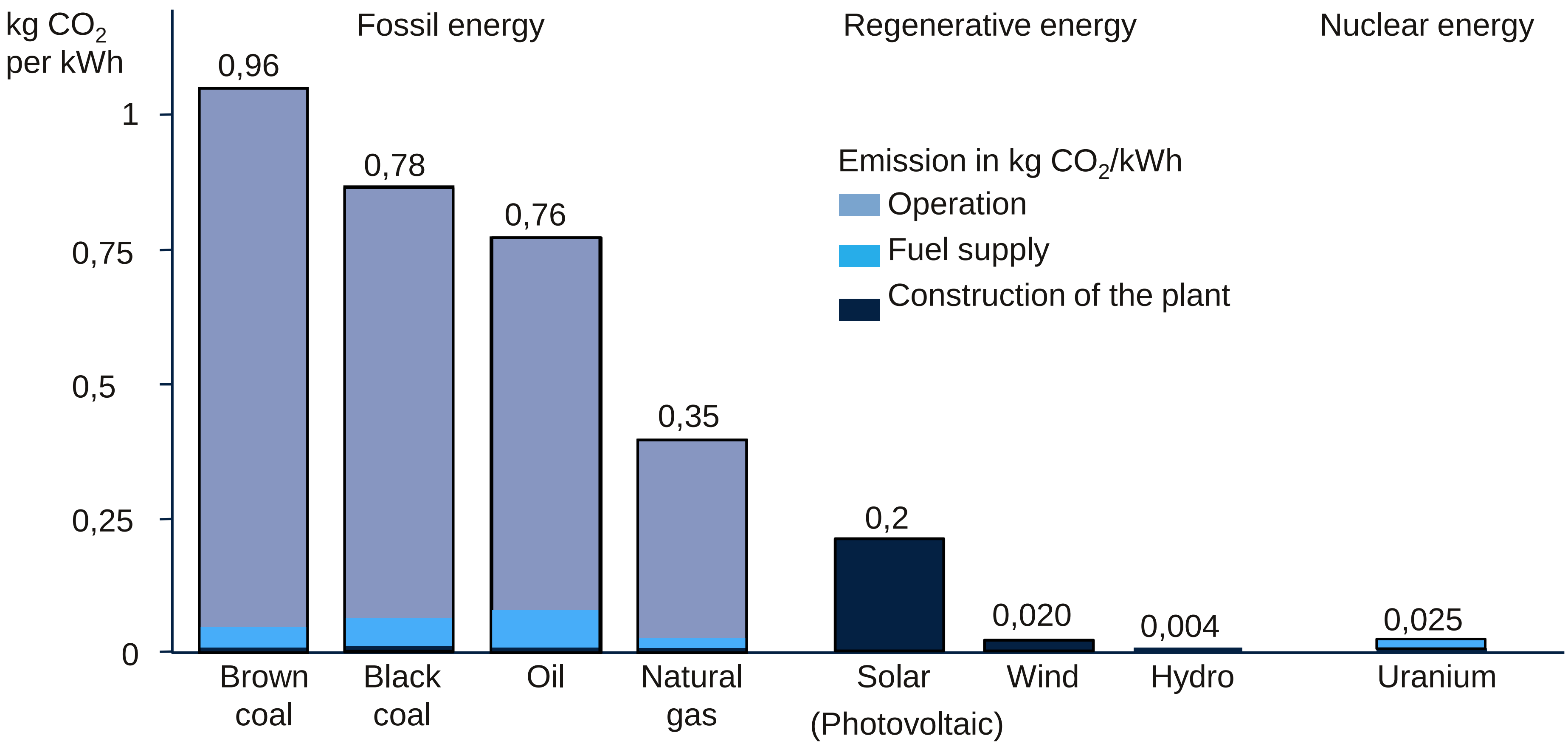
- **Brown coal power plant *Boxberg R* (Vattenfall):**

675 MW electrical, efficiency: 43.3%

Steam: Inlet temperature: 600°C, 286 bar pressure
Outlet: 39 mbar

Decrease of CO_2-production via increase of efficiency: From 1200 to 900 grams/kWh

CO_2-Emission of power plants

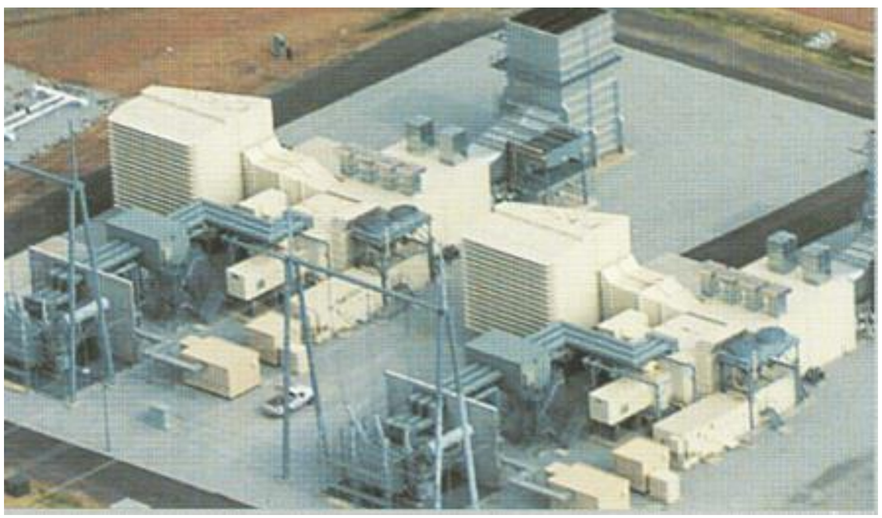


Source: Siemens AG, Germany

5. Design of large synchronous machines

Brown coal steam power plant *„Schwarze Pumpe", Germany*, 2 x 800 MW

Combined cycle power plant (Gas and steam turbine process), *Tapada do Outeiro, Portugal*, Gas and steam turbine on a single shaft, 3 x 333 MW = 1000 MW



Gas turbine power plant, *Cass county, Nebraska, USA*,

Turnkey project, 2 x 200 MW = 400 MW

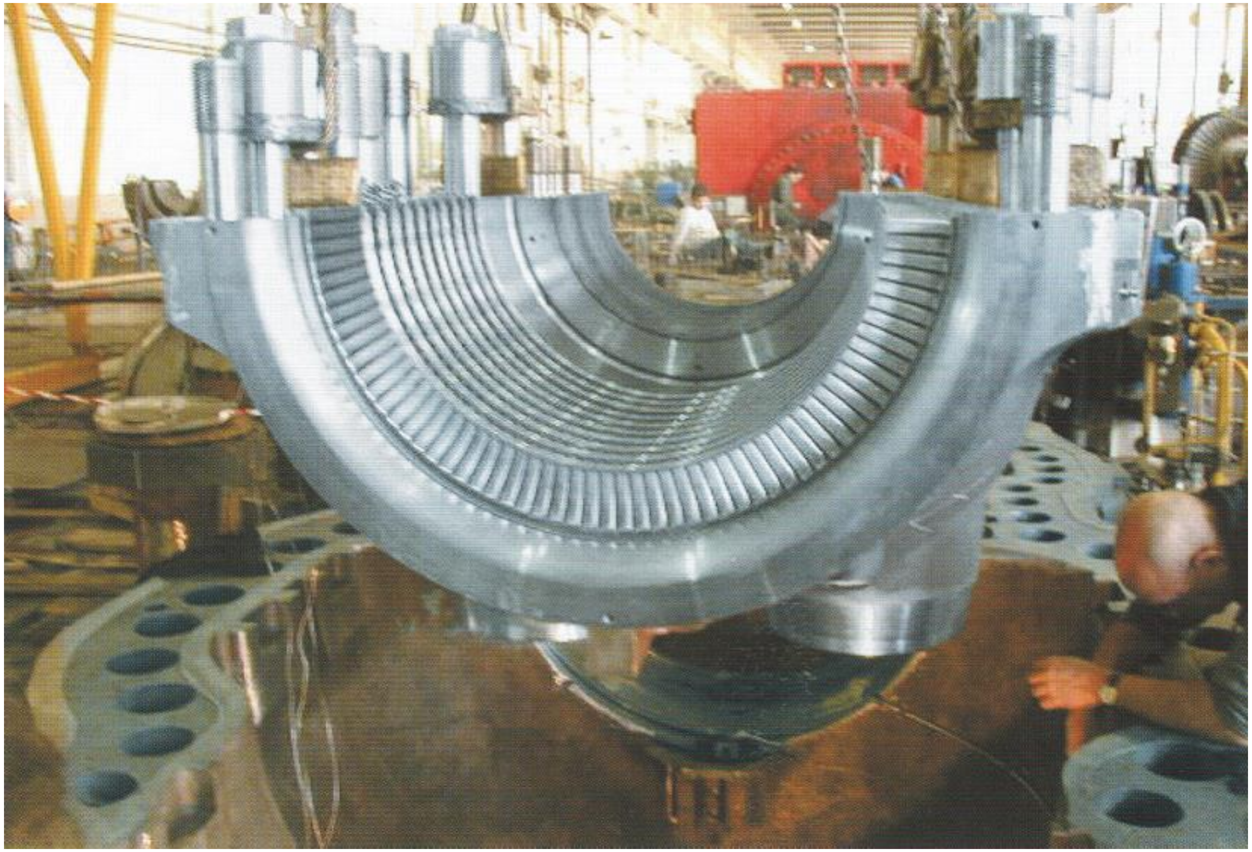
Source:

Siemens AG, Mülheim/Ruhr, Germany

Manufacturing of steam turbines

Source:

Siemens AG, Mülheim/Ruhr, Germany



- Mounting of one halve of the high pressure guiding blades into the high pressure housing.
- Note the thick housing and holes for bolts to sustain a steam pressure of 276 bar at 600°C steam temperature

Steam turbine manufacturing: Mounting of the low pressure rotor

Half of the housing of the low pressure steam turbine stage:

The guiding blades are visible

Low pressure steam turbine rotor with two-sided steam flow, made of rotor discs, total weight 260 tons

Source: Siemens AG, Mülheim/Ruhr, Germany

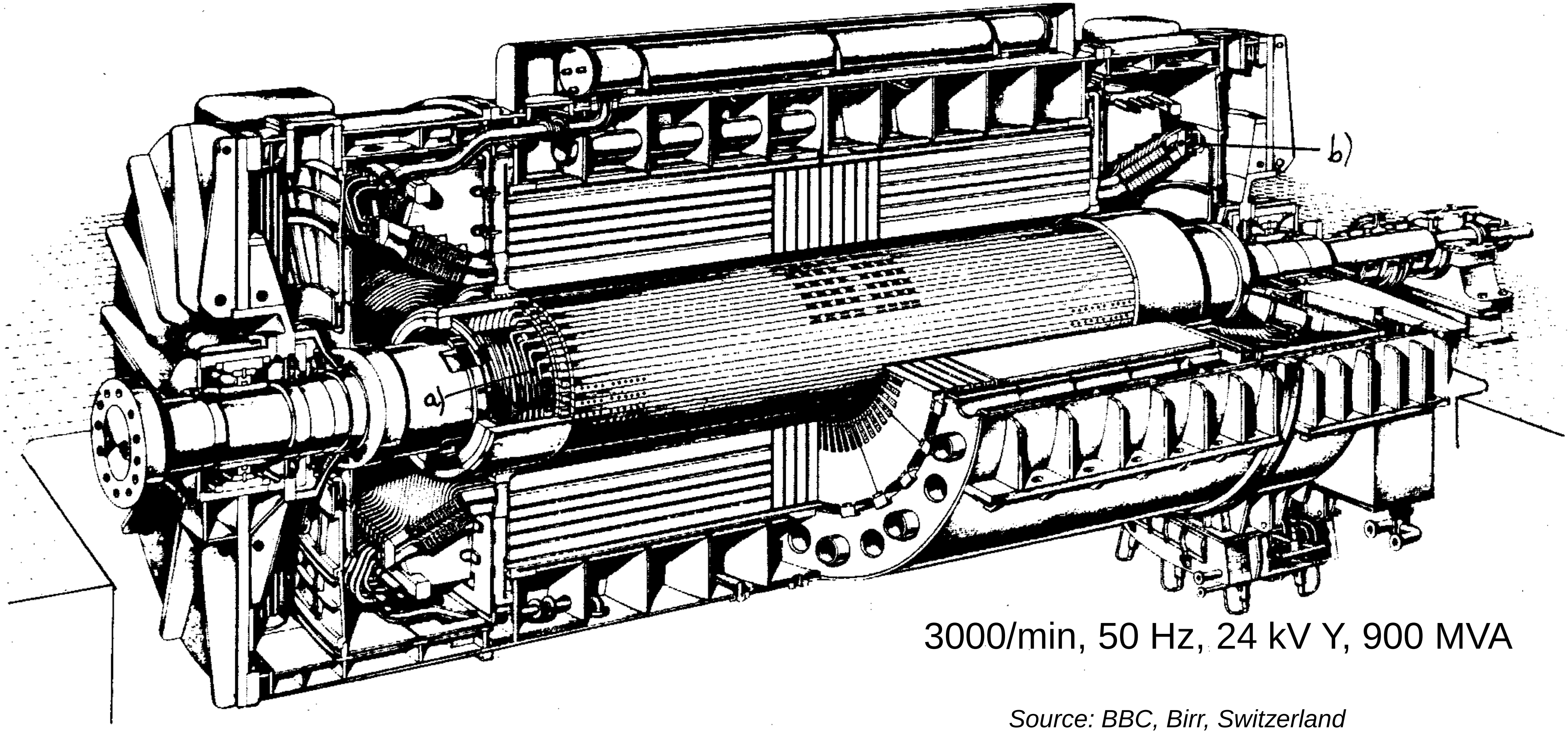
Steam turbine manufacturing: Mounting of the low pressure rotor

After placing the rotor in the housing, a careful alignment and adjustment of the bearing pedestals is necessary

Source: Siemens AG, Mülheim/Ruhr, Germany

Big 2-pole turbine generator for thermal power plant, driven by steam turbine

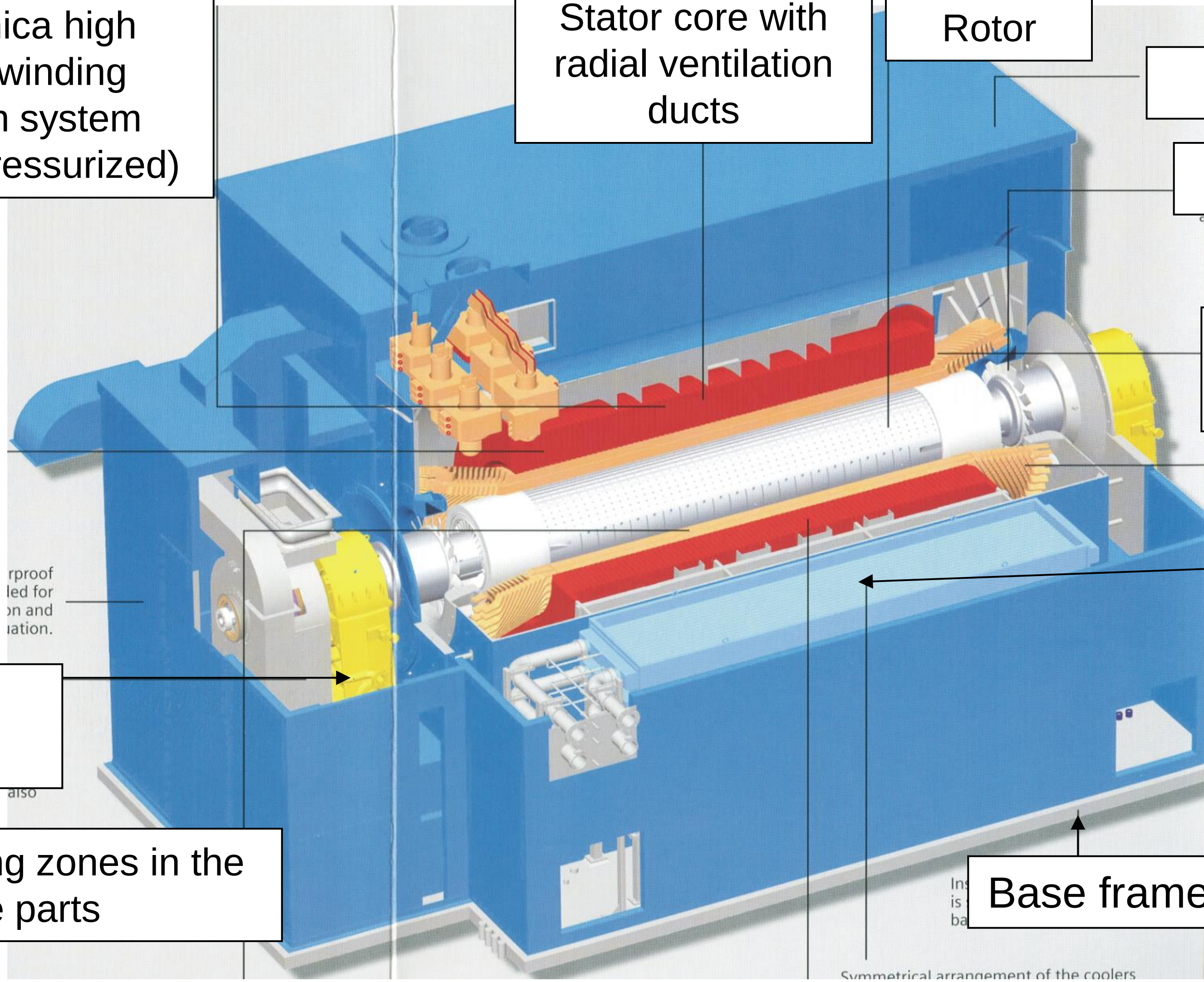
hydrogen gas cooled rotor, direct water cooled stator winding with hollow conductors



3000/min, 50 Hz, 24 kV Y, 900 MVA

Source: BBC, Birr, Switzerland

Basic elements of two-pole turbine generator



Source:

Siemens AG, Mülheim/Ruhr, Germany

Summary:

Types of power plants and related synchronous generators

Thermal power plants

- Best possible cycle efficiency given by *Carnot* cycle
- Gas turbines (max. power ca. 350 … 400 MW): Efficiency ca. 35 … 39 %
- Brown coal power plant: Efficiency up to 43 %
- Black coal power plant: Efficiency up to 46 %
- Combined cycle power plant (Gas + Steam): Efficiency up to 60 %

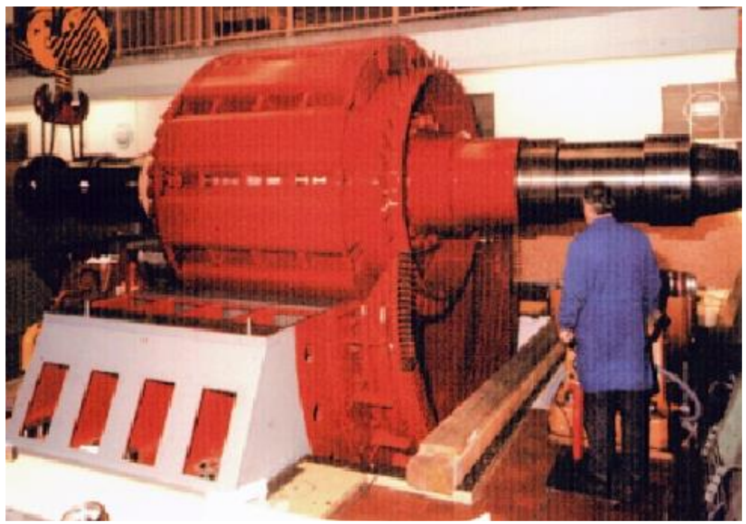
- Fast rotating (two- or four-pole) cylindrical rotor synchronous generator
- Intensive cooling necessary

5. Design of large synchronous machines

5.1 Main features of big synchronous machines

5.2 Design relationships for poly-phase synchronous machines

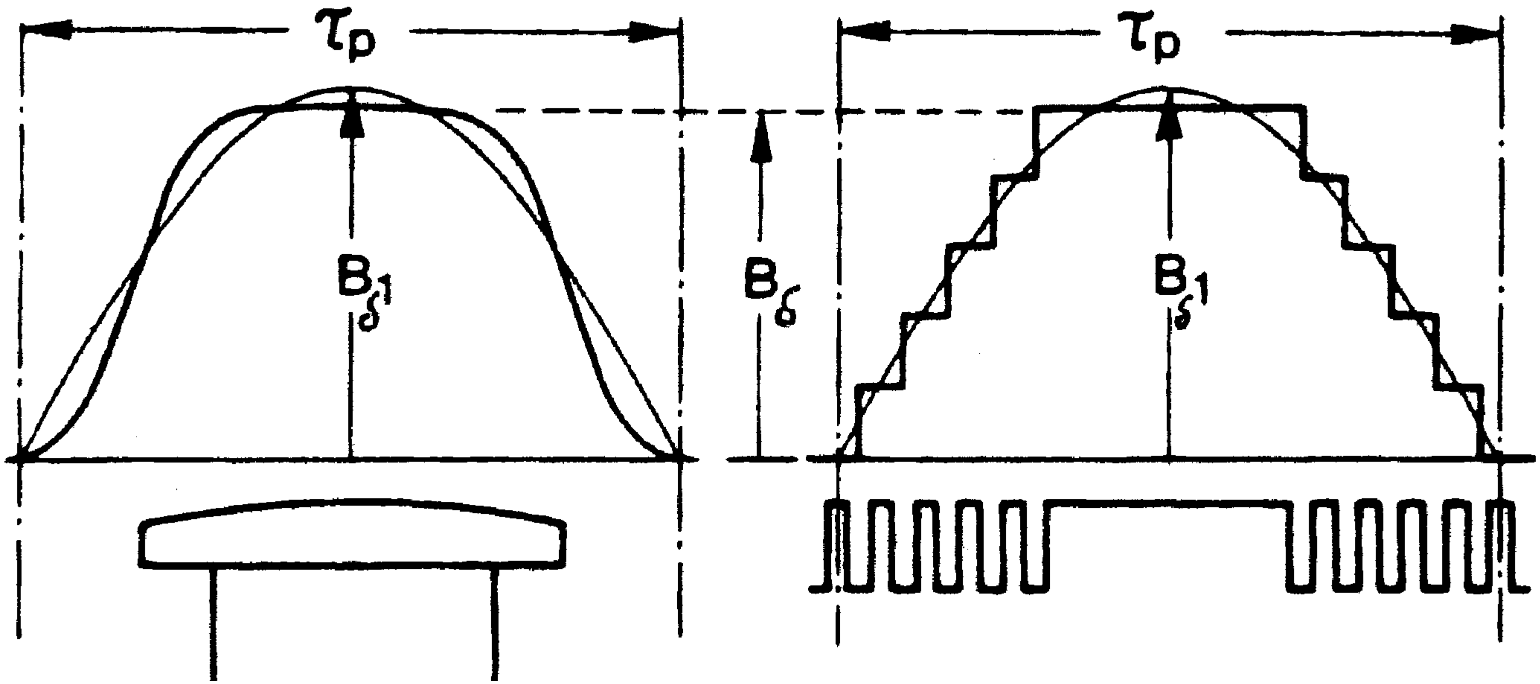
5.3 Special design problems and solutions



Source: Andritz Hydro, Austria

5.2 Design relationships for polyphase synchronous machines

Rotor *Fourier* fundamental magnetic field in air gap $B_{\delta 1}(x)$



Salient pole machine **Cylindrical rotor machine**

Shape factor of rotor air gap field: β

$$B_{\delta 1} = \frac{B_\delta}{\beta}$$

Source: Bohn, T. (Ed.), TÜV Rheinland

Design parameters

Apparent power $S = m_s \cdot U_s \cdot I_s$
(U_s: Stator voltage per phase, I_s: Stator current per phase (rms)
m_s: number of phases (e.g. 3)

Inner apparent power: $S = S_e$
(if stator leakage and resistance are neglected)

$S_e = m_s \cdot U_i \cdot I_s$

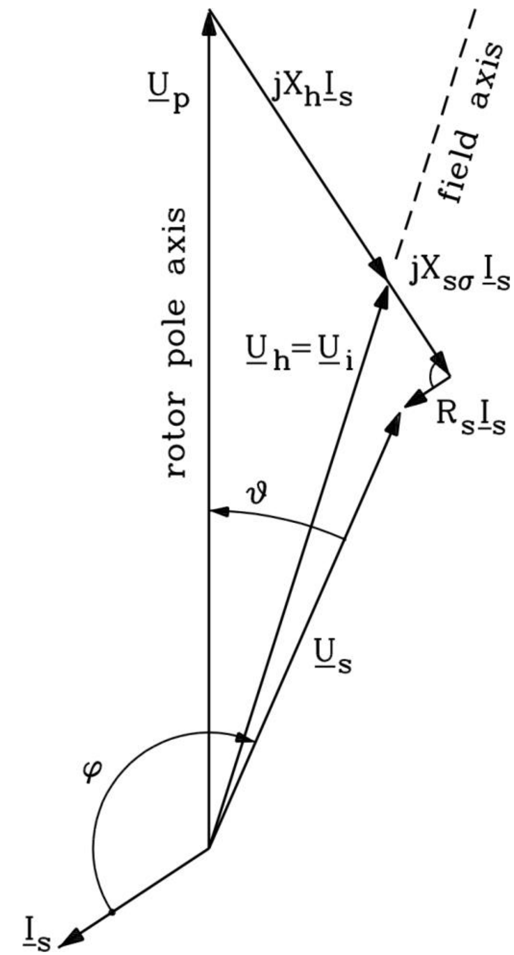
Fourier fundamental air gap field amplitude $B_{\delta 1}$

Flux of field fundamental $\Phi_1 = \frac{2}{\pi} \cdot \tau_p \cdot l_e \cdot B_{\delta 1}$

$U_s = U_i$ (induced voltage)

$$U_i = U_h = \frac{1}{\sqrt{2}} \cdot 2\pi f \cdot N_s k_{w1} \cdot \Phi_1$$

N_s : Turns per phase, k_{w1}: winding factor of fundamental
τ_p: pole pitch in middle of air gap, l_e : "equivalent" iron length



5. Design of large synchronous machines

Stator current loading (rms) at middle of air gap: $A_\delta = \dfrac{2m_s N_s I_s}{2p\tau_p}$

Inner apparent power: $S_e = \sqrt{2} \cdot \dfrac{k_{w1}}{ß} \cdot f \cdot 2p \cdot \tau_p^2 \cdot l_e \cdot A_\delta \cdot B_\delta$

Average air gap diameter: $d_\delta = (d_{si} + d_{ra})/2$

Pole pitch at stator bore: $\tau_p = \dfrac{d_\delta \pi}{2p}$

ESSON´s **power equation**

$$S_e = \frac{\pi^2}{\sqrt{2}} \cdot \frac{k_{w1}}{ß} \cdot A_\delta \cdot B_\delta \cdot d_\delta^2 \cdot l_e \cdot n = C_e \cdot d_\delta^2 \cdot l_e \cdot n$$

"inner" Esson´s number of utilization: $C_e = \dfrac{\pi^2}{\sqrt{2}} \cdot \dfrac{k_{w1}}{ß} \cdot A_\delta \cdot B_\delta = \dfrac{S_e}{d_\delta^2 \cdot l_e \cdot n}$

Esson´s number - power per volume and speed

Current loading at stator bore: $A = A_\delta \cdot \frac{d_\delta}{d_{si}} = A_\delta \cdot \frac{d_{si} + d_{ra}}{2d_{si}}$

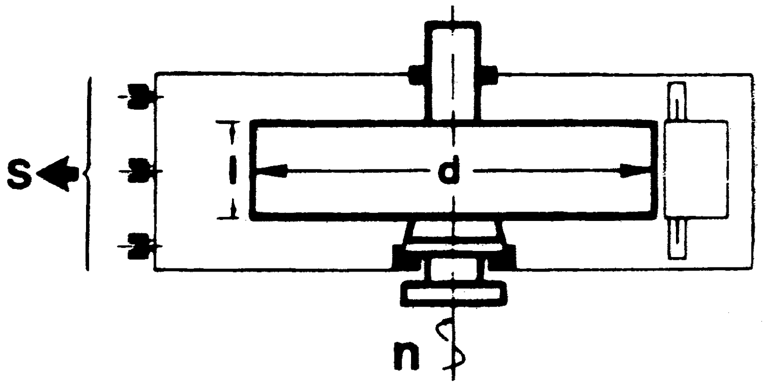
Stack length $l_{Fe} \approx l_e$

Inner power ≅ rated power: $S \cong S_e$.

***Esson´s* number C** ≅ inner *Esson*´s number C_e.

$$C = \frac{S}{d_{ra}^2 \cdot l_{Fe} \cdot n} = \frac{\pi^2}{\sqrt{2}} \cdot \frac{k_{w1}}{ß} \cdot \frac{d_{si}}{d_{ra}} \cdot \frac{1+(d_{si}/d_{ra})}{2} \cdot \frac{l_e}{l_{Fe}} A \cdot B_\delta = ca. \frac{\pi^2}{\sqrt{2}} \cdot k_{w1} \cdot A \cdot B_\delta$$

5. Design of large synchronous machines

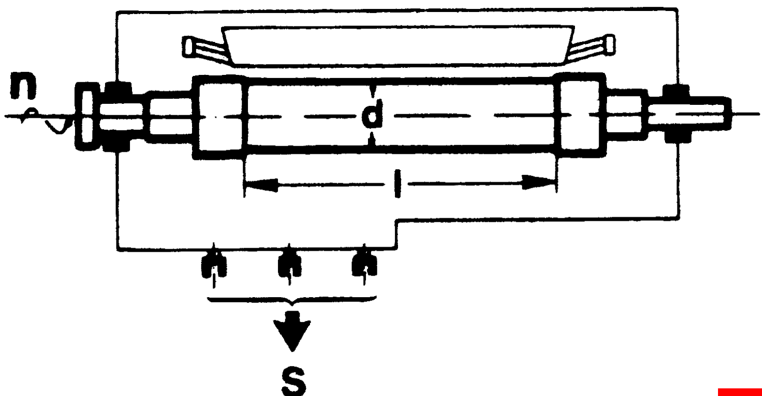


Salient pole machine:

Low speed | Big torque

High pole count | Big diameter

Short length



Cylindrical rotor machine:

High speed | Low torque

Low pole pole count | Small diameter

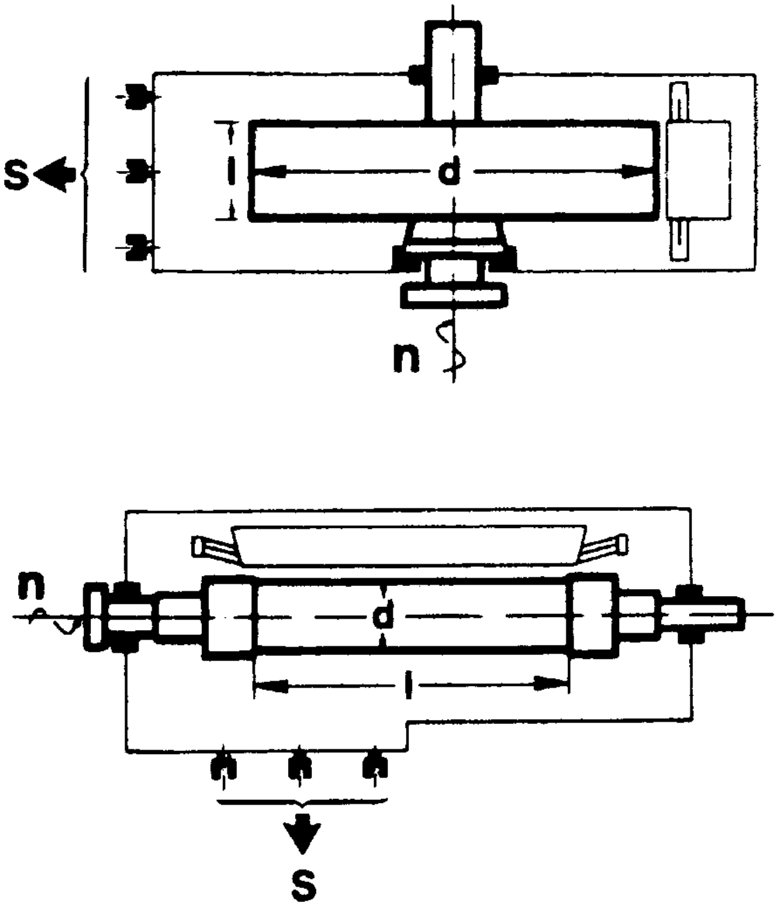
Big length

Source: Bohn, T. (Ed.), TÜV Rheinland

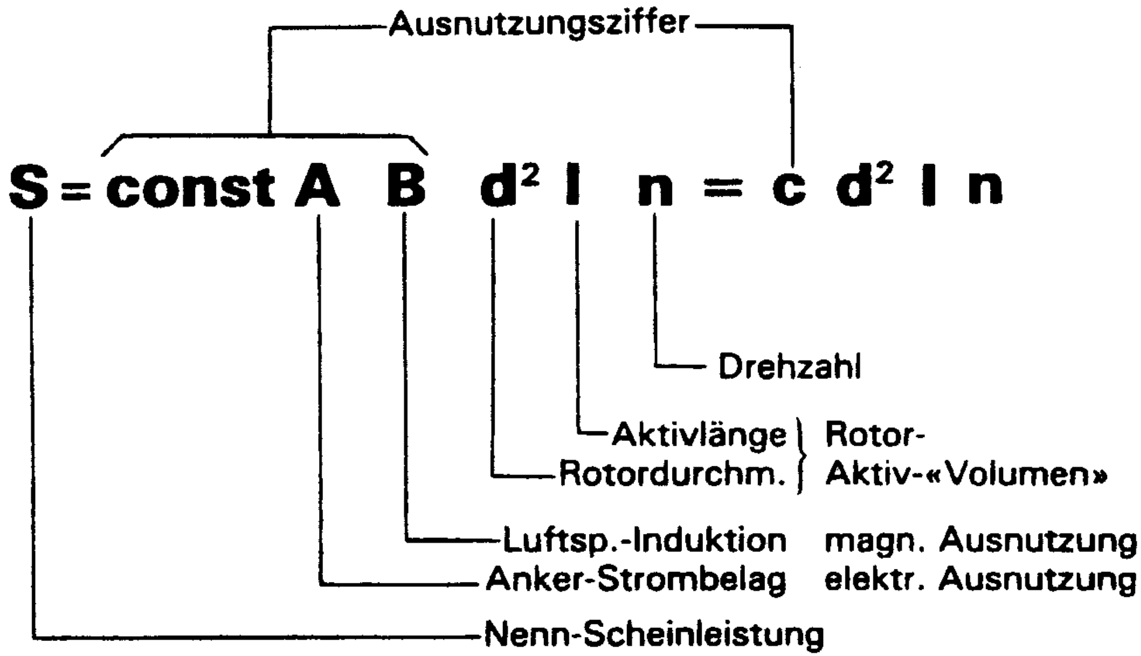
$$S = const. \cdot A \cdot B_{\delta} \cdot d^{2} \cdot l \cdot n$$

5. Design of large synchronous machines

„Shaping“ of synchronous machine main dimensions



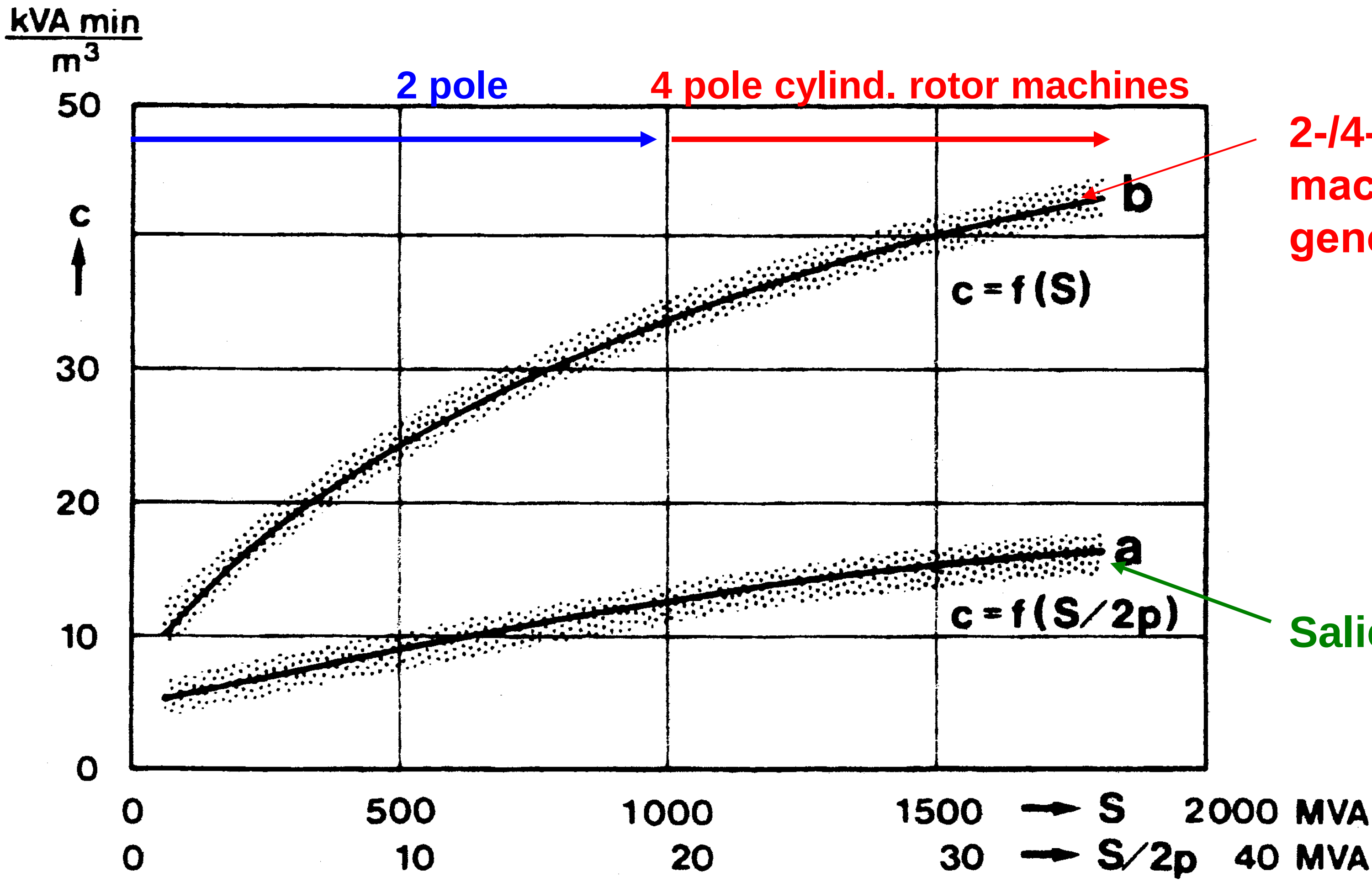
$$S = const\ A\ B\ d^2\ l\ n = c\ d^2\ l\ n$$



Source: Bohn, T. (Ed.), TÜV Rheinland

5. Design of large synchronous machines

Typical *Esson´s* numbers of large synchronous machines



2-/4-pole cylindrical rotor machines („turbine generators“)

Salient pole machines

Source: Bohn, T. (Ed.), TÜV Rheinland

5. Design of large synchronous machines

Example: Design parameters

- "Utilization" (*Esson´s number*) increases with rising rated power !
- At higher power: Better cooling methods are used: Current loading is increased !

Example:

$\beta = 0.95$, $k_{w1} = 0.92$, $l_{Fe} \cong l_e$, $d_{si} \cong d_{ra}$:

a) $B_\delta = 1.1$ T , indirect cooling with air: $A = 900$ A/cm:

$C = 668417$ VAs/m³ $= 11.2$ kVAmin/m³

corresponds with rated apparent power ca. 150 MVA, two-pole turbine generator.

b) $B_\delta = 1.15$ T direct water cooling (hollow conductors): $A = 2900$ A/cm:

$C = 37.7$ kVAmin/m³ *ca. 1400 MVA, four pole turbine generator*

c) Hydro power plant *Bieudron*/Wallis, Switzerland:

Data: $S_N = 465$ MVA ($\cos\varphi = 0.93$), $2p = 14$:

$S/(2p) = 33.2$ MVA/Pole: $C =$ ca. 13 kVAmin/m³

$\beta = 0.95$, $k_{w1} = 0.92$, $l_{Fe} \cong l_e$, $d_{si} \cong d_{ra}$, $B_\delta = 1.1$ T: $A = 1050$ A/cm

5. Design of large synchronous machines

Current loading A

a) Indirect air cooling: $A \sim 50...90 \cdot 10^3$ A/m

b) Direct air cooling: $A \sim 70...100 \cdot 10^3$ A/m

c) Direct hydrogen gas or water cooling of hollow conductors: :

Big hydro generators: direct water cooling: $A \sim 130 \cdot 10^3$ A/m.

Big turbine generators:

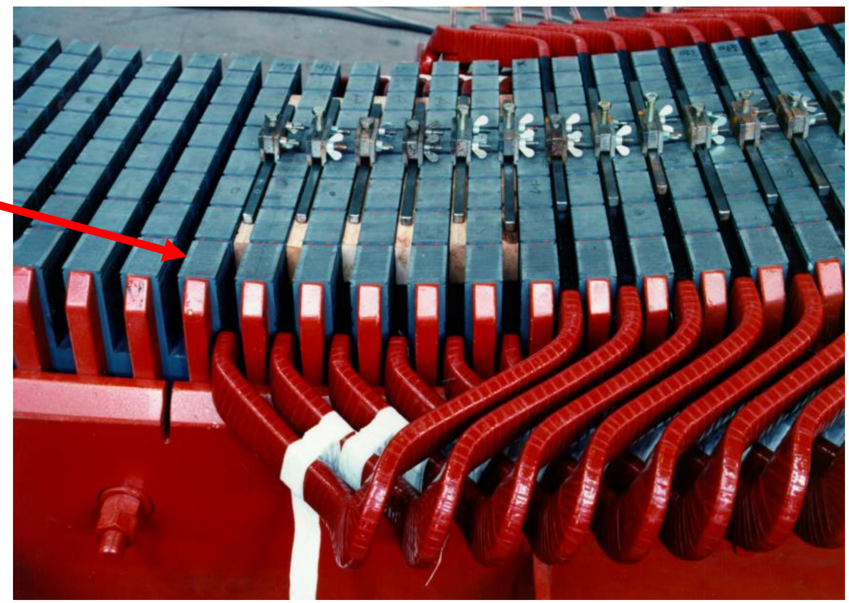
direct hydrogen gas cooling: $A \geq 120 \cdot 10^3$ A/m

direct water cooling: A = ca. $150...290 \cdot 10^3$ A/m

Air gap flux density amplitude B_δ

Limited to B_δ = 0.8...1.0...1.1 T

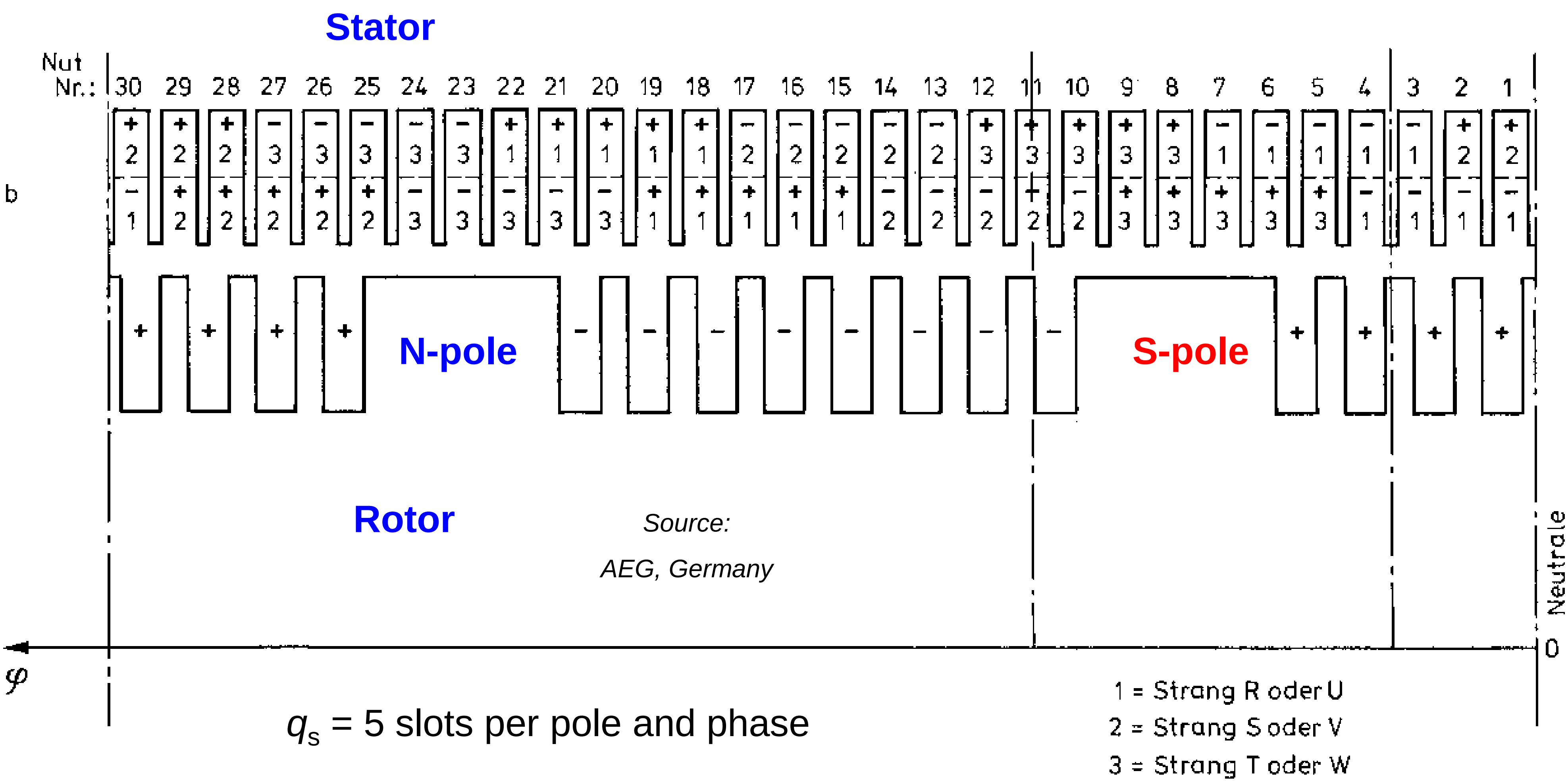
because of teeth saturation



Source:

Andritz Hydro, Austria

Slot scheme of a 2-pole turbine generator

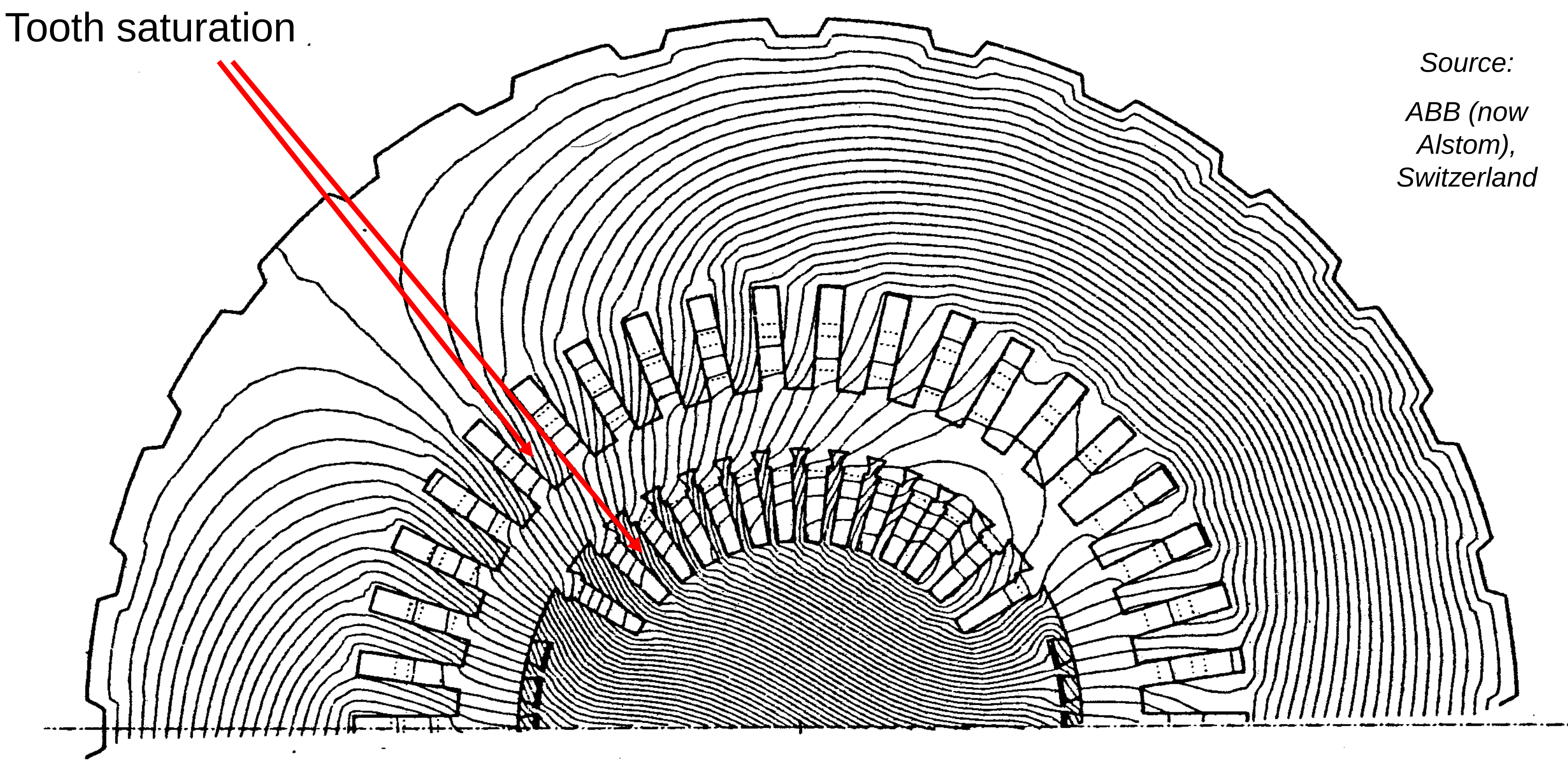


q_s = 5 slots per pole and phase

5. Design of large synchronous machines

Flux plot of 2-pole turbine generator at full load (cos phi = 0.8)

(calculated with numerical solution of *Maxwell´s* equations by Finite Element method)

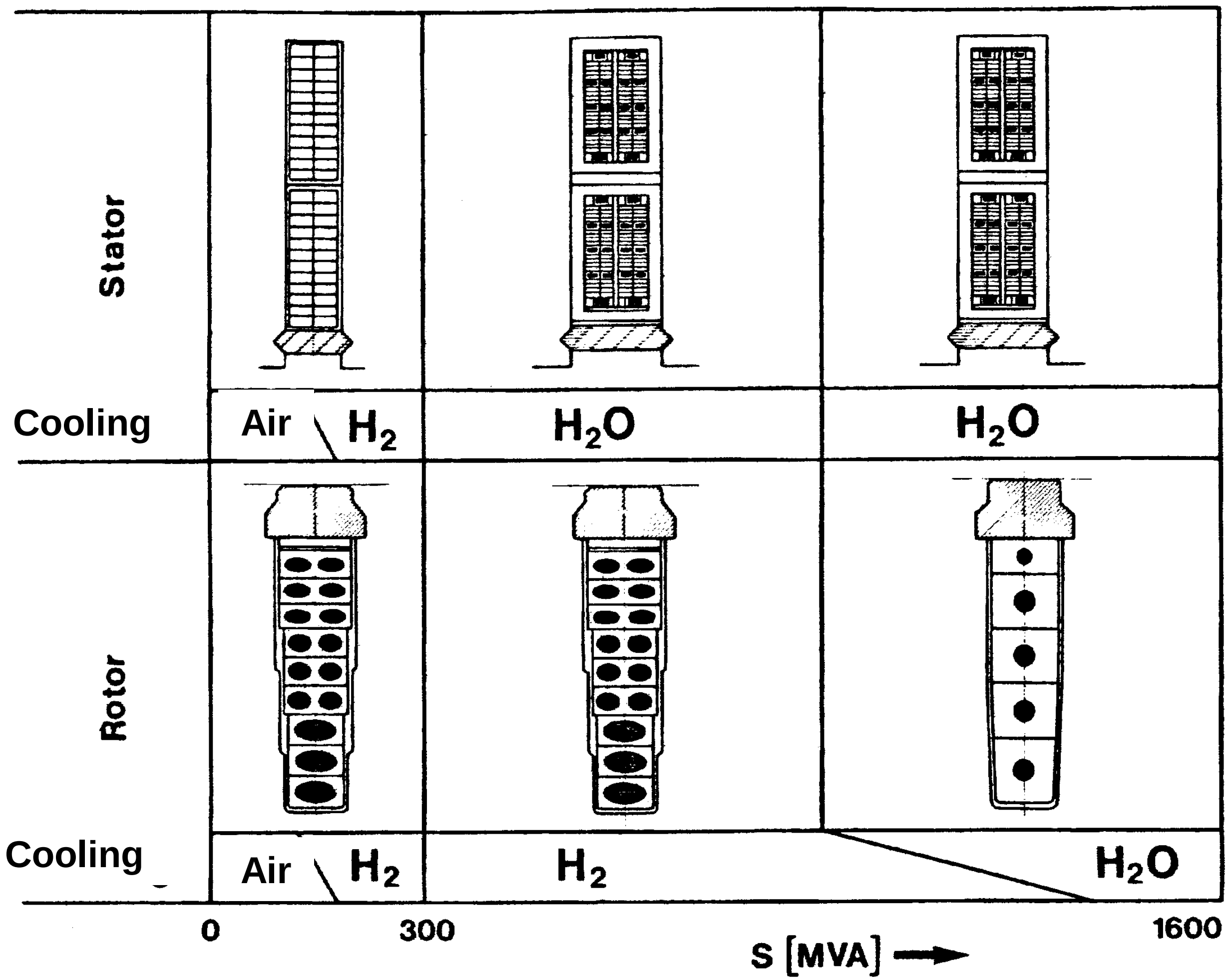


Source:

ABB (now Alstom), Switzerland

5. Design of large synchronous machines

Cooling systems of big cylindrical rotor synchronous machines



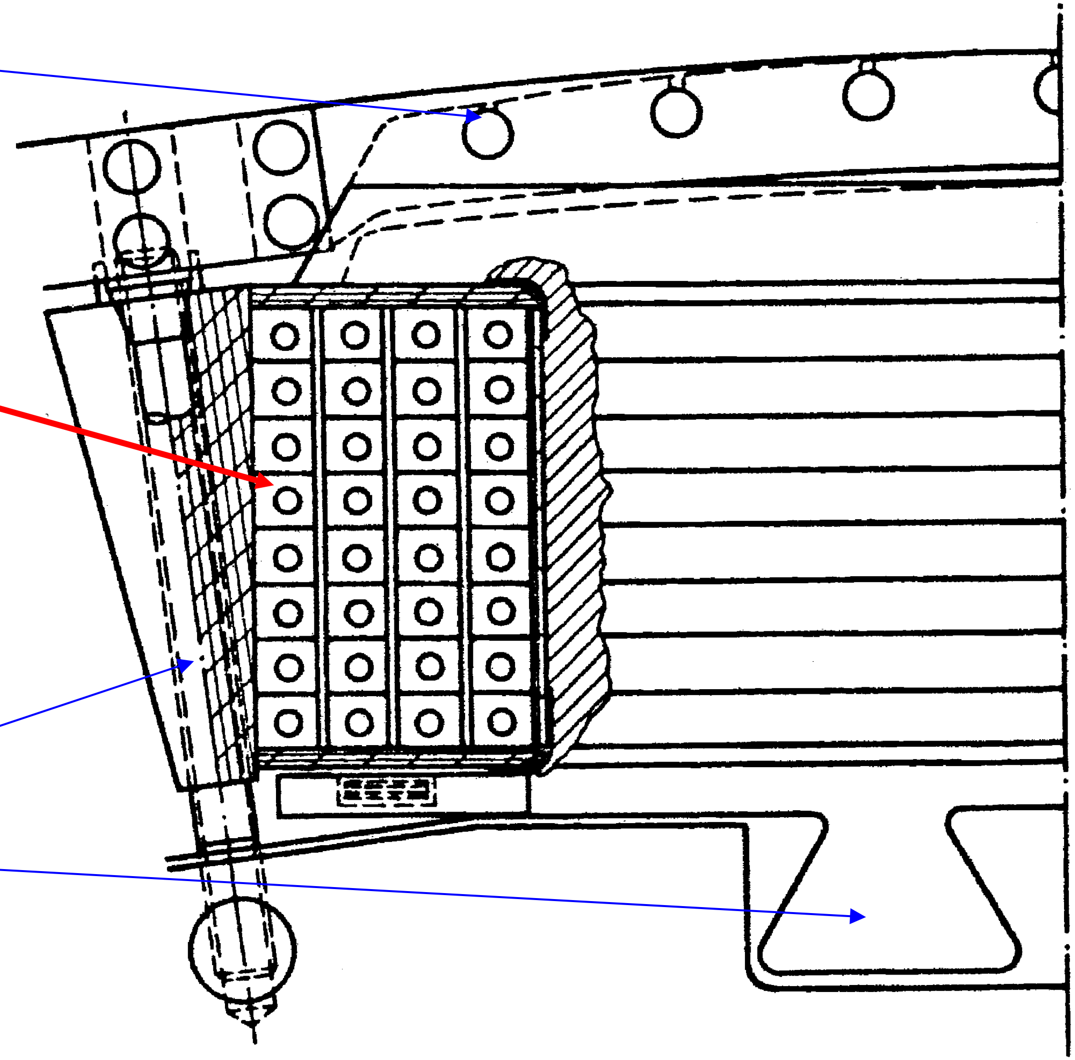
Source:

Bohn, T. (Ed.), TÜV Rheinland

5. Design of large synchronous machines

Damper bars and ring

Direct water cooling of field winding of salient pole rotor



Fixation of damper ring

Double dove tail fixation of pole

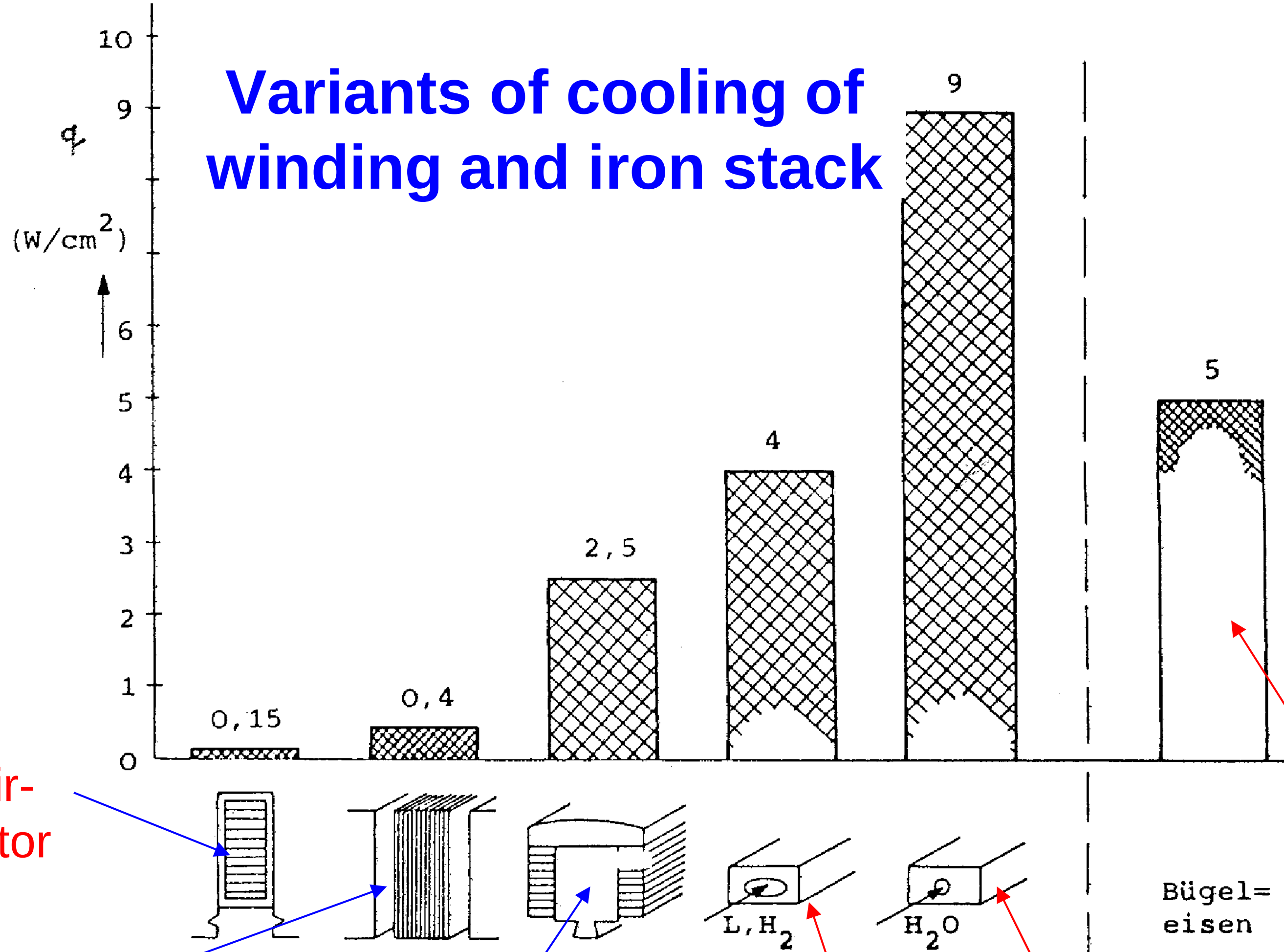
Source:

Gregori, F., TU Wien

5. Design of large synchronous machines

Variants of cooling of winding and iron stack

Heat flow density (W/cm²)



Source:

Neidhöfer, G., BBC, Switzerland

Indirect air-cooled stator winding

Stator iron stack packets

Directly air-cooled rotor pole winding

Air/hydrogen water

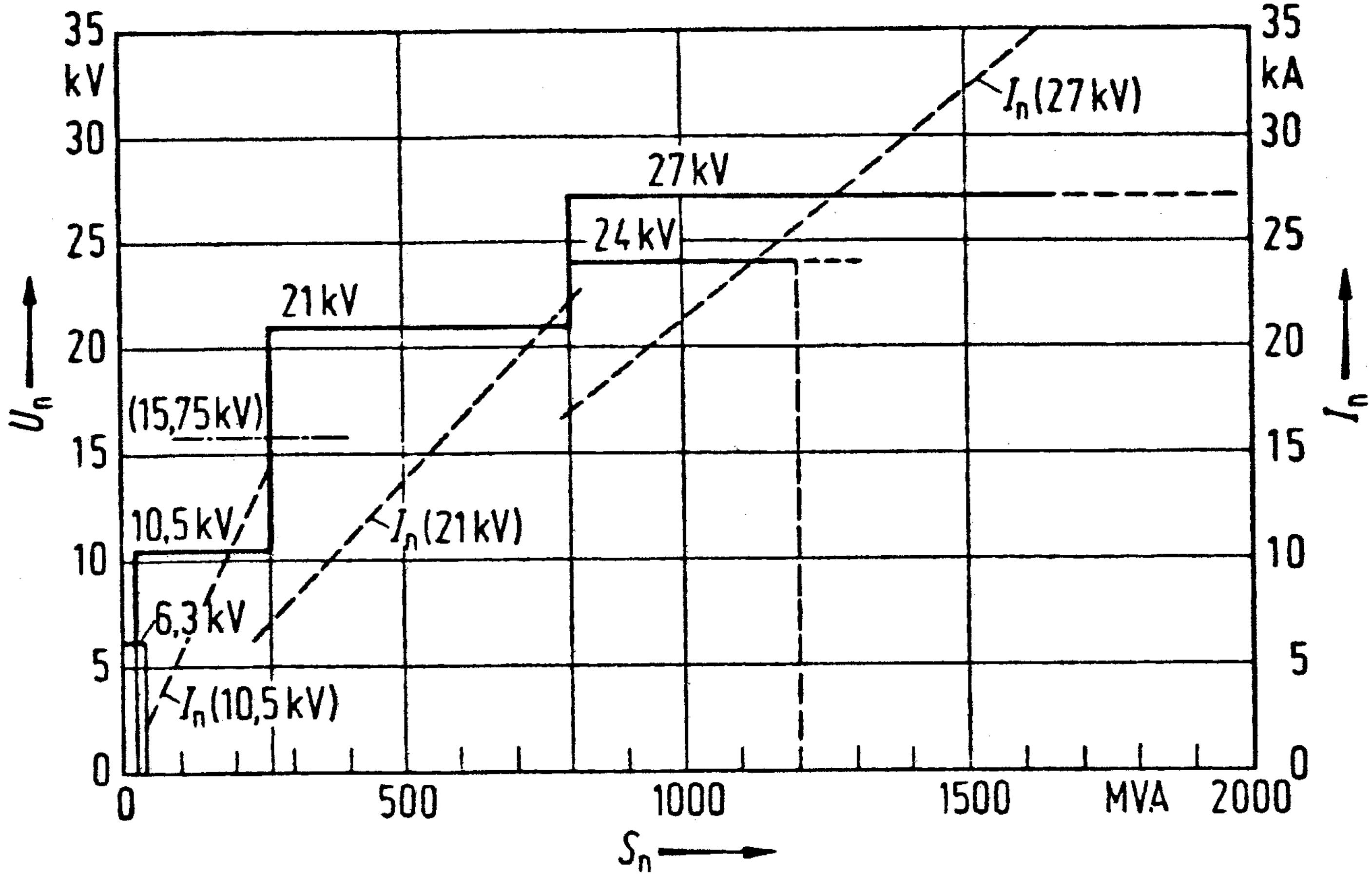
Directly cooled hollow conductors

For comparison:

Heat transfer of flat -iron

5. Design of large synchronous machines

Rated voltage U_n of stator winding increases with increasing apparent power S_n to limit rated current I_n

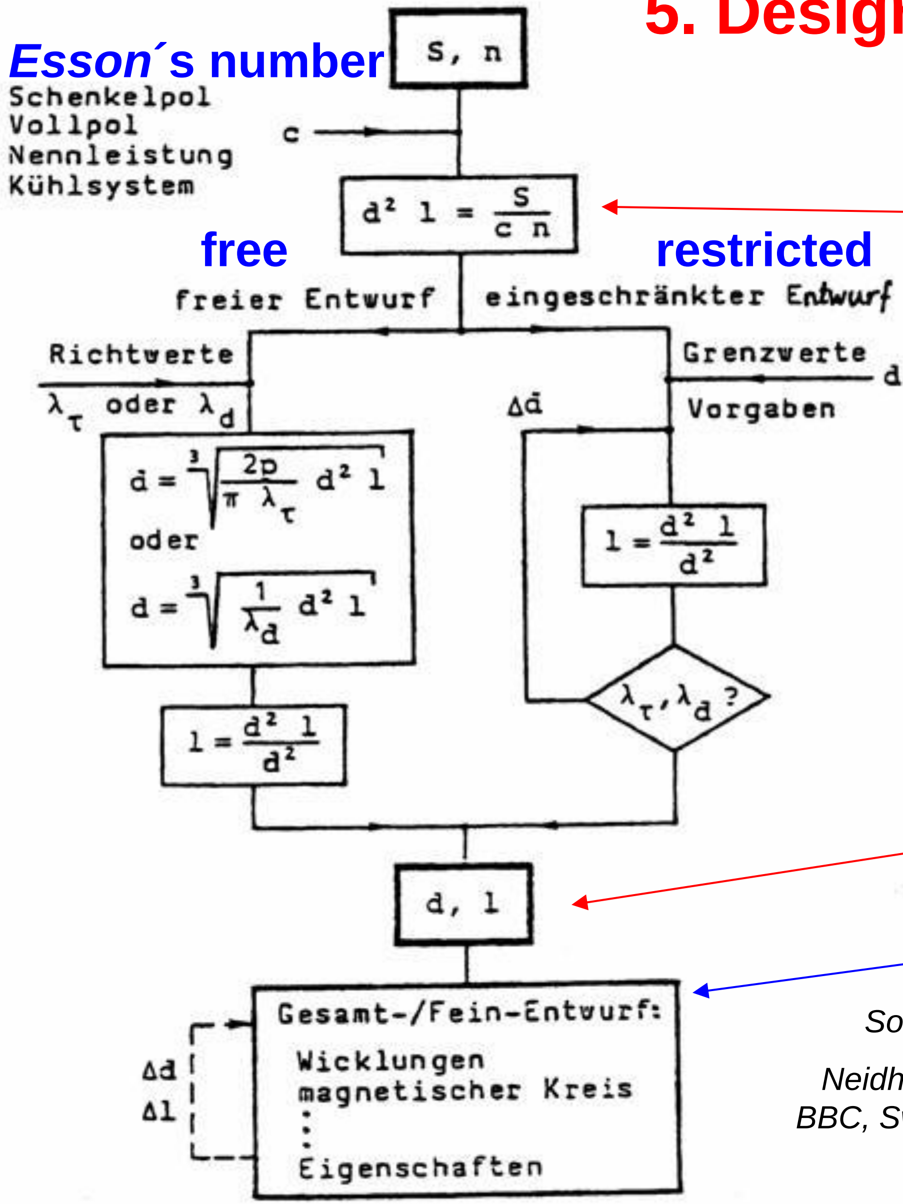


Source:

Bohn, T. (Ed.), TÜV Rheinland

5. Design of large synchronous machines

Free or restricted design



Volume

Typical values or limit values

Main dimensions *l*, *d*, 2*p*

Result of rough design

"Fine" design

Winding data

Magnetic circuit

Machine performance

Source:

Neidhöfer, G.; BBC, Switzerland

5. Design of large synchronous machines

Free design of salient pole machines: $\lambda_\tau = l_{Fe} / \tau_p$

S/2*p*	0.25	1	5	10	MVA/Pole
λ_τ	0.7...2	1...2.5	2...3.5	3...4.5	

Example:

Basic data: S = 480 MVA, $2p$ = 56, f = 50 Hz

Francis-Turbine: n = 107 min^{-1} over-speed n_{max} = 214 min^{-1} (= 2n)

Power per pole $S/2p$ = 480/56 = 8.57 MVA

*Esson´*s number $C \approx$ 8 kVA min/m^3

"Volume" $$d_{ra}^2 l_{Fe} = \frac{480000}{8 \cdot 107} = 560\,\mathrm{m}^3$$

Rotor diameter *d* with $\lambda_\tau \approx$ 4.5 $$d_{ra} = \sqrt[3]{\frac{56}{\pi \cdot 4.5} \cdot 560} = \underline{13\mathrm{m}}$$

Check: Surface speed: $v_{u,max}$ = 13π214/60 = 146 m/s

(below limit 200 m/s, is OK)

Stack length: l_{Fe} = 560/13^2 = 3.3 m

5. Design of large synchronous machines

ITAIPU hydro power plant, 2nd largest in the world

River *Parana*, *Brazil* (10 generators, 60 Hz) and *Paraguay* (10 generators, 50 Hz):

Total power about 14 GW

Basic data: (*Paraguay*, 50 Hz): S = 824 MVA $2p$ = 66 f = 50 Hz

Francis-Turbine $n = 90.9\ \mathrm{min}^{-1}$ $n_{max} = 170\ \mathrm{min}^{-1}$ (= 1.87n)

Power per pole: $S/2p$ = 824/66 = 12.48 MVA

Esson´s number: $C \approx 10.1\ \mathrm{kVA\ min/m^3}$

"Volume" $$d_{ra}^2 l_{Fe} = \frac{824000}{10.1 \cdot 90.9} = 896\,\mathrm{m}^3$$ (real value: 896.π/4 = 704 m³)

Rotor diameter: with $\lambda_\tau \approx 4.6$ $$d_{ra} = \sqrt[3]{\frac{66}{\pi \cdot 4.6} \cdot 896} = \underline{16\mathrm{m}}$$

Check surface velocity: $v_{u,max} = 16\pi 170/60 = 143$ m/s
(below limit 200 m/s)

Stack length $l_{Fe} = 896/16^2 = \underline{3.5\ \mathrm{m}}$

Summary:

Design relationships for poly-phase synchronous machines

- Rotor *Fourier* fundamental magnetic field considered for calculation
- Design parameters: Apparent power S, current loading A, air gap flux density B_δ
- *Esson*'s number C: Power per volume and speed = torque per volume
- Design rule: $S = const. \cdot A \cdot B_\delta \cdot d^2 \cdot l \cdot n = C \cdot d^2 \cdot l \cdot n$

- Cooling system depends on current loading
  → A < ca. 100 kA/m: indirect/direct air cooling;
  A > ca. 100 kA/m: direct gas or liquid cooling of hollow conductors
- Rated stator voltage increases with increasing apparent power to limit current

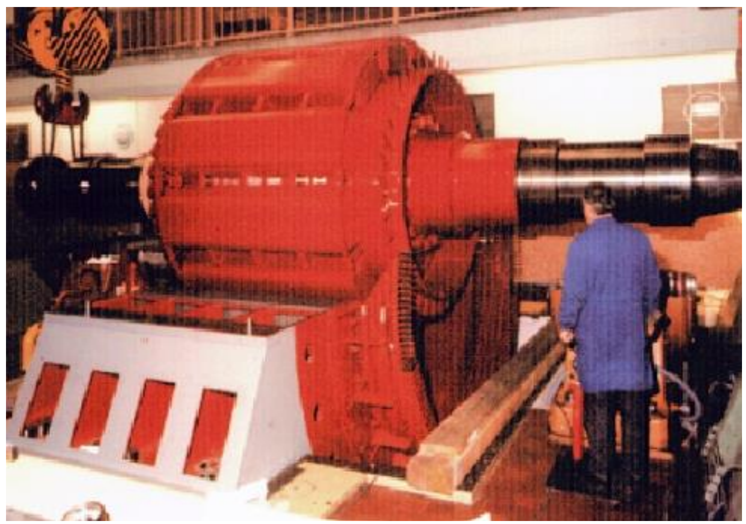
- Free (typical values) vs. restricted (limit values) design of main dimensions

5. Design of large synchronous machines

5.1 Main features of big synchronous machines

5.2 Design relationships for poly-phase synchronous machines

5.3 Special design problems and solutions



Source: Andritz Hydro, Austria

Elastic bending of rotors of turbine generators

- Rotor considered as elastic beam:
- diameter d, length L between bearings, mass density ρ, *Young´s* modulus E
- Rigid bearings

Bending vibrations with natural oscillation frequencies: $f_{b,k}$

$$f_{b,k} = \frac{1}{2\pi} \cdot \left(\frac{k\pi}{L}\right)^2 \cdot \sqrt{\frac{E}{\rho}} \cdot \frac{d}{4} \qquad k = 1, 2, 3, \ldots$$

k = 1: 2 nodes (first bending mode) k = 2: 3 nodes ("S-mode")
k = 3: 4 nodes, third bending mode

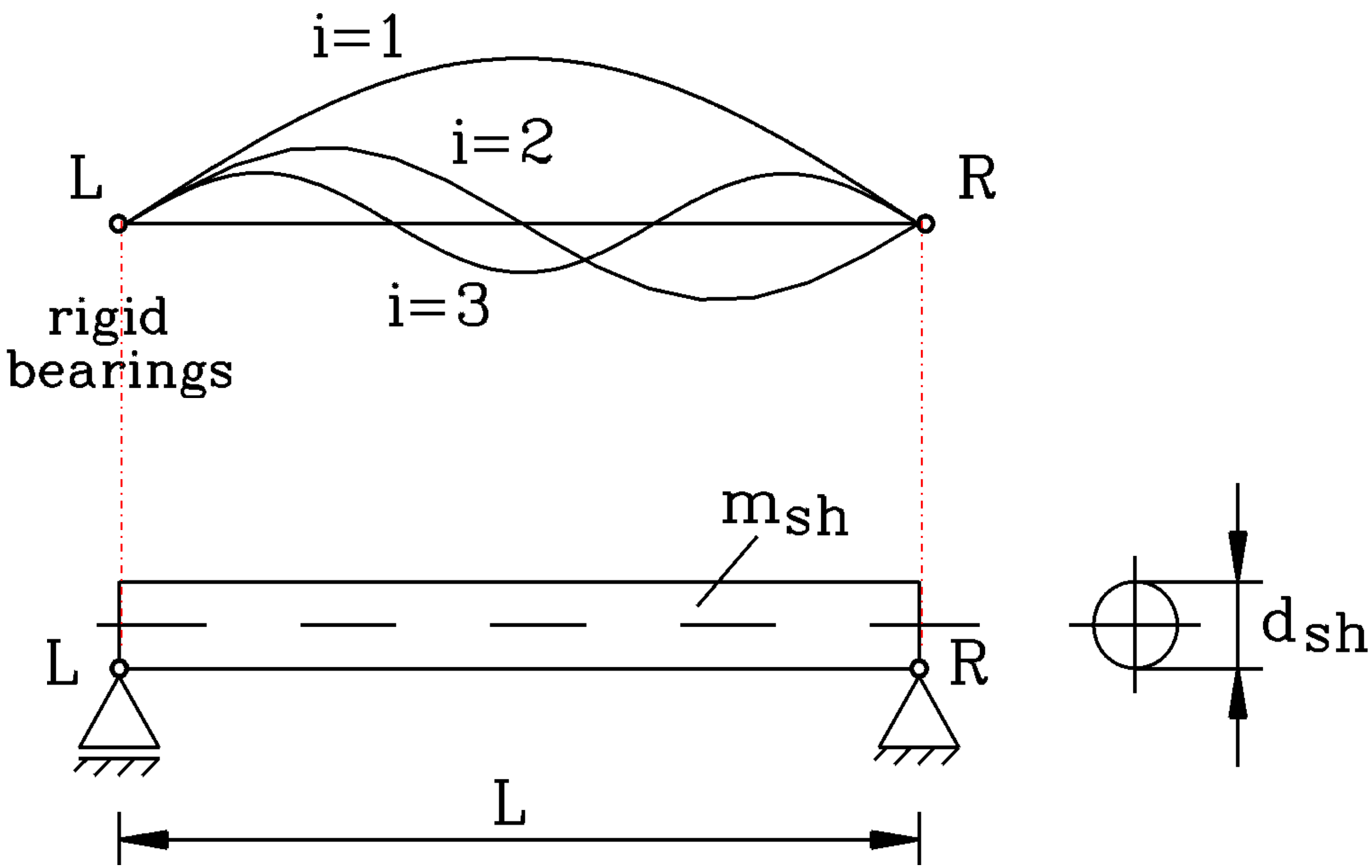
Example:

$L = 9$ m, $d = 0.9$ m, $\rho_{Steel} = 7850$ kg/m^3, $E_{Steel} = 210 \cdot 10^9$ N/m^2, $L/d = 10$, $l/d = 6$

k	1	2	3
$f_{b,k}$ / Hz	22.6	90.4	203.4

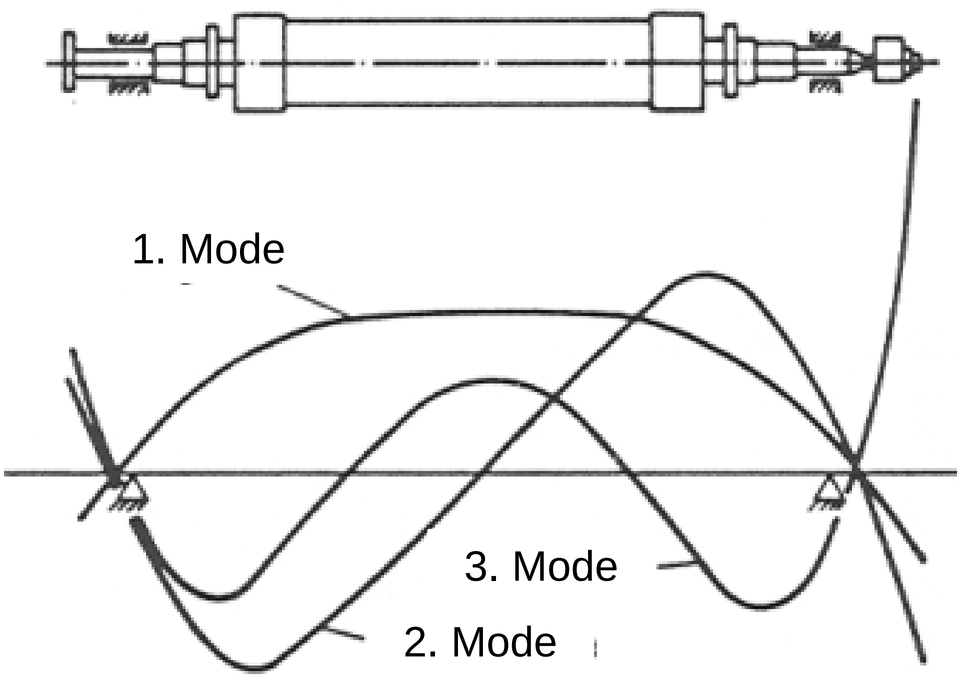
Excessive bending limits the ratio $\lambda_d = l / d$ to typically 4 ... 6.5 , maximum is ca. 7.

Elastic bending of rotors of turbine generators

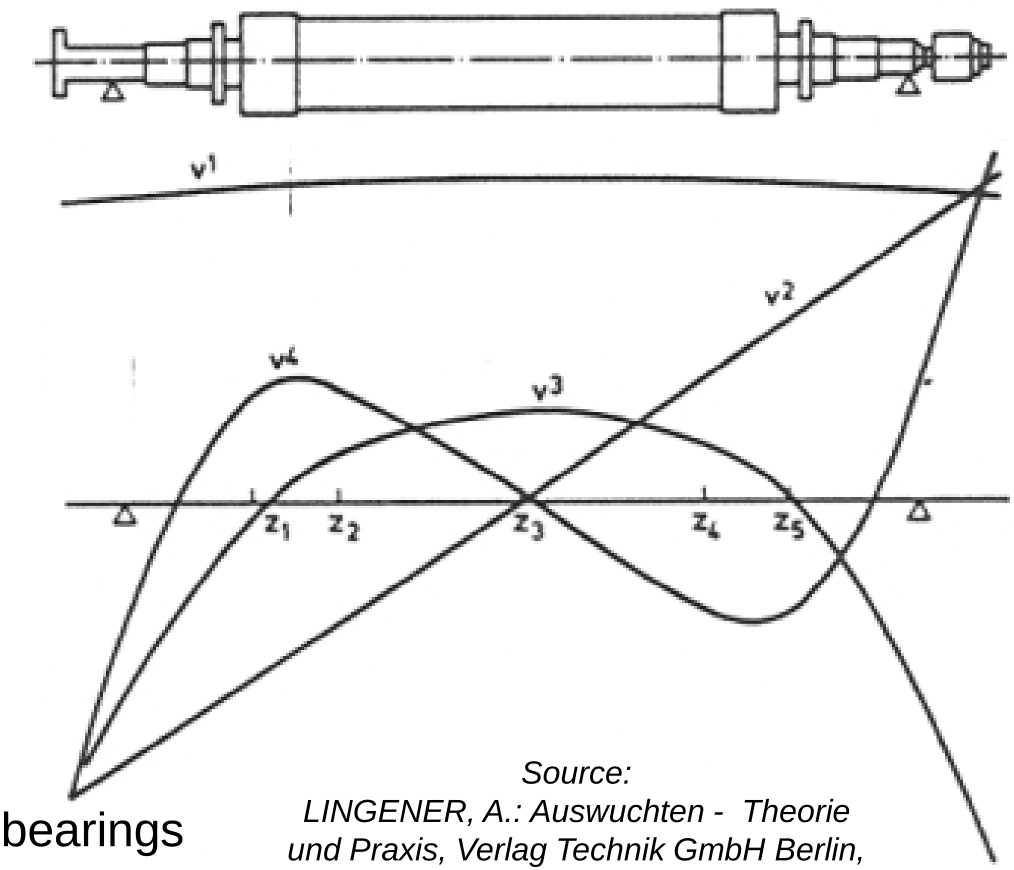


Excessive bending limits the ratio $\lambda_d = l / d$ to typically 4 ... 6.5 , maximum is ca. 7.

Rotor bending in rigid bearings



Rotor bending in elastic bearings



Calculated bending lines (exaggerated):

v^1, v^2: Vibration modes of rigid rotor in elastic bearings

v^3, v^4: 1. & 2. natural vibration mode of elastic rotor

z_1 ... z_5: Rotor planes for balancing: 2 planes for rigid rotor balancing, 3 planes for the 3 natural rotor vibration modes, rotor speed *n* **above** of their vibration frequencies

Source:
LINGENER, A.: Auswuchten - Theorie und Praxis, Verlag Technik GmbH Berlin, 1992

Example: TWO pole generator

Turbine generator, restricted design due to standardized rotor diameter:

Basic data: S = 800 MVA $2p$ = 2 f = 50 Hz

n = 3000 min^{-1} n_{max} = 3600 min^{-1} (= 1.2n)

Esson´s number: $C \approx$ 30 kVA min/m^3

"Volume": $$d_{ra}^2 l_{Fe} = \frac{800000}{30 \cdot 3000} = 8.89\ \text{m}^3$$

Rotor diameter d_{ra} = 1.15 m

given by internal standard (results in $v_{u,max}$ = 217 m/s, OK !)

Magnetically active length: l_{Fe} = 8.89/1.15^2 = 6.72 m ≈ 6.8 m

Length-diameter ratio: λ_d = 6.8/1.15 = 5.9 (is within limits)

5. Design of large synchronous machines

World´s largest machines are FOUR pole turbine generators

2000 MVA per machine is top power, but needs four poles *(Olkiluoto/Finland)* !
1000 MVA is maximum for TWO pole machines (limits of d = 1.25 m, l = 8.5 m)
(e.g. lignite coal thermal power plant *Lippendorf*/Germany, near *Leipzig)*
Nuclear power plant *Mülheim-Kärlich* (near *Cologne*):
Basic data: S = 1635 MVA $2p = 4$ f = 50 Hz
$n = 1500\ \mathrm{min}^{-1}$ $n_{max} = 1800\ \mathrm{min}^{-1}$ (= 1.2n)
Esson´s number: $C \approx 40$ kVAmin/m³

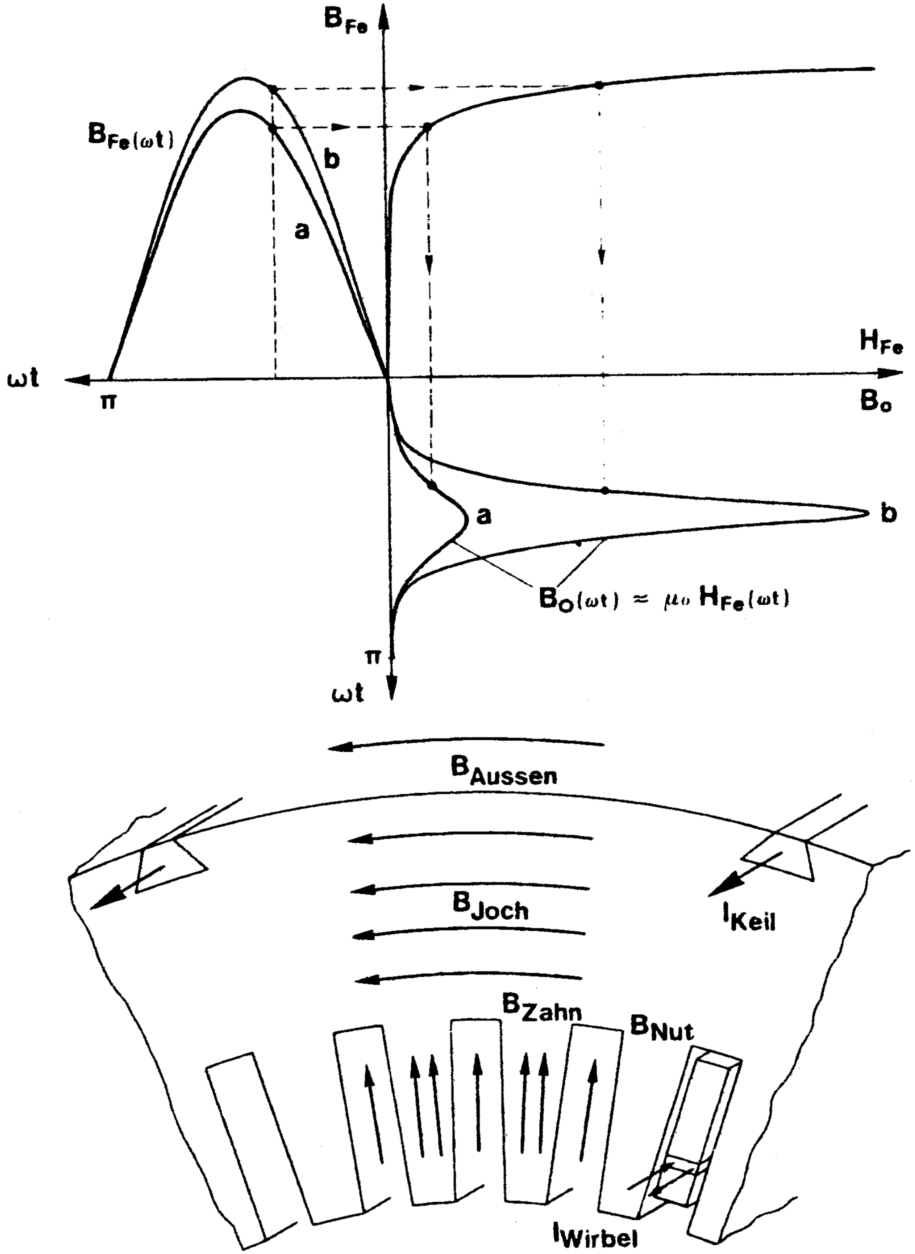
"Volume": $$d_{ra}^2 l_{Fe} = \frac{1635000}{40 \cdot 1500} = 27.25\ \mathrm{m}^3$$

Rotor diameter d_{ra} = 1.9 m
given by internal standard (results in $v_{u,max}$ = 179 m/s, no problem !)

Magnetically active length: $l_{Fe} = 27.25/1.9^2 = 7.55\ \mathrm{m} \approx 7.5\ \mathrm{m}$

Length-diameter ratio: $\lambda_d = 7.5/1.9 = 3.95$ (no problem, very stiff)

Flux density limit in iron



At high saturation flux leaves iron !

Flux passes also through slots B_{Nut} and outside of yoke B_{Aussen}

This causes additional eddy current losses in slot conductors and massive housing.

- Slot conductors must be made of strands (ROEBEL-bar)
- Conductive wedges must fix stator laminated yoke, act as low-resistive shielding cage
- Prevents field from reaching far out of machine

Source:

Neidhöfer, G.; BBC, Switzerland

Summary:

Special design problems and solutions

- Elastic bending of rotors of turbine generators limits ratio between length and diameter: typically $l / d = 4 \ldots 6.5$, maximum is ca. 7
- Different bending modes for rigid or elastic bearings
- Oscillation frequencies depend on geometry and material properties

- At high saturation flux leaves iron and causes additional eddy current losses in slot conductors and massive housing
- Counter-measures: ROBEL-bar, low resistive shielding cage with wedges