Large Generators and High Power Drives

Contents of lectures

1. Manufacturing of Large Electrical Machines
2. Heating and cooling of electrical machines
3. Eddy current losses in winding systems
4. Excitation of synchronous machines
5. Design of large synchronous machines
6. Wind generators and high power drives
7. Forces in big synchronous machines

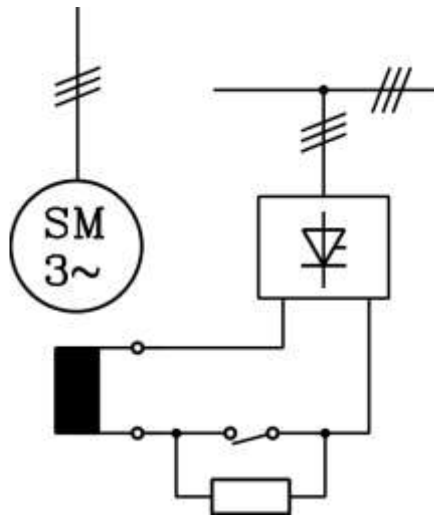
Source:

Siemens AG, Germany

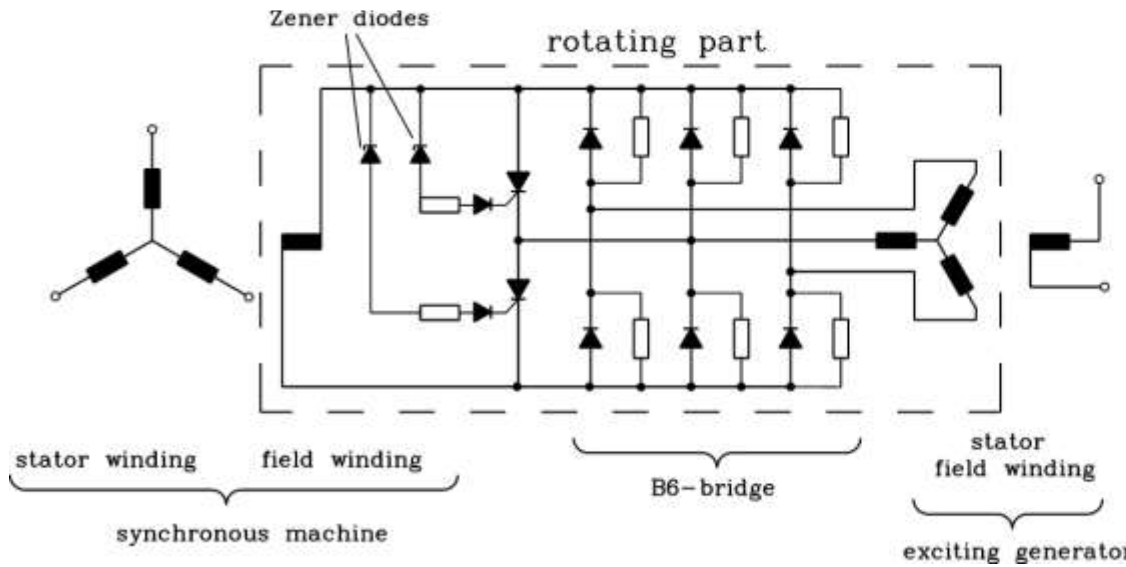
6. Wind generators and high power drives

Source: Vestas, Denmark

6.1 Silicon controlled excitation



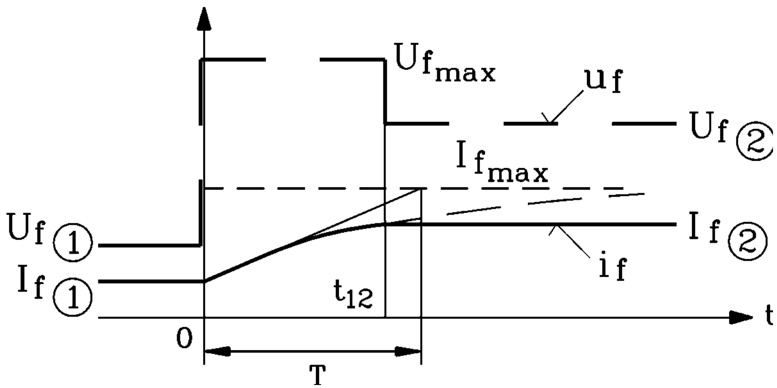
Converter excitation

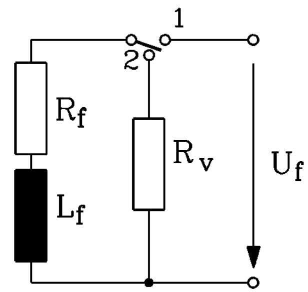


Brushless excitation

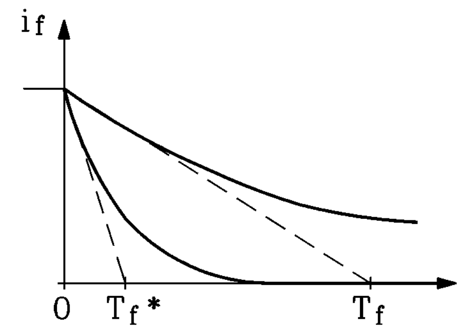
- **Converter excitation:** Controlled six-pulse rectifier bridge (B6C) generates from AC grid voltage a variable DC field voltage U_f, depending on thyristor ignition angle $\alpha \Rightarrow$ via 2 slip rings DC current flows to the rotor winding.
- **Brushless excitation:** Exciter generator is coupled to main synchronous machine rotor, being itself an **outer rotor synchronous machine**: Stator = "DC excited" magnetic field. Rotor: Three-phase AC winding, in which voltage U is induced. Rotating six-pulse B6-diode bridge rectifies U to DC field voltage U_f, being applied to rotor without any brushes or slip rings. By variable stator DC field current the rotor field voltage is varied.

High-speed excitation and de-excitation





a)



b)

High speed excitation *De-excitation: a) external resistance b) field current*

- **High speed excitation**: Quick rotor field **build-up**: Applying of ”ceiling voltage" U_{fmax} : Filed current rises in minimum time t_{12} from starting value I_{f1} to set-point value I_{f2}. At stator no-load condition rotor electrical time constant T is **Rotor open-circuit time constant $T_f = L_f/R_f$.**

- **Quick de-excitation:** Quick **de-magnetization** of rotor field: Applying an external field resistor R_v (switch is in position 2) to reduce rotor winding time constant T_f .

$$T_f^* = L_f/(R_f + R_v) = T_f/(1 + \frac{R_v}{R_f})$$

Example: At $R_v = 9R_f$ time-constant T is reduced to $T_f^* = T_f/10$, e. g. from 3 s to 0.3 s. After about 3 T_f^* = 1 s rotor field has decayed to zero.

Summary:

Silicon controlled excitation

- Converter excitation: DC field voltage is generated by a controlled six-pulse rectifier bridge $\Rightarrow$ two slip rings necessary
- Brushless excitation: Outer rotor exciter generator feeds rotating diode bridge rectifier, which generates the DC field voltage $\Rightarrow$ no slip rings required

- High speed excitation:
  Fast rotor field build-up by applying "ceiling voltage"
  Voltage build-up ruled by rotor open circuit time constant T_f
- Quick de-excitation: Rotor time constant is reduced by external field resistor

6. Wind generators and high power drives

Source: Vestas, Denmark

6. Wind generators and high power drives

6.2 Wind turbine generators

- Fixed speed drives: super-synchronous speed $n_{Gen} = (1-s) \cdot f_s / p$, s ~ -0.5 ... -1 %

  Cage induction generators, directly grid operated, super-synchronous speed

  geared wind turbines $n_T = n_{Gen} / i$ (i: gear ratio, typically 50 ... 100)

  stall turbine power control

  Rated unit power up to 1 MW

- Variable speed drives: speed varies typically n_T 50% ... 100%

  a) Geared doubly fed induction generators

  b) Gearless electrically or permanent excited synchronous generators

  c) Geared synchronous generators

  pitch turbine power control

  Rated unit power 1 ... 5 MW

6. Wind generators and high power drives

6.2 Wind turbine generators

6.2.1 Fixed speed wind energy conversion

6.2.2 Variable speed wind turbines: Doubly-fed induction machines

6.2.3 Gearless wind generators

6.2.4 “Multibrid” - PM wind generator – dual stage gear

6.2.5 „Small Hydro Power“

Source: Vestas, Denmark

6.2.1 Fixed speed wind energy conversion

- Generator speed: super-synchronous speed $n_{Gen} = (1-s)\cdot f_s/p$, s ~ -0.5 ... -1 %
  Small load dependent slip *s*, so speed is almost constant.
- As wind speed *v* varies, power varies, too: $P \sim v^3$
- Coarse and cheap adjusting of wind turbine speed by pole changing wind generator:
  Small 6-pole winding: $2p = 6$: $n_{syn} = f_s/p = 1000$/min at 50 Hz
  Big 4-pole winding: $2p = 4$: $n_{syn} = f_s/p = 1500$/min at 50 Hz
- Power variation: 4 poles: 100%, 6 poles: 30 %
- Two independent three phase windings in slots of stator, switched via mechanical pole changing power switch.

6. Wind generators and high power drives

Pole changing cage induction generator

Rated power: 1.3 MW

4-pole winding:

1500/min at 50 Hz

1800/min at 60 Hz

Water jacket cooling stator housing allows closed generator operation for outdoor use

Shaft end   Housing   feet   terminal box   Power terminal box

Bearing with lubrication opening

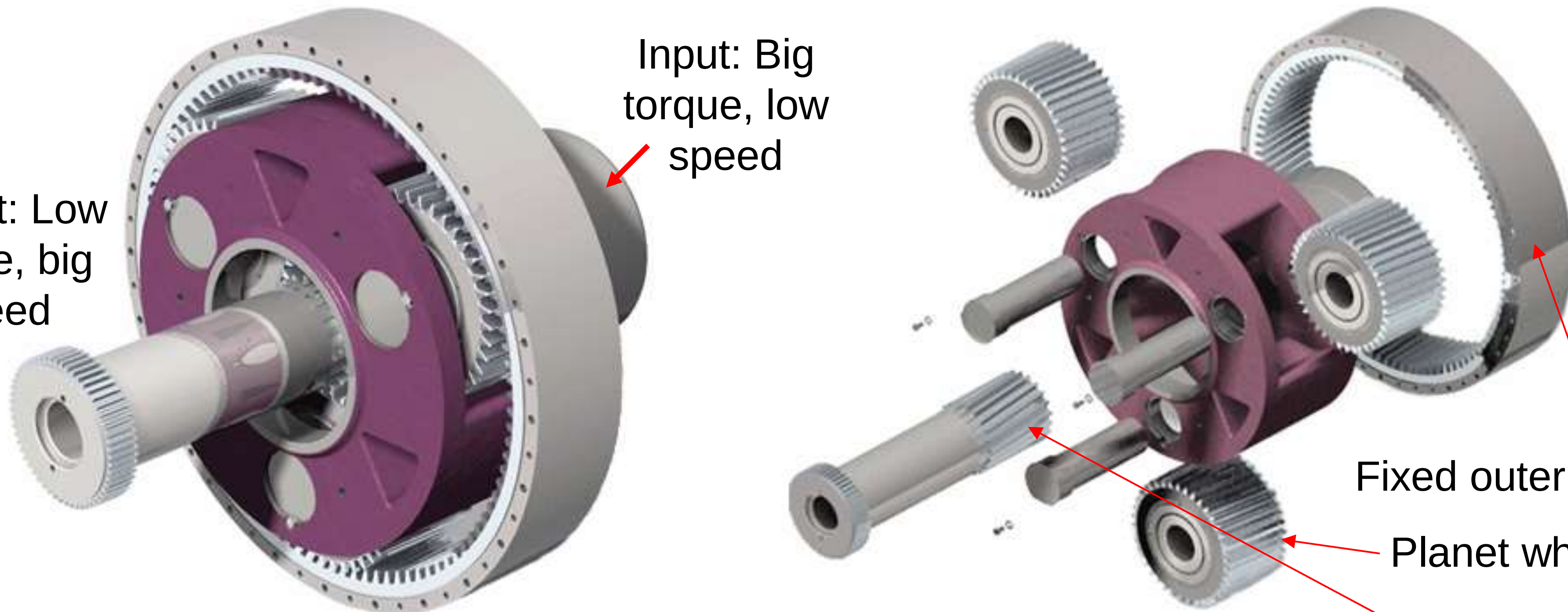
Source: Winergy, Germany

6. Wind generators and high power drives

Principle of planetary gear

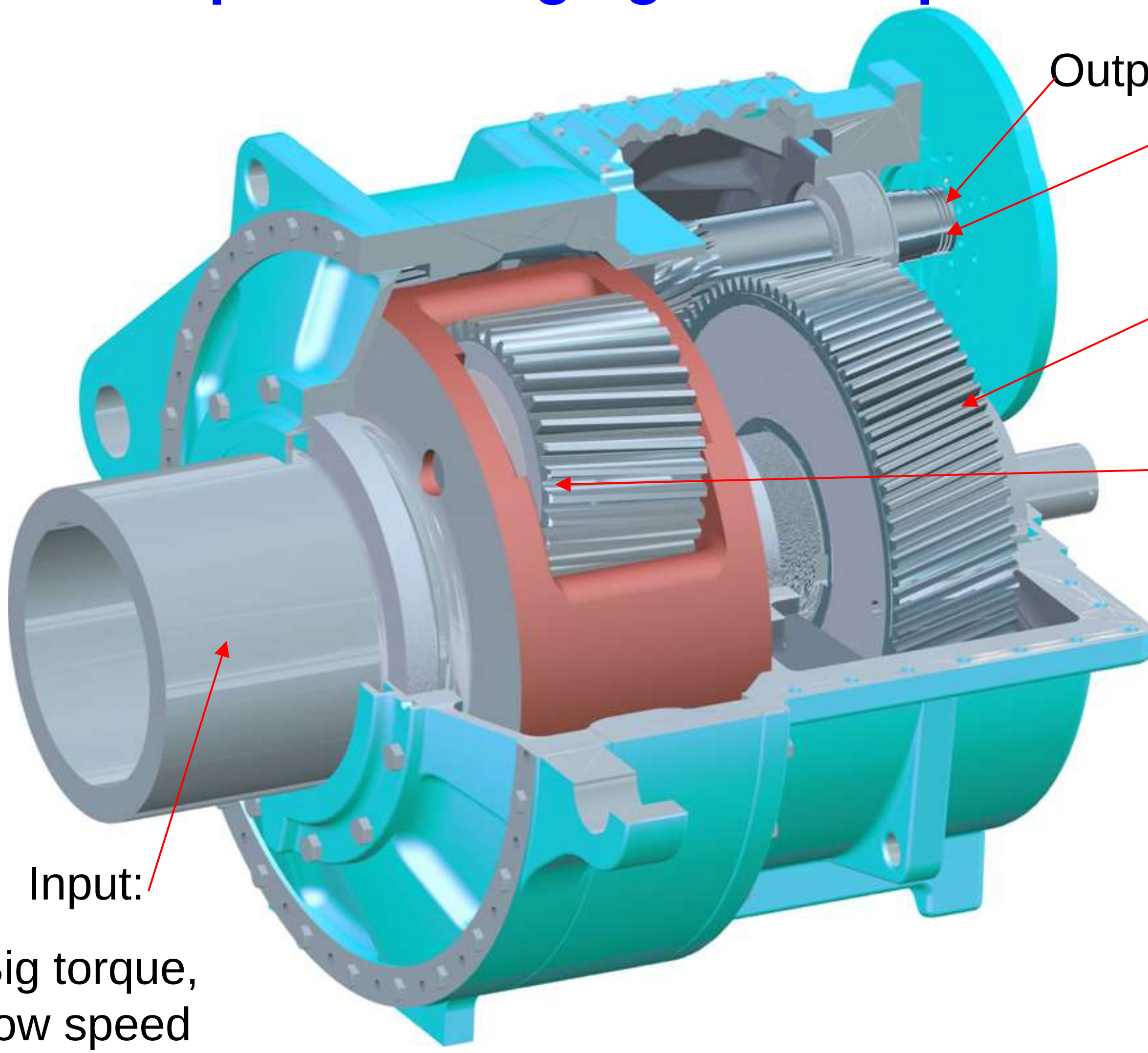
- First stage of a two- or three-stage gear is a planetary gear

- Input and output shaft are aligned, transmission i < 8 ... 9: $M_{out} = M_{in}/i$, $n_{out} = i \cdot n_{in}$



Source: GE Wind, Germany

Principle of 3 stage gear with planetary gear as 1st stage



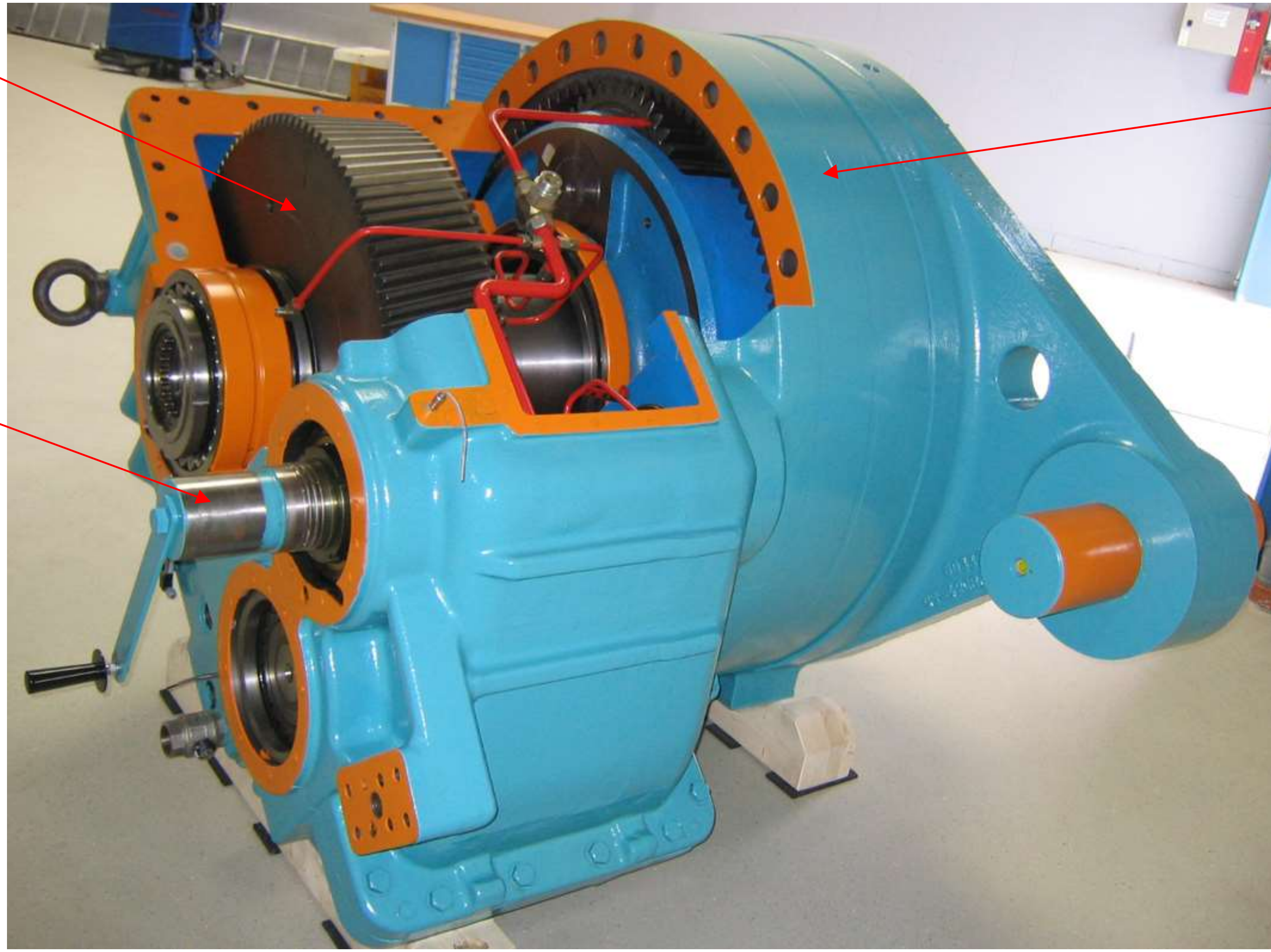
Source: GE Wind, Germany

6. Wind generators and high power drives

Planetary gear with two helical stages = 3 stage gear, *i* = 100

Second stage
= helical gear

Third stage:
helical gear at high speed e.g. 1500/min, low torque



First stage:

Planetary gear: Input at low speed , e.g. 15/min

Cut-view demonstration object

Source: GE Wind, Germany

6. Wind generators and high power drives

Finishing work on rotor blades of wind converter with fixed speed induction generator

Source:

Vestas, Denmark

Summary:

Fixed speed wind energy conversion

- Directly grid operated cage induction generators (super-synchronous operation)
- Speed is almost constant (small load depending slip)
- Stall control
- Multi-stage gear necessary, gear ratio $i \approx 50 \ldots 100$
  - first stage: planetary gear
  - second (and third) stage: helical gear
- Rated unit power up to 1 MW

6. Wind generators and high power drives

6.2 Wind turbine generators

6.2.1 Fixed speed wind energy conversion

6.2.2 Variable speed wind turbines: Doubly-fed induction machines

6.2.3 Gearless wind generators

6.2.4 “Multibrid” - PM wind generator – dual stage gear

6.2.5 „Small Hydro Power“

Source: Vestas, Denmark

6.2.2 Variable speed wind turbines: Doubly induction fed machines

- Fixed speed drives:

- Speed variation only by slip: $n_{Gen} = (1-s) \cdot f_s / p$, s ~ -0.5 ... -1 %
- Cage induction generators: Big variation of torque with slip (*Kloss* function)
- Wind power depends on speed: $P \sim n^3$
- Local wind speed fluctuation leads turbine speed fluctuation, which causes big power fluctuation, when wind turbine blade is shadowing centre pole
- Frequency of power fluctuation: $f = z \cdot n$ (z = 3: number of blades of wind rotor)

- Advantage of variable speed drives:

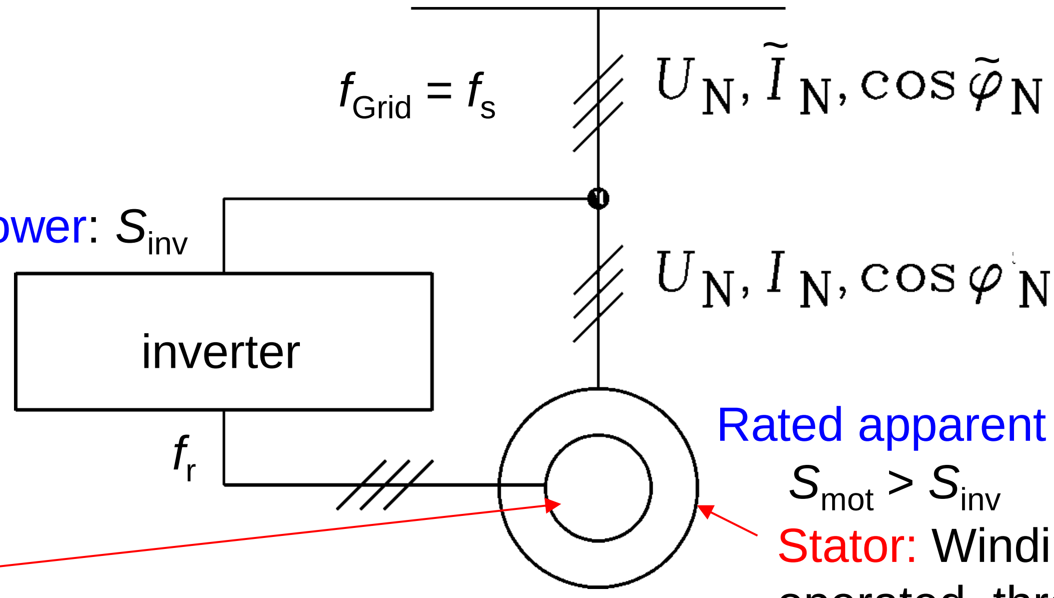
- "Stiff" *Kloss* function is replaced by speed controlled drive via inverter feeding.
- No big power fluctuations with 3-times turbine speed
- Turbine blades may be operated for optimum air flow angle, getting maximum turbine efficiency below rated speed

Doubly-fed asynchronous machine

- ***Aim*: ** Speed-variable operation with limited speed range, but corresponding smaller inverter of small power: $S_{inv} < S_{mot}$ (less cost!)

$$e.g.: \Delta n = \frac{n_{syn}}{3}: \quad \frac{2}{3} \cdot n_{syn} = n_{syn} - \Delta n \le n \le n_{syn} + \Delta n = \frac{4}{3} \cdot n_{syn} \Leftrightarrow S_{inv} = \frac{1}{3} \cdot S_{mot}$$

- ***Solution:*** Slip-ring induction machine with grid-fed stator winding and rotor winding fed by an inverter = DOUBLY FED asynchronous machine: $n_{syn} = f_{Netz}/p$



Grid

Machine

Rated inverter power: S_{inv}

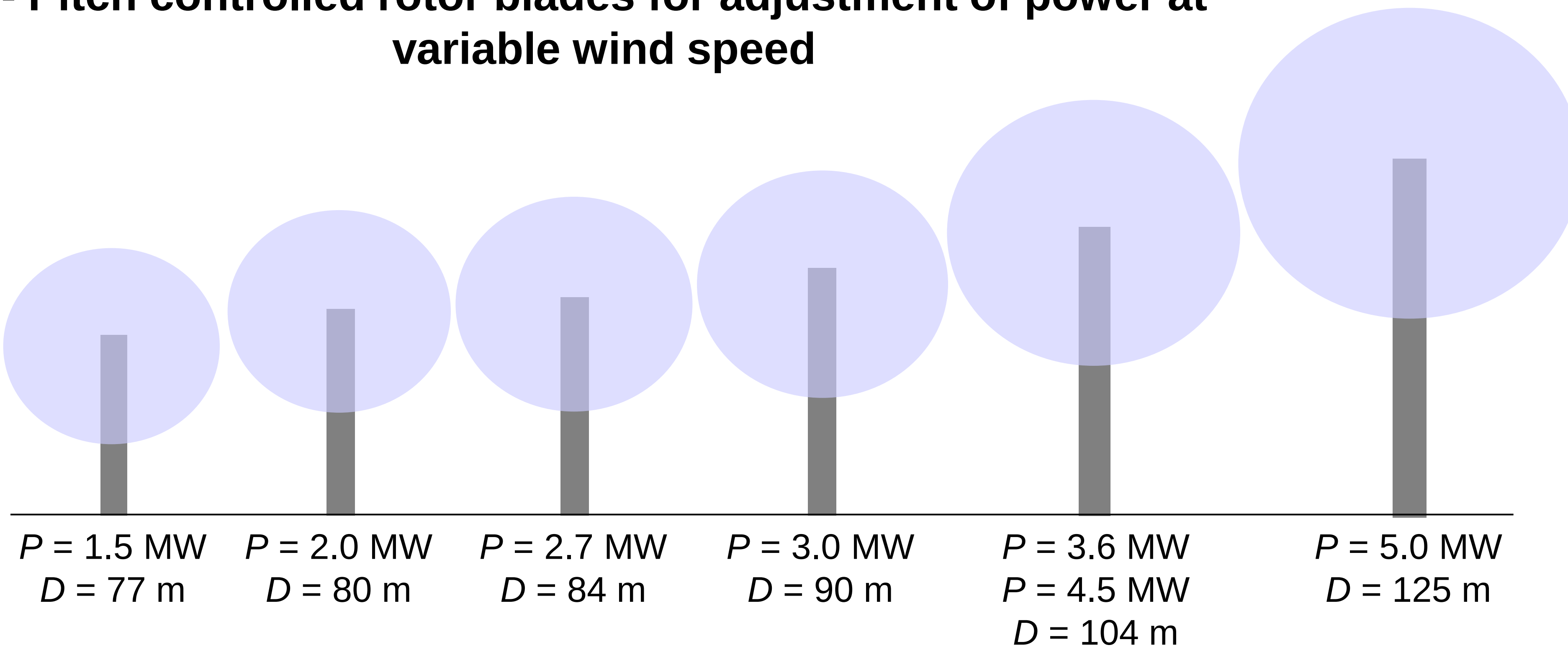
Rated apparent machine power: $S_{mot} > S_{inv}$

Stator: Winding is grid-operated, three-phase sinusoidal system

Rotor: Winding is inverter-fed with slip-frequent rotor voltage U_r

Wind generators – Power data

- **Pitch controlled rotor blades for adjustment of power at variable wind speed**



Pitch controlled variable speed wind energy converters up to 5 MW for on- and off-shore application

P / MW	D_R / m	n_R / min^{-1}	Company	Generator	v_{Rmax} /km/h	v, v_N /m/s	Gear *i*
1.5	70 77	10...19 9...17	*Repower* *Südwind*	DS-ASM DS-ASM	251 247	No data 3...20, 11.1	No data 104
2.0	80 90	9...19 7.4...14.8	*Vestas* *Made*	DS-ASM Optispeed Syn-G RG	287 251	4...25, 15 3...25	No data 101
2.7 2.75	84 92	6.5...18 n_{RN} = 15.6	*GE Wind* *NEG Micon*	DS-ASM DS-ASM	285	4.5...25 4...25, 14	No data 70.65
3.0	90	10...20	*Scan Wind*	PM-Syn	339	No data	gearless
3.6	104	8.5...15.3	*GE Wind*	DS-ASM	300	3.5...25, 14	No data
4.5	104	No data	*Enercon*	Syn-G SL	No data	No data	gearless
5.0	125	7...13	*Repower*	DS-ASM	306	4...30, 12	98.3

DS-ASM: Doubly-fed wind generator, PM-Syn: Permanent magnet synchronous generator

Syn-G RG: Electrically excited synchronous generator with rotating diode rectifier

Syn-G SL: Electrically excited synchronous generator with slip rings

Typical variable speed wind turbine data for off-shore

Rated power	3 MW	5 MW
Wind turbine rotor diameter	104 m	125 m
Speed range 1/min	8.5 ... 13 (Rated) ... 15.3	7 ... 11 (Rated) ... 13
Wind velocity m/s	3.5 ... 25	3 ... 25

Cut-in wind speed: typically 3 m/s

Cut-off wind speed: typically 25 m/s

Dominating electrical system: Geared doubly-fed induction generator

System components:

- Induction generator with wound rotor and slip rings, voltage < 1000 V (e.g. 690 V/ 50 Hz)
- Rotor side IGBT inverter (Insulated gate bipolar transistor)
- Inverter PWM control on rotor and grid side (Pulse width modulation)
- Three stage gear unit (transfer ratio per stage < 8): i = 70 ... 100 from low turbine speed to high generator speed
- Transformer (e.g. 690 V / 20 kV) for grid connection

Masses of variable speed wind energy converters (1)

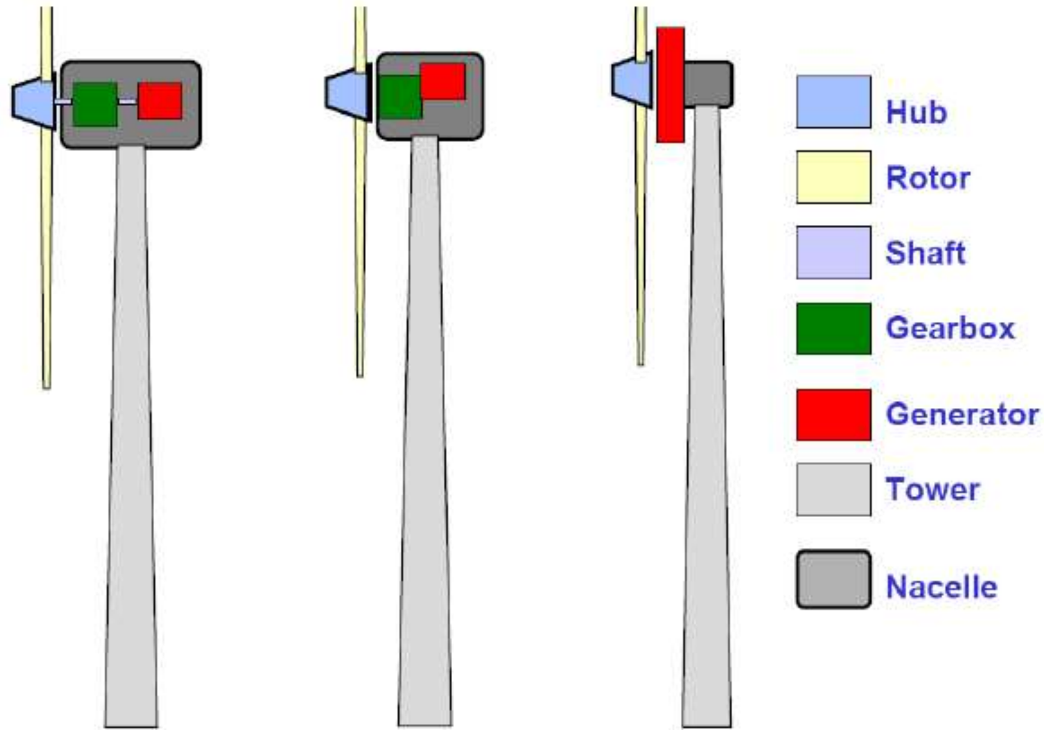
Rated power	3-blade wind rotor	Generator system: Doubly fed induction gen.	Nacelle	Wind rotor + Nacelle
1.5 MW *Südwind*	D_R = 77 m, 5.6 t per blade, in total with spider: 34 t	Gear: i = 104 14 t (300 l Oil) Generator: 7 t	Total nacelle mass: 61 t	Total mass: 84 t
5 MW *Repower*	D_R = 125 m, 19 t per blade, in total with spider: 110 t	Gear: i = 98.3 65 t Shaft + Bearing: 35 t	Total nacelle mass: 240 t *Length* x *Height*: 23 m x 6 m	Total mass: 350 t

Masses of variable speed wind energy converters (2)

Rated power	3-blade-wind rotor	Generator system: synchronous gen.	Nacelle	Wind rotor + Nacelle
4.5 MW *Enercon*	D_R = 104 m Rotor diameter	gearless, high pole count, electrically excited synchronous generator + inverter	No data	Total mass: 500 t
5 MW *Multibrid*	In total with spider: 100 t	Gear: i = ca.14 PM-Synchronous generator	Total nacelle mass: 130 t	Total mass: 230 t

Overview on different variable speed wind generator concepts

- **Conventional :** 15 RPM → 1:100 gearbox → 1500 RPM gen.
- **Hybrid:** 15 RPM → 1:6 gearbox → 90 RPM gen.
- **Multi-pole:** 15 RPM direct drive

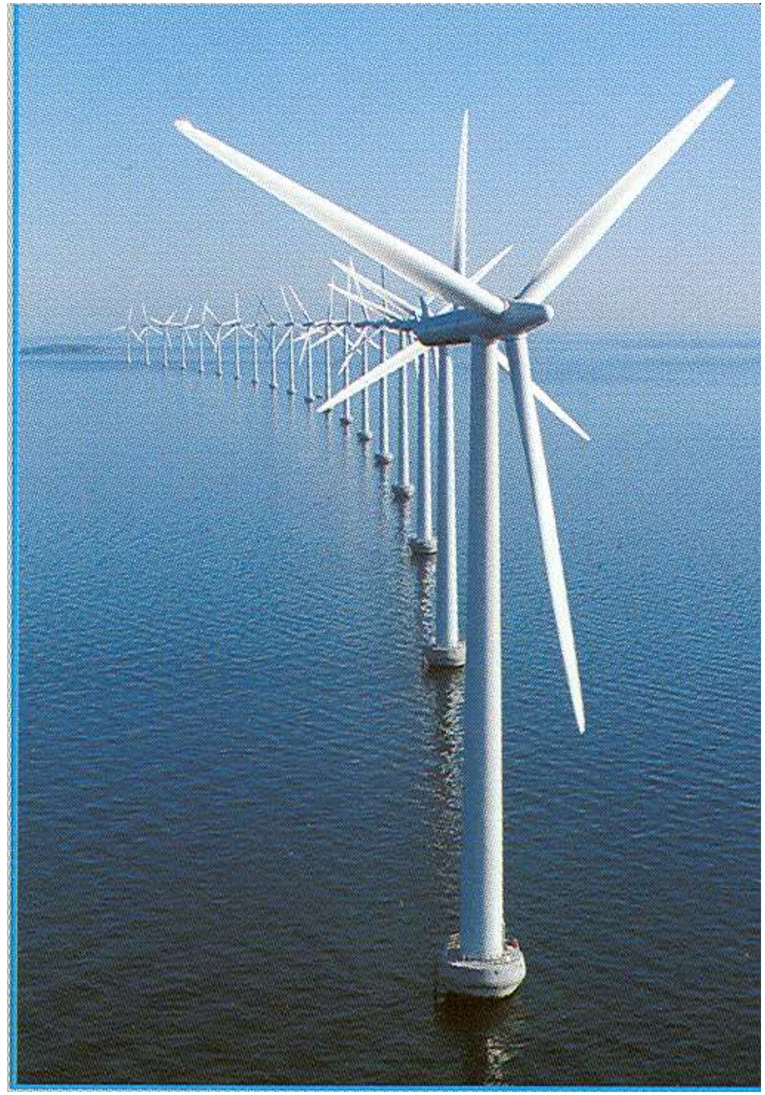


Source: DTU, Denmark

6. Wind generators and high power drives

Off-shore wind park near *Denmark*

- Variable speed wind turbines
- Pitch control
- Doubly-fed induction generators
- Yaw control to align wind direction



Source:

Winergy, Germany

Components of variable speed wind converter systems

Wind rotor:

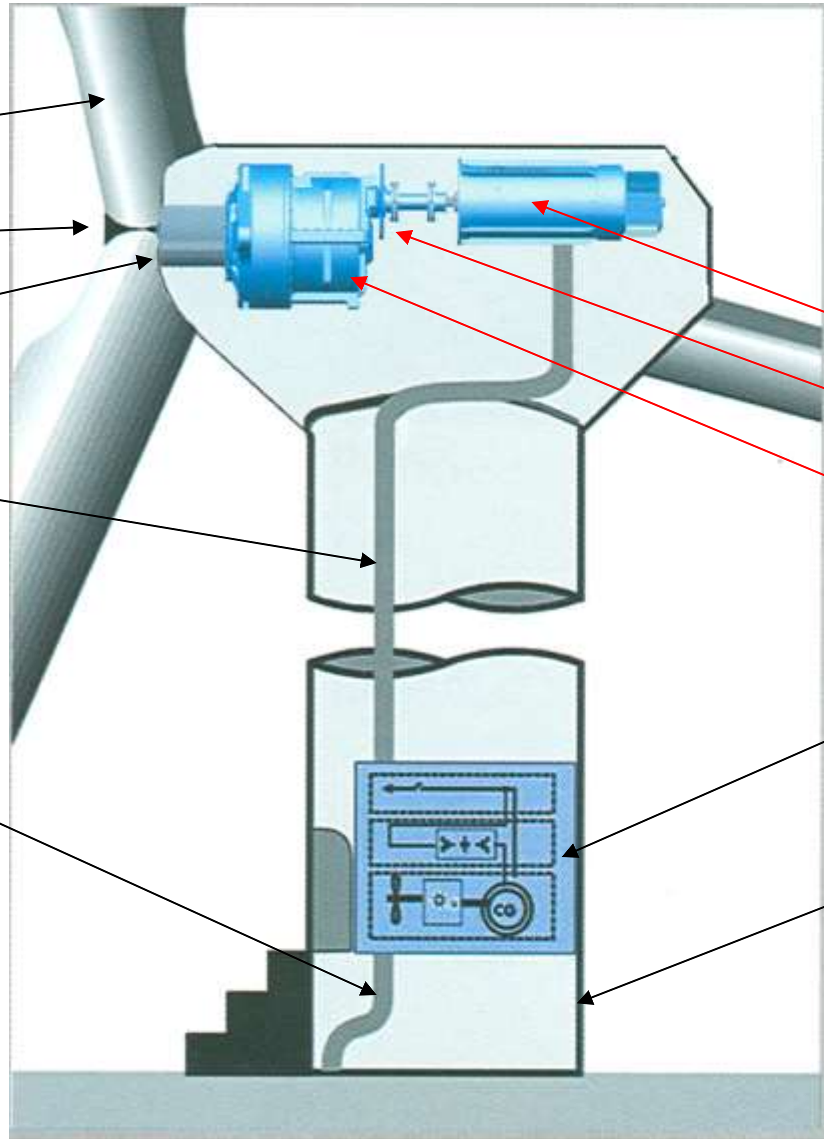
Blade

Spider

Turbine shaft

Generator three-phase cable

Transformer low-voltage three phase cable



Nacelle:

Induction generator

Generator shaft + coupling

Three-stage gear

Rotor side inverter

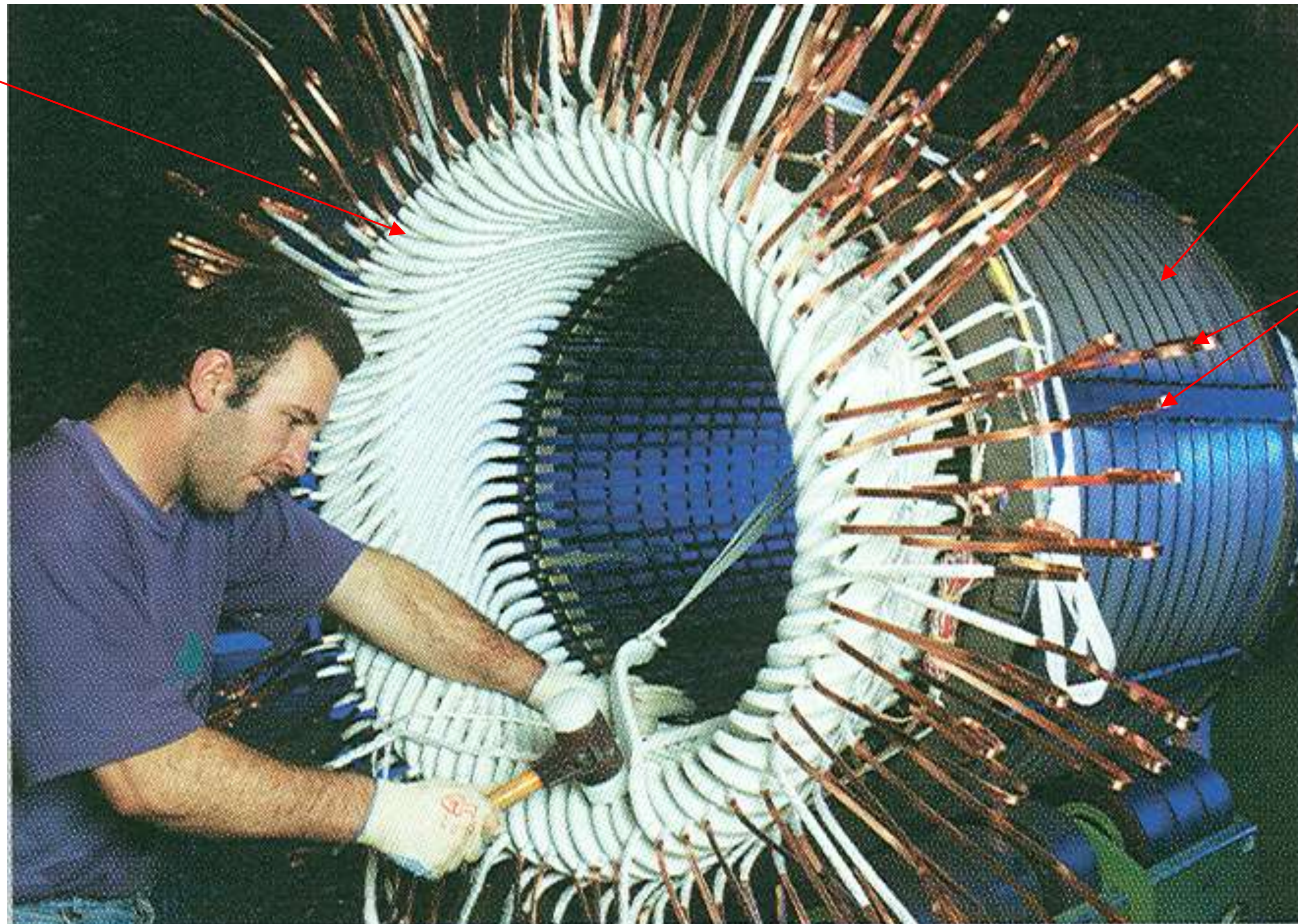
Centre pole

Source:

Winergy, Germany

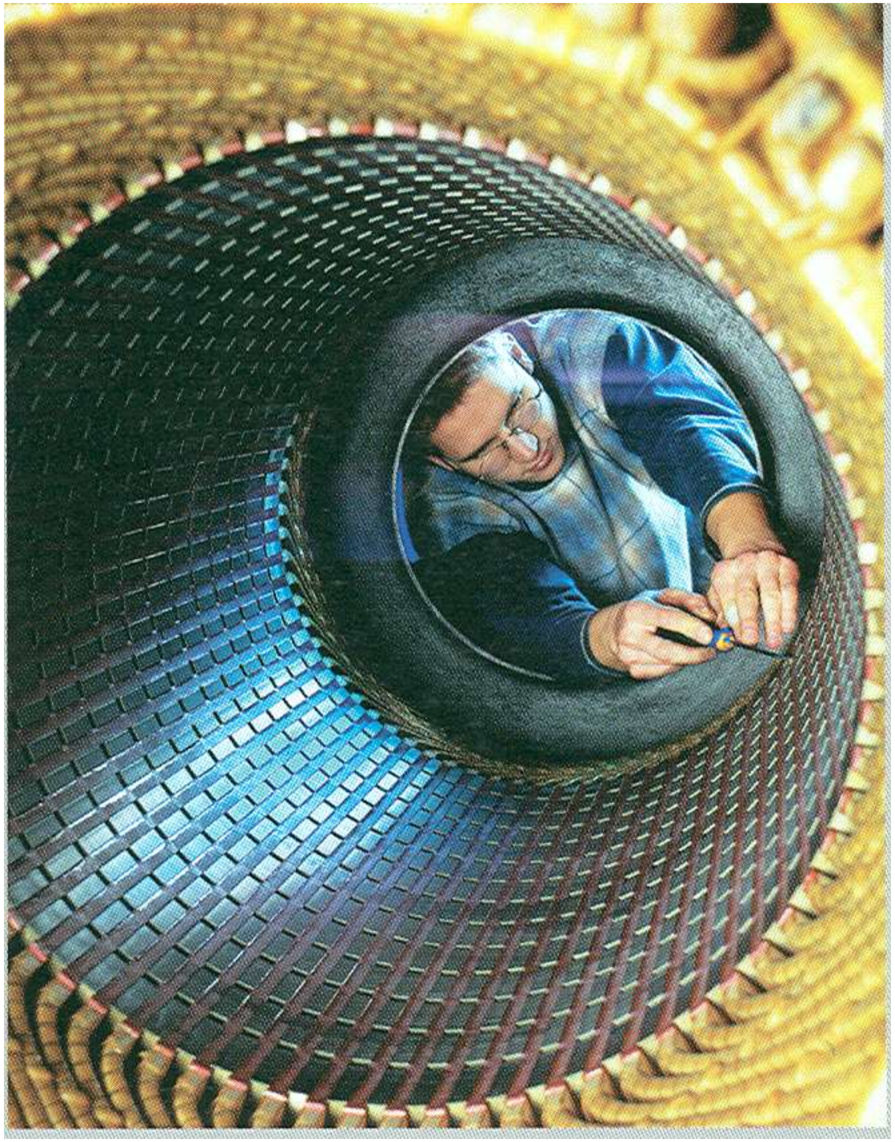
6. Wind generators and high power drives

Inserting the form-wound two-layer winding in induction generator stator



Source: Winergy Germany

6. Wind generators and high power drives



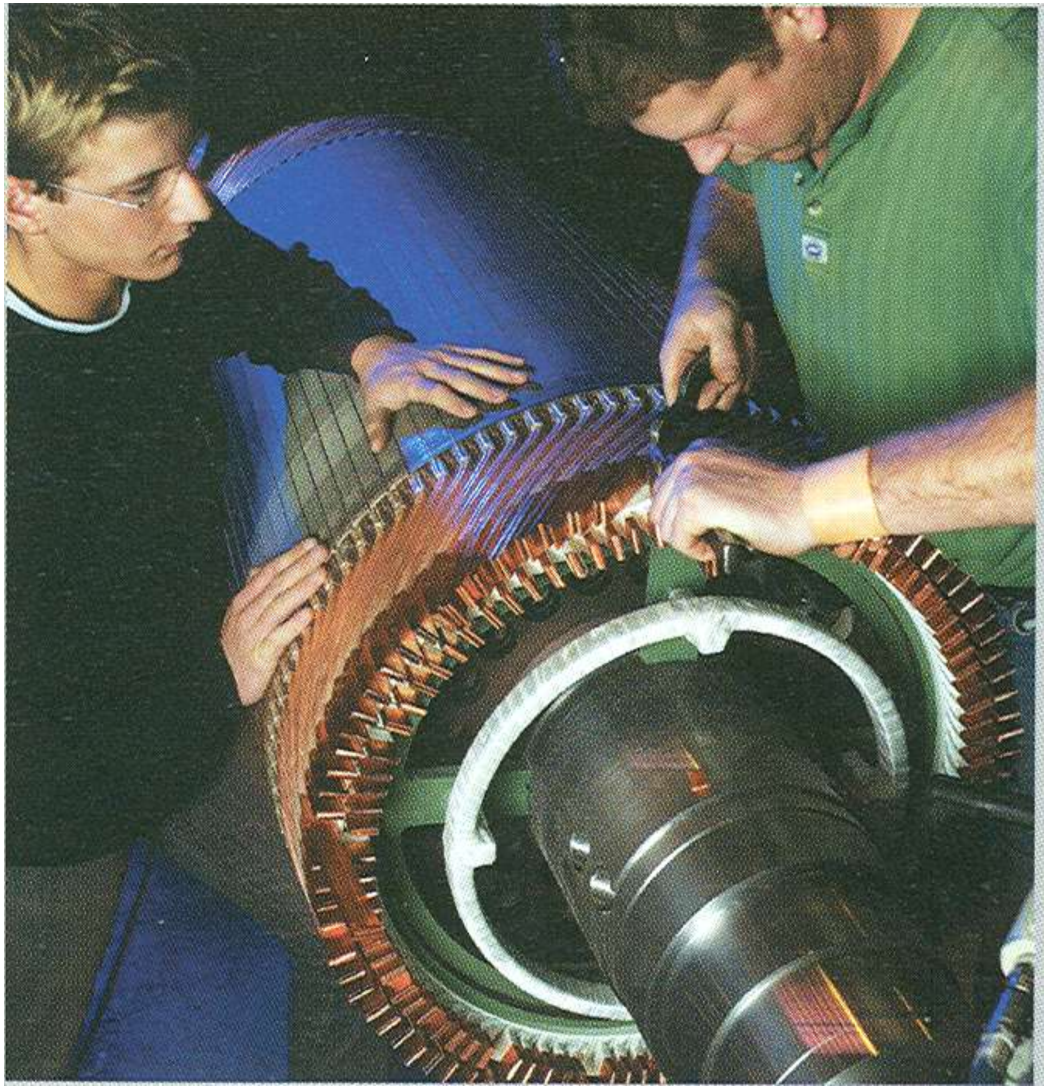
Stator three phase two-layer winding of induction generator

Source:

Winergy

Germany

6. Wind generators and high power drives



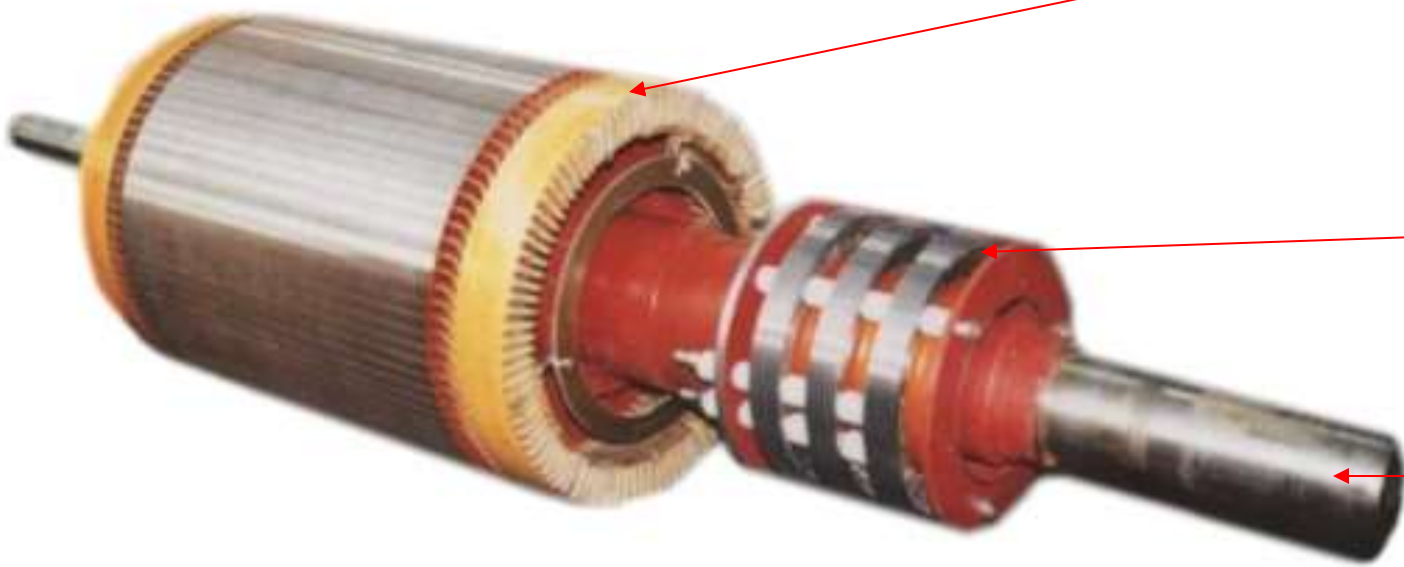
Rotor three phase two-layer winding of slip ring induction generator

Source:

Winergy

Germany

Wound rotor of slip ring induction machine



Two-layer three-phase rotor winding

Y connected

3 slip rings of the three phases

shaft end

Source:

GE Wind, Germany

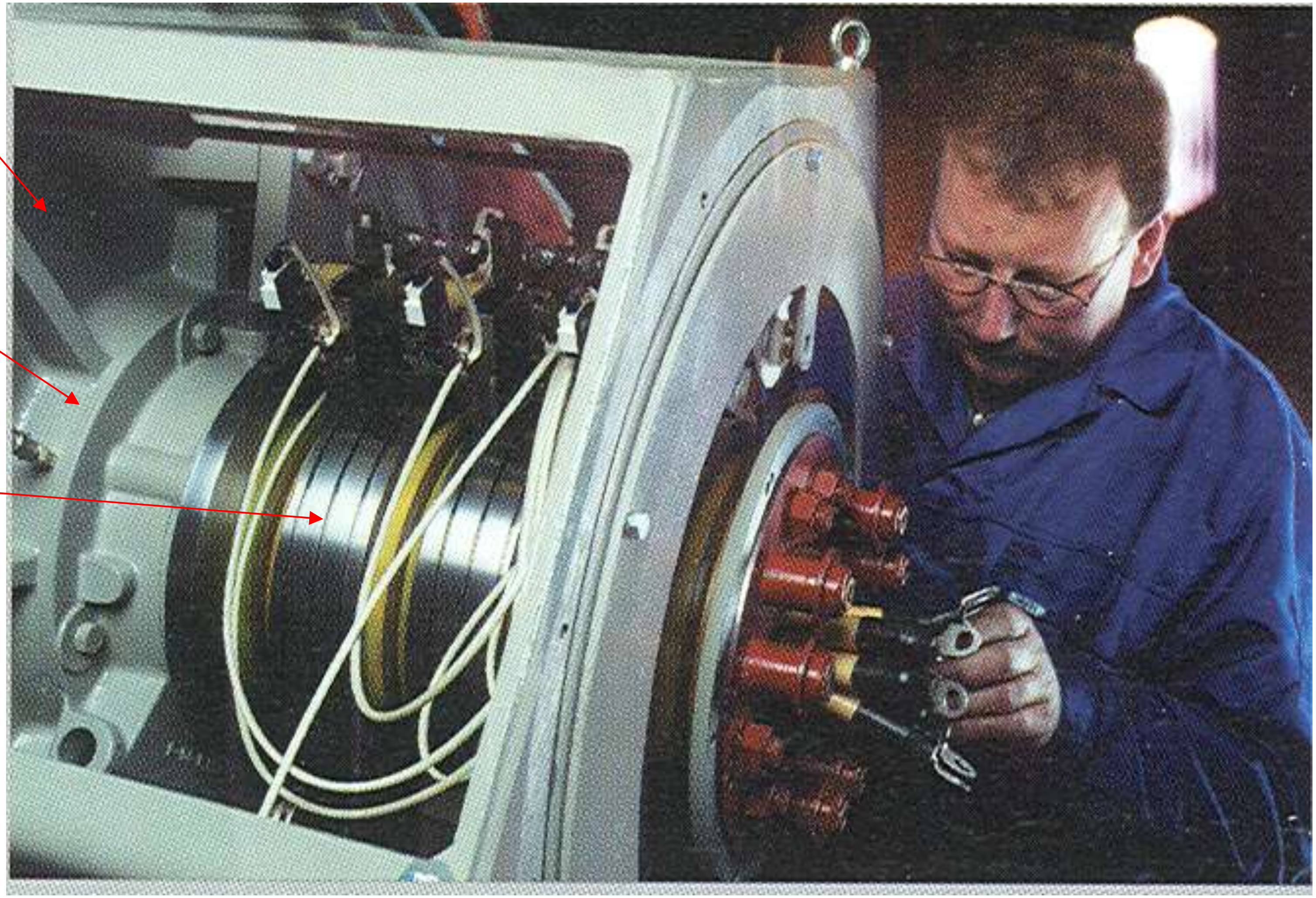
6. Wind generators and high power drives

Connecting rotor winding to slip rings

Non-drive end shield

bearing seat

slip rings with spiral slot to avoid aerodynamic levitation of brushes

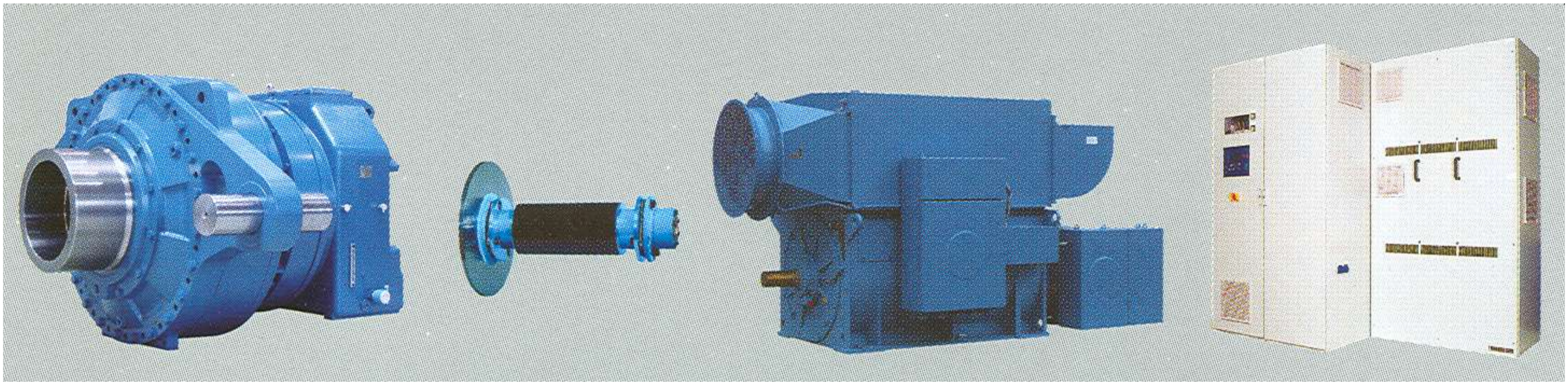


Source: Winergy Germany

Carbon slip rings instead of steel slip rings shall enhance brush life

Source: Winergy, Germany

Components of doubly-fed induction generator system 2 MW



Three-stage planetary gear | generator coupling | slip-ring induction generator | rotor side inverter

Source:

Winergy, Germany

Principle of doubly fed induction machine (1)

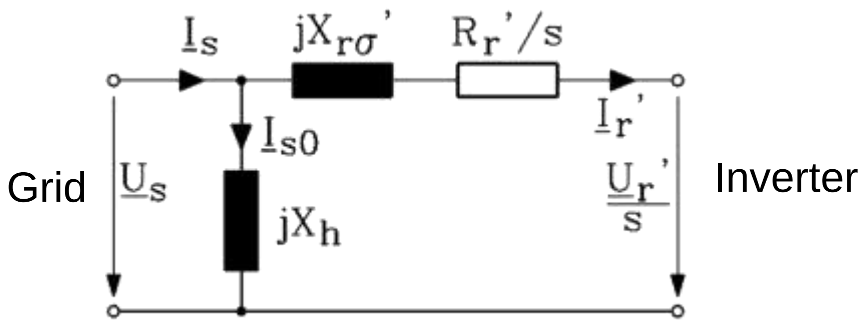
- *Aim*: Speed variable operation with small inverter: inverter rating less than motor rating $S_{inv} < S_{mot}$
- *Solution:* Line-fed slip-ring induction machine, fed by small inverter in the rotor via slip rings
- **but:** Speed range $n_{min} \le n_{syn} \le n_{max}$ small. If we want $n_{min} = 0$, we get $S_{inv} = S_{mot}$.
- **Inverter feeds with rotor frequency an additional rotor voltage U'_r into rotor winding.**

  - Via variable **amplitude** of $\underline{U}'_r$ the speed is changed,

  - Via **phase shift** of $\underline{U}'_r$ the reactive component of stator current $\underline{I}_s$ is changed

6. Wind generators and high power drives

Principle of doubly fed induction machine (2)



Simplified T-equivalent circuit per phase:

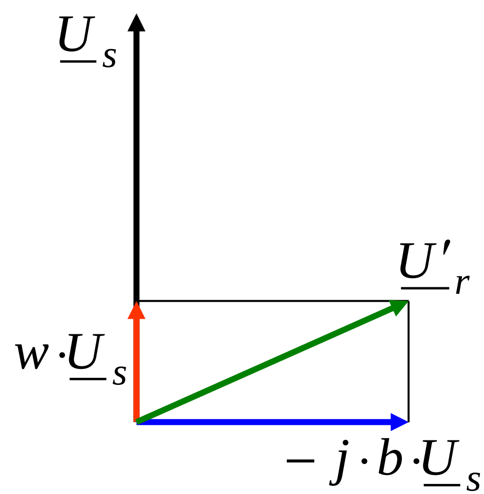
$$R_s = 0,\ L_{s\sigma} = 0$$

$$n_{min} \le n_{syn} \le n_{max}$$

$$\underline{U}_s = jX_h(\underline{I}_s - \underline{I}'_r) = jX_h \underline{I}_{s0}$$

$$\underline{U}'_r = -(R'_r + jsX'_{r\sigma})\underline{I}'_r + s\underline{U}_s$$

Rotor current: $$\underline{I}'_r = \frac{\underline{U}_s - \frac{\underline{U}'_r}{s}}{\frac{R'_r}{s} + jX'_{r\sigma}}$$



Rotor voltage of inverter:

$$\underline{U}'_r = \underline{U}_s \cdot (w - jb)$$

Simplified torque-speed curve of doubly fed machine (1)

- **Electromagnetic torque M_e** : Approximation for small slip s << 1:

$$\underline{I}'_r = \frac{s\underline{U}_s - \underline{U}'_r}{R'_r + jsX'_{r\sigma}} \approx \frac{s\underline{U}_s - \underline{U}'_r}{R'_r} = \frac{U_s}{R'_r}(s - w + jb) \qquad s \ll 1$$

$$P_{in} = P_\delta = m_s \operatorname{Re}\{\underline{U}_s \cdot \underline{I}'^*_r\} = m_s \frac{U_s^2}{R'_r}(s-w) \Rightarrow \boxed{M_e = \frac{P_\delta}{\Omega_{syn}} = \frac{m_s U_s^2}{\Omega_{syn} R'_r}(s-w)}$$

By real part of additional rotor voltage w the ***M_e-n-curves are shifted in parallel !***

- Torque is ZERO at **no-load slip $s_L = w$**.
  - If no-load slip s_L is positive (**SUB-synchronous no-load points**) ⇔ Active component of additional rotor voltage IN PHASE with stator voltage
  - If s_L is negative (**SUPER-synchronous no-load points**) ⇔ Active component of additional rotor voltage is in PHASE OPPOSITION with stator voltage

$$M_e = 0 \quad \Rightarrow \quad s - w = 0 \quad \Rightarrow \quad \boxed{s_L = w = \frac{U'_{r,active}}{U_s}}$$

- **Inverter rating:** $S_{Inv} = 3U_r I_r$
- At n_{min} (⇔ $s_{L,max}$) both U_r and S_{inv} are at maximum, defining inverter rating.

Simplified torque-speed curve of doubly fed machine (2)

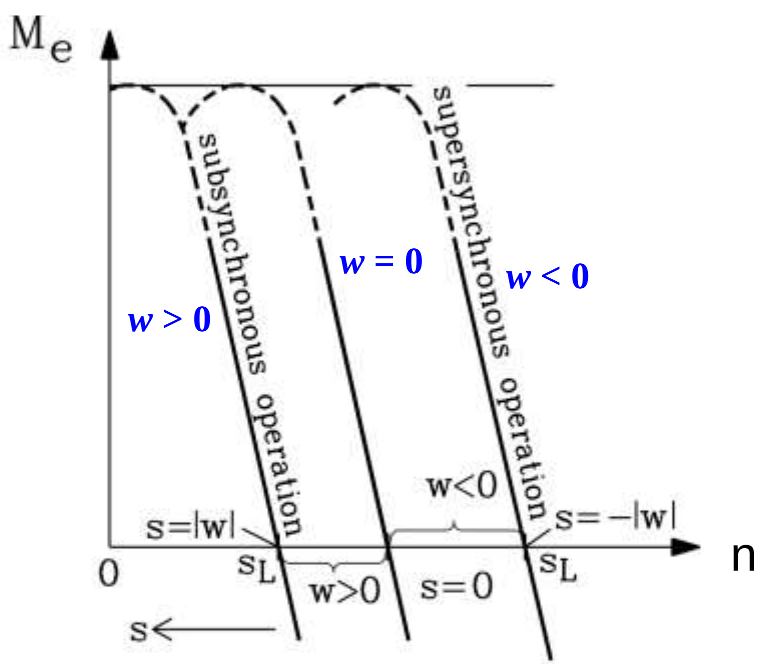
- **Elektromagnetic torque M_e,** simplified expression for small slip s << 1:

$$M_e = \frac{P_\delta}{\Omega_{syn}} = \frac{m_s U_s^2}{\Omega_{syn} R_r'}(s-w)$$

- *Via the „active" component of the inverter-output rotor voltage w the* ***M_e-n-curves are shifted in parallel.***

$$M_e = 0 \quad \Rightarrow \quad s - w = 0 \quad \Rightarrow$$

$$s_L = w = \frac{U'_{r,active}}{U_s}$$



Simplified torque-speed curve of doubly fed machine (3)

- Torque is zero at **no-load slip $s_L = w$**.
  - slip s_L is positive (**SUB-synchronous no-load operation point**) ⇔ active component of inverter-output rotor voltage is IN PHASE with stator phase voltage: $w > 0$
  - slip s_L is negative (**SUPER-synchronous no-load operation point**) ⇔ active component of inverter-output rotor voltage is IN OPPOSITE PHASE to stator phase voltage: $w < 0$

Inverter rated power

- **Inverter power:** $S_{inv} = 3U_r I_r = 3U'_r I'_r = 3 \cdot s_L U_s I'_r$

$$I'_{r,\max} = \left| \underline{I}_{sN} - \underline{I}_m \right| \approx I_{sN}$$

$$S_{inv,\max} = 3 \cdot s_{L,\max} U_s I'_{r,\max} \approx s_{L,\max} \cdot 3U_{sN} I_{sN} = s_{L,\max} S_N$$

$$\boxed{S_{inv,\max} = s_{L,\max} S_N}$$

- **Example:** $n_{min} = 0.7 n_{syn}$: $s_{L,max} = 0.3$: $S_{inv,max} = 0.3 \cdot S_N$

  $P_{e,N} = 1.5$ MW, $\cos\varphi_N = 0.8$, $S_N = 1.5/0.8 = 1.875$ MVA

  $S_{inv,max} = 0.3 \cdot 1.875 = 0.56$ MVA = 560 kVA

Example: $n_{min} = 0.7n_{syn}$: $s_{L,max} = 0.3$: $S_{inv,max} = 0.3 \cdot S_N$; $P_{e,N} = 1.5$ MW $\approx P_\delta$, $\cos\varphi_N = 0.8$,

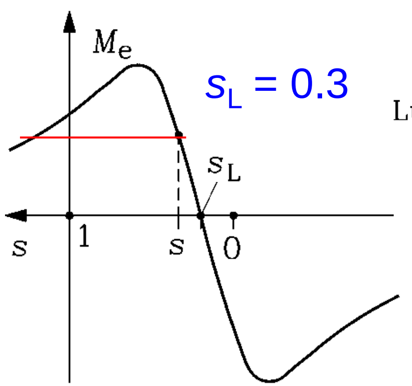
$f_N = 50$ Hz, $S_N = 1.5/0.8 = 1.875$ MVA, $S_{inv,max} = 0.3 \cdot 1.875 = 560$ kVA

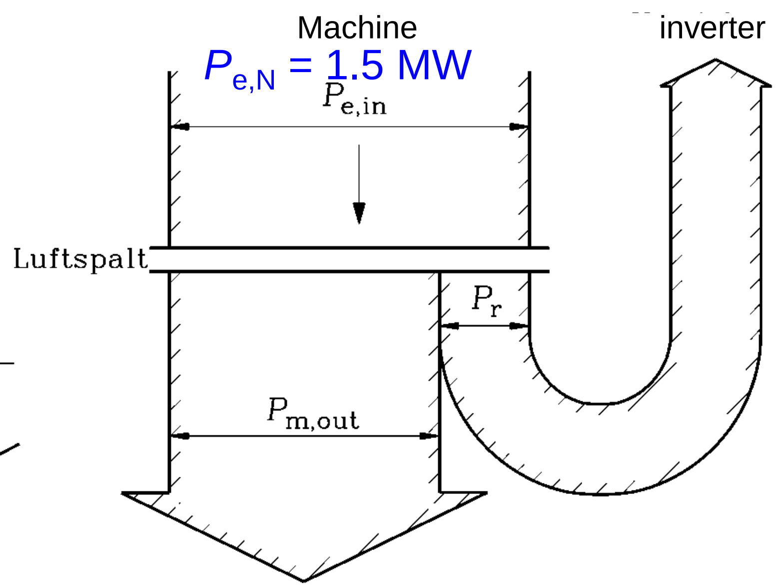
Machine: $2p = 4$, $n_{syn} = 1500$/min $\quad s_N = 1\% : n_N = (1 - s_N)n_{syn} = 1485/\min$

$$P_{m,out} = (1 - s_N)P_\delta = 1485kW \quad M_N = \frac{P_{m,out}}{2\pi n_N} = 9549Nm \quad P_{Cu,r} = s_N P_\delta = 15kW$$

$$s_L = 0.3, s = s_L + s_N = 0.31: n_{min} = (1 - s)n_{syn} = 1035/\min \quad P_{m,out} = (1 - s)P_\delta = 1035kW$$

$$M_N = \frac{P_{m,out}}{2\pi n_{min}} = 9549Nm \quad P_r = sP_\delta = 465kW \quad P_{Umr} = P_r - P_{Cu,r} = 465 - 15 = 450kW$$





Motor operation

SUB-SYNCHRONOUS

Losses:
only $P_{Cu,r}$ considered
(in the SANKEY-diagram (left) neglected)

$P_{m,out}$ = 1.5 – 0.465 = 1.035 MW

Doubly fed induction machine as wind generator

- Wind turbine **with variable speed** allows to extract **maximum possible wind power** at each wind velocity ***v*** .
- $P_{Wind} \sim v^3 \Rightarrow P_{Turbine} \sim n^3$
- Doubly fed induction machine used as **variable speed generator, operating at grid with constant grid frequency !**
- Additional rotor voltage with rotor frequency generated by 4-quadrant PWM inverter via slip ring fed into rotor winding.

- *Example:* Wind velocity varies between $0.54v_{max}$ and v_{max}:
- Generator and gear to turbine are designed hence for speed range $n_{syn} \pm 30\%$ ($s = \pm 0.3$):

Wind velocity	Generator speed	slip	add. voltage	power
v_{max}	$n = 1.3n_{syn} = n_{max}$	$s = -0.3$	$w = -0.3$	$P = 100\%$
$v_{min} = 0.54v_{max}$	$n = 0.7n_{syn} = 0.54n_{max}$	$s = +0.3$	$w = +0.3$	$P = 15\%$

- Rated power of inverter at steady state operation and rated torque:

$$P = 0.15 = 0.54^3$$

$$P_{Inverter} = sP_\delta \approx sP_N = 0.3P_N$$

Here inverter rating is only 30% of generator rating, thus it is a very cheap solution, which is used nowadays widely at big wind turbines 1.5 ... 8 MW.

Doubly-fed induction generator with heat exchanger

Air-inlet fan Feet Power terminal box Slip ring terminal box

Air-air heat exchanger above

Doubly-fed induction generator

4 poles

2000 kW at 1800/min, 50 Hz and slip -20%

Rotor frequency 10 Hz

Source:

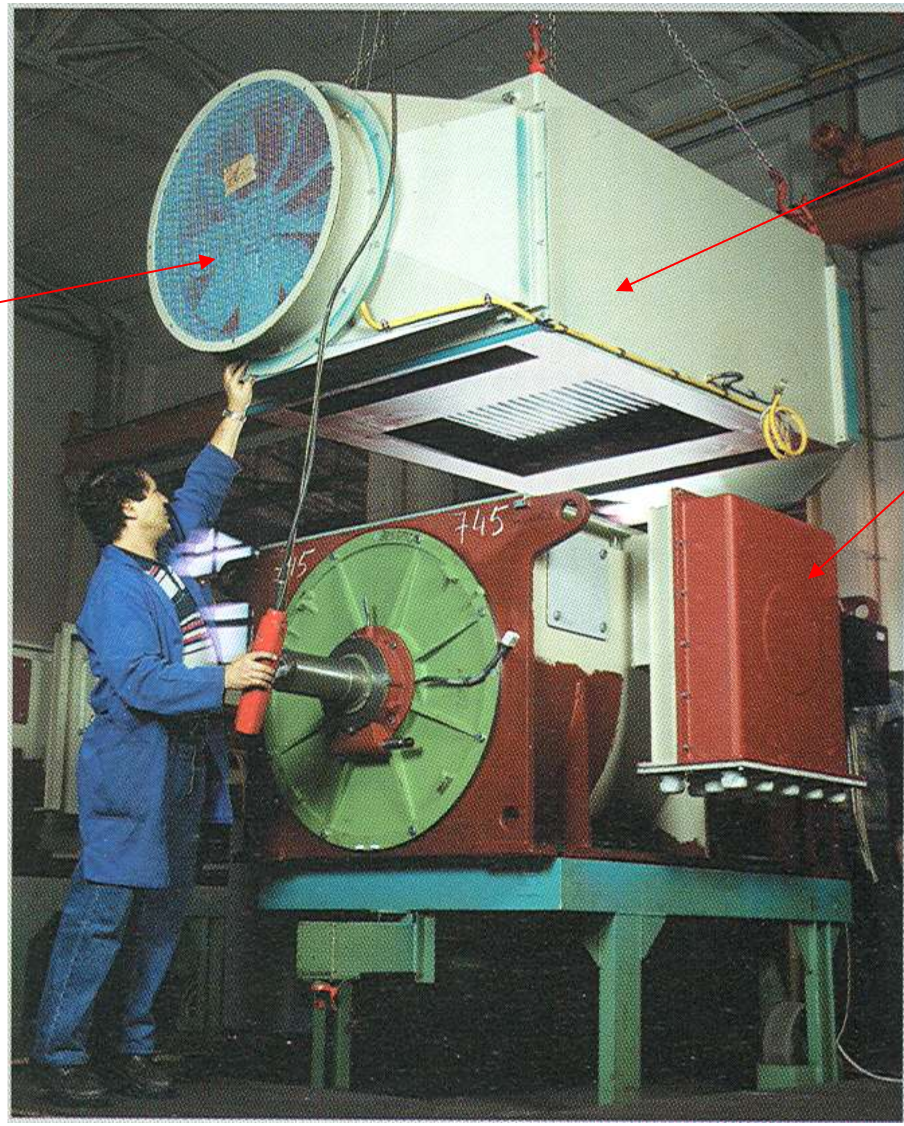
Winergy

Germany

Doubly-fed induction generator

1500 kW at 1800/min

Air inlet fan



Air-air heat exchanger

Generator terminal box

Mounting of air-air heat exchanger on slip ring induction generator

Source:

Winergy

Germany

Example: Rating for doubly-fed generators

Wind power rating	3 MW
Generator cooling / Thermal class	Air-Air heat exchanger / Class F
Generator rating	3.3 kV / 616 A / 50 Hz
Apparent power / power factor	3.5 MVA / 0.88 inductive load
Real power / Generator mass	3.1 MW / 14.6 t
Slip range / Rotor voltage at stand still	+ / - 30 % / 2443 V at 50 Hz
Rotor: rated current / apparent power	748 A / 950 kVA
Generator frame size / dimensions *LxBxH*	630 mm / 3.8x2.6x1.7 m^3
Full load efficiency	97.1 %
Turbine speed/ Gear transmission ratio	11.9 / min / 990/11.9 = 83.2

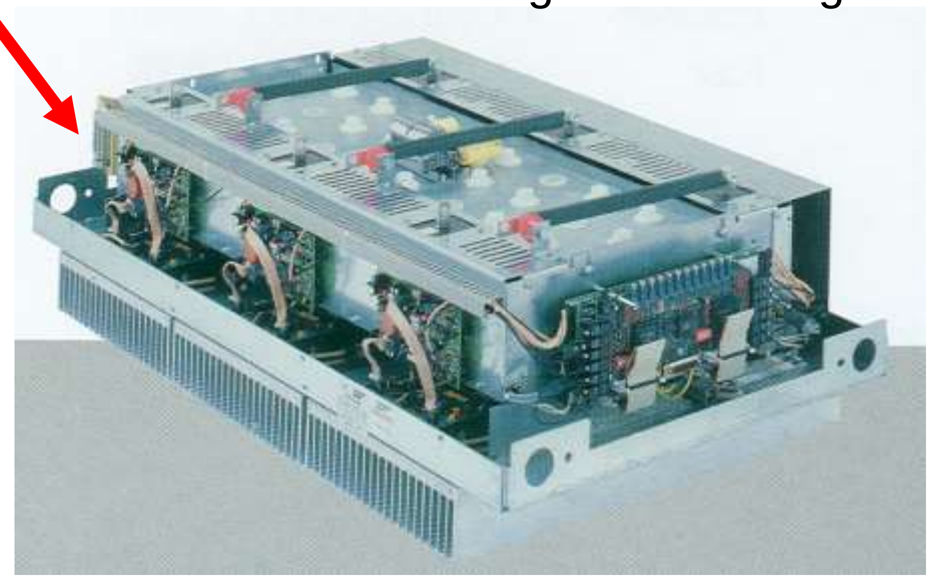
6. Wind generators and high power drives

Fan units

Filter chokes

Rotor side PWM voltage source inverters

Air cooled IGBT-inverter bridge with cooling fins



Air-cooled power electronic circuit for a 1.5 MW-wind converter has a rating of about 450 kVA

Grid side: 690 V

Rotor side: Rated rotor current

Source:

Winergy

Germany

6. Wind generators and high power drives

Inverter rating for doubly-fed generators

Rated power of wind converter	3 MW
Rated voltage / Current / Frequency	732 V / 748 A / <15 Hz; 50 Hz
Rated apparent power	950 kVA
Inverter unit / full-load efficiency	800 kW / 820 A / 97 %
Dimensions *LxBxH* / Mass	0.9x0.6x2.45 = 1.3 m^3 / 1045 kg
Crowbar:	ca. 1.3 m^3, ca. 1 t
Control unit for grid voltage break down 15 %	ca. 1.3 m^3, ca. 1 t

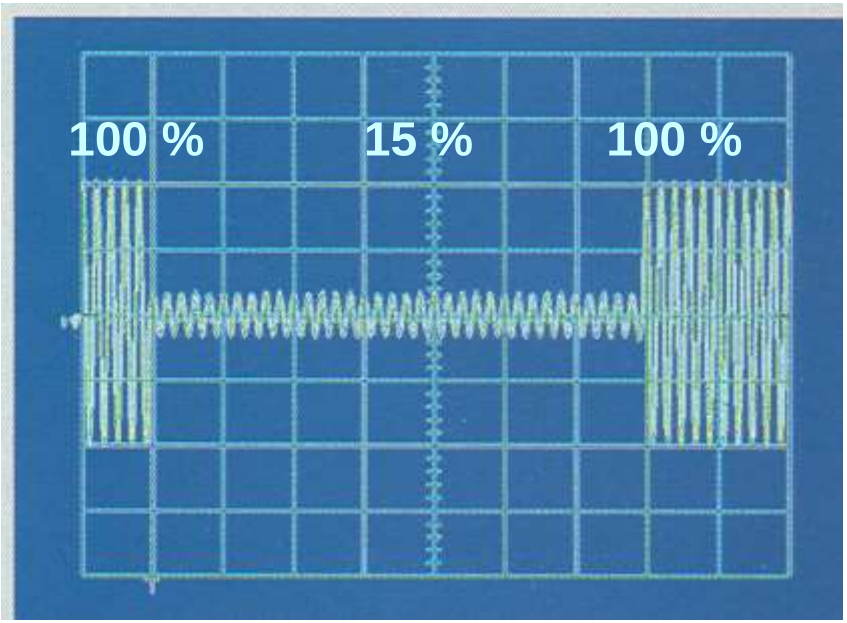
Crow bar: Thyristor switch short-circuits rotor side inverter in case of stator side winding fault. Otherwise transient rotor over-voltage and big rotor short circuit current would destroy rotor side power electronics.

Control unit for voltage break down: Is necessary to fulfil demand of TSO (transmission system operators), that wind converters have to stay at the grid even in case of voltage break down 15% of rated voltage.

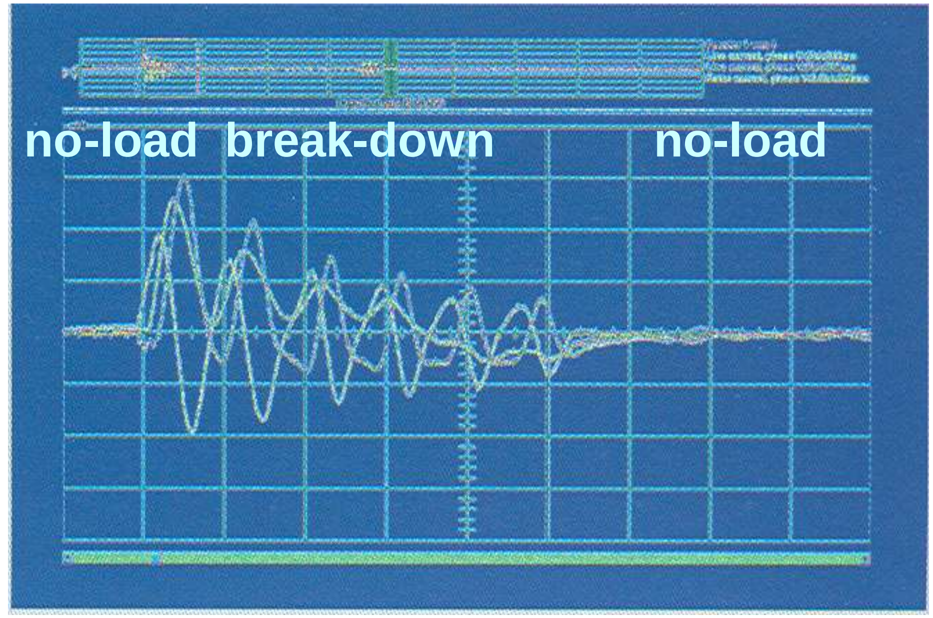
6. Wind generators and high power drives

15% voltage break-down during 0.7 s

Generator terminal voltage



Generator transient currents



0.1 s/div. Measured voltage break-down response in test lab

TSO-demand (transmission system operators) ("E.ON"-demand):
Wind converters have to stay at the grid even in case of voltage break down 15% of rated voltage, in order to help stabilizing the grid.

Source: Winergy Germany

Electric drive system assembly with doubly fed induction generator 1.5 MW variable speed

Air-air heat exchanger spider

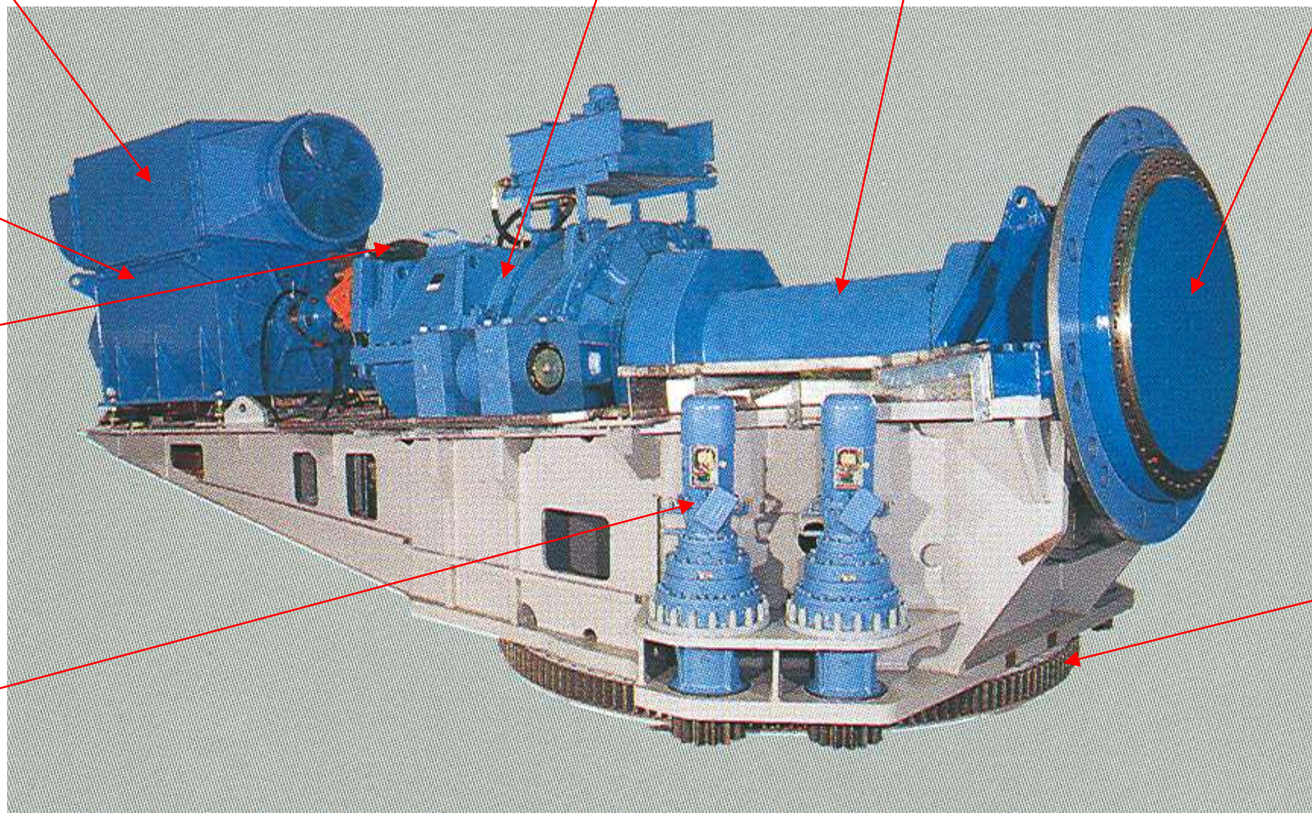
Three-stage gear unit

turbine shaft

turbine flange for wind rotor

Induction generator

Brake system



Cog wheel for yaw positioning

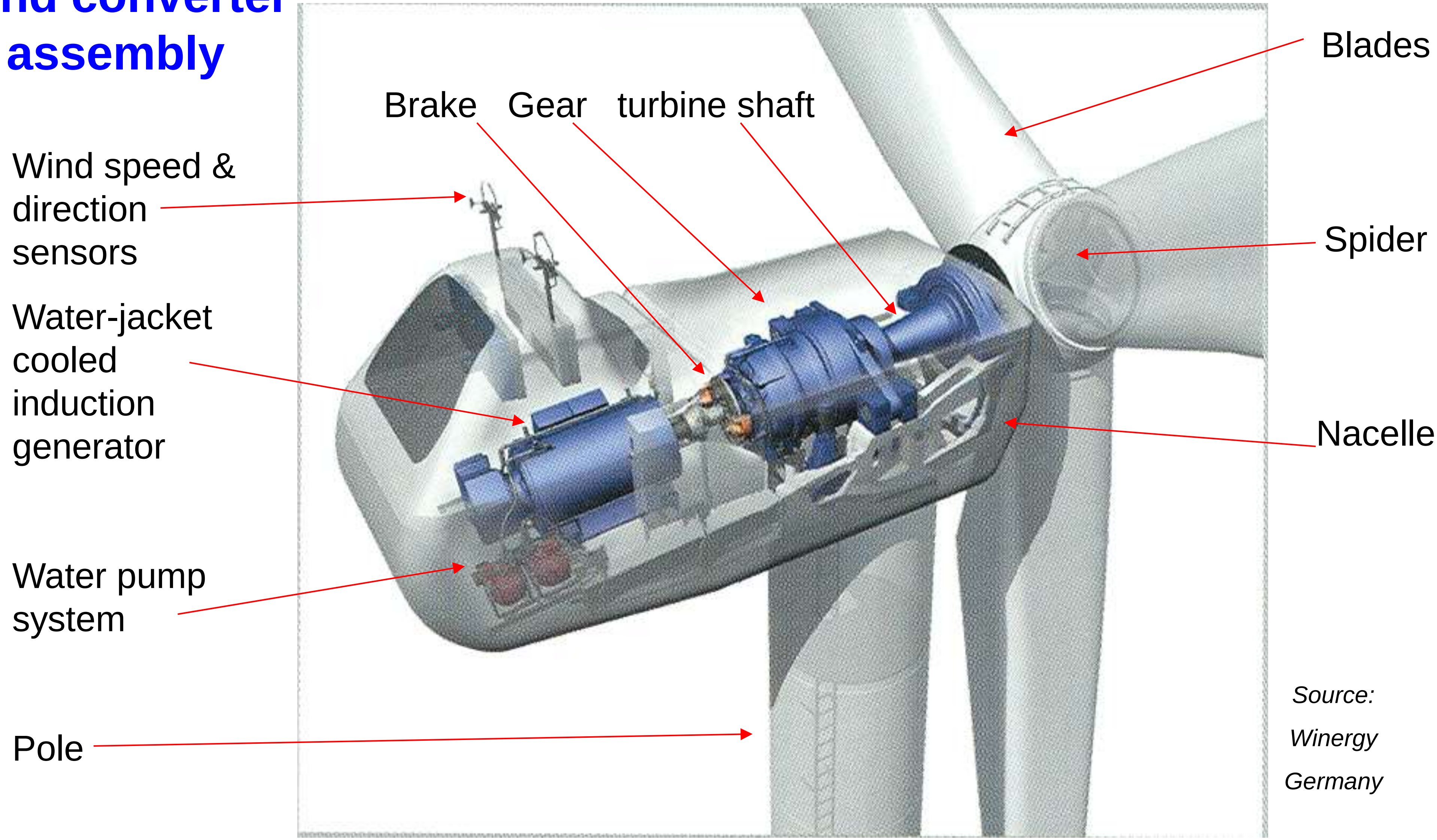
Inverter-fed induction motors for yaw positioning

Source:

Winergy, Germany

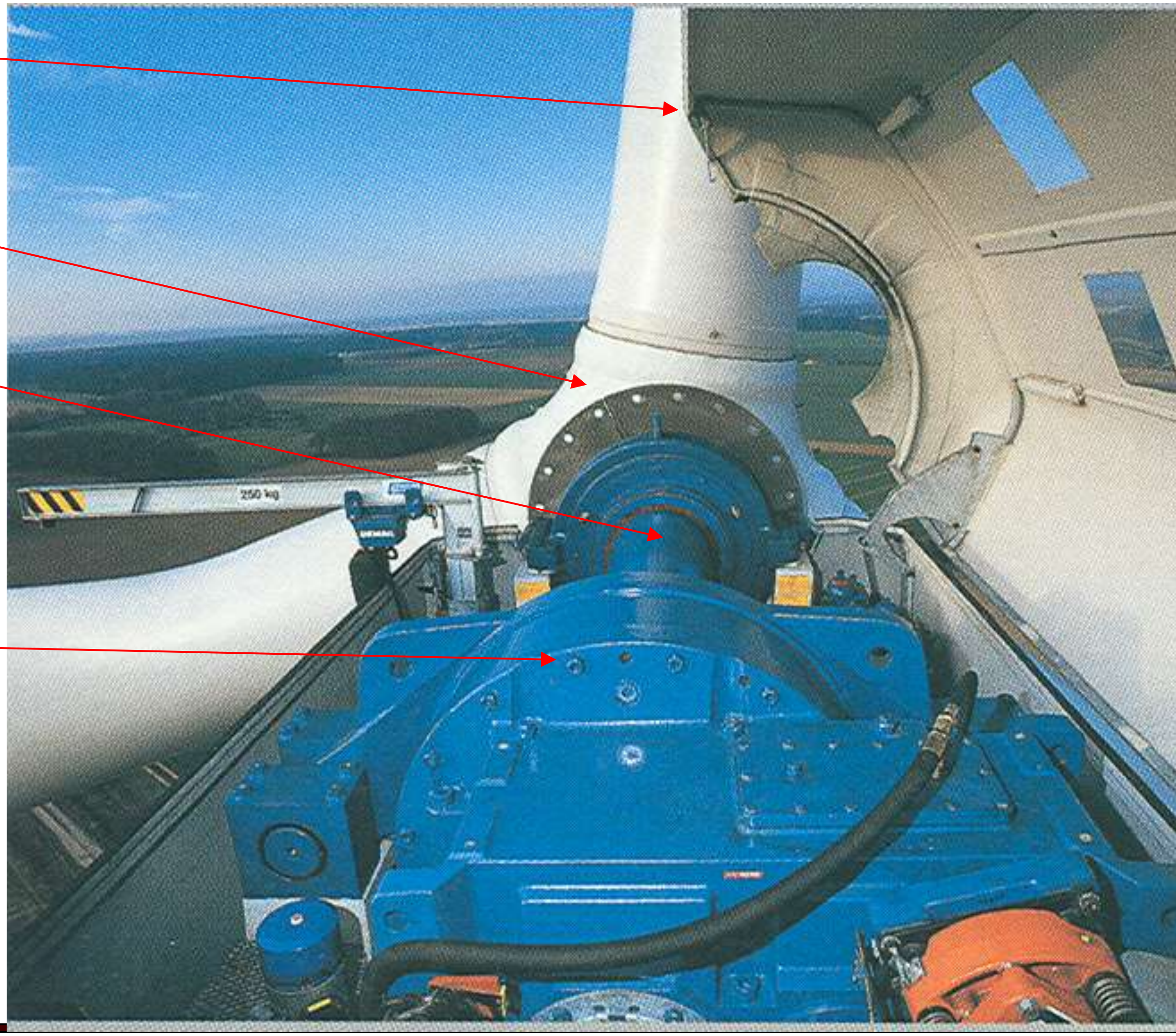
6. Wind generators and high power drives

Wind converter assembly



Source: Winergy Germany

Mounting of drive assembly in nacelle



Source: Winergy Germany

6. Wind generators and high power drives

Totally enclosed induction generator with shaft mounted fan

Generator coupling

Gear

Installation of monitoring system for generator unit

Source:

Winergy

Germany

Summary:

Variable speed wind turbines: Doubly-fed induction machines

- Maximum possible wind power extraction at each wind velocity v: $P \sim v^3$
- Speed control via inverter feeding, but with small inverter rating
- Pitch control of rotor blades

- Geared doubly-fed wound rotor induction generator with rotor side IGBT inverter and three slip rings
- Inverter feeds an additional rotor voltage into rotor winding
  $\Rightarrow$ In-phase voltage component gives parallel shift of M-n-curves
- For wind speed variation ±30 % a slip shift $s = \pm 30$ % and hence only a small inverter power is required: $P_{\mathrm{Inverter}} \approx s \cdot P_N$

6. Wind generators and high power drives

6.2 Wind turbine generators

6.2.1 Fixed speed wind energy conversion

6.2.2 Variable speed wind turbines:
Doubly-fed induction machines

6.2.3 Gearless wind generators

6.2.4 “Multibrid” - PM wind generator
– dual stage gear

6.2.5 „Small Hydro Power“

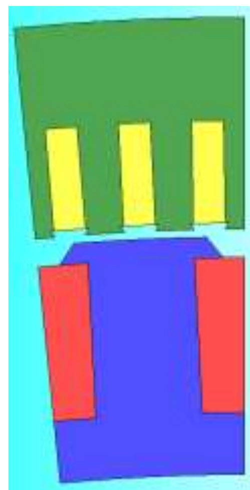
Source: Vestas, Denmark

6. Wind generators and high power drives

6.2.3 Gearless wind generators

- ***Gearless: Turbine speed = generator speed:*** High pole count and low frequency are needed !
- An induction generator with small pole pitch and relatively big air gap needs a big magnetizing current. So power factor is poor (below 0.6), leading to lower efficiency !
- Synchronous generators with electrical or permanent magnet excitation are used !

Integer-slot q = 1 round wire low voltage single layer stator 3-phase winding manufacturing



Integer-slot q = 1 stator winding, rotor electrical excitation

Rotor: Electrical excitation, rotor pole shoes skewed to reduce cogging. Double-skew avoids axial force

Source: Enercon, Aurich, Germany

6. Wind generators and high power drives

Gearless wind turbines with PM synchronous generators

- Synchronous generators with permanent magnet excitation do not need rotor exciter slip-rings and don not need any rotor excitation power!

Source: Siemens AG, Germany

Permanent magnet synchronous wind generator: 3 MW, 606 V, 3360 A, f = 13.6 Hz (via inverter feeding)

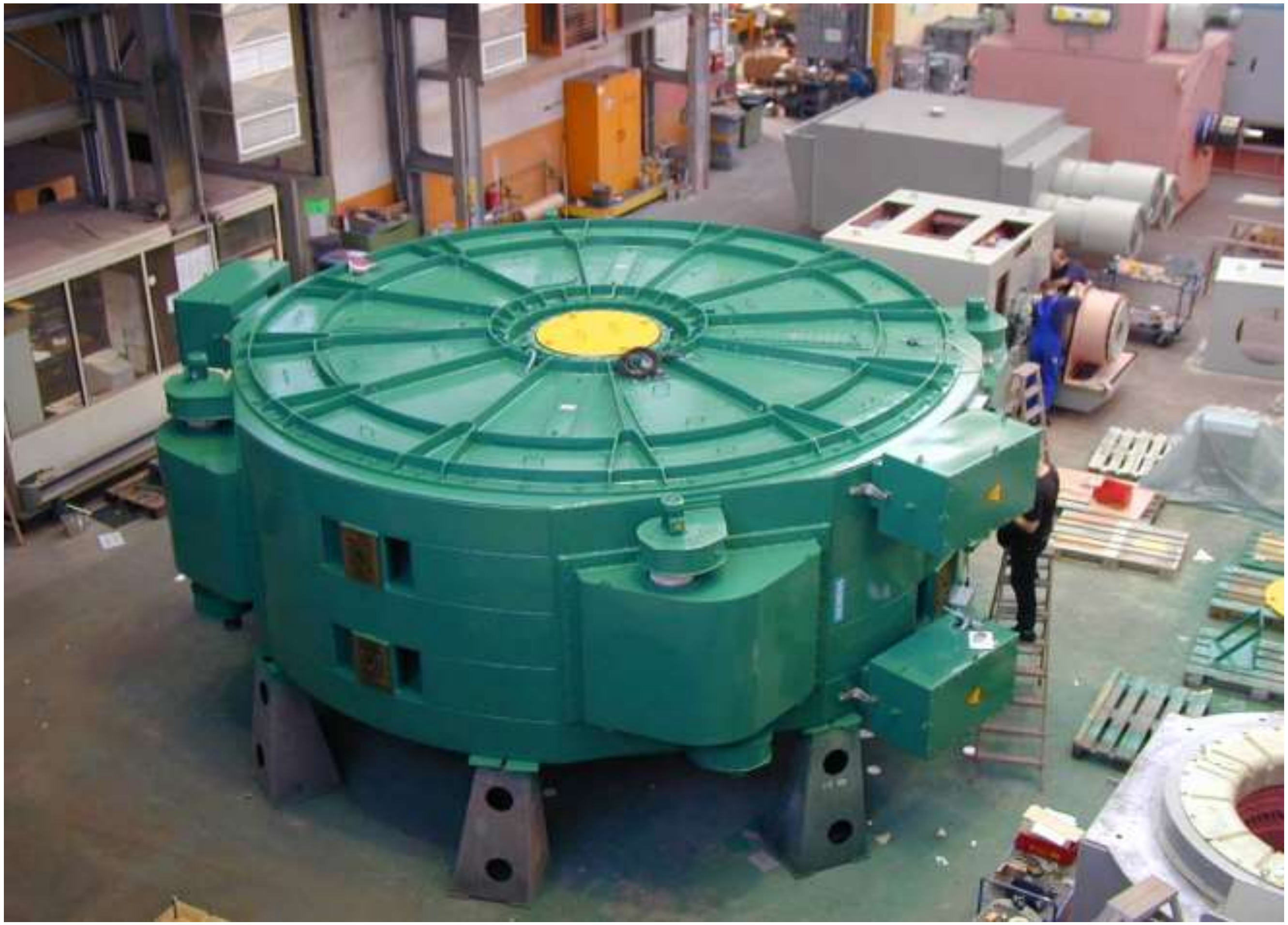
cos phi = 0.85 under-excited, speed 17 / min, efficiency 95.5%, rated torque: 1685 k Nm (!)

Outer diameter of generators: ca. 5.8 m, axial length: ca. 2.3 m

Mass ca. 85 t, high pole count: typically 90 ... 100 poles

Gearless permanent magnet wind generator

Scanwind / Norway 3 MW, 17/min



Wind rotor diameter 90 m

Three-blade rotor

Pitch control

Variable speed operation

10 ... 20/min

Gearless drive

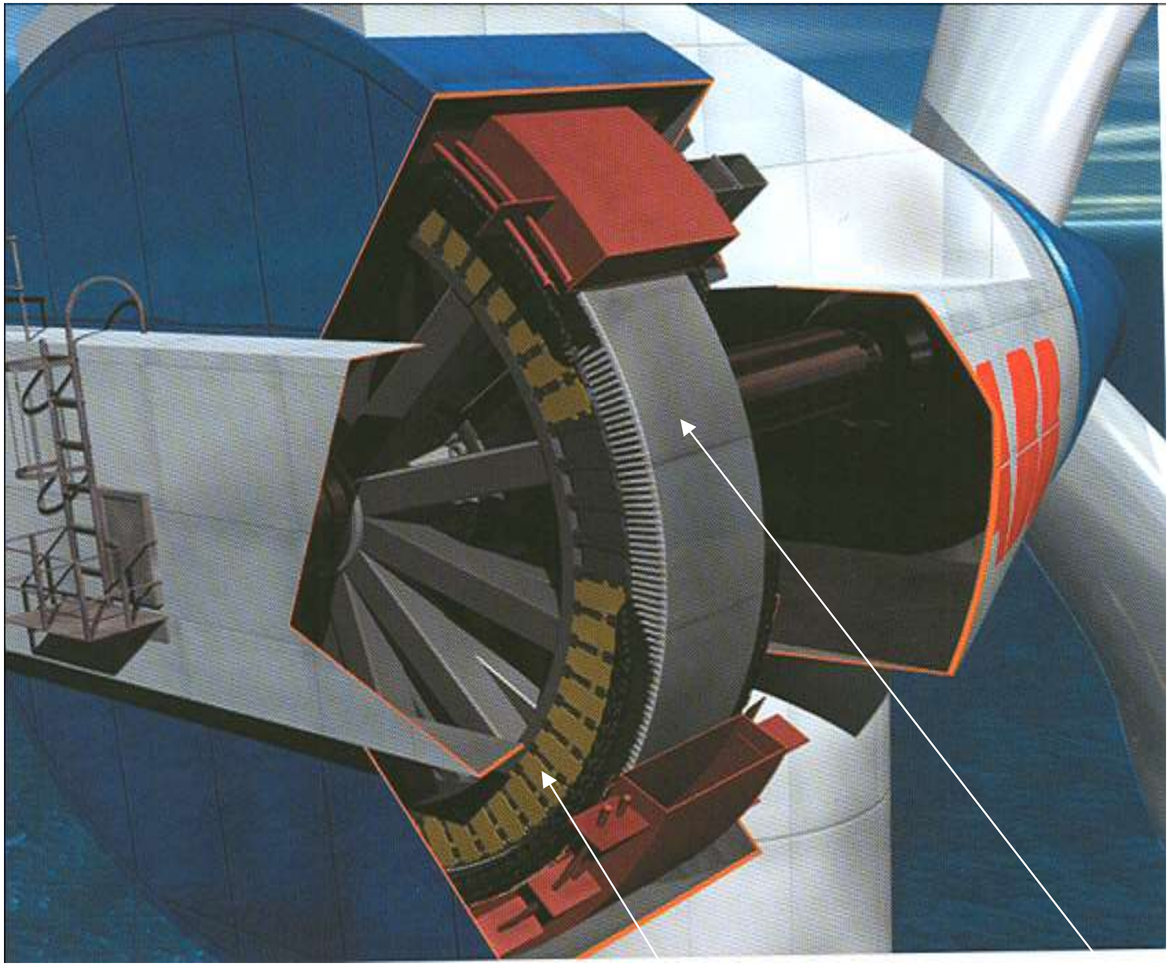
IGBT inverter 690 V

Source:

Siemens AG

Germany

Gearless permanent magnet wind generator



- High pole count synchronous generators have a small flux per pole.

- So height of magnetic iron back in stator and rotor may be small = thin ring shape of generator.

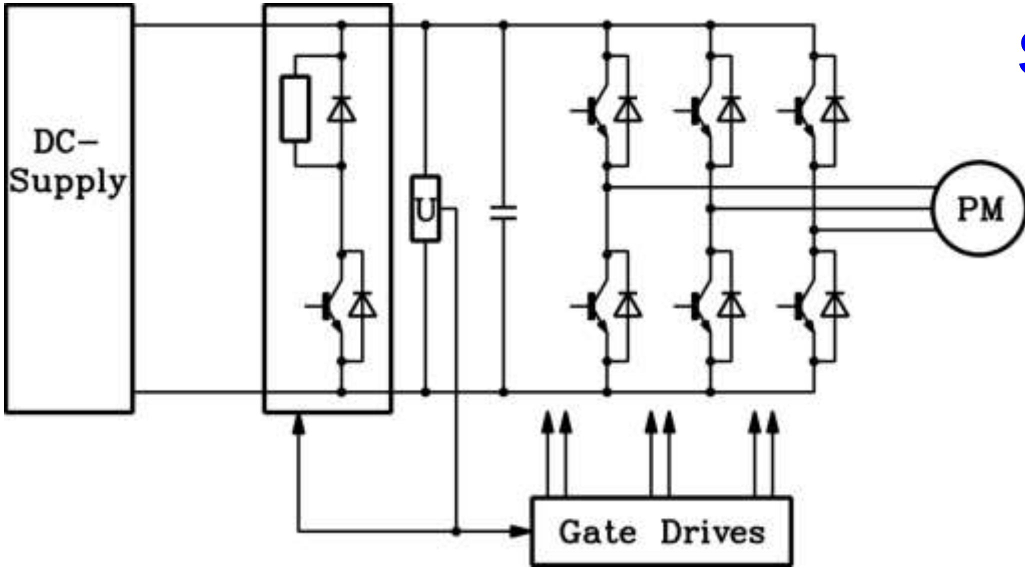
- Good possibility to integrate generator with turbine

- HV stator winding to save transformer

Source: ABB, Sweden

Magnet rotor high voltage stator with winding

6. Wind generators and high power drives

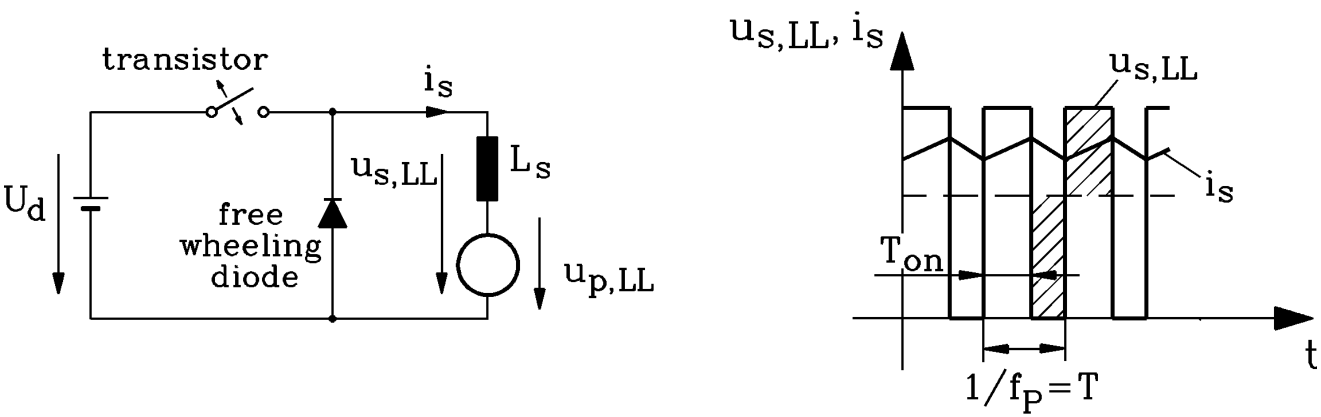


Stator feeding via IGBT inverter

DC link voltage source inverter with switching transistors and free-wheeling diodes

R_s neglected:

$$U_d - U_{p,LL} \approx L_s \cdot di_s / dt$$

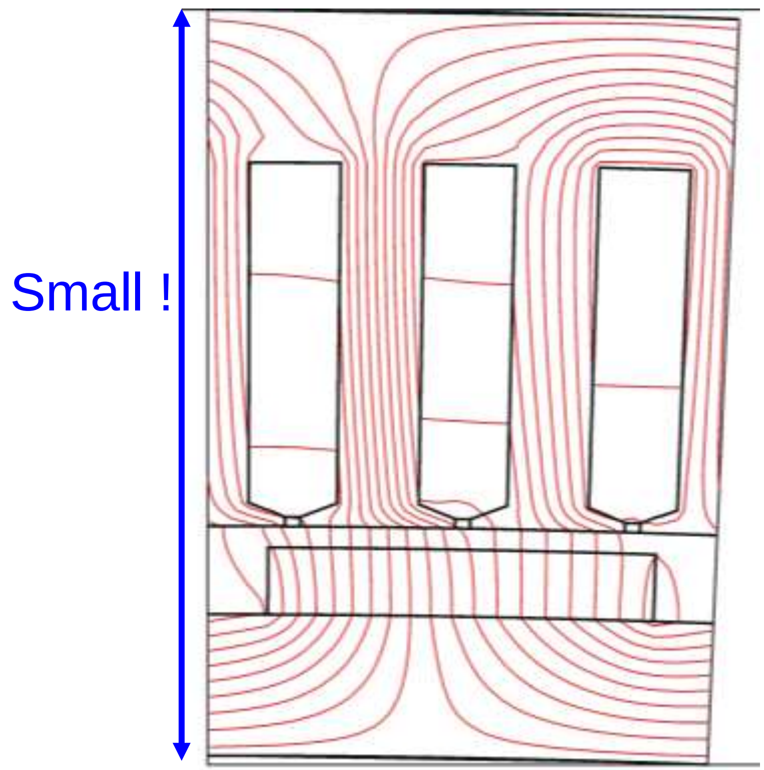


a)   b)

a) Equivalent switching scheme of DC link voltage source inverter, connected to the two phases with switching transistor and free-wheeling diode,

b) Current ripple and chopped inverter voltage

Gearless high pole count wind generator



1.5 MW-wind generator:

Numerically evaluated total magnetic field per pole pitch at rated data:
1320 A, 690 V, $\cos\varphi = 0.85$

Comparison to electrically excited synchronous generator with high pole count:

- Permanent magnets avoid excitation losses: efficiency increases, temperature level decreases, exciter feeding converter not needed, so in spite of expensive permanent magnets (ca. 40 Euro / kg) still an interesting alternative.

• BUT: Danger of de-magnetization due to stator magnetic field at overload. This must be avoided by deliberate generator design (e.g. at sudden short circuit).

6. Wind generators and high power drives

Permanent magnet wind generator: inner stator

Design for direct coupling to wind turbine without gear

21 / min rated speed

1.2 MW

690 V rated voltage

Grid side IGBT-Inverter

Generator side: Diode rectifier and step-up converter

Source:

Innowind, Germany

Goldwind, Urumqi, Xinjiang, China

6. Wind generators and high power drives

Transportation of 1.2 MW permanent magnet wind generator to plant site

Outer PM rotor to increase torque by increased bore diameter

Inner stator with 3-phase winding, operated by inverter

Source:

Innowind, Germany

Goldwind, Urumqi

Xinjiang, China

6. Wind generators and high power drives

Mounting of permanent magnet wind generator onto nacelle

Centre pole height 69 m

Steel pole mass 96 t

Wind rotor diameter 62 m

Speed 21 /min

Source:

Innowind, Germany

Goldwind, Urumqi

Xinjiang, China

PM wind generator: Mounting of 3 blade wind rotor

1.2 MW turbine

wind rotor diameter 62 m

pole height 69 m

speed 21/min

pitch control

electrical pitch drives

Nacelle and rotor mass: 81 t

Source:

Innowind, Germany

Goldwind, Urumqi

Xinjiang, China

6. Wind generators and high power drives

1.2 MW gearless permanent magnet wind generator in operation

1.2 MW turbine

wind rotor diameter 62 m

pole height 69 m

speed 21/min

pitch control

electrical pitch drives

Nacelle and rotor mass: 81 t

Centre pole mass: 96 t

PM generator

Source:

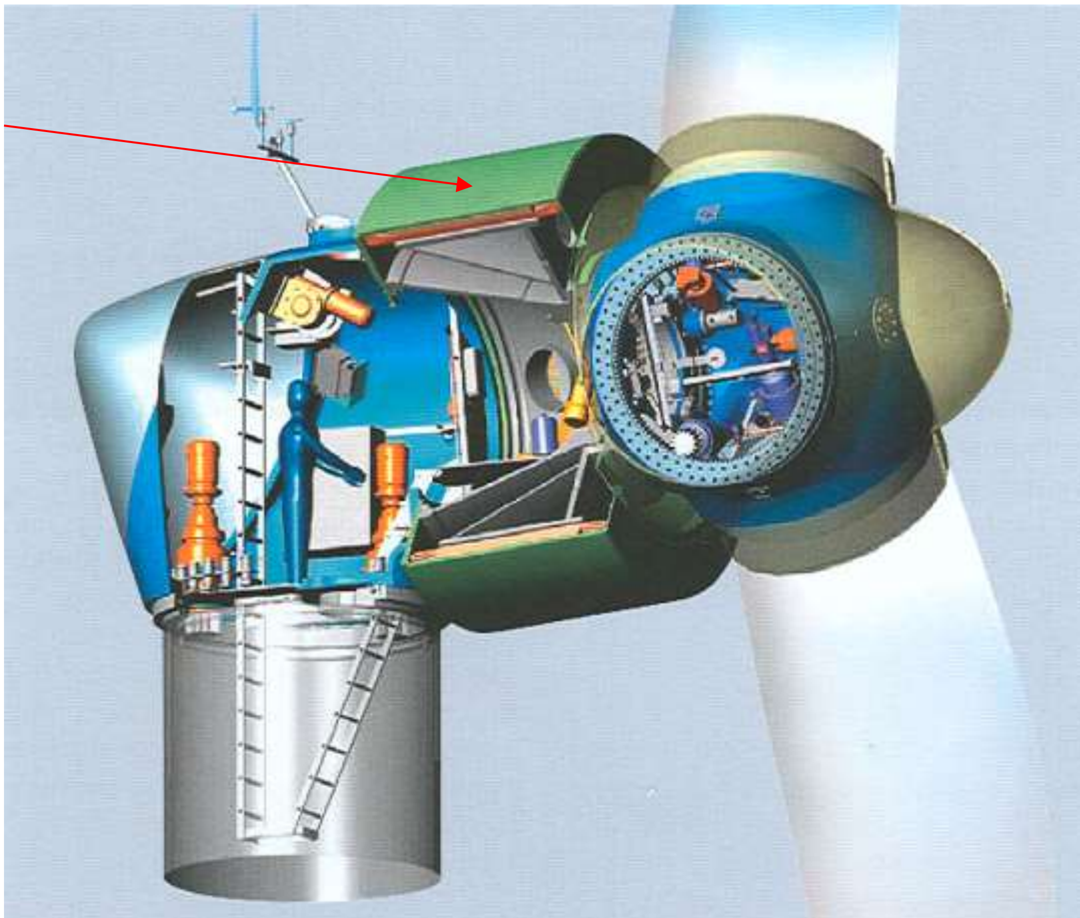
Innowind, Germany

Goldwind, Urumqi, Xinjiang, China

6. Wind generators and high power drives

Gearless wind turbine *Zephyros Z72* with inner rotor permanent magnet wind generator (ABB)

PM generator



Source:

J. Salo, ABB Technik 2/2009

6. Wind generators and high power drives

6 MW Gearless wind turbine *"Advanced High Density"* permanent magnet wind generator (*Converteam & Alstom*)

PM generator

Source: Alstom Power, now GE

- Large wind turbine 6 MW (2012): here: gearless PM high-pole count synchronous generators with grid-side inverter, planned for off-shore near *Zeebrugge (Belgium)*

6. Wind generators and high power drives

Source: Siemens AG

Gearless wind turbine *“Siemens Wind Turbine SWT” with* permanent magnet synchronous generator (*Siemens*)

3.0 MW-type
SWT 3.0-101

Ratings:

PM generator	Turbine Rotor diameter
2.3 MW	113 m
3.0 MW	101 m
6.0 MW	120 m
7.0 MW	154 m

6. Wind generators and high power drives

Gearless *"Siemens Wind Turbine SWT"* with PM synchronous generator

Mounting of the PM generator SWT-6.0-120

Ratings:

PM generator 6.0 MW

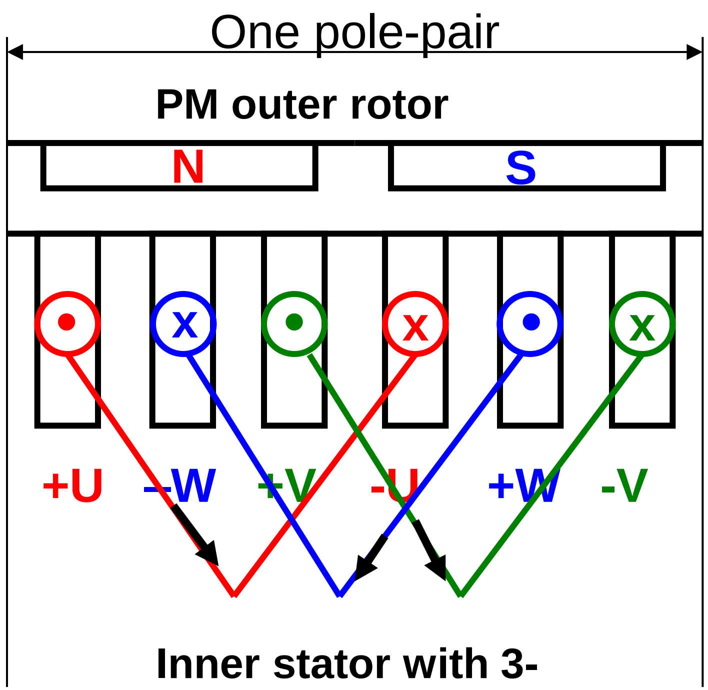
Mass of nacelle and rotor: 350 t

Turbine rotor diameter: 120 m

Single casted rotor blades

Source: Siemens AG

Gearless modular outer rotor PM synchronous generator with distributed 3-phase winding $q = 1$



- Single layer integer-slot winding
- Asymmetric arrangement of winding overhang of 3rd phase W
- One pole-pair can be wound as a modular pre-fabricated segment
- Large generator diameters can be realized, which are necessary for huge rated torque in gearless applications, as the generator is assembled from modular segments on-site
- No transportation problems due to generator outer diameters or more than 3.5 m!
- Outer rotor design increases the air gap diameter and for a given *Lorentz* force the electromagnetic torque!
- Centrifugal forces press magnets to rotor construction!

Source: Siemens AG, registered patent

6. Wind generators and high power drives

Gearless modular outer rotor PM synchronous generator with distributed 3-phase winding $q = 1$

One generator module

Source: Siemens AG, published in: antriebstechnik 2012, no.11

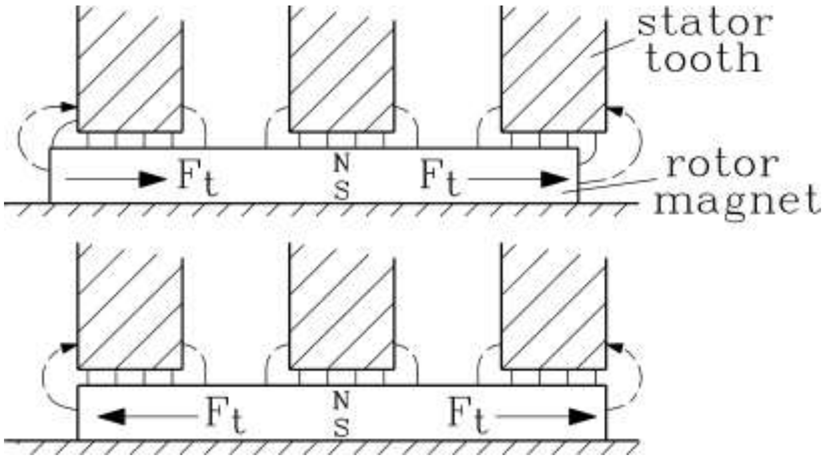
6. Wind generators and high power drives

12 MW wind turbine gearless generator *Haliade-X 12 MW* (*GE*)

Planned to start at 2021

Source: GE

Reduction of cogging torque in PM synchronous generators



- The unbalanced tangential rotor magnet force shifts the rotor into a balanced position.

- Hence a "cogging" occurs, which deviates from the aimed smooth torque production.

- It may excited disturbing torsion vibrations in the shaft.

- An integer-slot winding (e. g. $q = 1$) causes a considerable cogging torque, which with fractional slot windings can be considerably reduced.

- But fractional slot windings cause additional harmonic field waves, which generate additional eddy-current losses in the rotor magnets and the rotor iron back

- The cogging can be reduced by

a) skewing the rotor magnets or the stator slots

b) by staggering the magnet rows in axial direction. By that a skewing is approximated.

c) by shifting the rotor magnet poles e. g. per pole pair the N- and S-pole are shifted each towards each other by a quarter of a stator slot pitch

see: *Literature:* Richter, R.: Ankerwicklungen für Gleich- und Wechselstrommaschinen, Springer, Berlin, 1922

Summary:

Gearless wind generators

- Generator speed identical with turbine speed
- High pole count, low stator frequency $\Rightarrow$ stator feeding via IGBT inverter
- Small flux per pole $\Rightarrow$ small iron back $\Rightarrow$ ring shaped generator
- Due to poor power factor of induction machines with relatively big air gap, only synchronous generators with electrical or PM excitation are used
- PM generators do not need any excitation power or slip rings, but: de-magnetization at overload must be avoided
- Reduction of cogging torque by skewing, staggering of magnets, and use of fractional slot stator winding

6. Wind generators and high power drives

6.2 Wind turbine generators

Source: Vestas, Denmark

6.2.1 Fixed speed wind energy conversion

6.2.2 Variable speed wind turbines: Doubly-fed induction machines

6.2.3 Gearless wind generators

6.2.4 "Multibrid" - PM wind generator – dual stage gear

6.2.5 „Small Hydro Power"

6.2.4 “Multibrid” - PM wind generator – dual stage gear

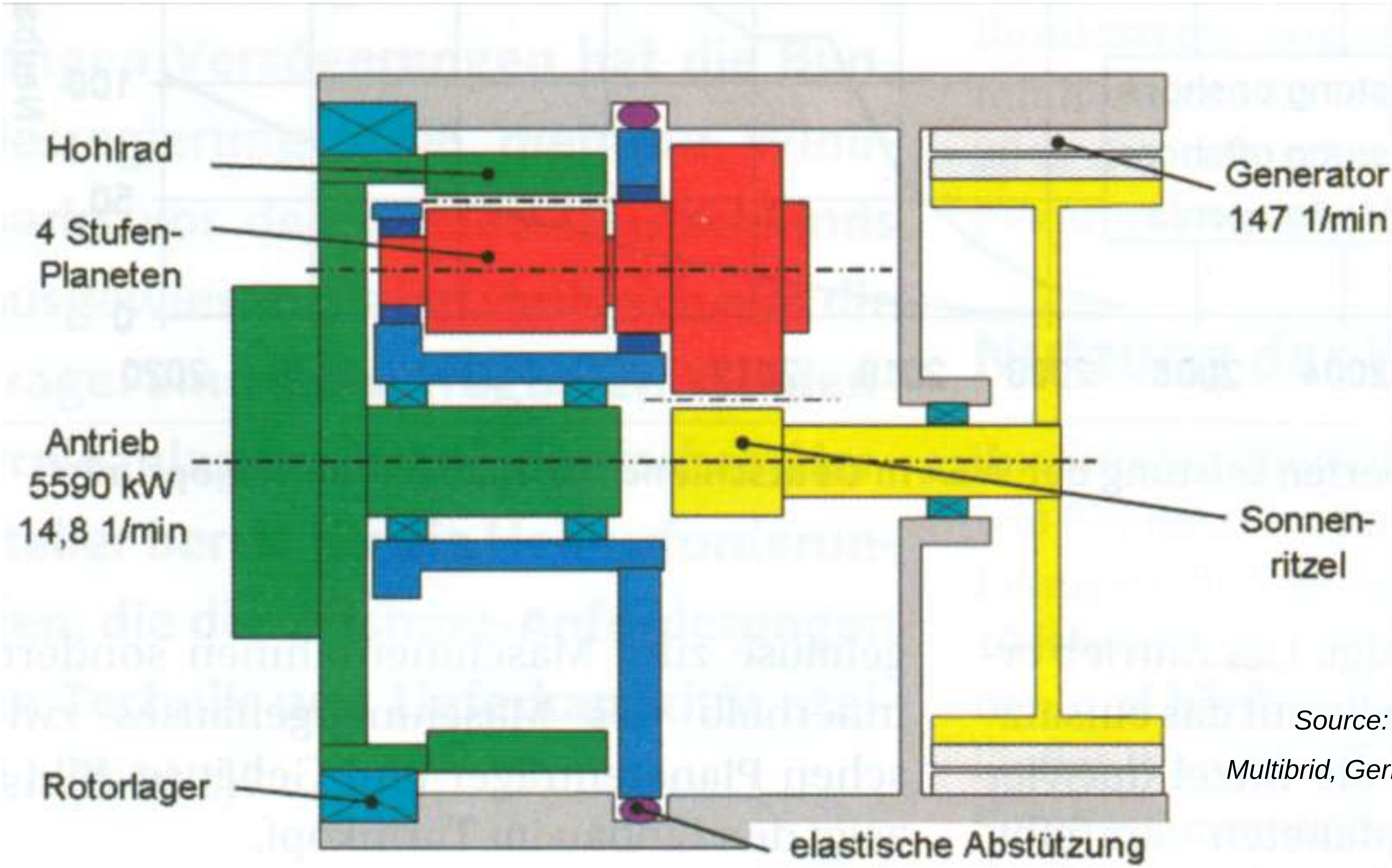
- **Only dual stage gear:** Medium generator speed ca. 150/min reduces generator size in comparison to gearless generator systems

- Special planetary gear with second stage reduces gear size and avoids high speed stage

- **Overall mass reduction** in comparison to the gearless system due to smaller generator, which outweighs the increased mass due to the gear

Source: Multibrid, Germany

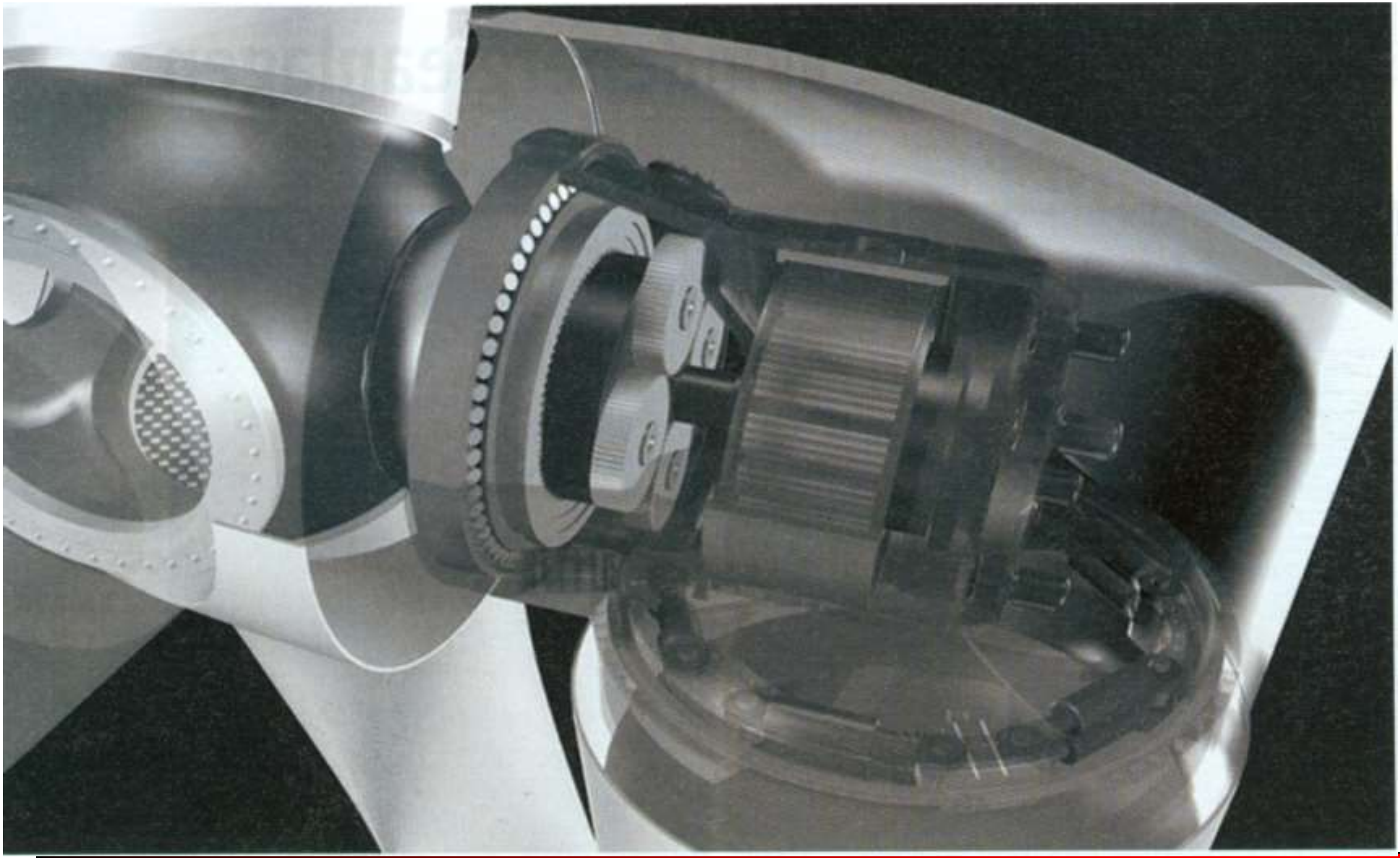
"Multibrid" - Dual stage gear, 5.5 MW, transfer ratio 1:10



Source:

Multibrid, Germany

"Multibrid" - permanent magnet wind generator – dual stage gear

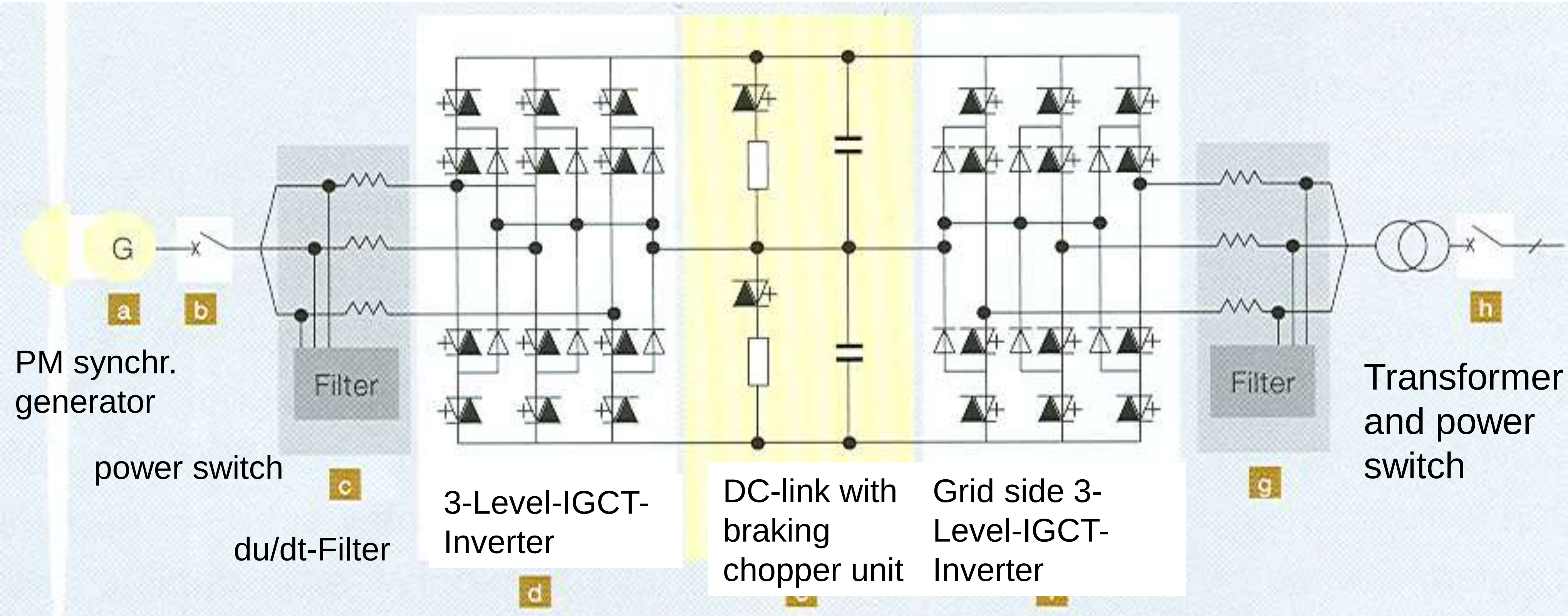


Source:

Multibrid, Germany

Inverter topology for the 5 MW "Multibrid" PM wind generator system

ABB 6000 Inverter: Four-quadrant inverter, 100% real or reactive power on grid side possible

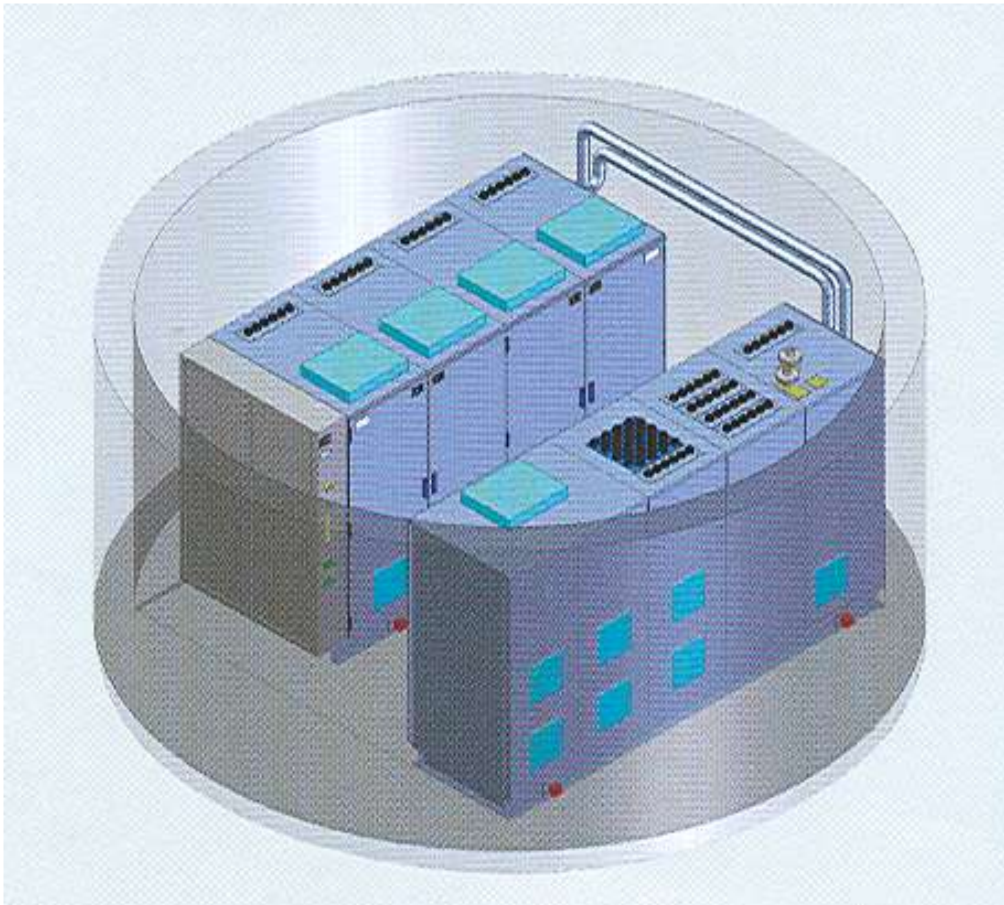


IGCT: Integrated Gate-Commutated Thyristor

Source: M. Nyfeler, A. Moglestue, ABB Technik 3/2010

Inverter topology for the 5 MW "Multibrid"

Arrangement of the inverter for the 5 MW "Multibrid" - permanent magnet wind generator system inside the mast on a single platform



Source:
M. Nyfeler, A. Moglestue,
ABB Technik 3/2010

"Multibrid" - permanent magnet wind generator systems

a) Companies: *"The Switch"* (PM generator), *Moventas* (gear), tested at *DeWind*

two-stage gear: Wind turbine:15/min to Generator: 400/min, i = 26.7, 3 MW

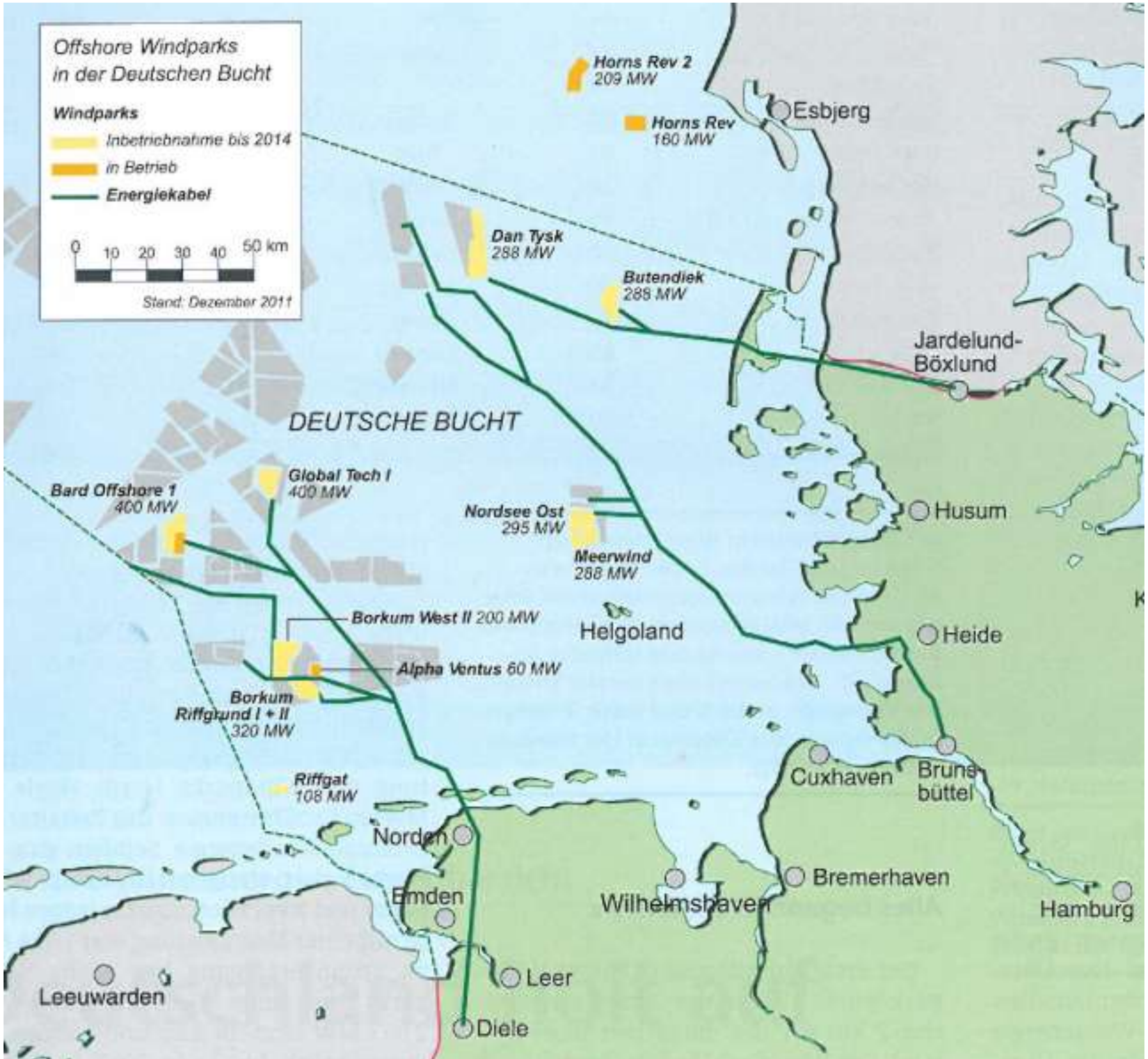
Gear: Length: 3 m, Diameter: 2.3 m, Mass 35 tons, Generator integrated into gear

Rated power 7 MW under development!

b) Company *Winergy*: "Hybrid Drive" as Multibrid-concept

with overall maximum efficiency 94% at 3 MW, mass 31 tons

Modular PM generator concept



6. Wind generators and high power drives

Danish & German off-shore wind parks in the *North Sea*

State of Sept. 2015:

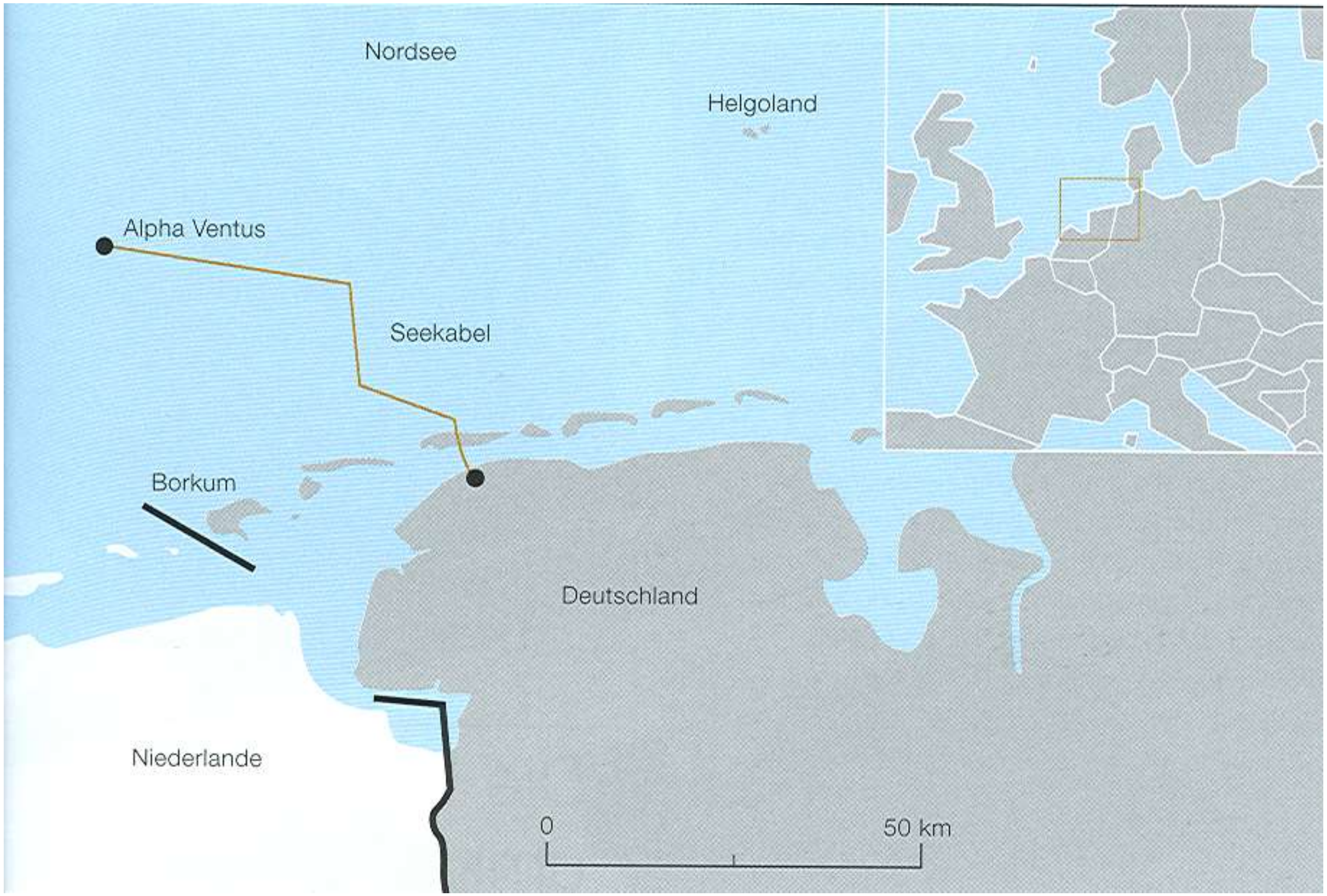
In operation:
Denmark:
e.g. *Horns Rev 1+2* and others

Germany:
e.g. *Alpha Ventus,HelWin1+2, BorWin 1+2, SylWin 1*

Source:
Windenergie Agentur Bremerhaven
WAB, BWK 64, 2012, p.42

6. Wind generators and high power drives

"First" *German* off-shore wind park *ALPHA VENTUS*, 60 MW 45 km north of *Borkum* island in the *North Sea*



Joint project of *E.on, EWE, Vattenfall:* 60 MW, 4200 full-load hours = 252 GWh/a

- 12 wind turbines with 5 MW each
- Six Multi-brid PM synchr. generators
- Six doubly fed induction generators of *Repower* (now: *Senvion*)
- 800 m distance between turbines

Source: M. Nyfeler, A. Moglestue, ABB Technik 3/2010

6. Wind generators and high power drives

Off-shore wind power plant 5 MW of *ALPHA VENTUS* with doubly-fed induction generator

- Nacelle elevation 90 m above sea level

- Sea depth 30 m

- Rotor max. height 148 m

- 1000 t per complete turbine plant

- Rotor diameter 116 m, blade tip speed 324 km/h, rotational speed 14.8 /min

Source: M. Nyfeler, A. Moglestue, ABB Technik 3/2010

Mounting of the rotor of an off-shore wind mill at *Alpha Ventus*

The mounting of the 5 MW-wind mill rotor is the last step of erecting the plant

A huge crane on a floating platform is needed.

Erecting wind mills off-shore is much more expensive than on-shore, especially in deep water.

Source:
Alpha Ventus, BWK 64, 2012, p.42

Large Generators and High Power Drives

Summary:

"Multibrid" - PM wind generator – dual stage gear

- Medium size generator and gear, medium speed
- Overall mass reduction in comparison to gearless system
- Special planetary gear, transfer ratio *i* = 10
- Four quadrant inverter with Integrated Gate-Commutated Thyristors (IGCT)

6. Wind generators and high power drives

6.2 Wind turbine generators

6.2.1 Fixed speed wind energy conversion

6.2.2 Variable speed wind turbines: Doubly-fed induction machines

6.2.3 Gearless wind generators

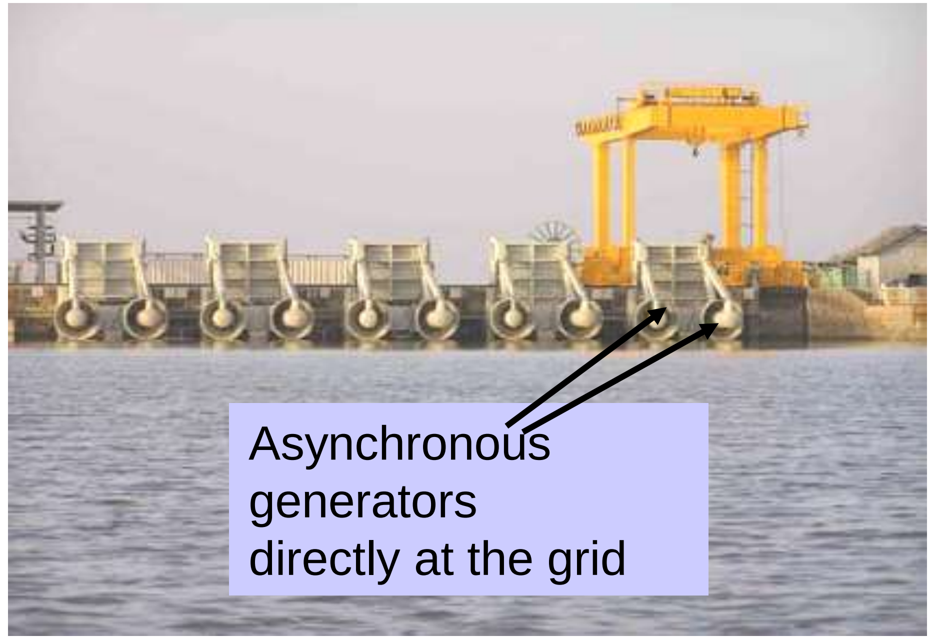
6.2.4 "Multibrid" - PM wind generator – dual stage gear

6.2.5 „Small Hydro Power"

Source: Vestas, Denmark

6.2.5 „Small Hydro Power“

Freudenau/Danube, Vienna Austria



Djebel Aulia/Nile, Sudan

Matrix turbine: Use of rest water flow over river barrages via several smaller turbines in matrix arrangement

Propeller turbine with fixed blade position: Good integration within the river barrage

Power per turbine unit: ca. 200 … 500 kW

Source: Andritz Hydro, Austria

6. Wind generators and high power drives

„Small Hydro Power“ matrix Turbines with PM generators

Ashta II building site

Ashta I building site

Source: Andritz Hydro, Austria

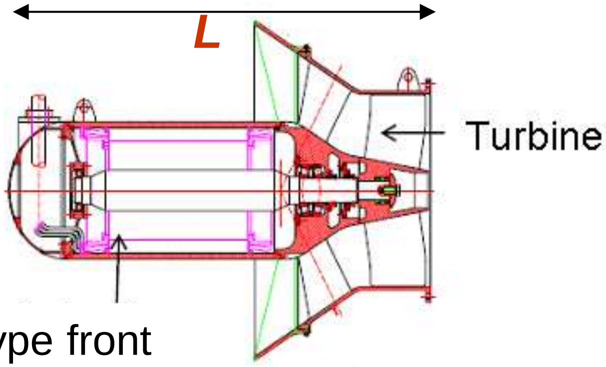
Matrix turbine project *Ashta, Albania*, river *Drin*:

Ashta I: 24 MW, 3.3 kV, 50 Hz, head 5 m, turbine speed: 300/min
Matrix array of 45 “20-pole PM generators” 530 kW each,
turbine runner diameter 1320 mm
Ashta II: 45 MW, 3.3 kV, 50 Hz, head 7.5 m,
turbine speed: 375/min
16-pole PM generators, turbine runner diameter 1320 mm

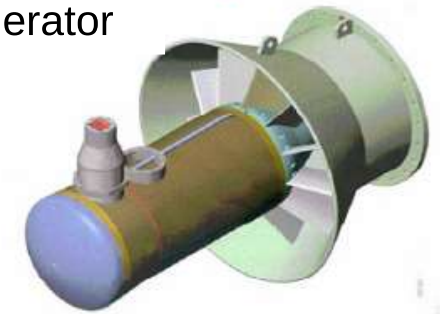
The bulb generators are manufactured by *Gamesa, Spain.*

6. Wind generators and high power drives

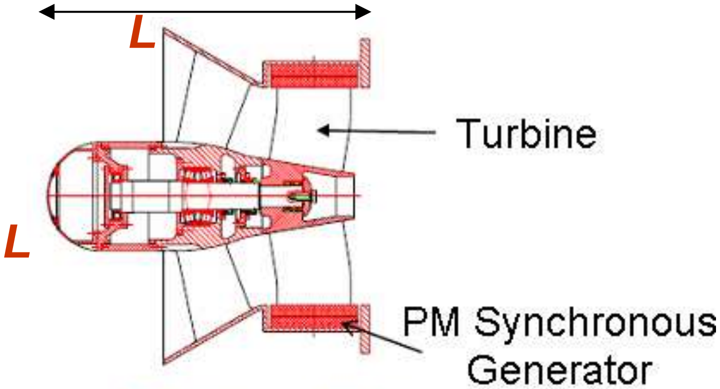
Front PM generator vs. straight flow rim generator



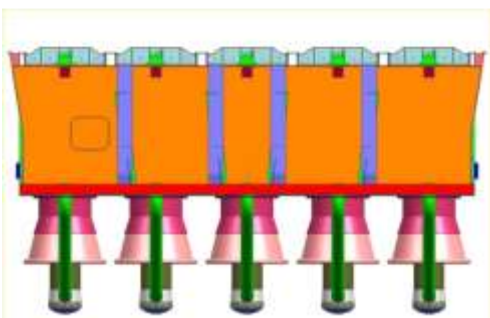
Bulb type front PM generator



Reduction of length *L*

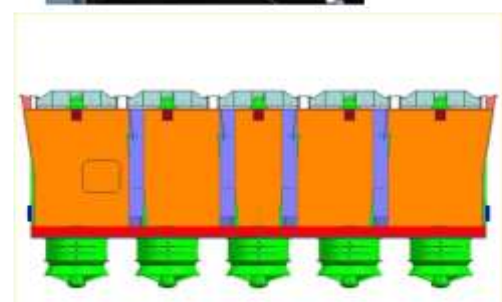


Straight flow generator



Source:

Andritz Hydro, Austria



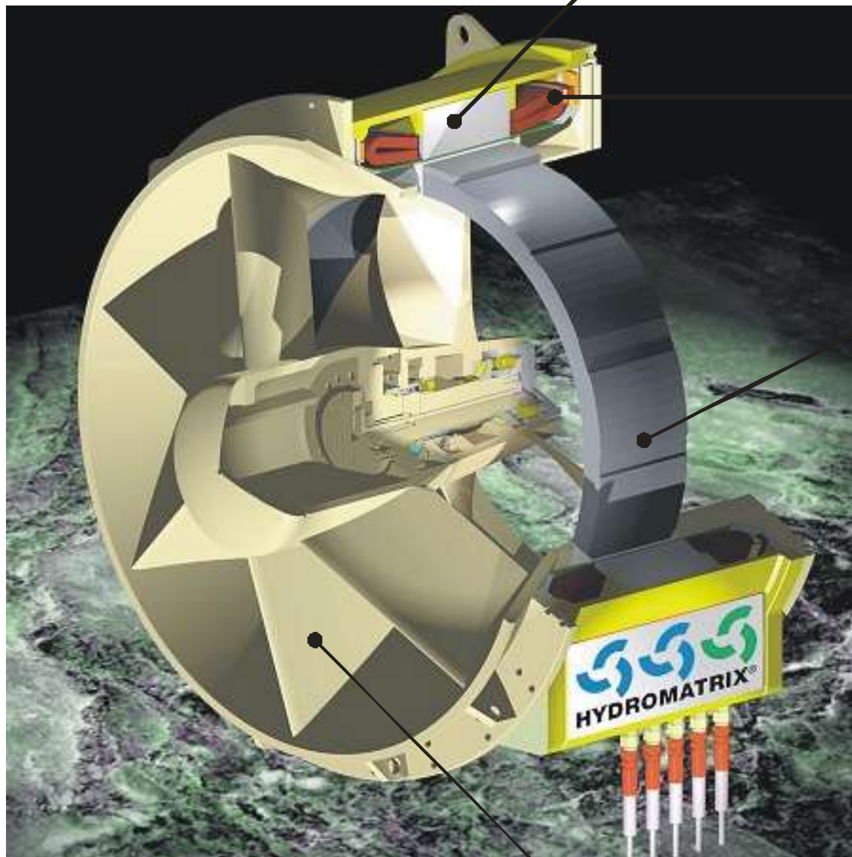
Straight flow PM rim generator for „Small Hydro Power“

Straight flow Turbine with PM-rotor at outside of blade runner

Cylindrical tube is sealing stator bore

PM-rotor is running in water without any sealing

Application in matrix turbines



Source:

Andritz Hydro, Austria

Generator operates at the grid, copper cylinder as damper cage necessary

Straight flow rim PM generator prototype 700 kVA, 14 poles, 50 Hz

The test rig of a *StrafloMatrix*^{TM} unit at the *Agonitz* plant, *Austria*

Source: Andritz Hydro, Austria

StrafloMatrix™ prototype, *Agonitz* power plant, *Austria*

Source: Andritz Hydro, Austria

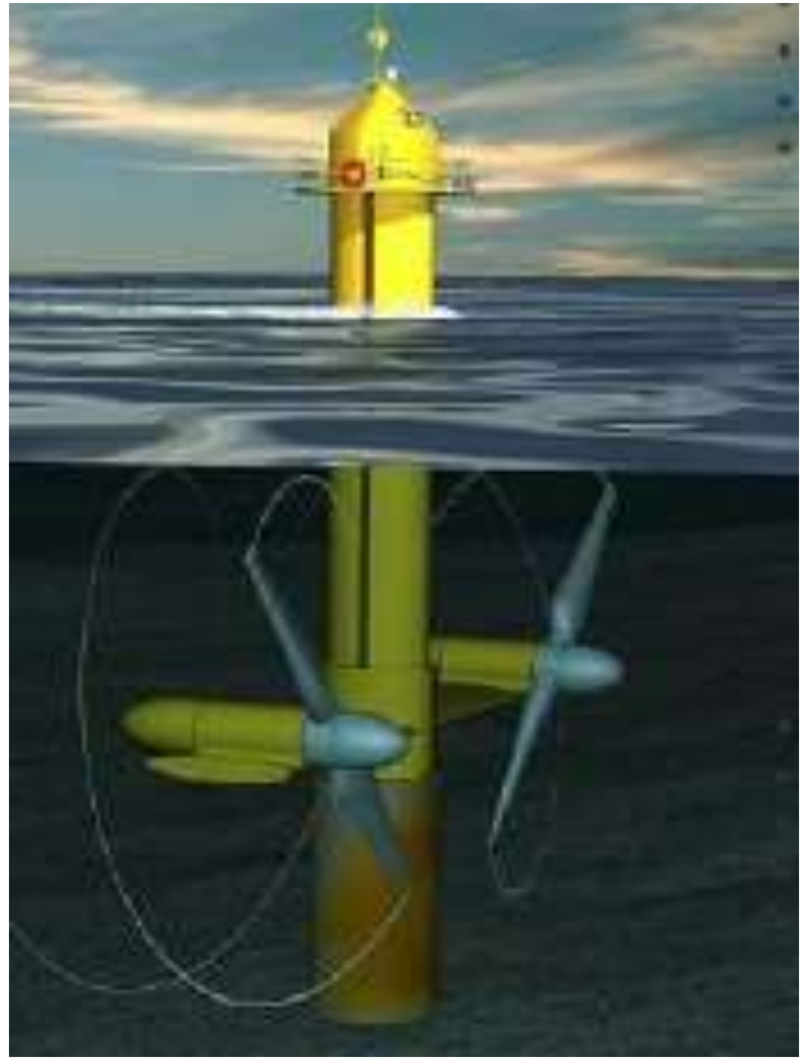
Type	Synchronous
Apparent power	700 kVA
Head	8.5 m
Speed	428.6 rpm
Runner diameter	1120 mm
Stator line-to-line voltage	3.3 kV

Installation of the StrafloMatrix™ turbine-generator unit in *Agonitz*, *Austria* (March, 2004)

6. Wind generators and high power drives

Sub-sea tidal hydro turbines

- Like a sub-sea wind turbine system with geared generators
- 10…20 /min depending on tidal flow
- At the same power much smaller than wind turbines due to the 1000-times bigger mass density of water with respect to air“
- Expected future: “Tidal farms” with 40 turbines
- Optimistic estimate: Tidal and wave power plants will supply 10…15% of *England´s* electrical power



Source: Marine Current Turbines, Bristol, UK

Strangford Lough pilot project

- Pitched 600 kW-Propeller, 16 m diameter
- Coast of Northern Ireland *(Strangford Lough)* pilot project with 2 turbines

Source:

Marine Current Turbines, Bristol, UK

6. Wind generators and high power drives

Strangford Lough (Northern Ireland) tidal power pilot project

- Since Nov. 2008: Two 600 kW propeller turbines, 16 m diameter, supply 1500 households

- „SeaGen“ gearless permanent magnet synchronous generators, manufactured by *Siemens AG*

Source:

Siemens AG, Germany

Sub-sea tidal hydro turbines

- Prototype of a fixed-blade sub-sea tidal turbine with a gearless PM synchronous generators directly coupled inside

- The generator is connected via a cable to the inverter on-shore

- The turbine rating is ca. 1 MW. The mass of the total construction ca. 1000 t to be put only by weight on the sea level (ca. 1 kW/ton)

Source: Voith Hydro, Heidenheim, Germany

- Sea depth ca. 30 m, tidal velocity ca. 3 .. 5 m/s, e.g. near *Channel island Guernsey* (project status)

Three-blade tidal turbine

Successful installation and commissioning of the HS1000, a 1 MW tidal turbine with pitched blades, in the waters of the *European Marine Energy Centre (EMEC), Orkney Islands*

Source: Andritz Hydro, Austria

Summary:

„Small Hydro Power"

- Matrix turbine: Several smaller turbines in matrix arrangement
- Generators operated directly at the grid
- Reduction of axial length by using straight flow rim generator

- Sub-sea tidal stream hydro turbine with variable speed and inverter
- For same power rating as a wind turbine much smaller dimensions due to higher mass and thus power density of water

6. Wind generators and high power drives

Source: Vestas, Denmark

6. Wind generators and high power drives

6.3 Inverter-fed high power AC motors

Power limits of motors:

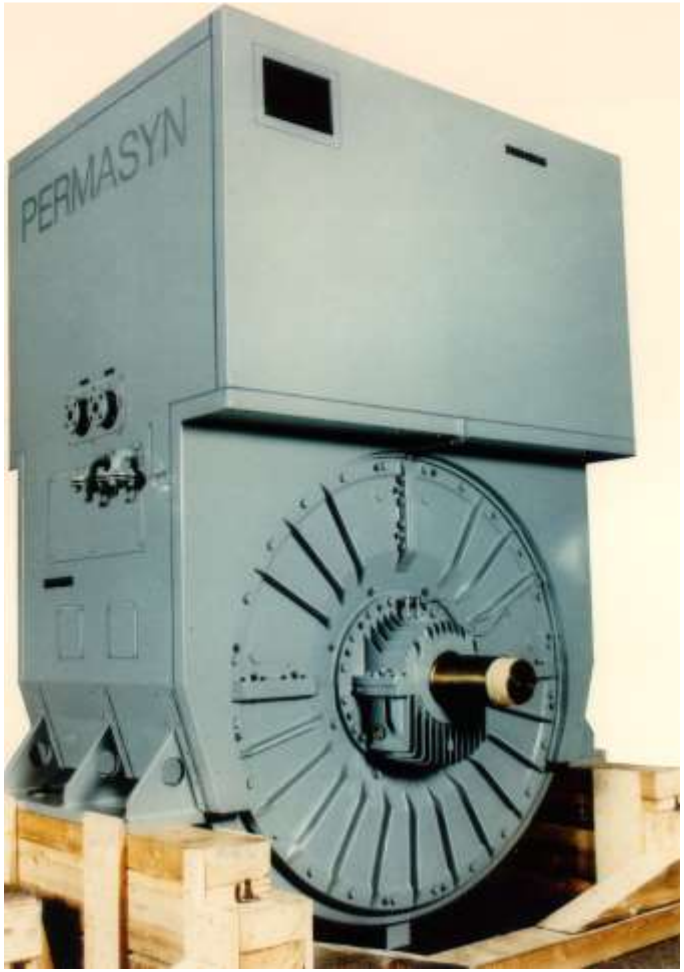
- DC machines: 10 ... 15 MW at about 100 /min as first motor unit in cold strip mills

- AC induction machines: 30 ... 40 MW as doubly-fed slip ring induction machines in rotary frequency converters from 3-phase, 50 Hz to single phase, 16.7 Hz for railways, e.g. *German railways, Ulm;* biggest cage induction machines are usually smaller in power (e.g. 10 ... 15 MW)

- AC synchronous machines: 100 MW as inverter-fed variable speed drives for blowers in big wind tunnels (e.g. *NASA* research centre, *Langley, USA)*

- AC induction motor-generators: 340 MW, as doubly-fed slip ring induction machines in pump storage power plants, with cyclo-converter as rotor feeding inverter unit, e.g. *Japan, Germany (Goldisthal, Thuringia)*

PM synchronous machine with IGBT voltage source inverter supply



First Permanent Magnet Motor built in1987

Nominal Power: 1.100 kW
Nominal Speed: 230 / min

- Converter integrated into the upper motor housing.
- Motor built as drive for submarine.
- Surface mounted magnets.
- Oil cooled sleeve bearings.
- Top mounted heat exchanger.

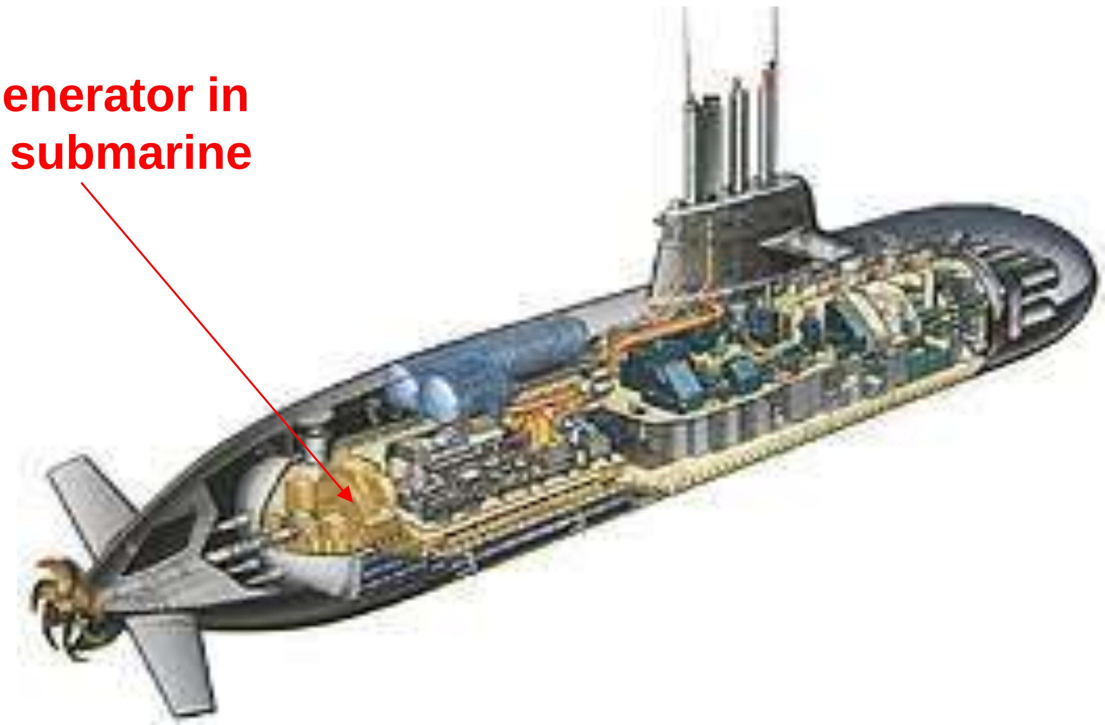
Source: Siemens AG, Germany

6. Wind generators and high power drives

Permanent magnet synchronous machines for submarine propulsion

„Permasyn“ Permanent Magnet Motor for Class 212 of fuel cell powered submarines of HDW ship yard/*Germany* for *German* and *Italian Navy*

PM Motor/Generator in backside of submarine



Source:

Siemens AG, Germany

6. Wind generators and high power drives

Fuel cell powered submarine at HDW ship yard/*Germany*

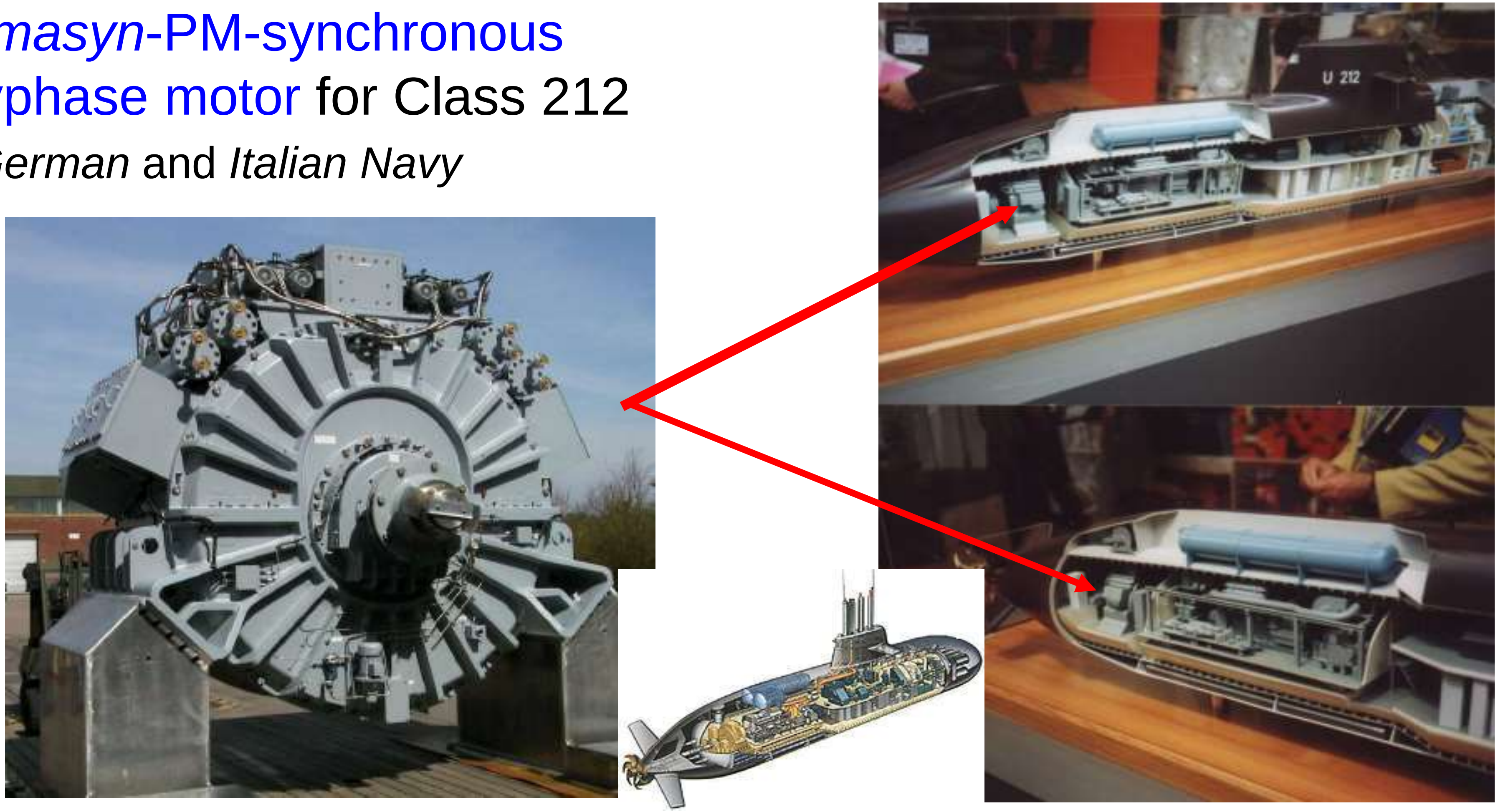
Source:

HDW, Germany

6. Wind generators and high power drives

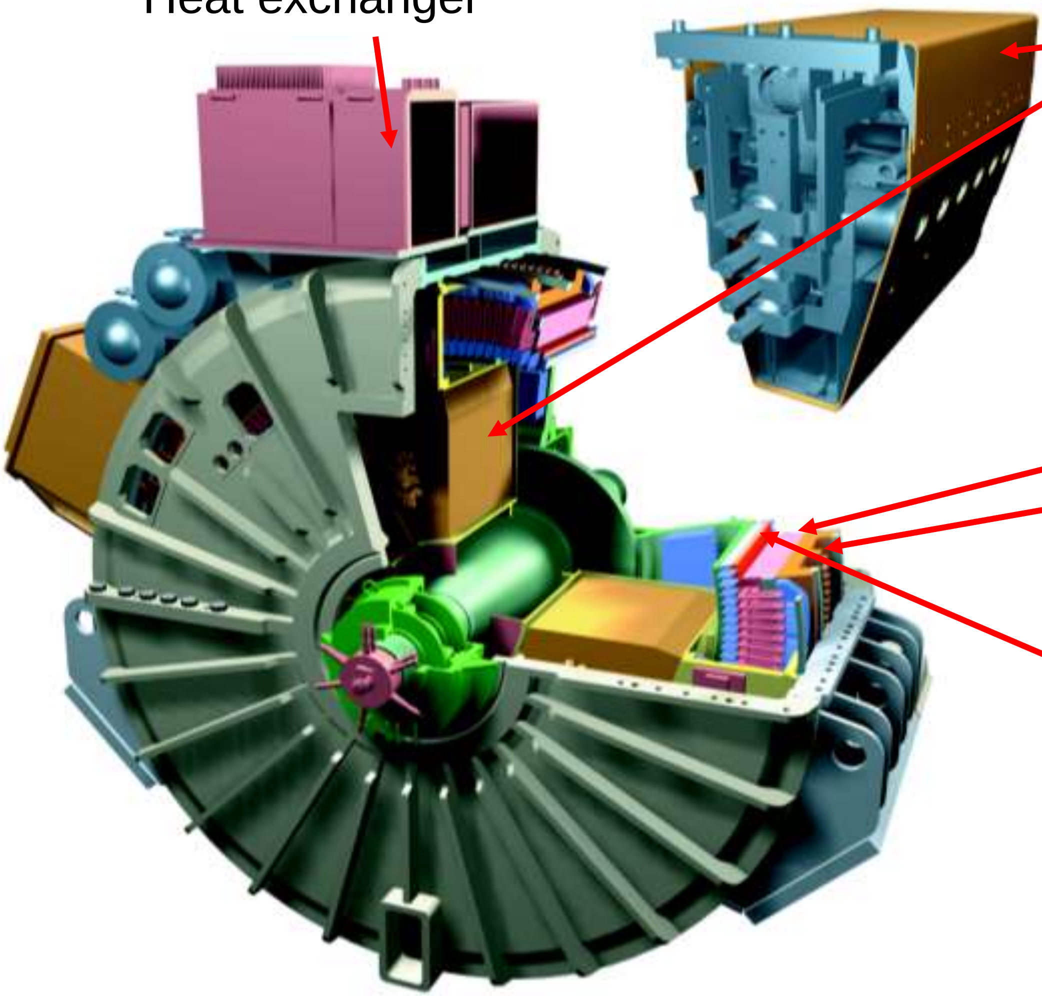
Permasyn-PM-synchronous polyphase motor for Class 212

for *German* and *Italian Navy*



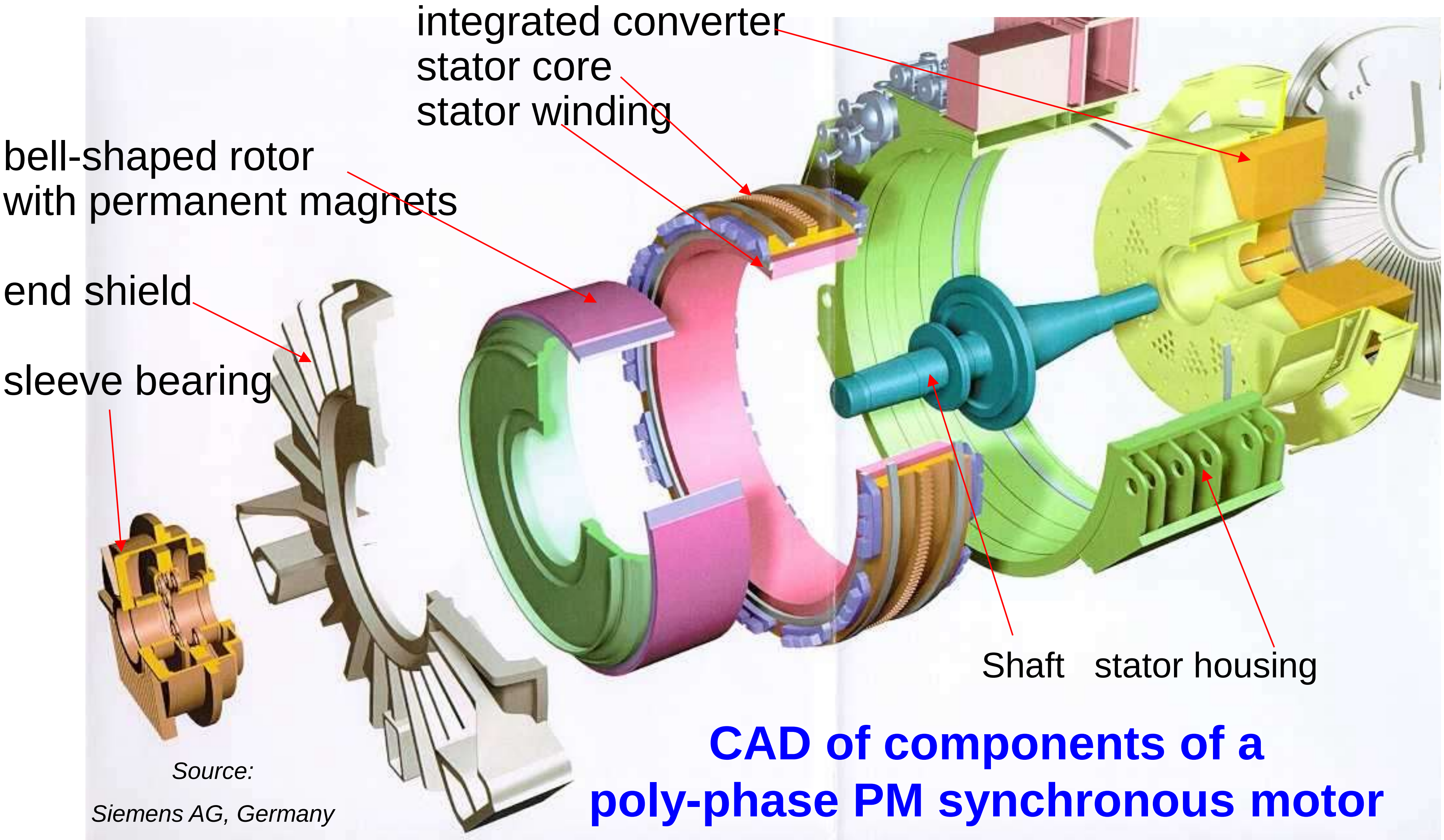
Source: Siemens AG, Germany

Design of permanent magnet synchronous motor



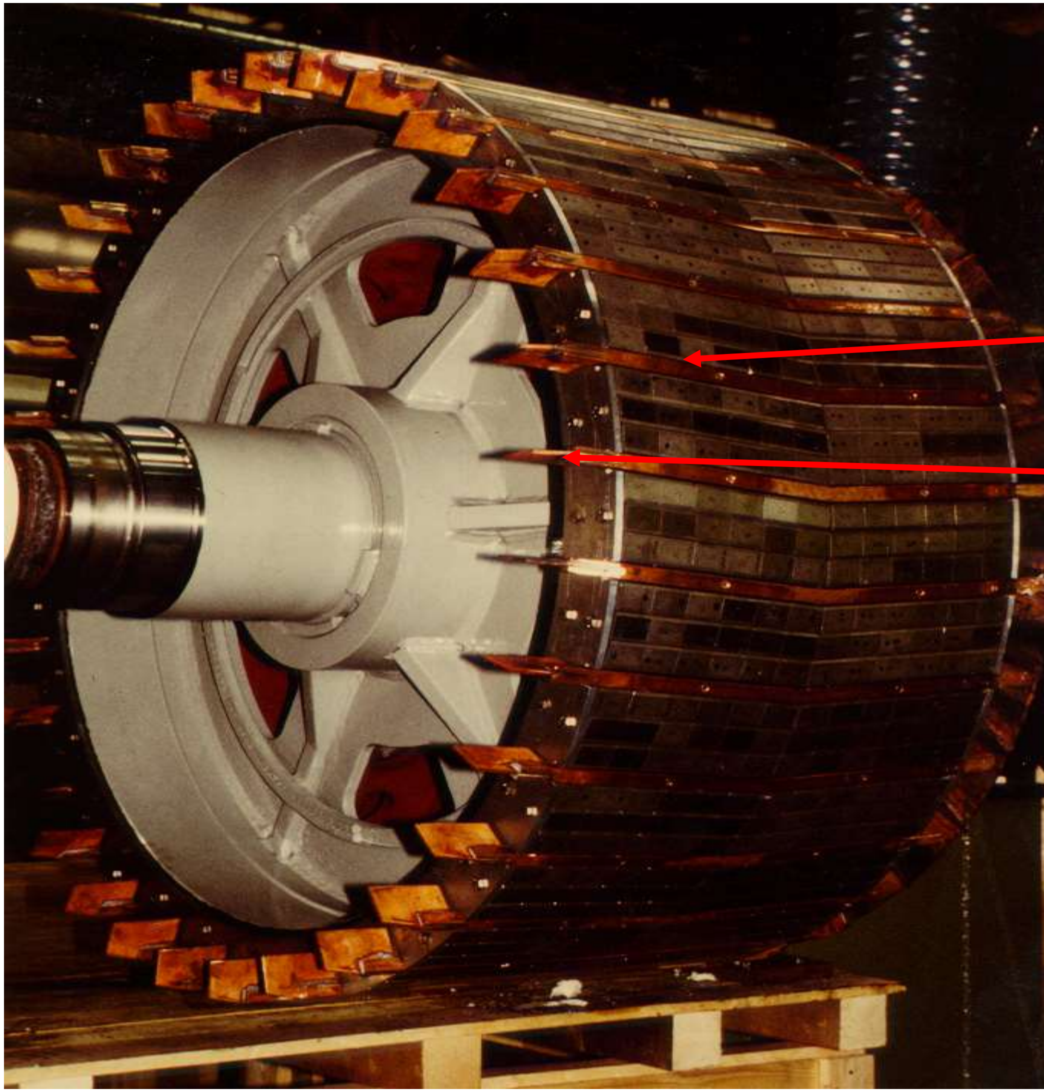
*) Poly-phase winding e.g. $m = 9$

Source: Siemens AG, Germany



CAD of components of a poly-phase PM synchronous motor

6. Wind generators and high power drives



Rotor of the first built PM Synchronous Motor for Submarine propulsion

Skewed rotor magnets to reduce cogging torque

Cooling fins to dissipate rotor magnet eddy current losses and to enhance internal air flow

High pole count (32 poles) for slow speed operation

Source:

Siemens AG, Germany

Inverter-fed induction machines with field-oriented control

Voltage source inverter with “high-voltage” DC link

(e.g. DC 3 kV)

a) HV IGBT with 6.5 kV blocking voltage

or

b) IGCT (Integrated Gate Commutated Thyristor)

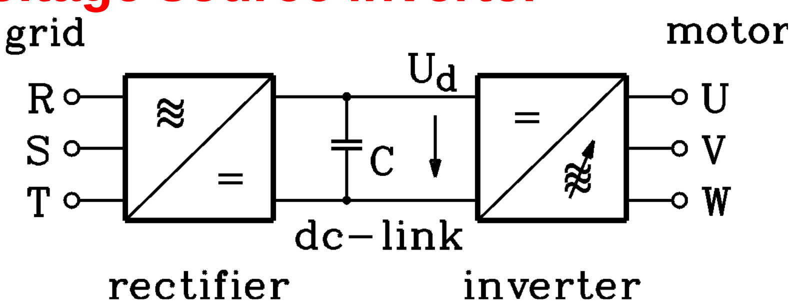
Cage induction motor

Source:

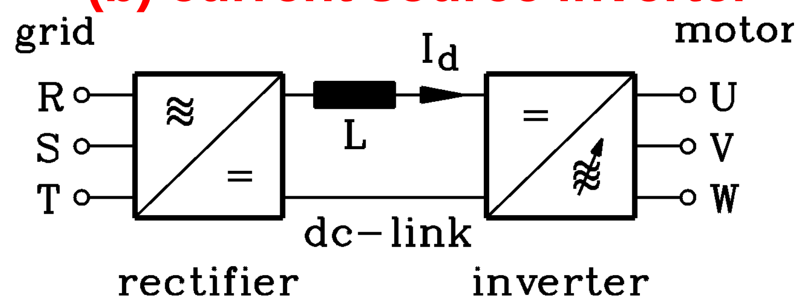
Siemens AG

Variable speed operation of induction machine

(a) voltage source inverter



(b) current source inverter



DC link capacitor *C*	DC link inductor (choke) *L*
U_d: DC link voltage	I_d: DC link current
controlled AC voltage, variable frequency	controlled AC current, variable frequency
motor-side inverter operates independently	motor winding part of motor-side inverter
parallel operation of motors possible	each motor needs a separate inverter
motor break down slip: $s_b = \frac{r_r}{\sigma \cdot x_r} = 0.1 \ldots 0.2$. Motor can operate without control within slip range 0 ... s_b	motor break down slip: $s_b = \frac{r_r}{x_r} = 0.005 \ldots 0.02$ Motor operating in unstable slip range > s_b. Control is needed for stable performance.

6. Wind generators and high power drives

Comparison of voltage and current source inverters

Voltage source inverter	*Current source inverter*
Stator voltage is pulse width modulated voltage pattern	Stator voltage: sinusoidal due to induction by machine flux (excited by impressed currents)
Stator current nearly sinusoidal with ripple due to voltage switching	Stator current consists of 120° blocks (six step current mode).
Grid side: diode rectifier - no power flow to grid ! For electric braking chopped DC link brake resistor is needed (Costly alternative: grid side PWM converter)	Grid side: controlled thyristor bridge for variable rectified voltage U_d for adjusting positive $I_d > 0$. At $U_d < 0$, $\alpha > 90°$ regenerative brake power flow $U_d I_d < 0$ to grid is possible.
IGBT-power switches: power range 0.1 kW ... 3 MW, low voltage 1000 V. Bigger power rating with IGCT- or GTO-power switches up to 30 ... 50 MW with medium voltage e.g. 6300 V.	Thyristor power switched: big induction and synchronous motors (1 ... 100 MW) World-wide biggest motor: 100 MW in NASA centre */Langley/USA*, super wind channel

DC link current source inverter

- For cage induction machines:

The motor side converter has to be self-commutated. That means, the current hand-over e.g. from phase U to phase V is done by the power electronics itself, independently if the load is a motor or a passive element (three-phase *R*-*L*-combination etc.)

Self-commutating elements are power transistors (usually IGBTs) and gate turn-off thyristors (GTOs or IGCTs).

For biggest power conventional thyristors must be used for their big current /voltage capability. They are NOT self-commutating, so an additional RLC-series resonance circuit with auxiliary thyristor is needed to switch off the thyristor.

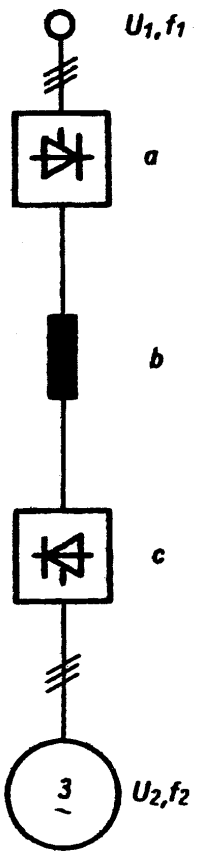
- For synchronous machines ("synchronous" converter):

The over-excited synchronous machines gives such a phase shift between voltage and current, that motor side converter EVEN with thyristors may commutate without auxiliary resonance circuit; like the line -commutation.

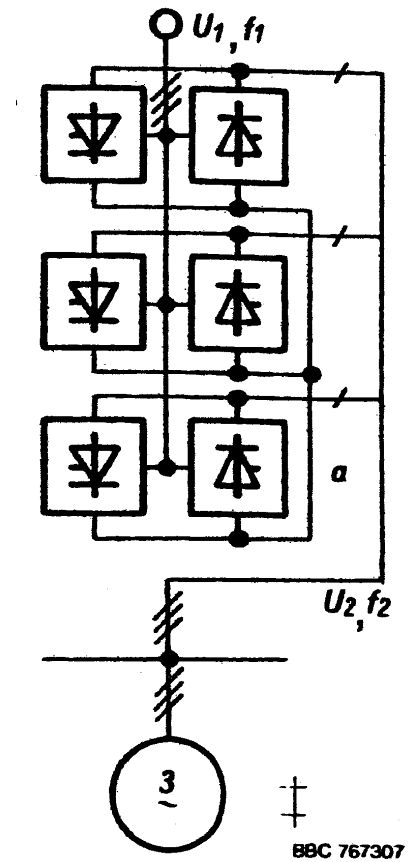
Hence the converter is very simple, called synchronous converter, being used as standard for big variable speed synchronous machines.

6. Wind generators and high power drives

Inverter-fed synchronous machines



Synchronous converter Feeding **Cyclo-converter**



a	Line-commutated converter
b	DC current link: choke for reduction of current ripple
c	Machine-commutated converter
U_1, f_1	Line voltage & frequency
U_2, f_2	Machine voltage & frequency

Source: Neidhöfer, G.; BBC, Switzerland

Large Generators and High Power Drives

Summary:

Inverter-fed high power AC motors

- PM synchronous motors for ships e.g. submarines, cruise-ships
- Fed by IGBT voltage source inverter or cyclo-converters

- Large variable speed AC machines for pump storage plants (e. g. *Goldisthal*, *Germany*)
- Energy extraction from grid for storage is increased with variable speed pumping
- Synchronous and doubly fed induction motor-generators used

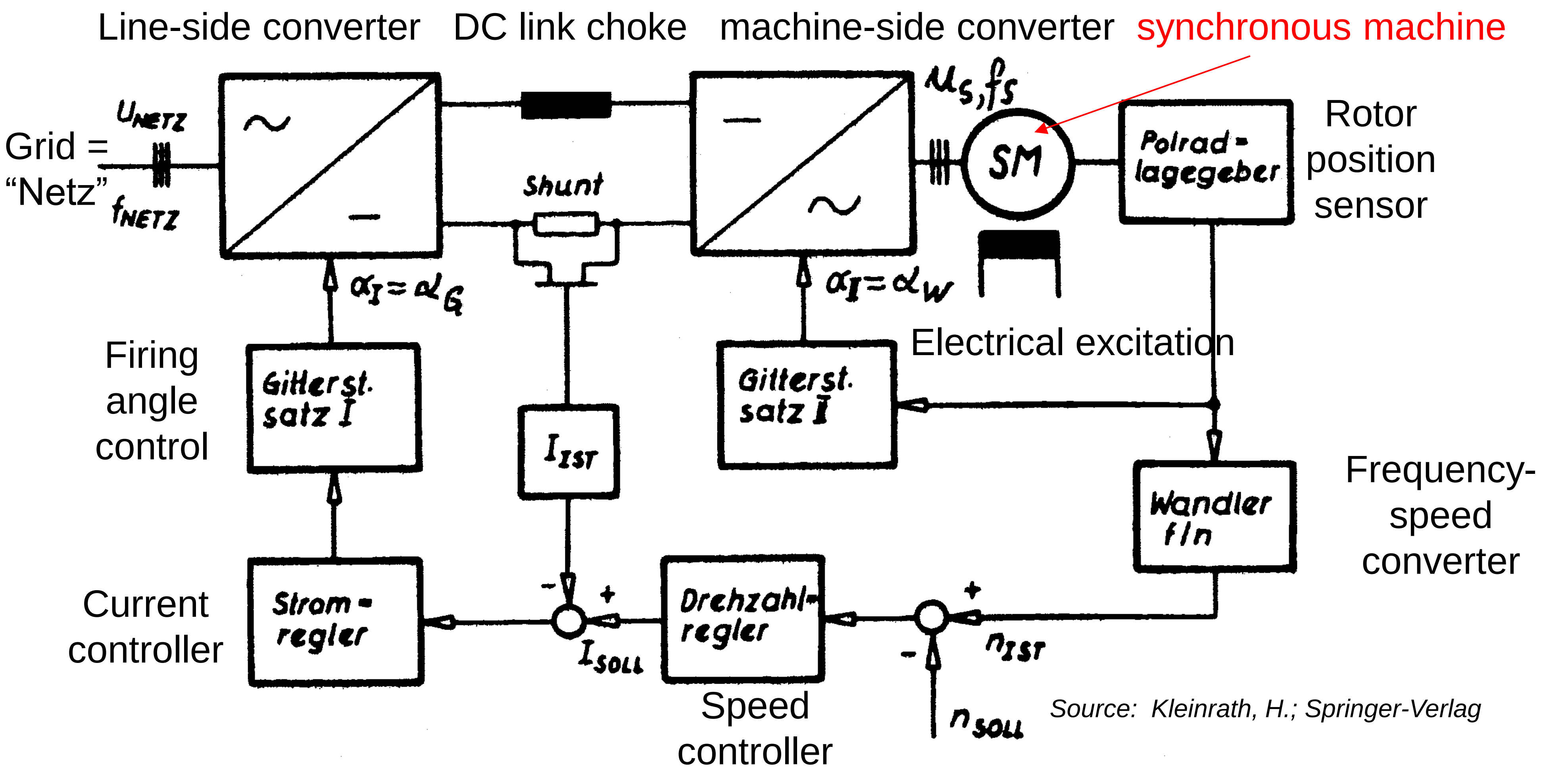
- Variable speed operation of induction machines:
    - Voltage source inverter (IGBT-, IGCT- or GTO-power switches: pulsed stator voltage, nearly sinusoidal current
    - Current source inverter (Thyristor power switches): sinusoidal stator voltage, block current, regenerative power flow inherently possible

6. Wind generators and high power drives

Source: Vestas, Denmark

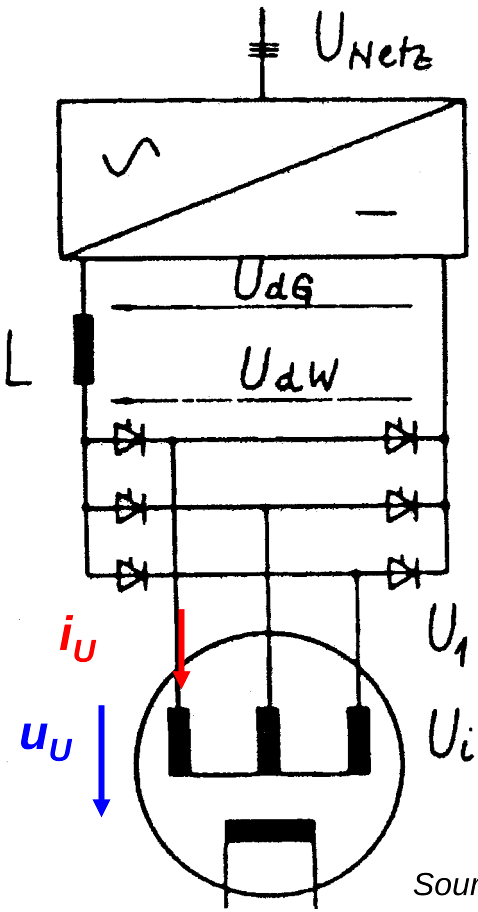
6. Wind generators and high power drives

6.4 Synchronous converters for synchronous motors



Source: Kleinrath, H.; Springer-Verlag

Motor-side voltage and current with synchronous converter feeding (six-pulse bridges B6C)”



Grid = “Netz”

Line-side converter = rectifier (G)

u_{mot}

DC current link

Machine-side converter = inverter (W)

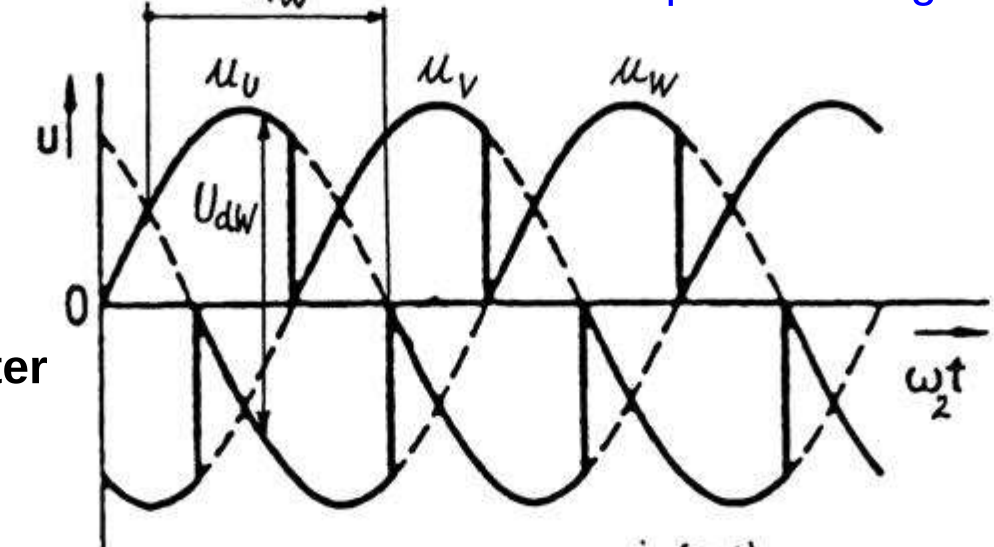
Three-phase stator winding

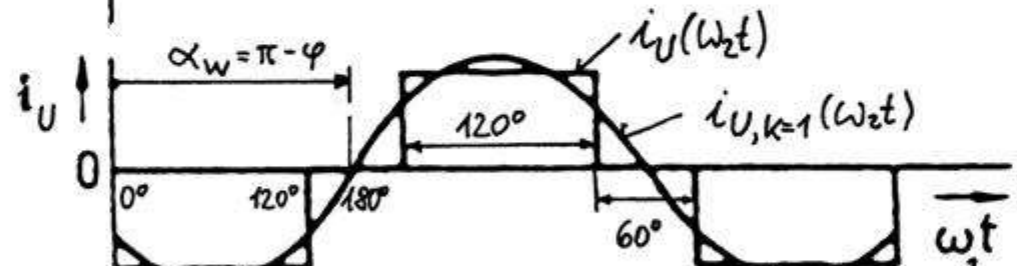
i_{mot}

Rotor excitation

Source: Kleinrath, H.; Springer-Verlag

Machine phase voltage

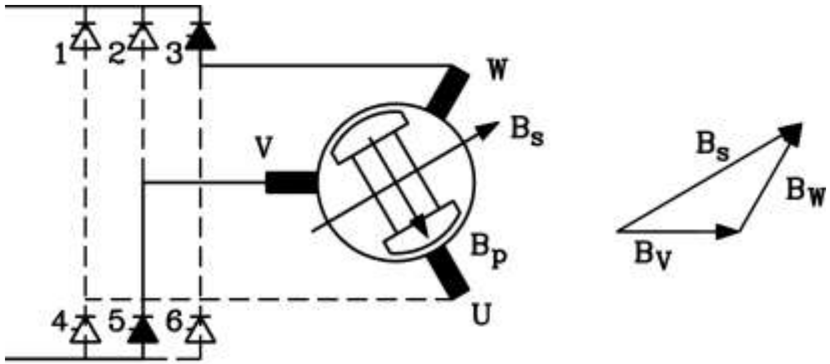


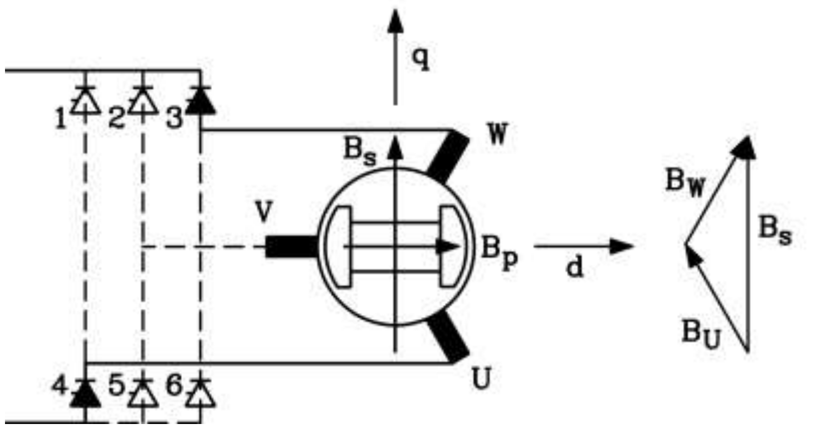


Machine phase current

Machine-side converter operation - rotor position control

Source: Kleinrath, H.; Springer-Verlag





- Depending on rotor position, the stator winding is fed with three-phase current system so, that stator field has always **a fixed relative position** to rotor field. Measurement of rotor position with e. g. **incremental encoder** or **resolver**. Rotor cannot be pulled out of synchronism, as stator field is always adjusted to rotor position.
- E.g. stator current is fed as pure *q*-current:

$$I_s = I_{sq}, I_{sd} = 0$$

Result: Stator field axis B_s is perpendicular to rotor field axis B_p.

Torque for a given stator current I_s is maximum, because at $L_d = L_q$ only I_{sq} will produce torque with rotor field.

$M_e = m_s \cdot U_p \cdot I_{sq} / \Omega_{syn}$ or with $U_p = \omega_s \Psi_p / \sqrt{2}$: $M_e = p \cdot m_s \cdot \Psi_p \cdot I_{sq} / \sqrt{2}$

6. Wind generators and high power drives

Speed and torque control of synchronous converter machines

- Line-side converter rectifies three-phase line voltage: firing angle α_G : $U_{dG} = U_{d0} \cdot \cos(\alpha_G)$

$$U_{d0} = U_{Grid} \cdot \sqrt{2} \cdot (3/\pi)$$

- The current I_d is smoothed via the big choke L, so it is nearly a DC current: “DC current source inverter”

- The machine-side converter “chops” the DC current into AC blocks of 120° with 60° pause in between. The machine-side line-to-line voltage U_s is transformed into DC voltage of DC link with firing angle α_W according to $U_{dG} = U_{dW} = -U_{dW0} \cdot \cos(\alpha_W)$ with $U_{dW0} = U_s \cdot \sqrt{2} \cdot (3/\pi)$.

- Motor operation $\alpha_W > 90°$,
- Generator operation $\alpha_W < 90°$.

- Motor voltage U_s is directly proportional to speed, if R_s is neglected: $U_s \approx U_i \sim n\Psi_h$

$$\underline{U}_s \approx \underline{U}_i = j \cdot 2\pi \cdot p \cdot n \cdot L_s \cdot \underline{I}_s + \underline{U}_p$$

Rotor position encoder allows control of phase angle between machine voltage and current, so that current may be e.g. in phase with U_p, giving directly torque:

$$M = \frac{3U_p I_s}{2\pi n} = 3p \cdot \frac{\hat{\Psi}_p}{\sqrt{2}} I_s$$

Power flow in synchronous converter machines

- Phase shift between machine voltage and current equals machine-side converter firing angle: $\cos\varphi \approx -\cos\alpha_W$.
- FOURIER-fundamental of machine phase block current: $I_s = \frac{\sqrt{6}}{\pi} \cdot I_d$
- Power balance:

$$P = U_{dG} I_d = U_{dW} I_d = -U_{dW0} \cos(\alpha_W) I_d = -U_s \sqrt{2} \cdot (3/\pi) \cos(\alpha_W) I_d =$$

$$= U_s \sqrt{2} \cdot (3/\pi) \cos\varphi \cdot I_d$$

$$P = \sqrt{3} U_s (\sqrt{6}/\pi) I_d \cos\varphi = \sqrt{3} U_s I_s \cos\varphi$$

$$P = \sqrt{3} U_s I_s \cos\varphi \approx \sqrt{3} U_i I_s \cos\varphi \sim U_i \sim n \Psi_h$$

- Speed control is done with line-side converter: $\underline{\underline{U_{dG} \sim n}}$

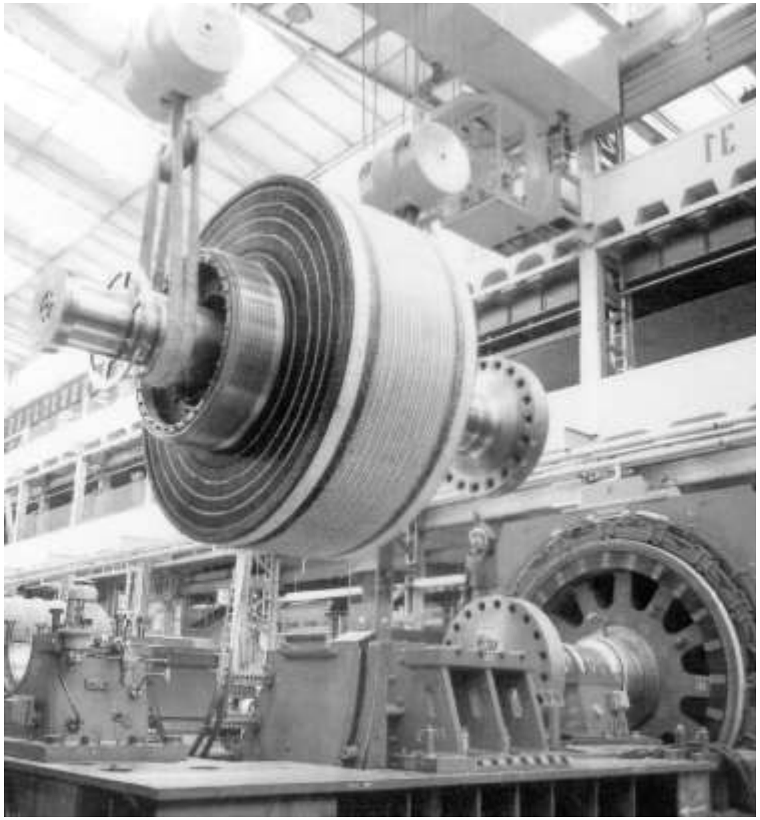
- **Four quadrant operation** ($n > 0$, $n < 0$ at $M > 0$, $M < 0$) **possible with synchronous converter !**

Comparison: Synchronous converter motor with DC motor

Synchronous converter motor	Separately excited DC motor
Line-commutated converter	Line-commutated converter
DC link, machine-side converter, rotor position encoder	Commutator, brushes
Electrically excited static magnetic field (rotating)	Electrically excited static magnetic field (in stator)
Rectified voltage U_{dG}	Rectified voltage U_a
Induced AC machine voltage U_i	Induced DC machine voltage U_i
DC link current I_d	DC armature current I_a
Voltage drop at R_s and machine inductance L''_d	Voltage drop at R_a
Rotor field current I_f	Stator field current I_f

Application: Strip mill motor (1st stage)

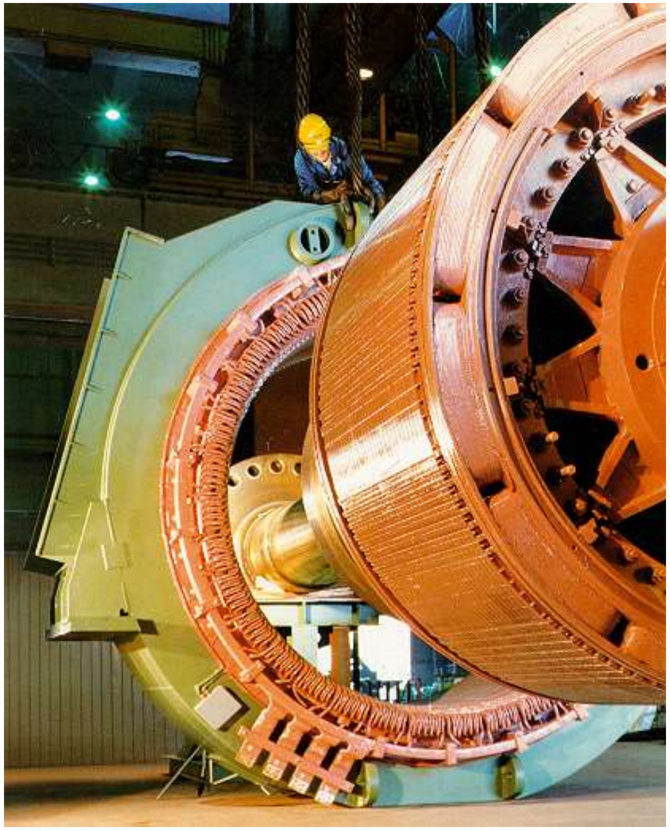
Old concept



DC machine: Twin drive 2x12 = 24 MW

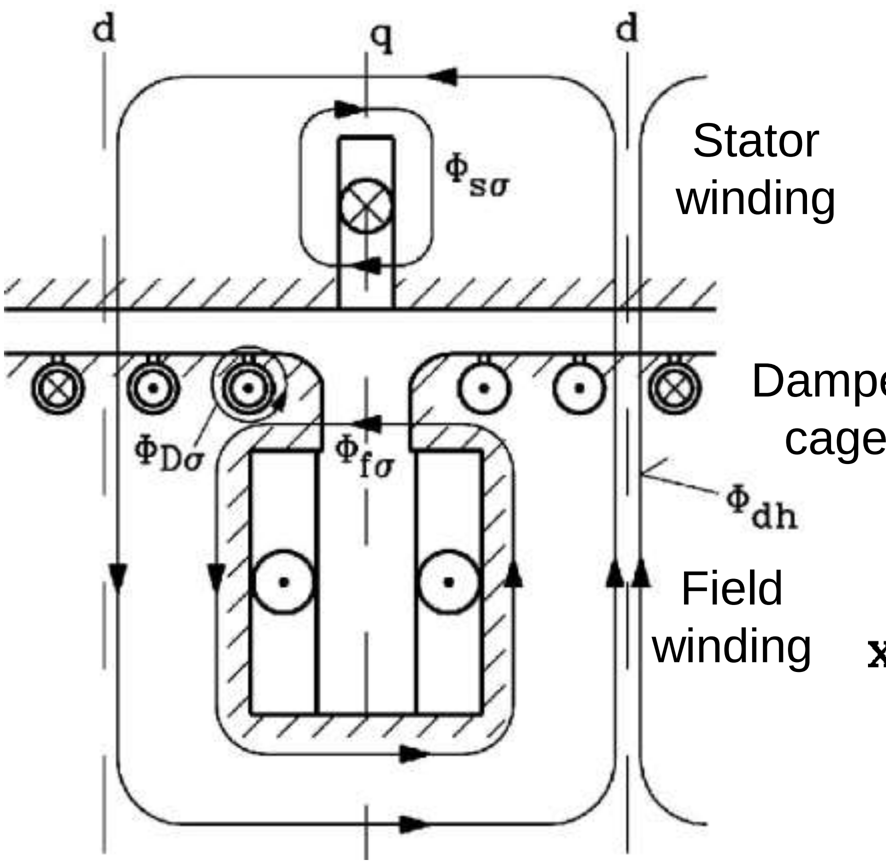
Source: Siemens AG, Germany

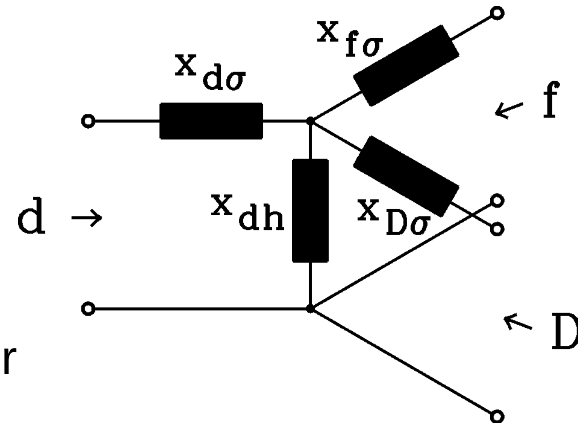
Nowadays



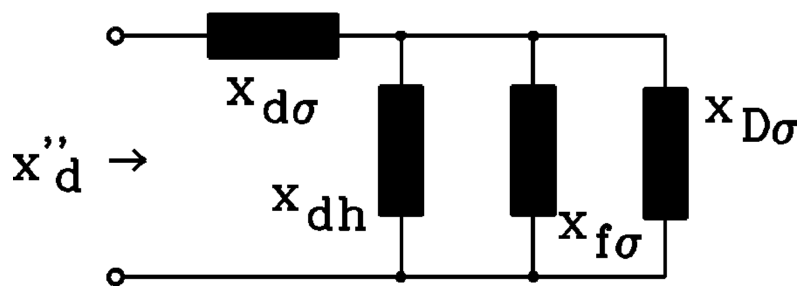
Synchronous converter machine:
12 poles, cylindrical rotor, 1.78 MNm,
10.9 MW, 58.5 … 112.5/min

Sub-transient inductance L_d'' during commutation





- Damper cage = short circuit
- Field winding: Nearly short circuit via low inner resistance of DC exciter voltage source

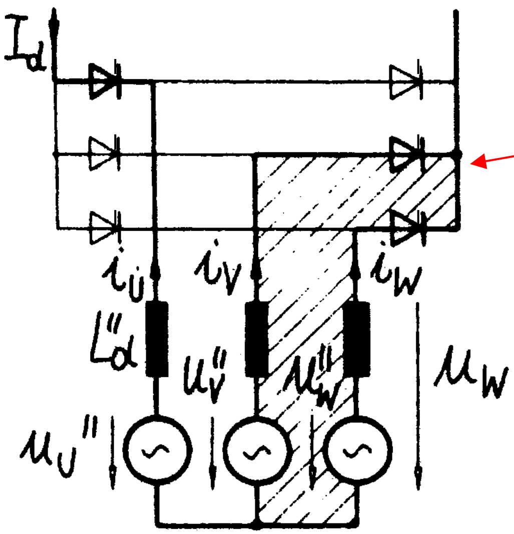


Resulting stator inductance L_d'' is about stator leakage inductance

Changing stator current causes flux linkage change with rotor winding = “three winding transformer”

$$L_d'' = L_{s\sigma} + \frac{L_{dh} L_{f\sigma} L_{D\sigma}}{L_{dh} L_{f\sigma} + L_{dh} L_{D\sigma} + L_{f\sigma} L_{D\sigma}}$$

Machine current commutation e.g. from V to W



During commutation from V to W: Both thyristors conducting

$$i_V + i_W = I_d \qquad u_V - u_W = 0$$

Changing current causes changing flux linkage with rotor field winding: Resulting stator side inductance is reduced to L_d''

$$u_V = u_V'' + L_d'' \frac{di_V}{dt} = u_V'' - L_d'' \frac{di_W}{dt} \qquad u_W = u_W'' + L_d'' \frac{di_W}{dt} = u_V$$

$$u_W'' - u_V'' + L_d'' \frac{di_V}{dt} - L_d'' \frac{di_W}{dt} = 0 \quad \Rightarrow \quad 2L_d'' \frac{di_W}{dt} = u_W'' - u_V'' = u_k''$$

Commutation voltage u_k'' causes current i_V to decrease to zero !

Voltage ↓

Current ↑

Generator reference system

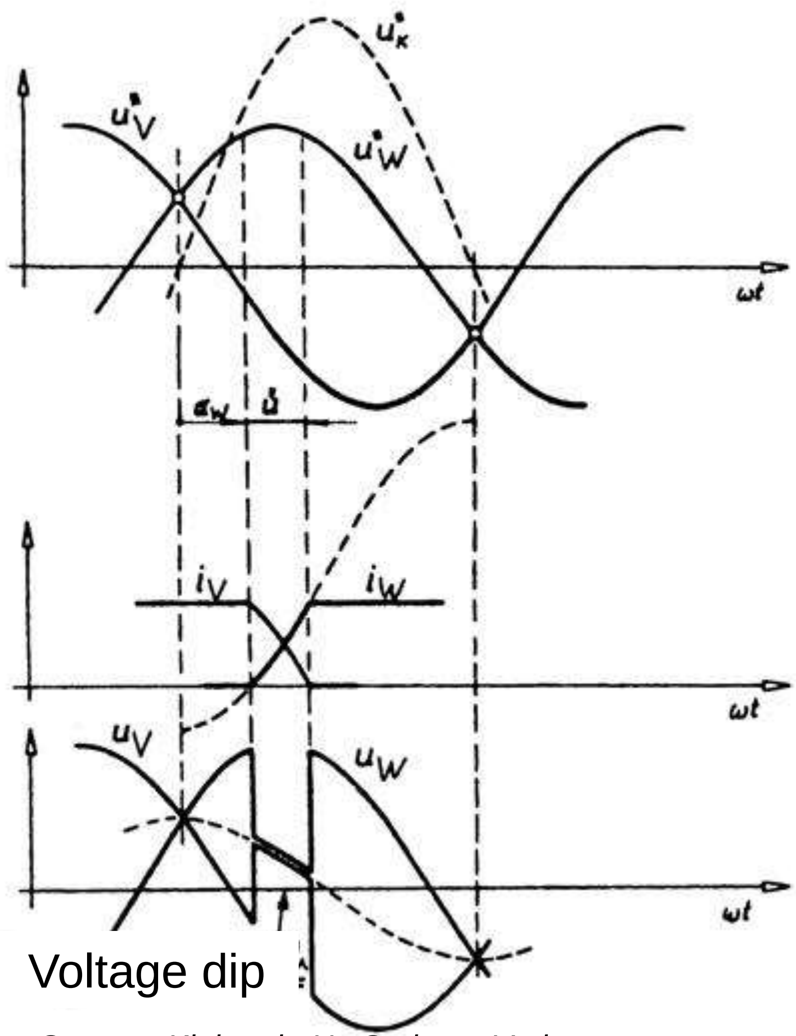
$$u_k'' = \sqrt{2} \cdot \sqrt{3} \cdot U_{s,Phase} \sin(\omega t + \alpha_W) = \hat{U}_s \sin(\omega t + \alpha_W)$$

At begin of commutation: $i_W(0) = 0$, at end after time t_k: $i_W(t_k) = I_d$

$$i_W(t) = \frac{\hat{U}_1}{2\omega L_d''} \left(\cos\alpha_W - \cos(\omega t + \alpha_W)\right) \qquad 0 \le t \le t_k$$

Source: Kleinrath, H.; Springer-Verlag

Current and voltage during commutation (1)



Voltage dip

Source: Kleinrath, H.; Springer-Verlag

- During commutation: Voltage dip: $u_V = u_W = \frac{u''_V + u''_W}{2}$

- At the end of commutation: Current in phase W:

$$i_W(t_k) = I_d = \frac{\hat{U}_s}{2\omega L''_d}\left(\cos\alpha_W - \cos(\omega t_k + \alpha_W)\right)$$

- Commutation duration t_k expressed as angle: $ü = \omega t_k$

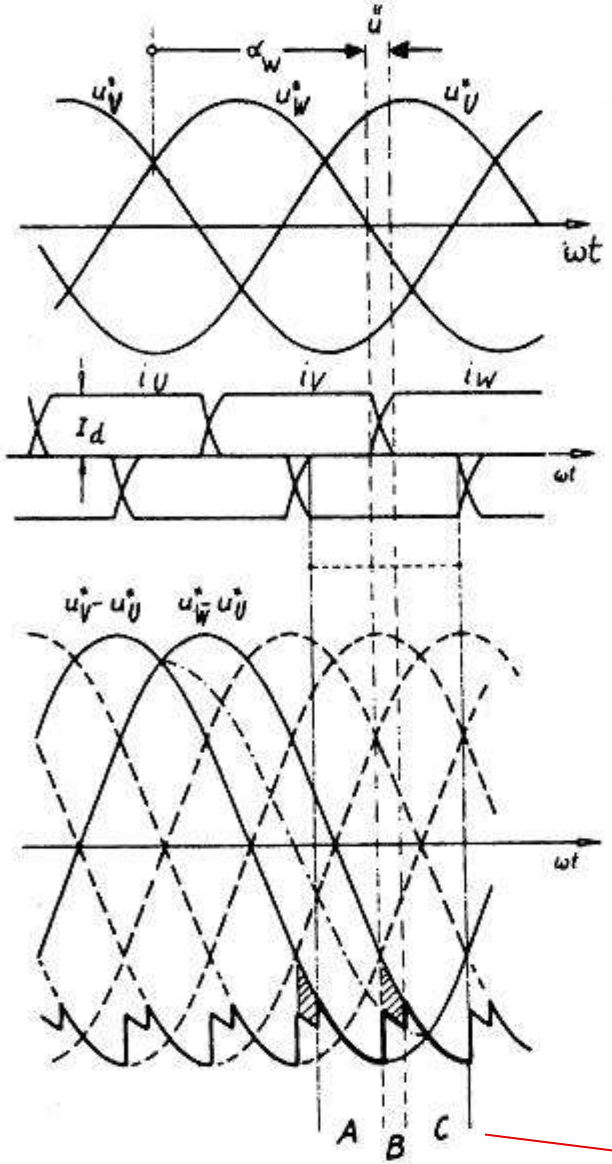
- Condition for maximum duration: $\alpha_W + ü_{max} = \pi$

$$ü_{max} = \omega t_{k,max} = \arccos\left(1 - \frac{2\omega L''_d I_d}{\hat{U}_s}\right)$$

Current is lagging to voltage in generator arrow system = current has to be capacitive. Otherwise commutation is not possible, because voltage u_k'' has then wrong direction. It then does not help decreasing current i_V !

Capacitive current needs over-excited synchronous machine; **with induction machine NOT possible** !

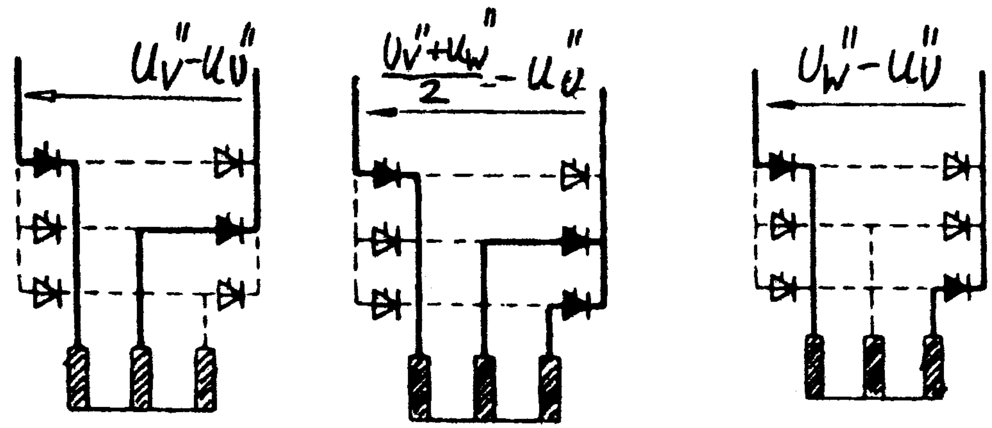
Current and voltage during commutation (2)



Source: Kleinrath, H.; Springer-Verlag

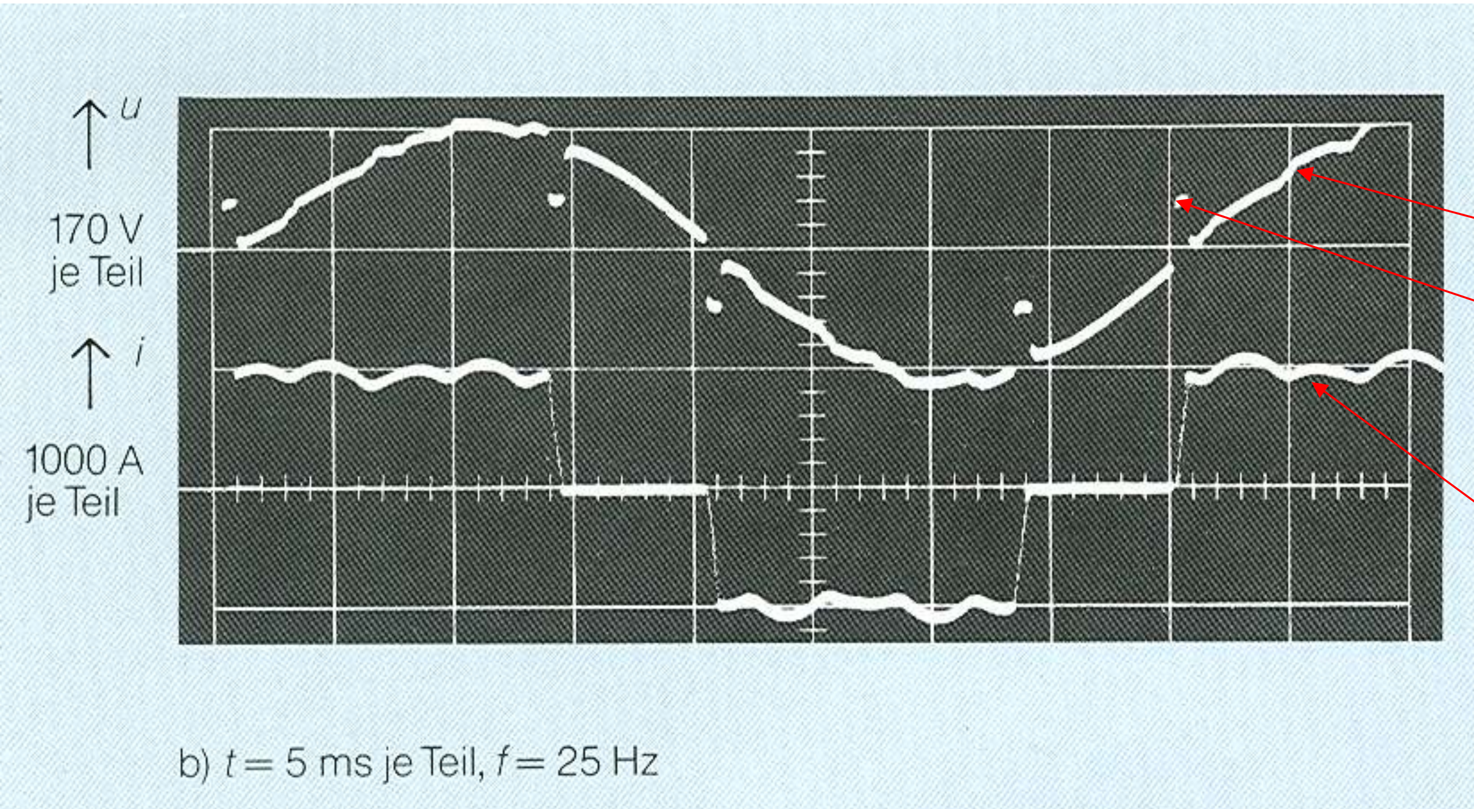
- Current curve during commutation is co-sine function, so current is not ideally block-shaped !

- During commutation machine voltage dips !



(A) prior (B) during (C) after commutation

Phase current and voltage in 6-pulse synchronous converter machines



1500/min, 25 Hz, 2-pole machine

- Induced phase voltage
- Voltage sag (dip) during current commutation
- Block-shaped phase current

Source: Siemens AG

Features of machine-side current commutation

$$\ddot{u}_{\max} = \omega t_{k,\max} = \arccos\left(1 - \frac{2\omega L_d'' I_d}{\hat{U}_s}\right)$$

- Current curve during commutation is co-sine function, so current is not ideally block-shaped !

- During commutation machine voltage dips !

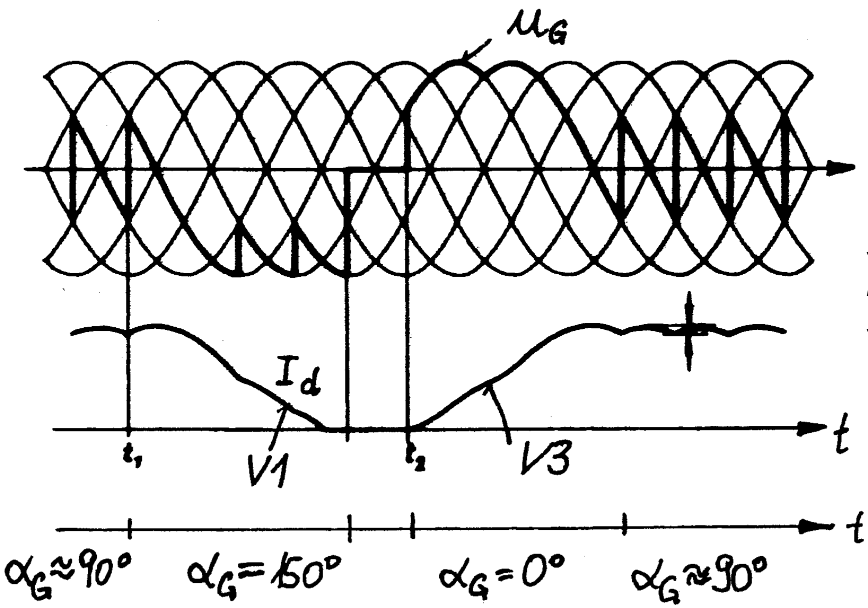
- At operation with big firing angle $\alpha_W \to \pi$ the commutation duration *ü* must be short !

- This needs high machine voltage $U_s \sim n$, so works better at high speed !

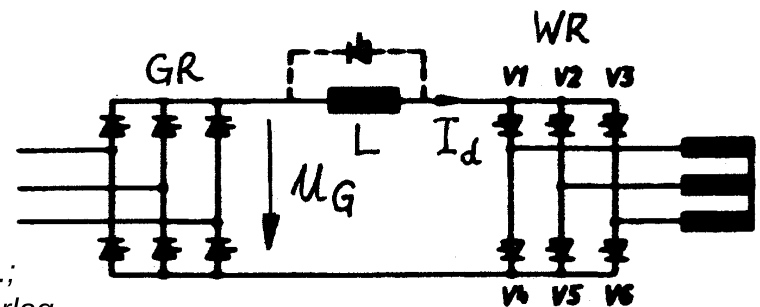
- Further small L_d'' is needed, which demands machines WITH damper cage and SMALL stator leakage !

Starting the synchronous converter machine

- At low speed n (ca. below 10% rated speed) the machine voltage $U_s \sim n$ is so small, that commutation does not work !
- An alternative method for starting the converter from zero speed is needed !



Source: *Kleinrath, H.; Springer-Verlag*



Example: Commute current from V to W:

- Commutation is done with line-side converter, which at zero speed has to operate at firing angle $\alpha_G = 90°$.

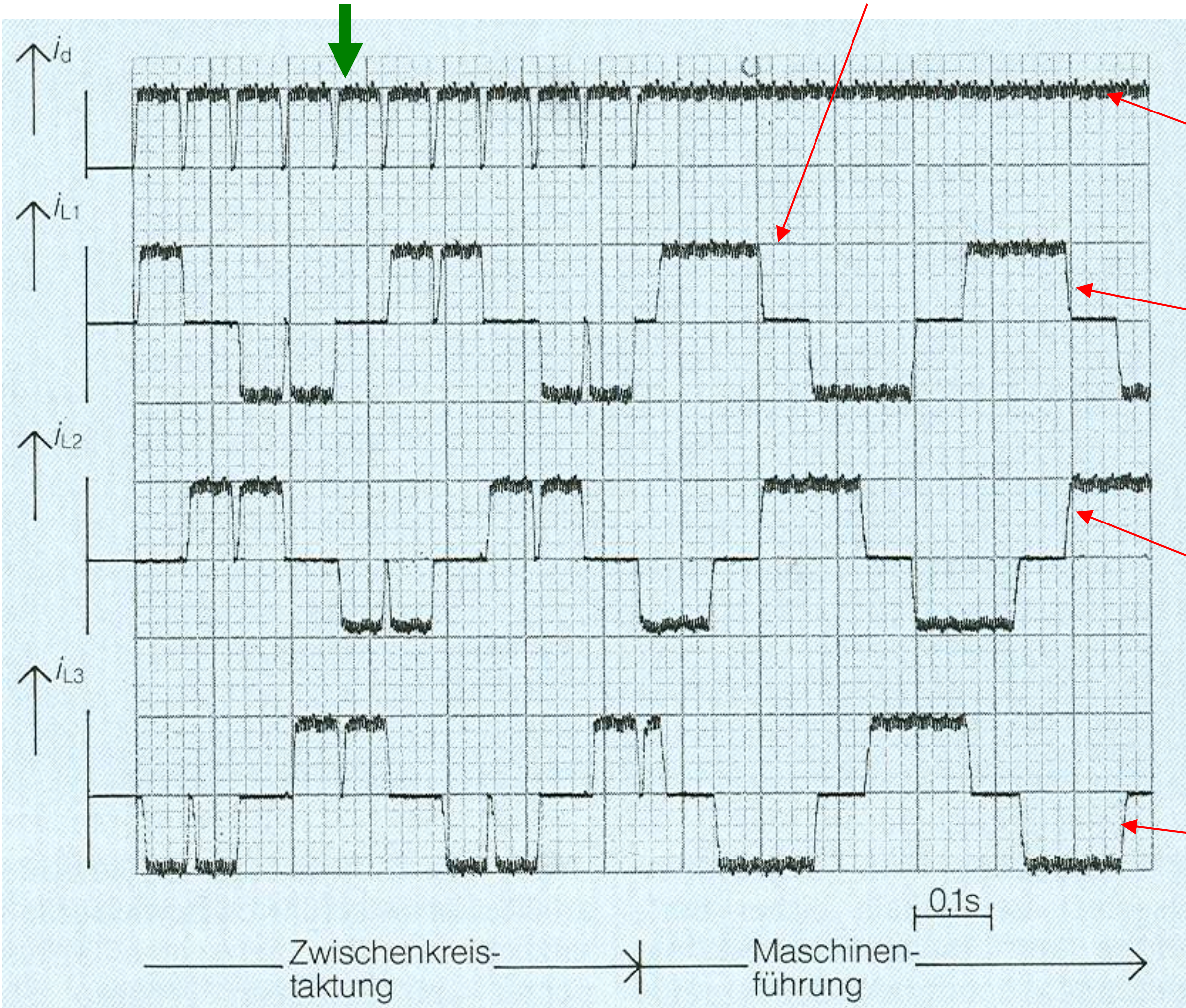
- By shortly operating the line-side converter with $\alpha_G = 150°$, the DC link voltage $U_{dG} = U_{d0} \cdot \cos(\alpha_G)$ gets negative, forcing e.g. current in thyristor V1 (phase V) to zero.

-Then after a short pause (time t_2) line-side converter is operated with $\alpha_G = 0°$, giving maximum positive voltage. Thyristor V3 is fired, so current in phase W begins to flow !

Currents in 6-pulse synchronous converter machines

Starting by line-side switching

motor commutation



DC-link current

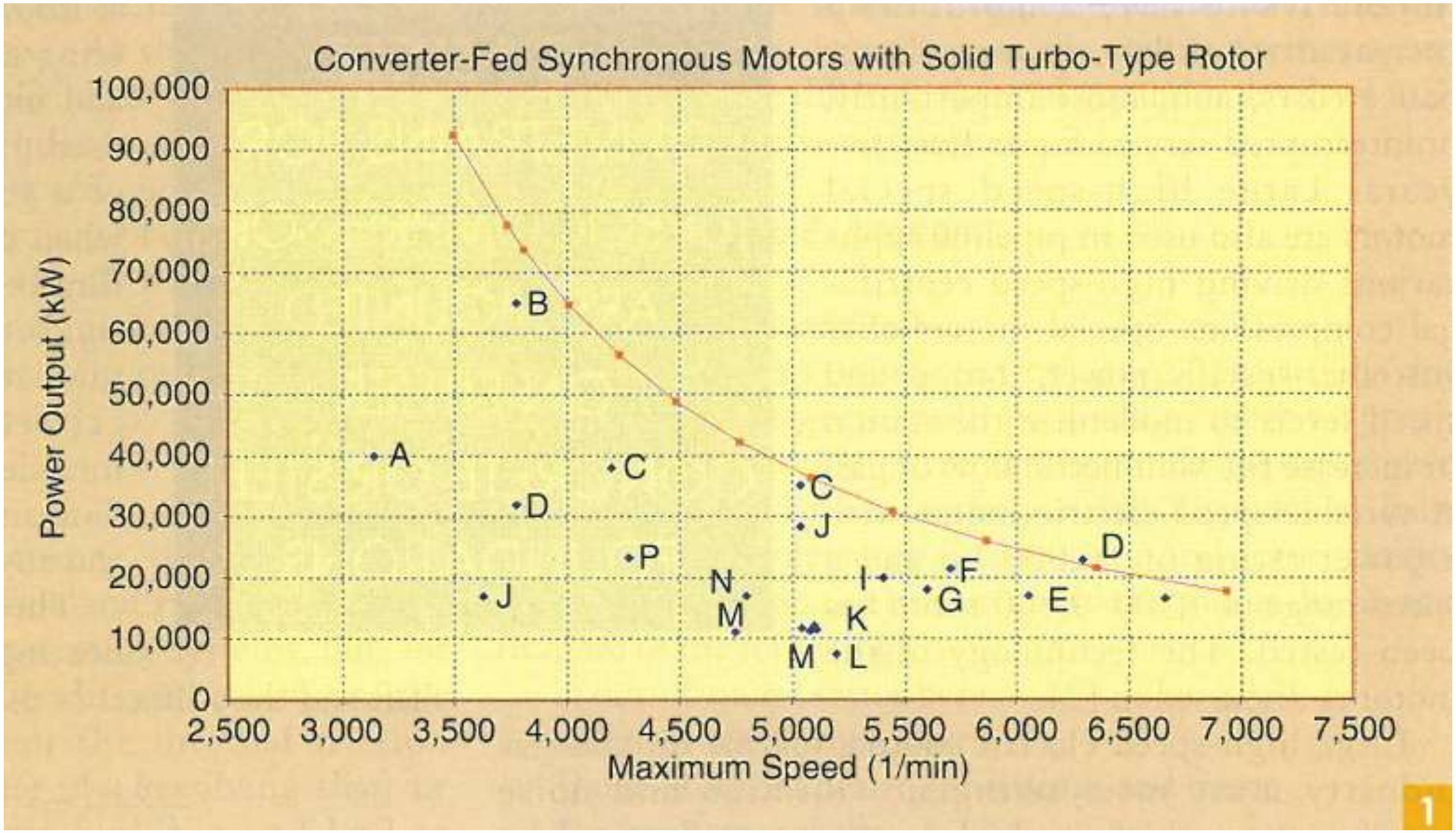
Phase U current

Phase V current

Phase W current

Source: Siemens AG

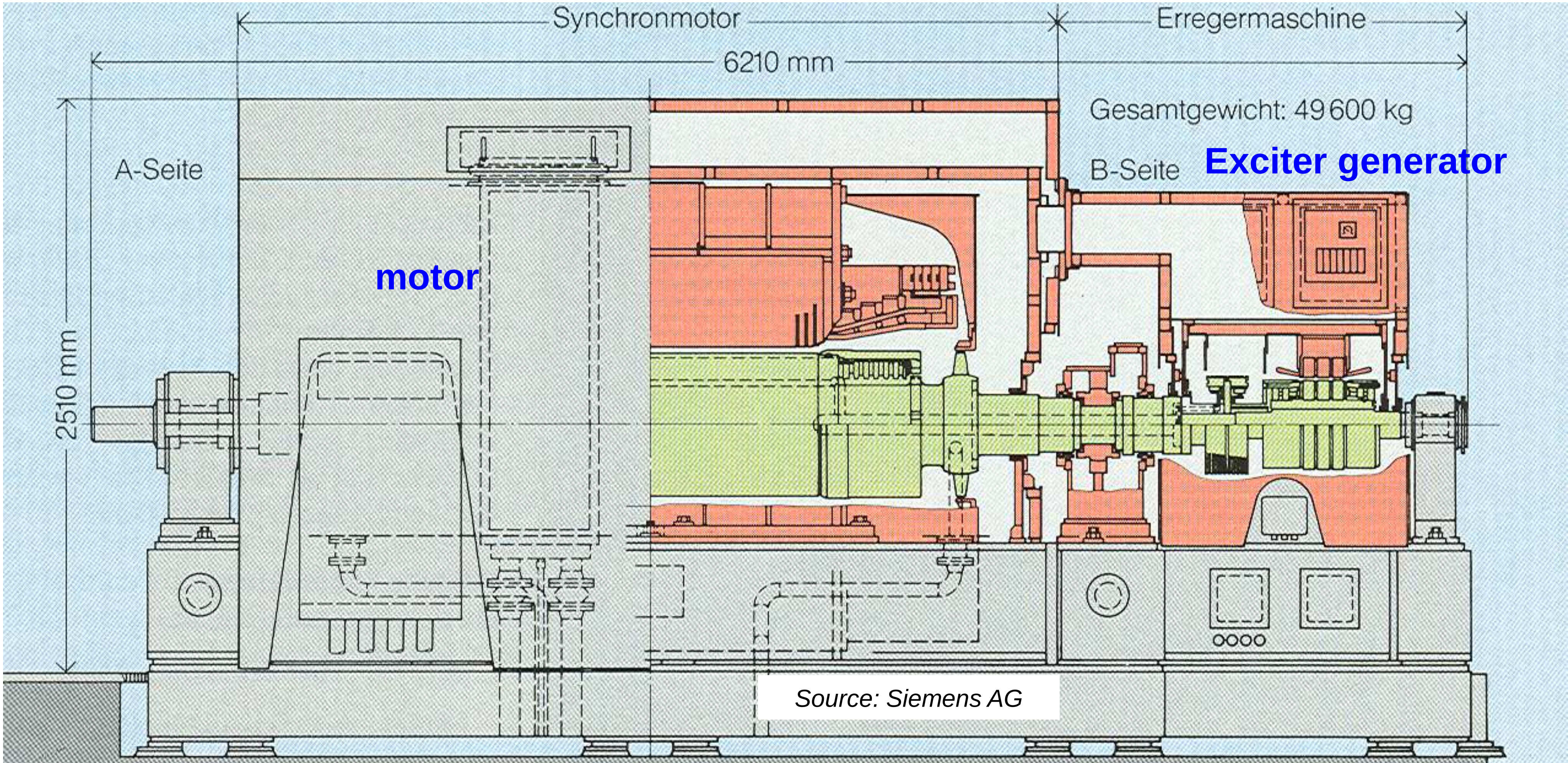
Typical ratings of converter-fed synchronous motors with solid turbo-type rotor ($2p = 2$)



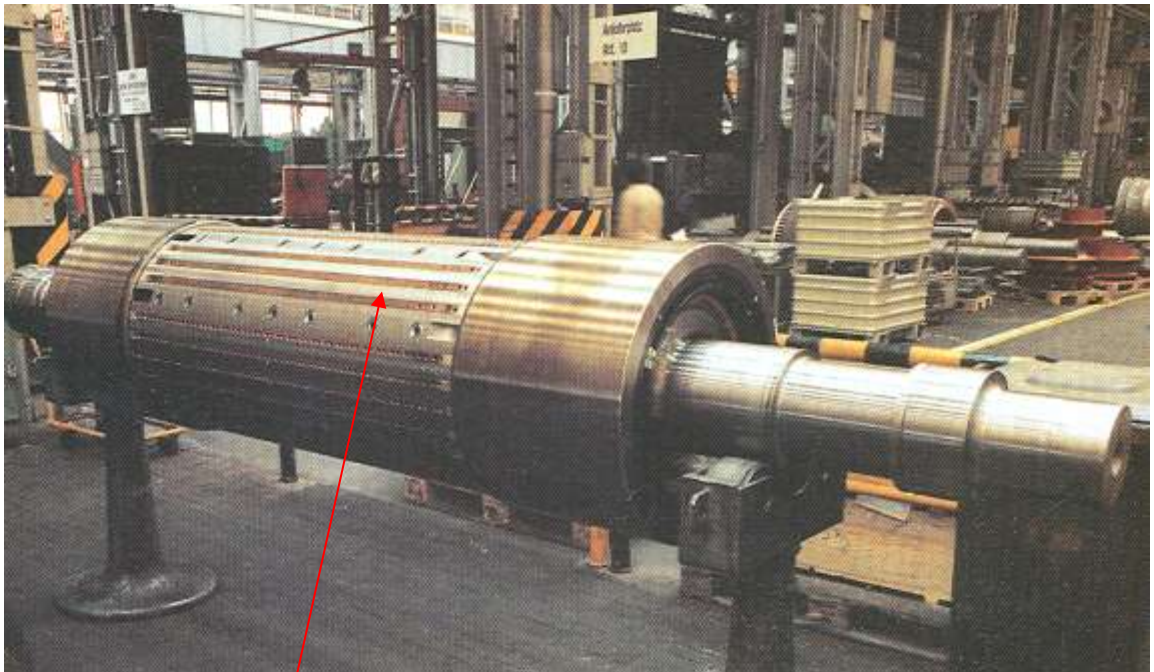
Source: Siemens AG & IEEE Ind. Appl. Magazine, Vol. 20/6, 2014

Two-pole high speed converter-fed synchronous motor

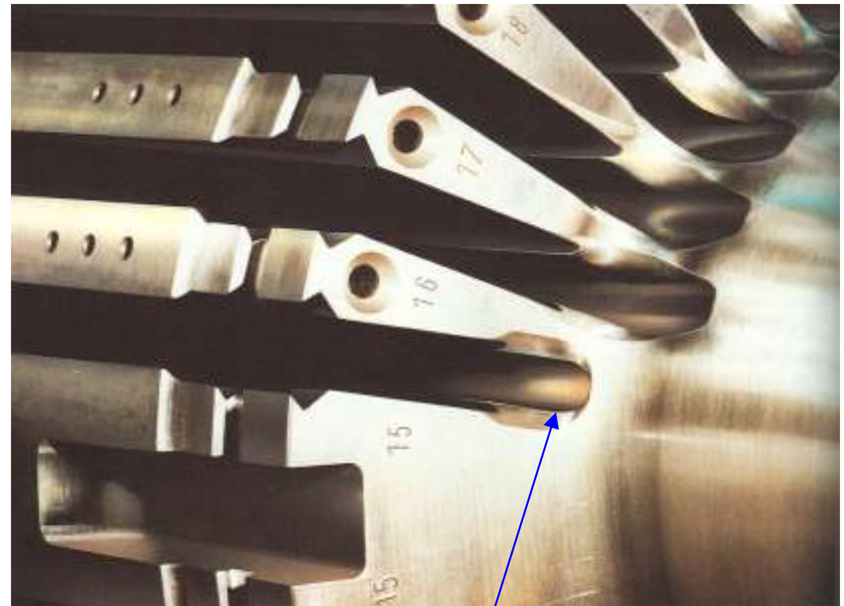
15 MW, 5100/min, brushless excitation, massive steel rotor, two poles



Massive steel rotor of two-pole high speed converter-fed synchronous motor (compressor drive)



Conducting rotor slot wedges as damper bars



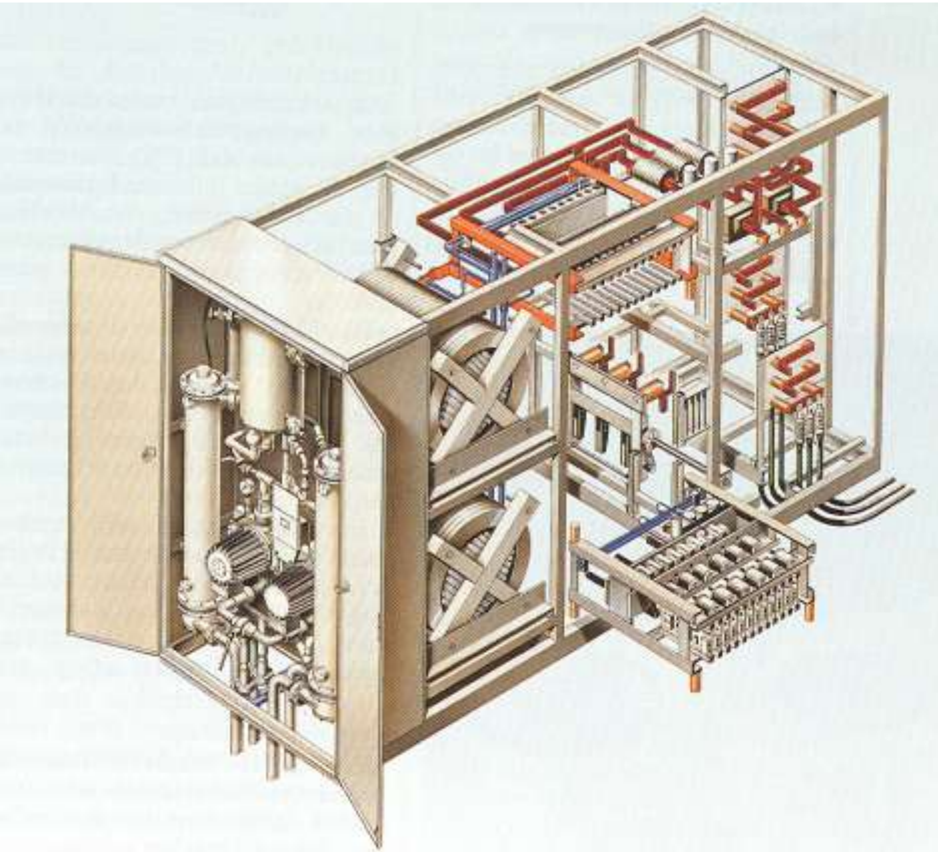
Highest mechanical stress

Milled rotor slots prior to mounting of rotor winding

17 MW, 6100/min

Source: Siemens AG

High voltage synchronous 6-pulse converter

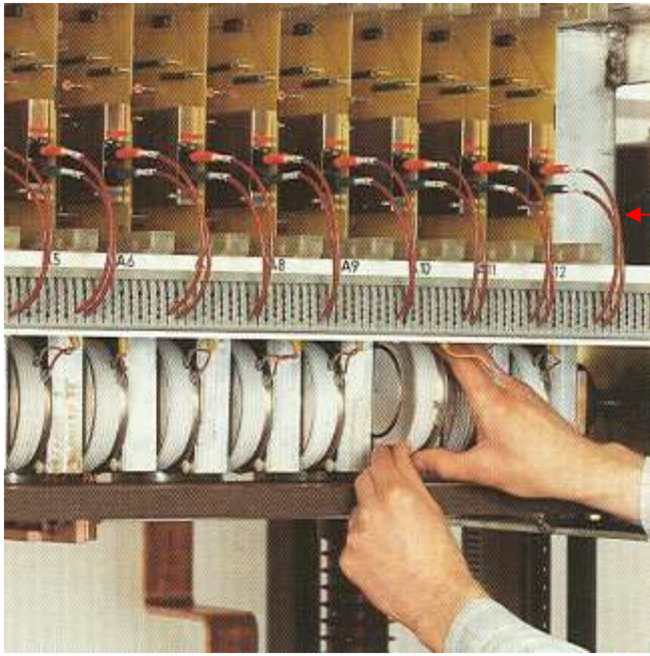


Liquid cooled 6-pulse thyristor converter

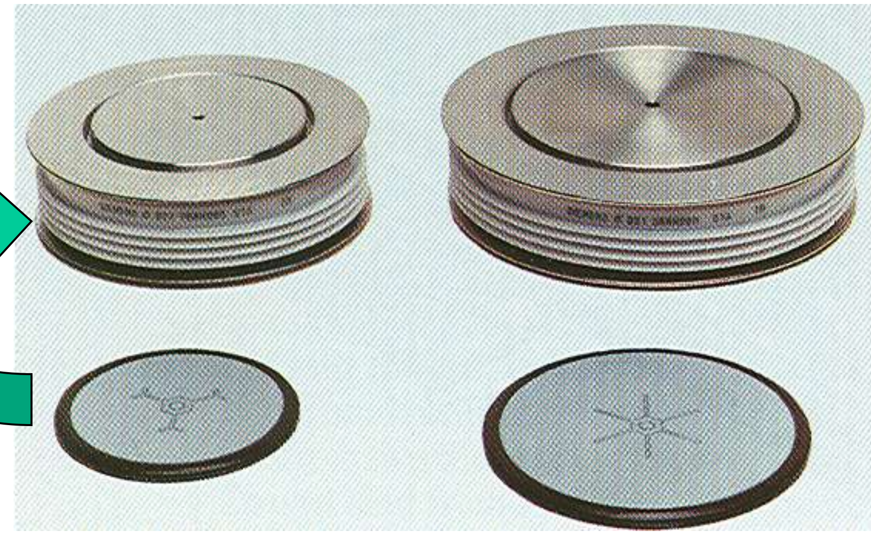
Three-phase six-pulse converter

Source: Siemens AG

High voltage synchronous 6-pulse converter



Opto-electronical gate ignition

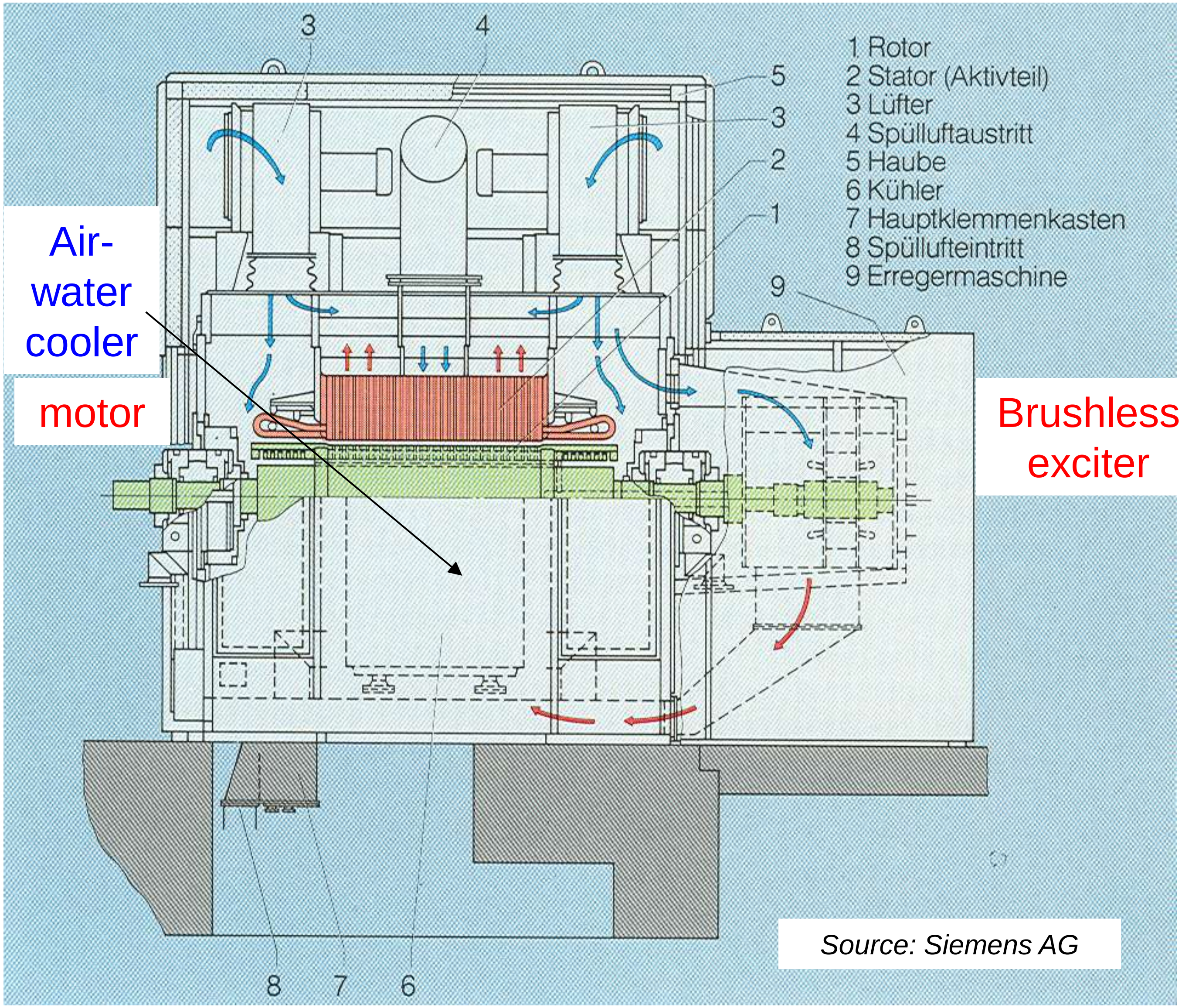


Series connection of ***n*+1** thyristors per phase for high voltage

Thyristors: Blocking voltage 5.2 kV

rated current 1.5 kA r.m.s. 2.6 kA

Source: Siemens AG



Air-cooled synchronous high speed motor

17 MW

Compressor drive

4000 … 6060/min

12-pulse operation

2 x 7200 V, 101 Hz

Air-cooled synchronous high speed motor under test

Load machine with mounted cooler hood

DC link choke of load machine

17 MW Compressor drive

4000 … …4850/min

2 x 7200 V, 80.8 Hz

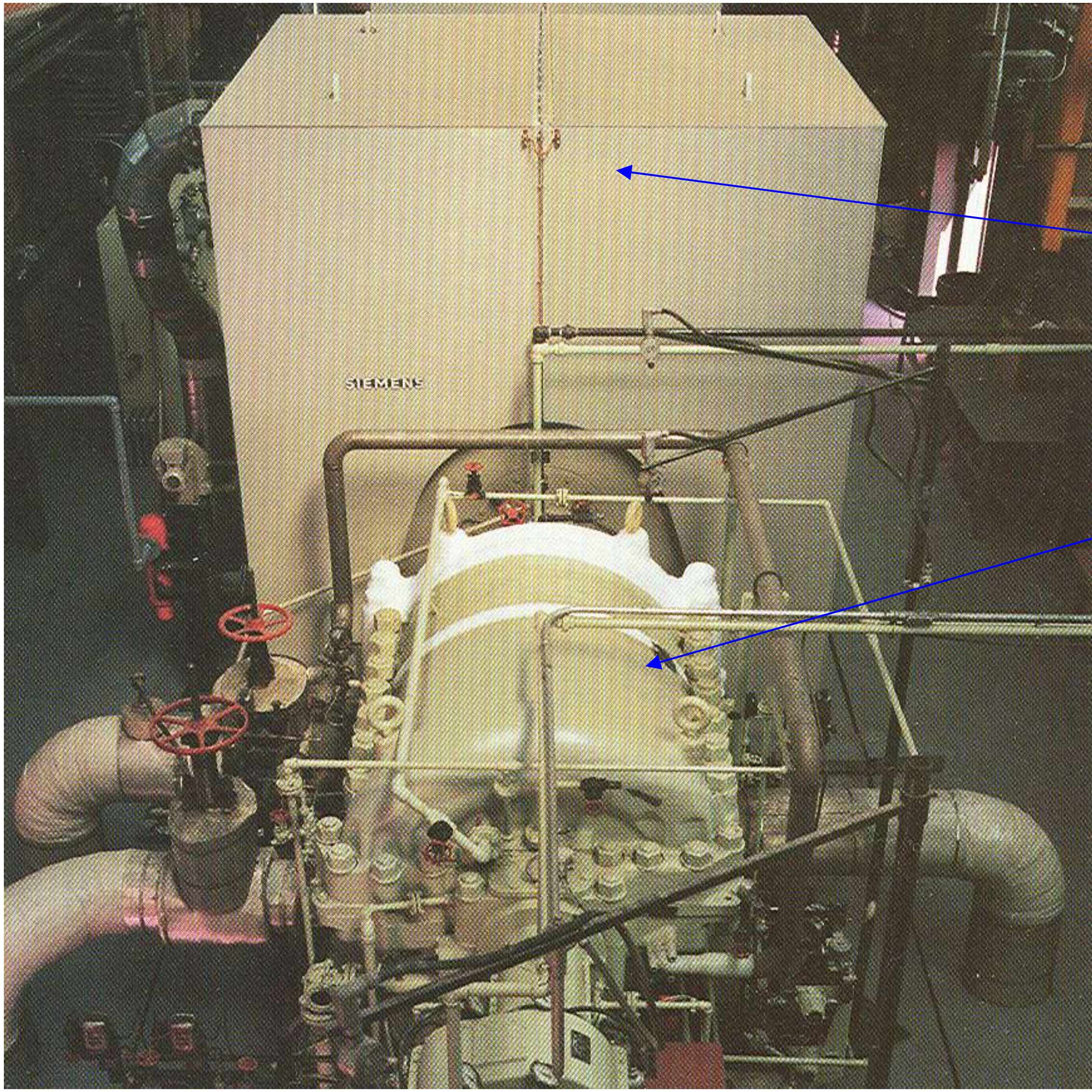
Feeding 12-pulse converters

DC link choke of load machine

Tested motor with dis-mounted cooler hood

Back-to-back testing of two identical machines

Source: Siemens AG



17 MW compressor drive

Two-pole synchronous motor and mounted cooler

Compressor for refrigeration in oil refinement process (petrol production)

17 MW, Compressor drive

4000 … 4850/min

12-pulse operation

2 x 7200 V, 80.8 Hz

Source: Siemens AG

Synchronous converter motor application (1)

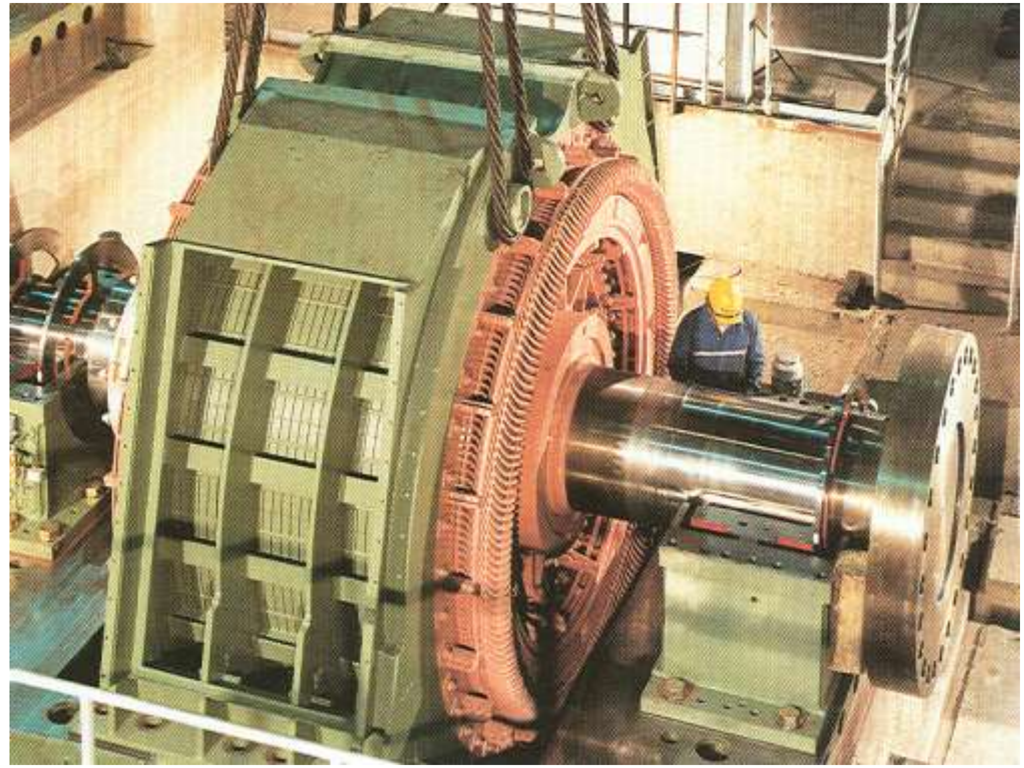
Source: Siemens AG

Feeder pump motors for thermal power plant boiler 15.1 MW at 5100/min

Natural gas pipeline: Gas compressor 18 MW at 5200/min, explosion proof „pressurized“ EEx p

Synchronous converter motor application (2)

Extrusion drive 2 MW at 120 … 1500/min at protection IP54 and explosion proof EEx e

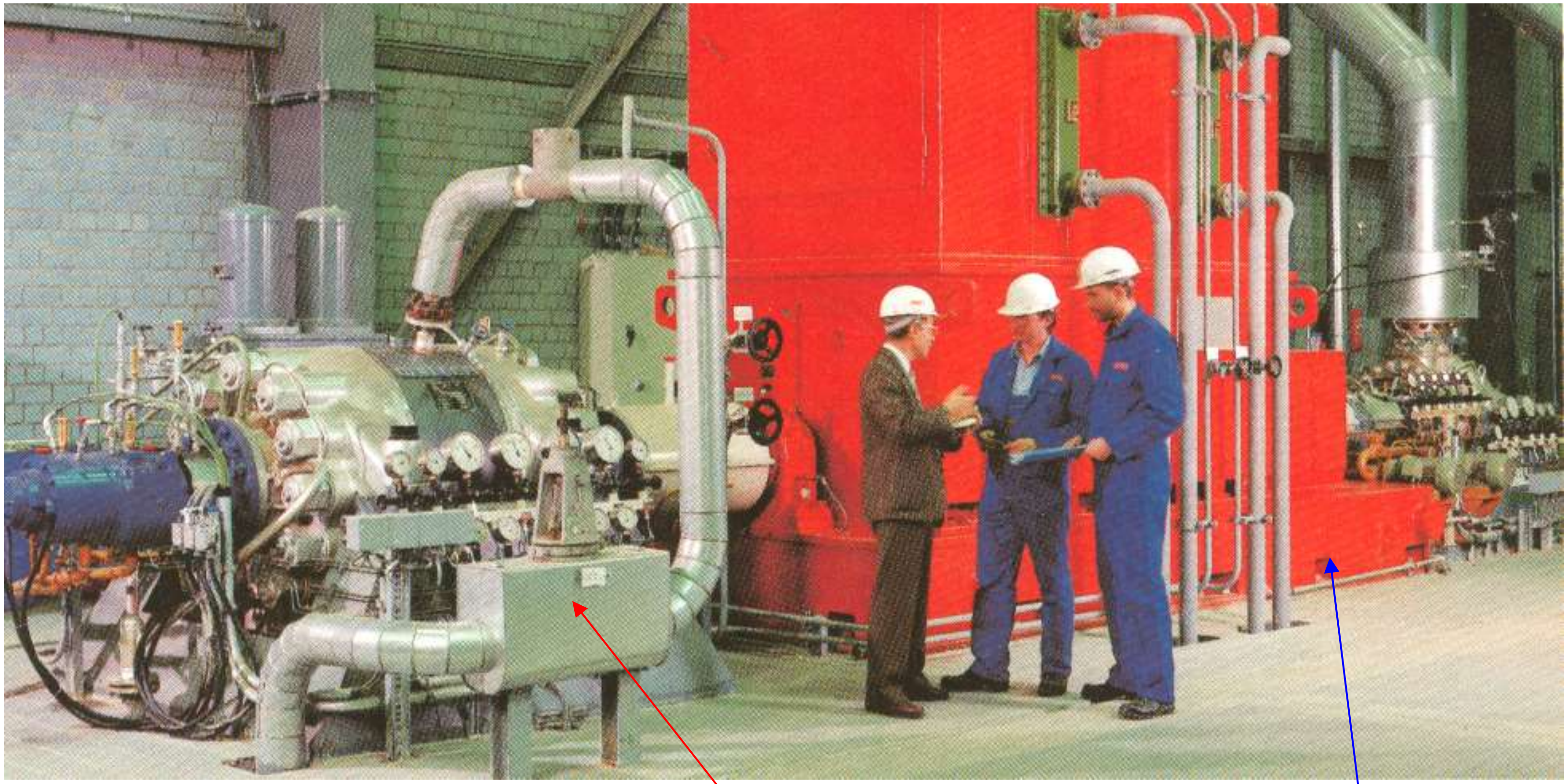


Main drive of 5.5 m rig of cold strip mill (1st stage of milling process)

10.9 MW at 58.5 … 112.5/min, peak 26.5 MW

Source: Siemens AG

Synchronous converter motor application (3)



Thermal power plant: Feeding water pump for the boiler and two-pole synchronous motor with massive cylindrical rotor, 10 MW, 5222/min, speed-variable drive

Left: *Prof. Neidhöfer*, honorary professor of *TU Darmstadt*

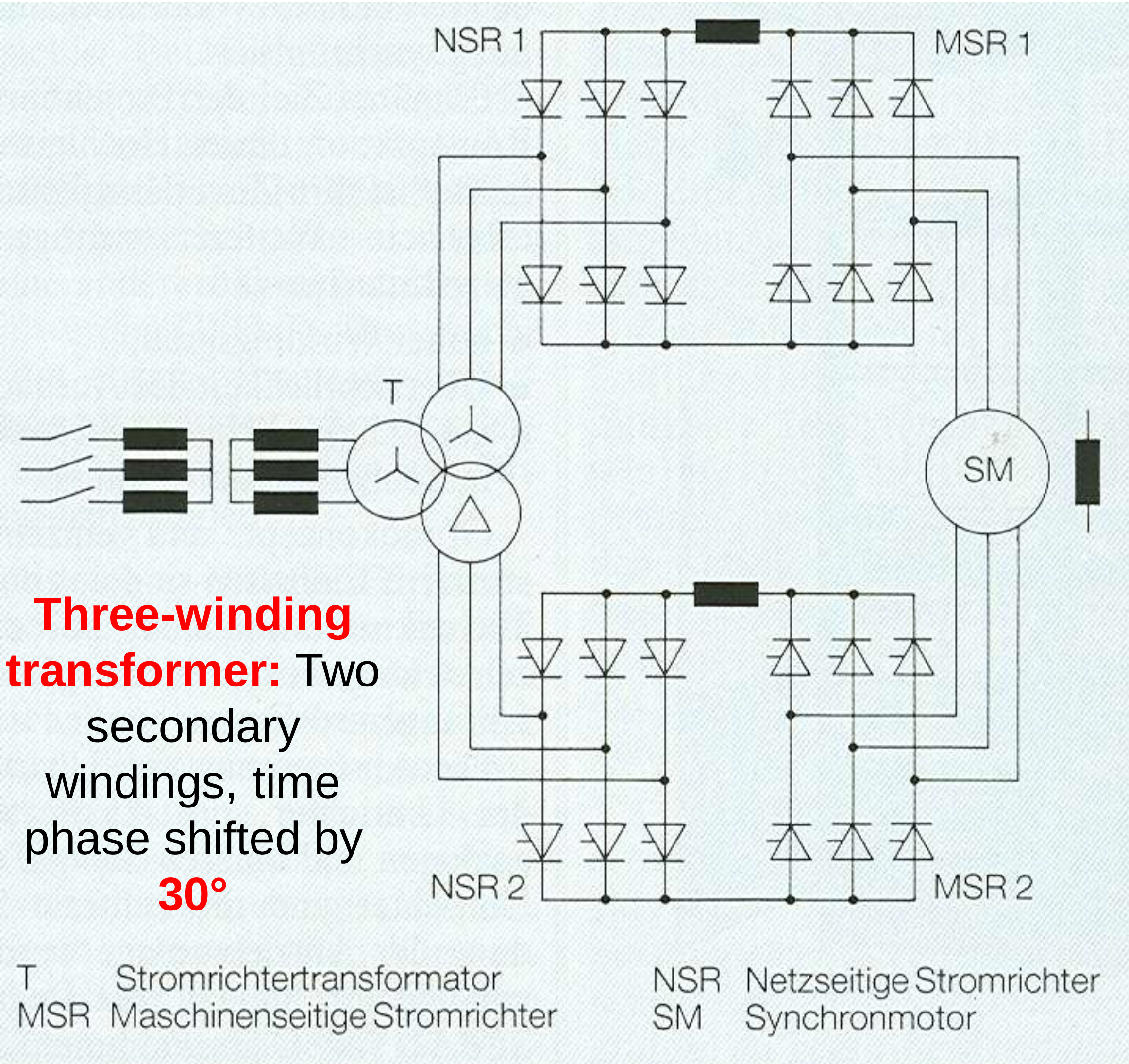
Source: Alstom Power, Birr, Switzerland, former BBC

Synchronous converter motor application (4)

65 MW, 3600/min, 60 Hz, two-pole with rotating exciter machine, for liquefaction of natural gas. Two such motors are installed at *Hammerfest, Norway*.

Source: Siemens AG, Germany

12-pulse synchronous converter machine



Three-winding transformer: Two secondary windings, time phase shifted by **30°**

-Two three-phase winding systems are put into the slots

- Phase sequence:

North pole: 0…180°

+U1 +U2 –W1 –W2 +V1 +V2

South pole: 180°…360°

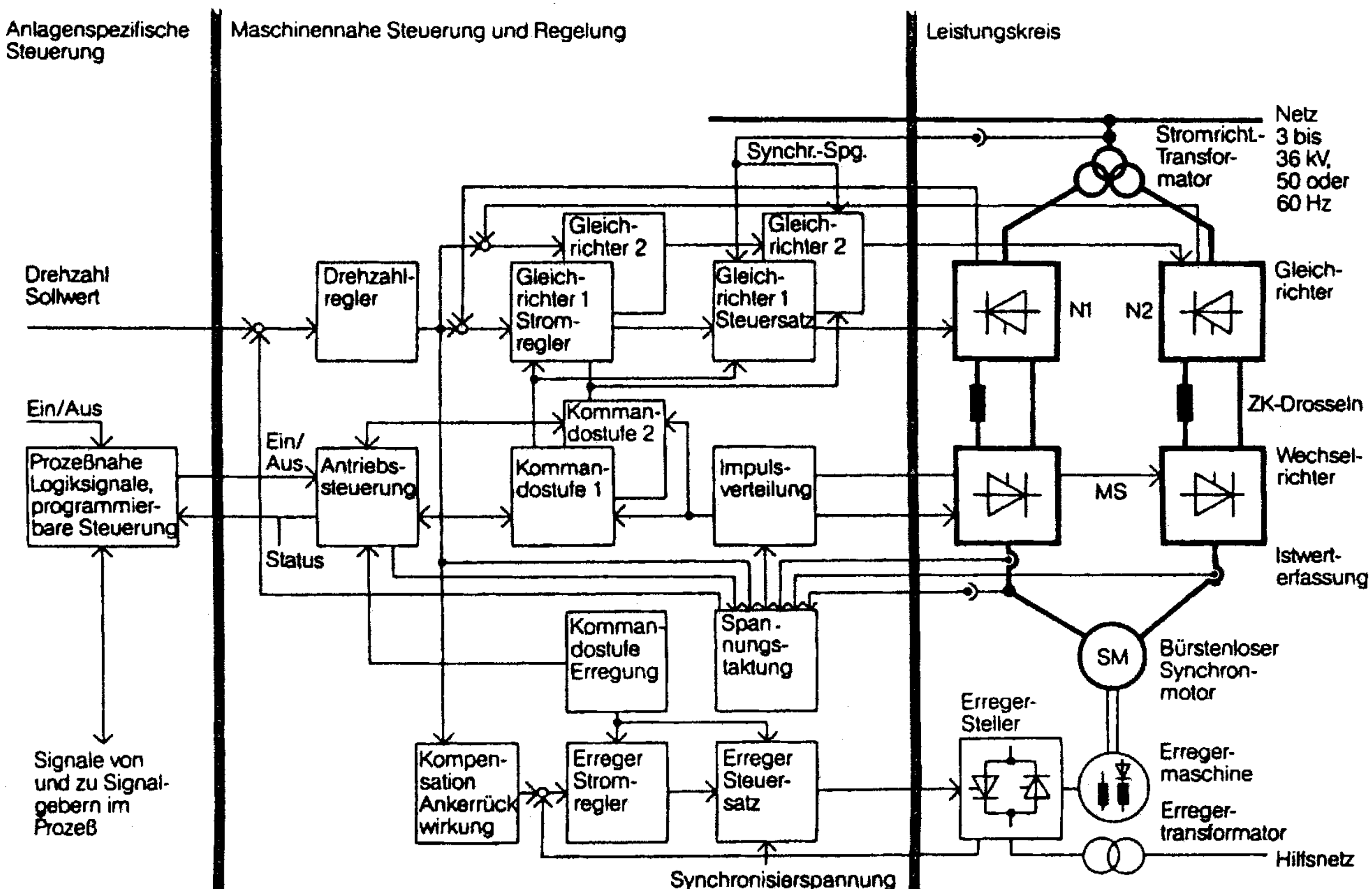
-U1 -U2 +W1 +W2 -V1 -V2

- Space phase shift between System 1 and 2: **30°**

-Acts like being fed from 12-pulse bridge converter !

Source: Siemens AG

12-pulse synchronous converter machines



Source: Siemens AG

-Two six-pulse bridge converters operated in parallel with a six.phase machine (2x3 phases !)

- Phase shift between the 2 systems by 30° with a special transformer with 2 secondary windings, one in star, one in delta connection !

- Result is 12-pulse rectification, so reduced harmonics in DC link occur !

Three winding transformer for 12-pulse motor operation

18 MVA, oil-cooled, for cold strip mill

Three phase operation at grid frequency:

Upper transformer:

Primary star winding 1, secondary star winding

Inter-yoke to decouple both secondary windings

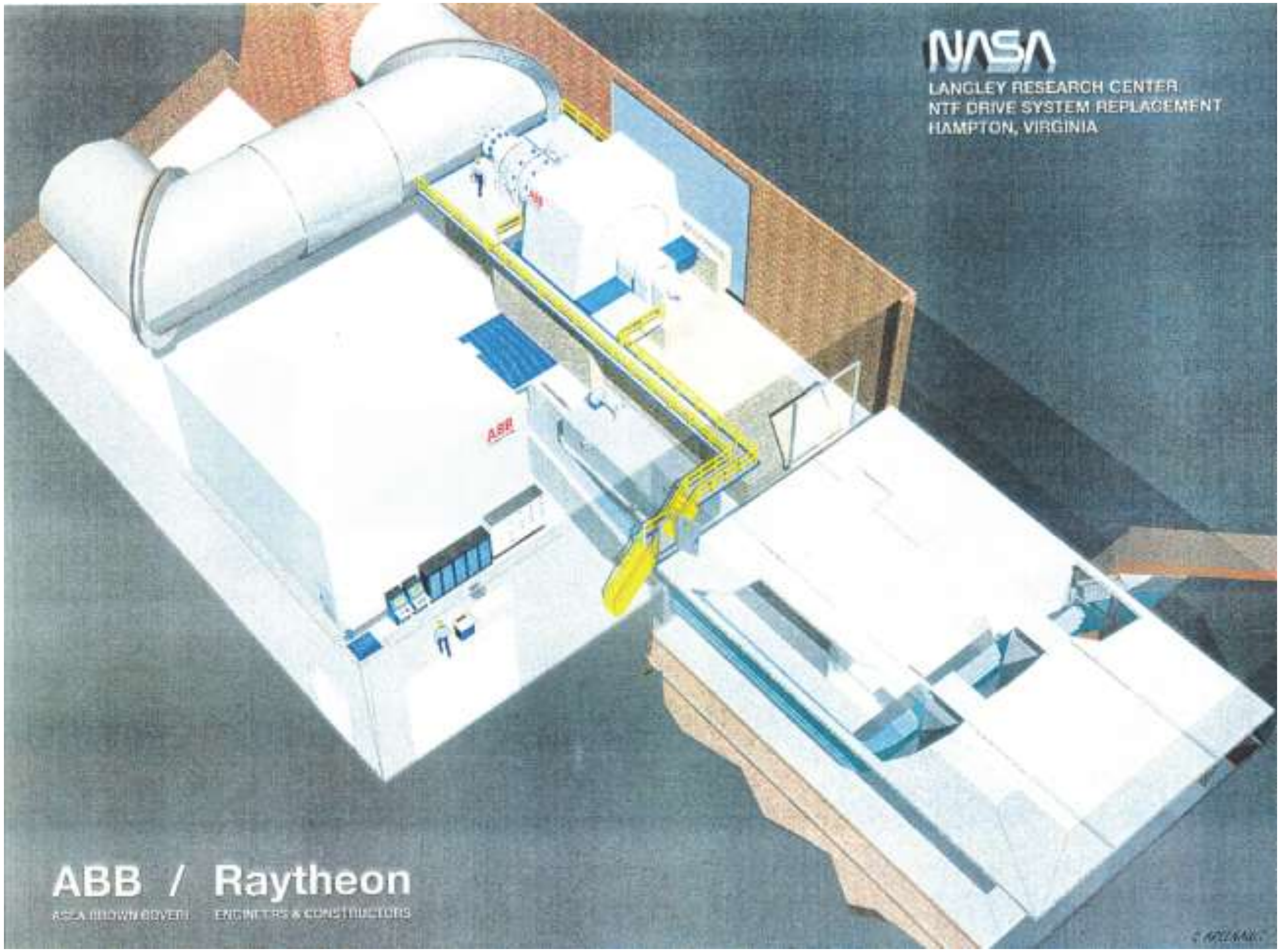
Lower transformer:

Primary star winding 2, secondary delta winding

Primary windings 1 and 2 are connected in parallel

Source: Siemens AG

12-pulse synchronous converter operation of a salient pole synchronous motor (1)



NASA *Langley* Research Center, *Hampton*, *Virginia*, *USA*

Synchronous 12-pole motor as wind tunnel drive

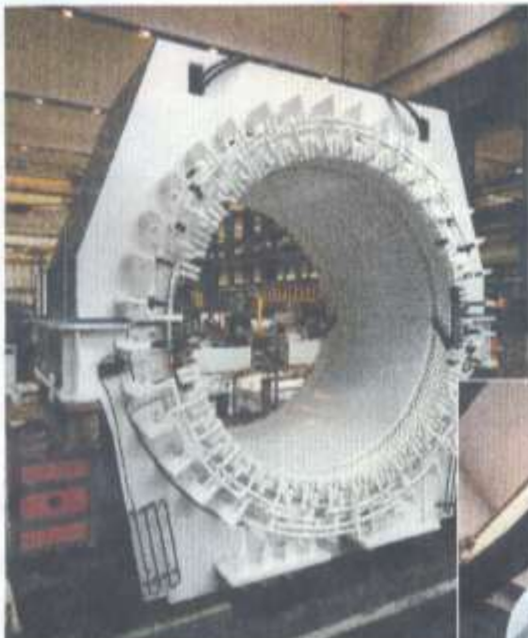
100 MW, two thyristor current source inverters in parallel: 2 x 12.5 kV = 12-pulse operation

36 … 60 Hz
360 … 600/min

Source: ABB, Switzerland

12-pulse synchronous converter operation of a salient pole synchronous motor (2)

NASA Langley Research Center - National Transonic Facility - Drive System



NASA

1 x 100 MW, 2 x 12.5 kV
360 .. 600 rpm

Drive Motor for a Wind Tunnel Fan

Test Section:

Length	:	7.6 m
Area	:	2.5 x 2.5 m
Total Length Windtunnel	:	150 m

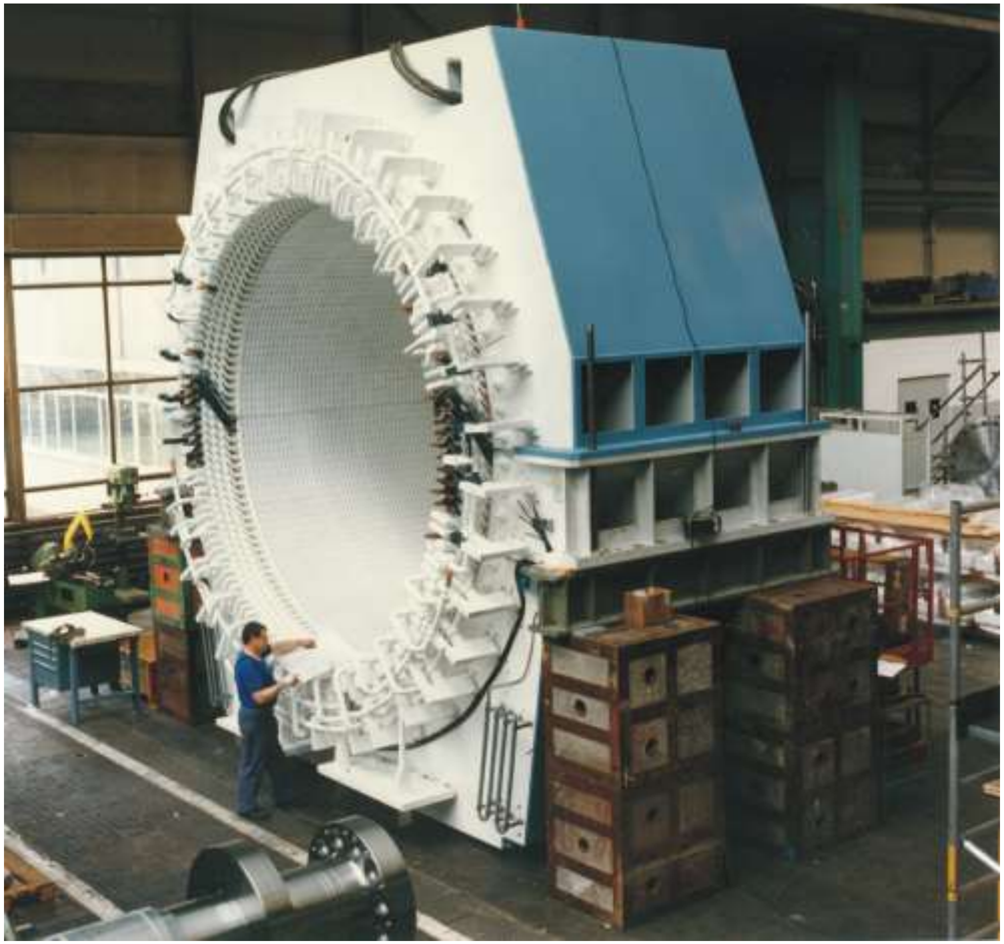
12-pole synchronous salient pole motor

$$n_{syn,max} = f_{s,max}/p = 60/6 = 10/s = 600/min$$

ABB Power Generation Ltd.
KWHT HYDRO_ 1/ 98-09-16/DS

Source: ABB, Switzerland

12-pulse synchronous converter operation of a salient pole synchronous motor (3)



Stator of the 12-pole synchronous salient pole motor

Under construction

Source: ABB, Switzerland

Rotor of the “*Langley*” 12-pole synchronous salient pole motor - under construction


Source: ABB, Switzerland

Summary:

Synchronous converters for synchronous motors

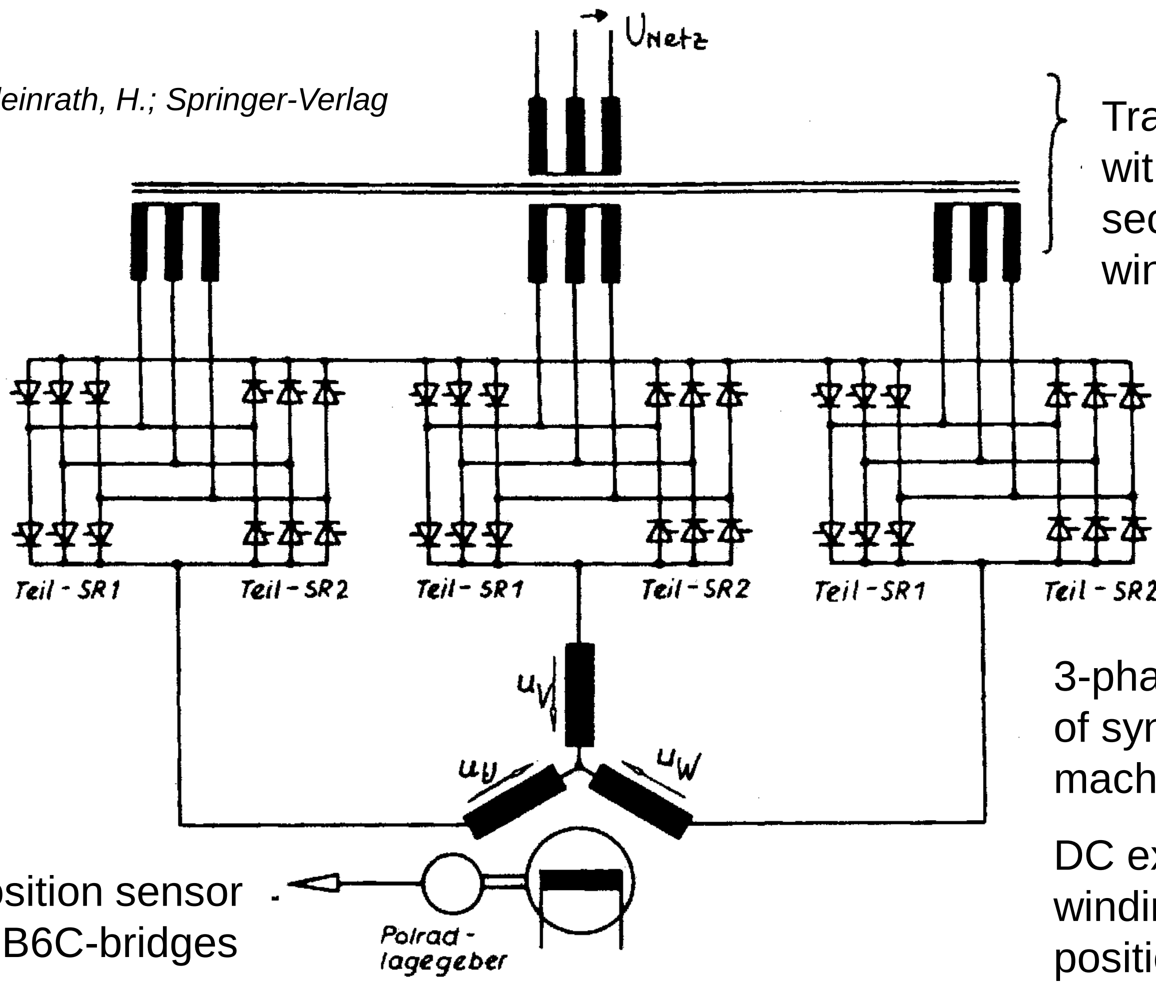
- DC link current source inverter
- Self commutating even with thyristors due to phase shift in over-excited operation, four quadrant operation possible
- Used for big variable speed synchronous machines
- Small sub-transient inductance L_d'' is needed for fast current commutation
  $\Rightarrow$ machine with damper cage and small stator leakage inductance necessary
- For low speed the machine voltage (U_s ~ n) is too low, no motor-side current commutation possible $\Rightarrow$ start-up by line-side switching
- Reduced DC link harmonics with 12-pulse operation = two inverters fed by two 30° phase shifted winding systems from a three-winding transformer (“Yyd”)

6. Wind generators and high power drives

Source: Vestas, Denmark

6.5 Cyclo-converter driven synchronous motors

Source: Kleinrath, H.; Springer-Verlag



Six-pulse bridges B6C

Transformer with 3 secondary windings

2 anti-parallel B6C bridges per phase:

SR1 and SR2

3-phase stator winding of synchronous machine

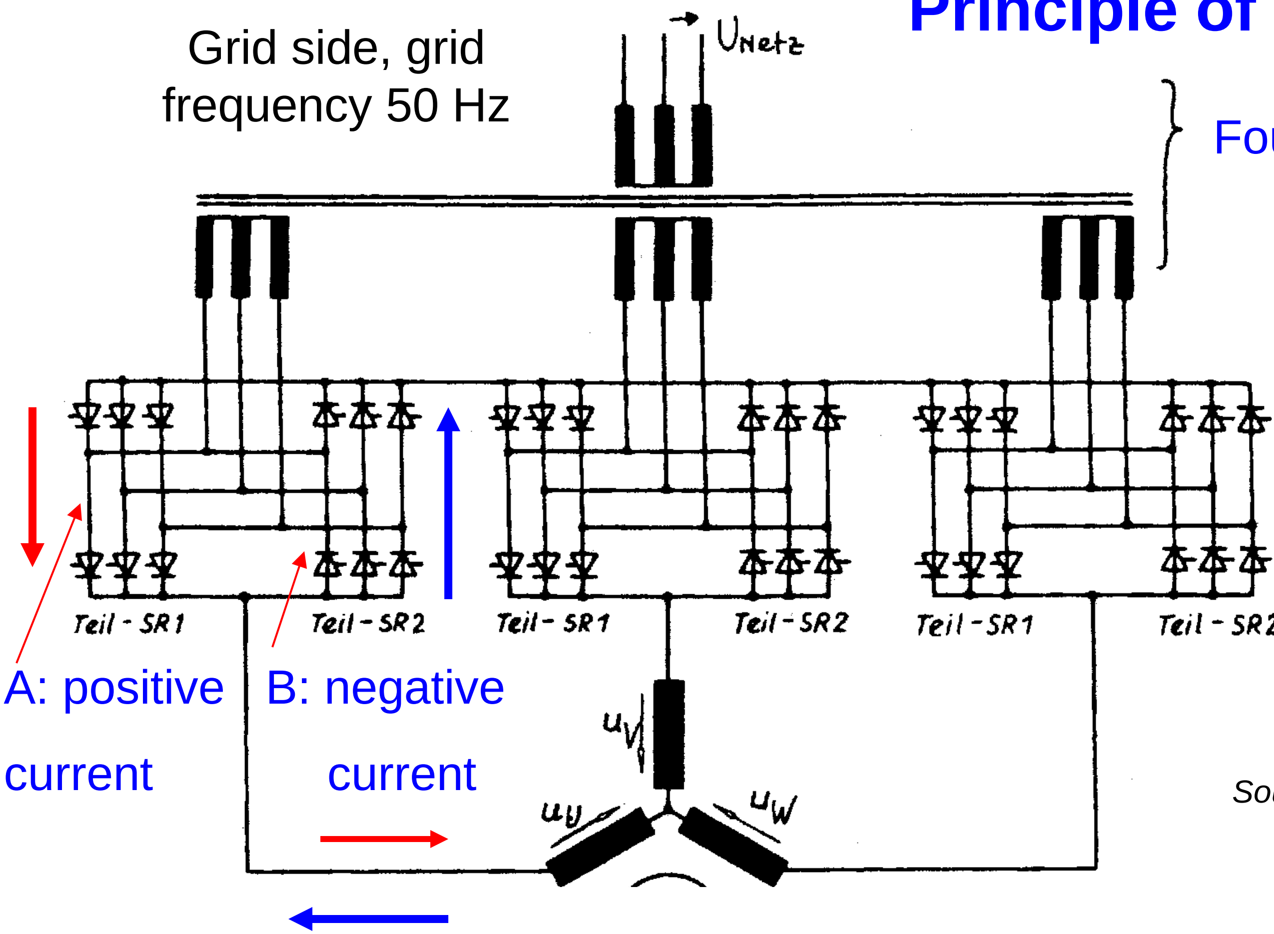
DC excited rotor winding with rotor position sensor

Rotor position sensor controls B6C-bridges

Principle of cyclo-converter

Grid side, grid frequency 50 Hz

Four-winding transformer for feeding the converter



Thyristor controlled anti-parallel rectifier bridges B6C

A: positive current

B: negative current

Source: Kleinrath, H.; Springer-Verlag

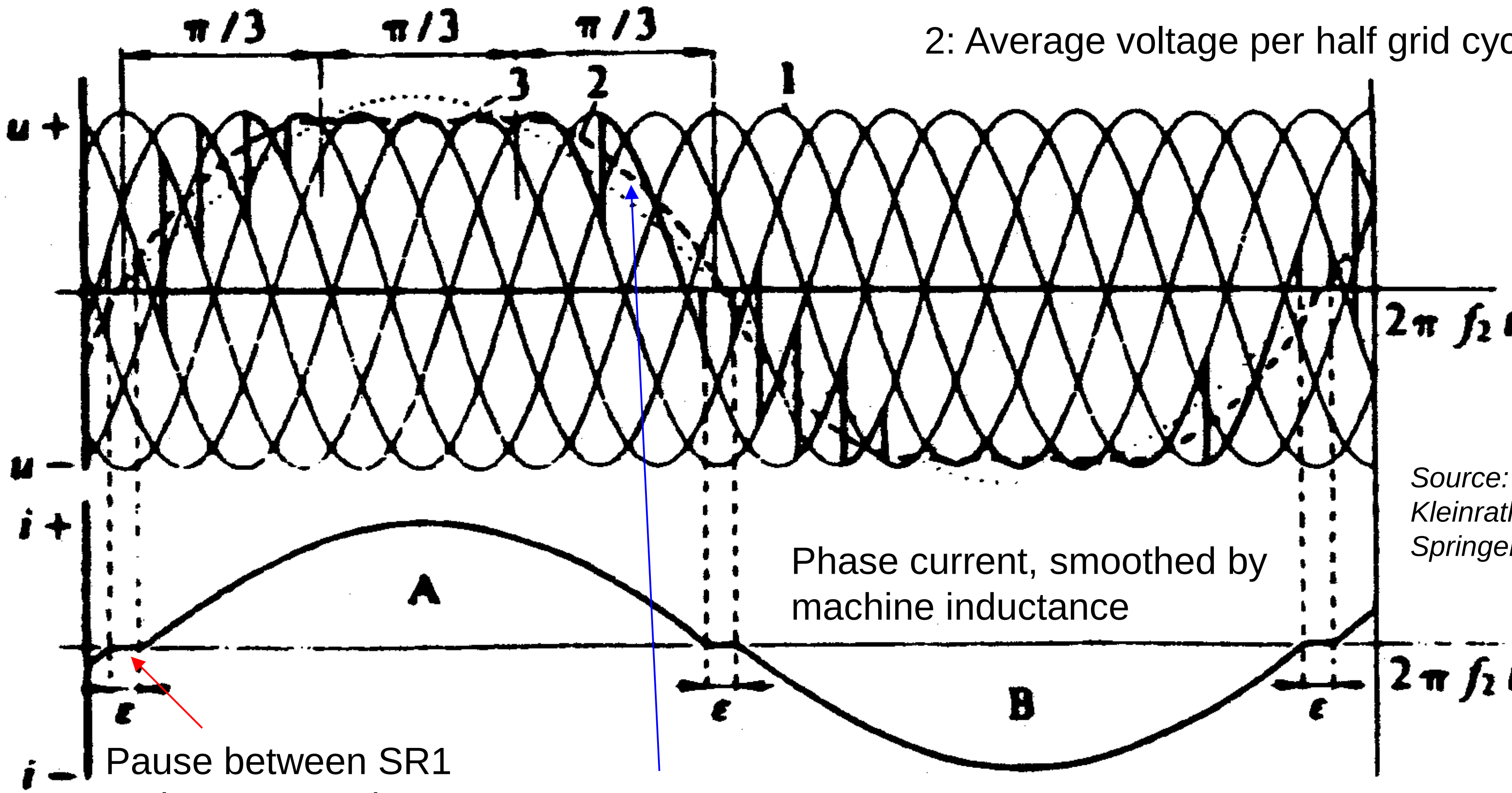
Output frequency f_{out} < 50% of input grid frequency, so well suited for low frequency operation

Current and voltage waveform of cyclo-converter operated synchronous machine

3: *Fourier* fundamental voltage

1: line voltage, bold line: rectified voltage

2: Average voltage per half grid cycle



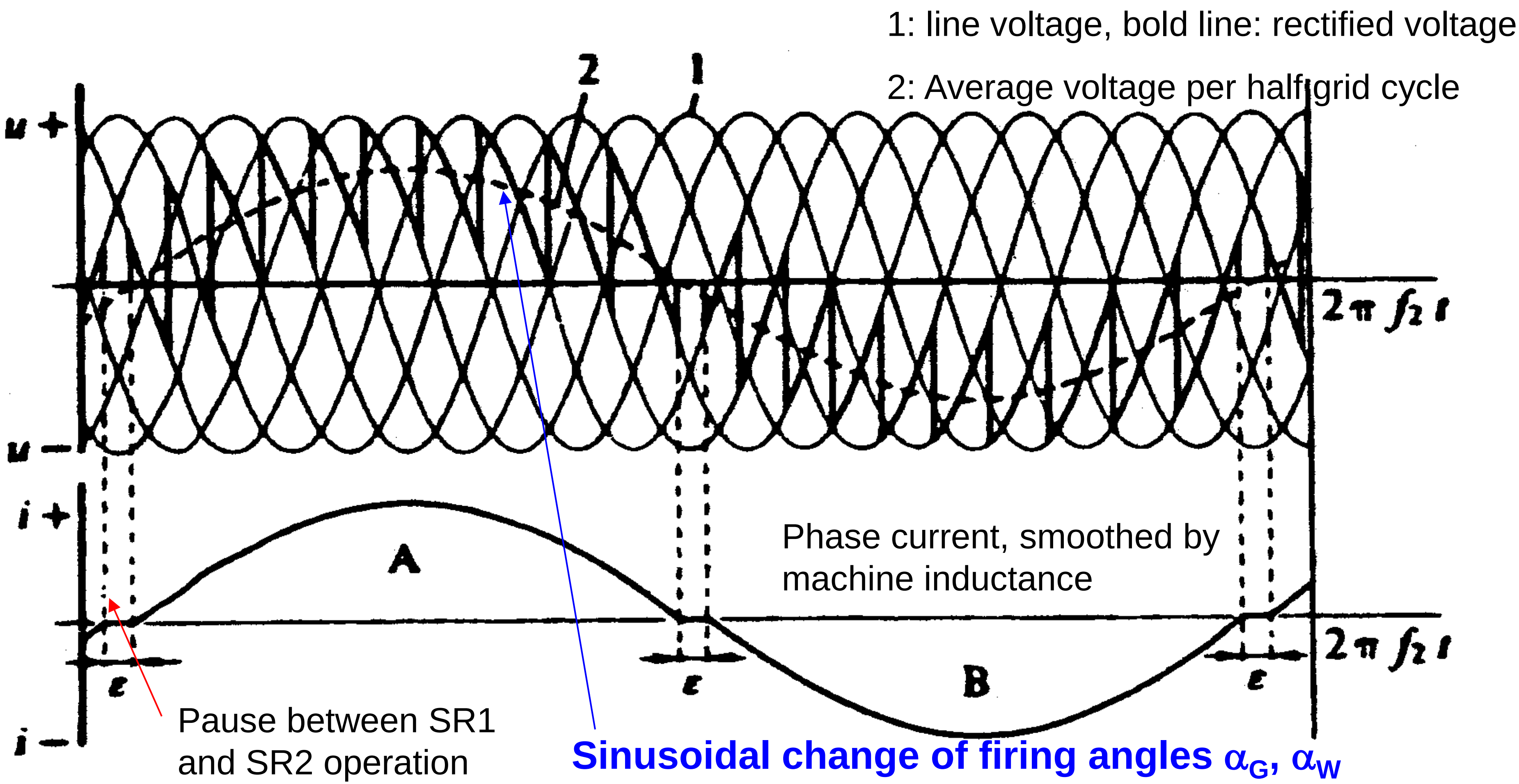
Phase current, smoothed by machine inductance

Pause between SR1 and SR2 operation

Trapezoidal change of firing angles α_G, α_W

Source: Kleinrath, H.; Springer-Verlag

Sinusoidal control of firing angle



Source: Kleinrath, H.; Springer-Verlag

Function of cyclo-converter

- Per phase: Two anti-parallel B6C bridges SR1 and SR2

- SR1 = G: converter rectifies three-phase line voltage: firing angle α_G : $U_{dG} = U_{d0} \cdot \cos(\alpha_G)$ and conducts positive half wave of phase current !
By continuous variation of α_G between $\alpha_{G,max}$ = 90° to $\alpha_{G,min}$ (e.g. = 0°) and back to 90° the voltage varies sinusoidal between zero and maximum voltage and back to zero, thus generating a more or less positive half wave of a new AC voltage ! (OPERATION "A")

- SR2 = W: converter rectifies three-phase line voltage: firing angle α_W : $U_{dW} = U_{d0} \cdot \cos(\alpha_W)$ and conducts negative half wave of phase current !
By continuous variation of α_W between $\alpha_{W,max}$ = 90° to $\alpha_{W,min}$ (e.g. = 0°) and back to 90° the voltage varies sinusoidal between zero and negative maximum voltage and back to zero, thus generating a more or less negative half wave of a new AC voltage ! (OPERATION "B")

- During SR1-operation the anti-parallel bridge SR2 is locked and vice versa. Between positive and negative half wave there is a pause ε, where both SR1 and SR2 are locked !

- This operation is phase shifted by 120° in phase V and by 240° in phase W; thus a new voltage system with variable frequency is generated ! By varying $\alpha_{G,min}$, $\alpha_{W,min}$ the amplitude of voltage is varied, so $U_s \sim f_s$ is possible !

6. Wind generators and high power drives

Control of firing angles

- Trapezoidal change of firing angle leads to nearly trapezoidal phase voltage.

- Sinusoidal change of firing angle leads to nearly sinusoidal phase voltage.

- Trapezoidal control gives a 15% higher fundamental voltage amplitude than sinusoidal one.

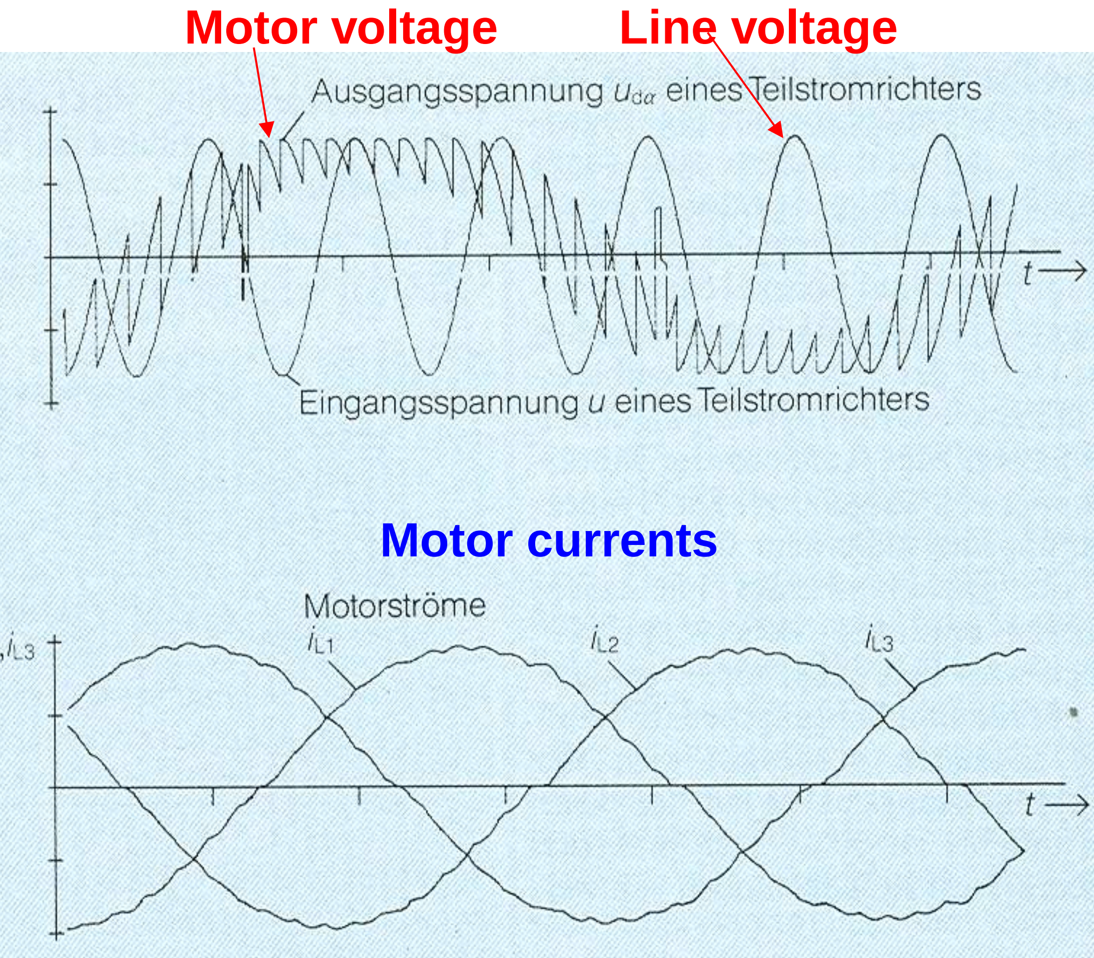
- Grid side frequency f_1 is a multiple of machine side frequency f_2.
  Smallest multiple is $f_1 = 2 f_2$, if a changing of firing angle shall be possible.
  So maximum output frequency has to stay below 50% of input frequency !

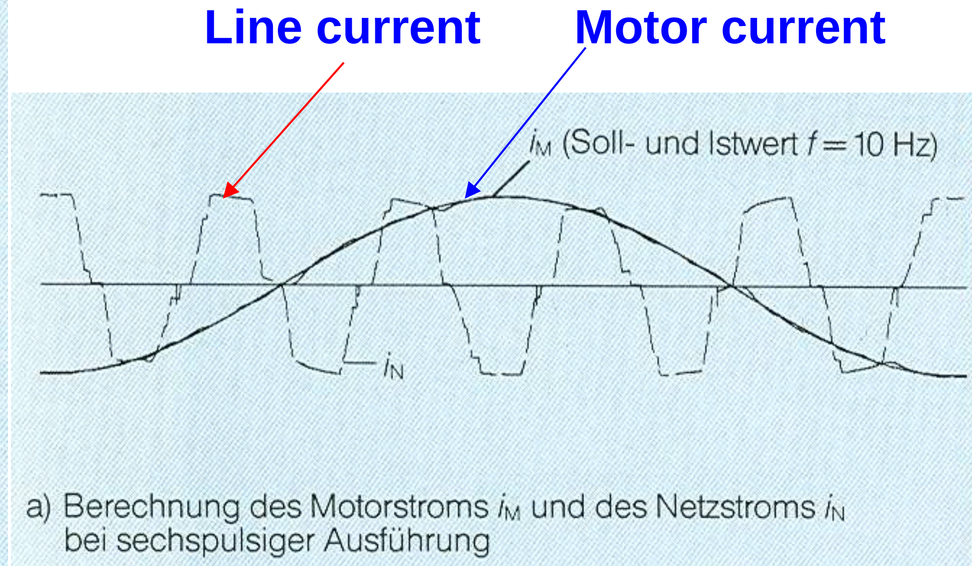
- Cyclo-converter synchronous machines are used for low speed operation: $n = f_2/p$

- **Typical applications:** Mills, grinders, rotating ovens, ship propeller drives, rotor side converters for big slip-ring induction generators:

$f_2 = f_r = s \cdot f_r$, $s_{max} = 0.2 ... 0.3$: e.g. *Goldisthal* power plant, $f_{max} = 5$ Hz

Currents and voltages of cyclo-converter





6-pulse operation, *f* = 10 Hz

Source: Siemens AG

All electric ship - Twin electric POD drive

Synchronous motors inside

Yawing nacelles with integrated synchronous propeller-motors take over the function of the steering unit, being at the same time the propulsion unit (POD drive)

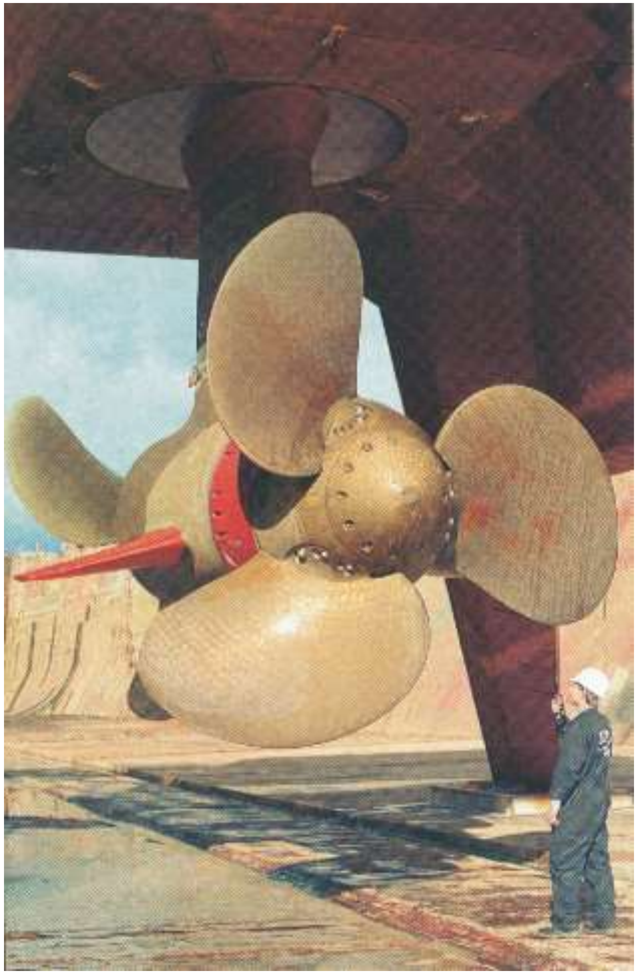
Direct drive gearless propeller motors with cyclo-converter feeding

Variable speed drive

Cruising passenger ship „Elation“: 2 x 14 MW,0...150/min

Source: ABB, Finland

Schottel POD drive with PM synchronous motor



- Double propeller arrangement with front and rear propeller

- Front and rear propeller different to be adjusted to the water flow

- Between the two propellers is the PM synchronous motor arranged:
  with PM inner rotor and PM beneath iron pole shoes

- Two POD drives per ship as direct drives;
  no steering rudder, variable speed drive

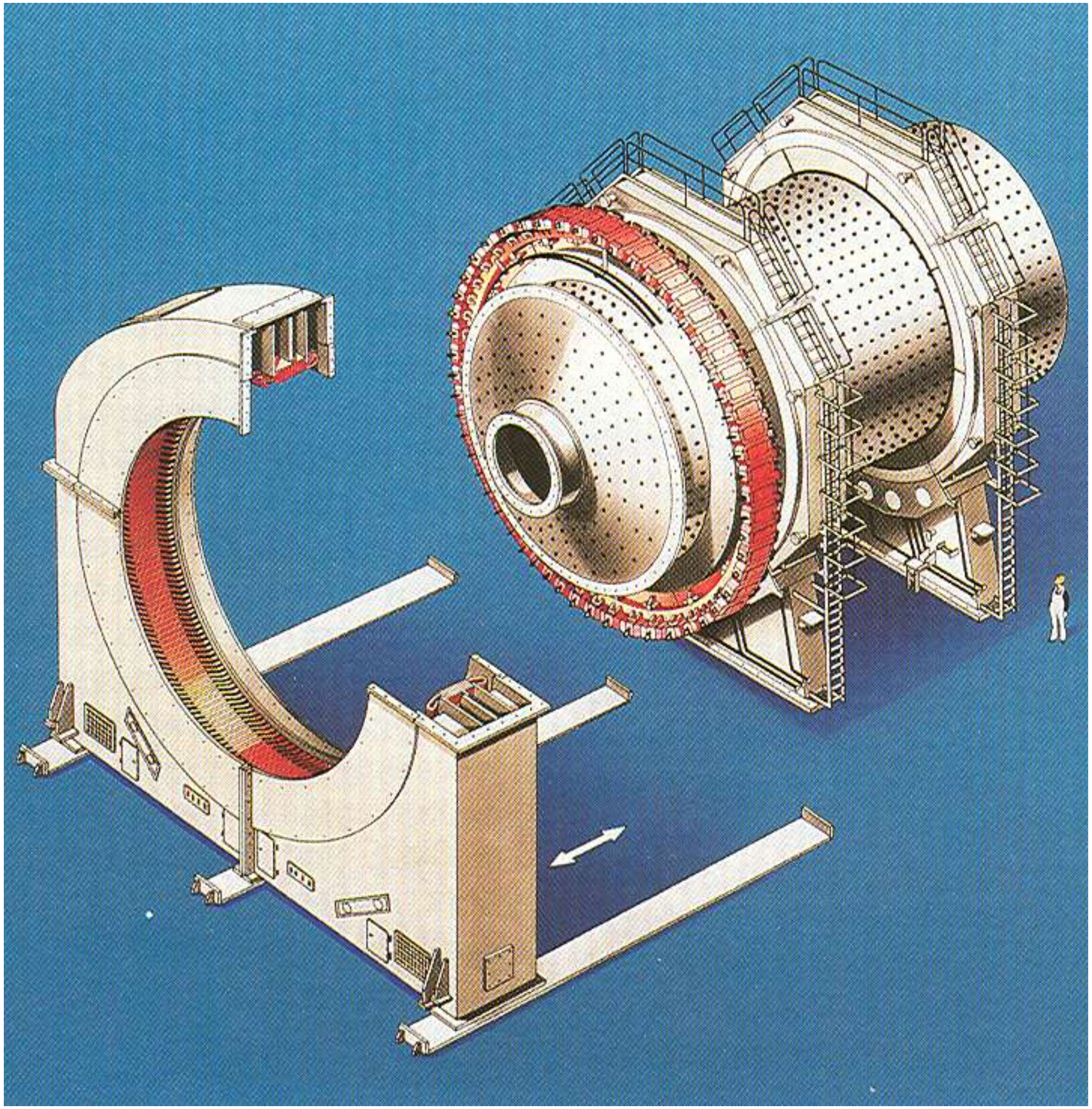
Source: Schottel & Siemens AG, Germany

Cyclo-converter driven synchronous motor for elevator

Rope drum

- Coal mine main elevator
- High-pole count synchronous motor
- 2.65 MW at 47/min
- Rated torque: 538.4 kNm
- Peak torque: 550%: 2.96 MNm !
- Speed control: Redundant tachometer in front visible

Source: Siemens AG



Cyclo-converter driven synchronous ring motor

- Extreme low speed drive for: Coal mill, ore mill, oven for cement production

- High-pole count synchronous motor: e.g. 60 poles at 5 Hz:

n = 5 /min !

-Rotor directly mounted on outer contour of mill or oven = “direct drive”

- Typical data: 12 MW, 11 m diameter (!), 8 … 10 /min

Source: Siemens AG

Summary:

Cyclo-converter driven synchronous motors

- Two antiparallel B6C thyristor bridges for each phase of the 3-phase winding
- Output frequency limited to half of grid frequency = low frequency converter
- Voltage variation by variation of the firing angle α:
    - Sinusoidal change: sinusoidal stator voltage
    - Trapezoidal change: trapezoidal stator voltage, 15 % higher fundamental amplitude
- Typical applications:

a) High torque machines: mills, grinders, rotating ovens, ship propeller drives;

b) Rotor side converter for large doubly-fed induction machines

6. Wind generators and high power drives

Source: Vestas, Denmark

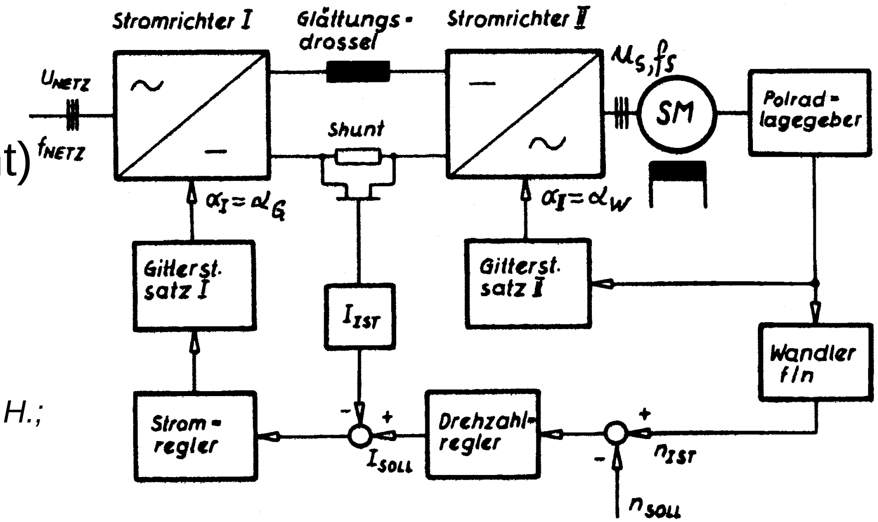
6.6 Harmonic effects in inverter-fed synchronous machines

Line side harmonics in synchronous converter drives:

Firing angle α_G causes line side power factor $\cos\varphi_{Grid} = \cos\alpha_G$, so at low speed (= low DC link voltage U_d = low $\cos\alpha_G$) and full torque (= big current) **reactive power Q** is big, but real power P is low:

$$P = 2\pi \cdot n \cdot M = U_d I_d = 3U_{Grid} I_{Grid} \cos\varphi_{Grid}$$

$$Q = 3U_{Grid} I_{Grid} \sin\varphi_{Grid}$$



Source: Kleinrath, H.; Springer-Verlag

- Grid current is block shaped AC current: It contains current harmonics $I_{grid,k>1}$
Harmonic frequencies: $5f_{Grid}$, $7f_{Grid}$, ... = e.g. 250 Hz, 350 Hz, ...
Harmonics cause distortion of line voltage due to non-linear voltage drop at reactances!

- Machine side AC current is not ideally smoothed in DC link, as DC link choke is not infinitely large. So also on line side small current and voltage harmonics with multiples of machine side frequency occur("**Inter-harmonics**").

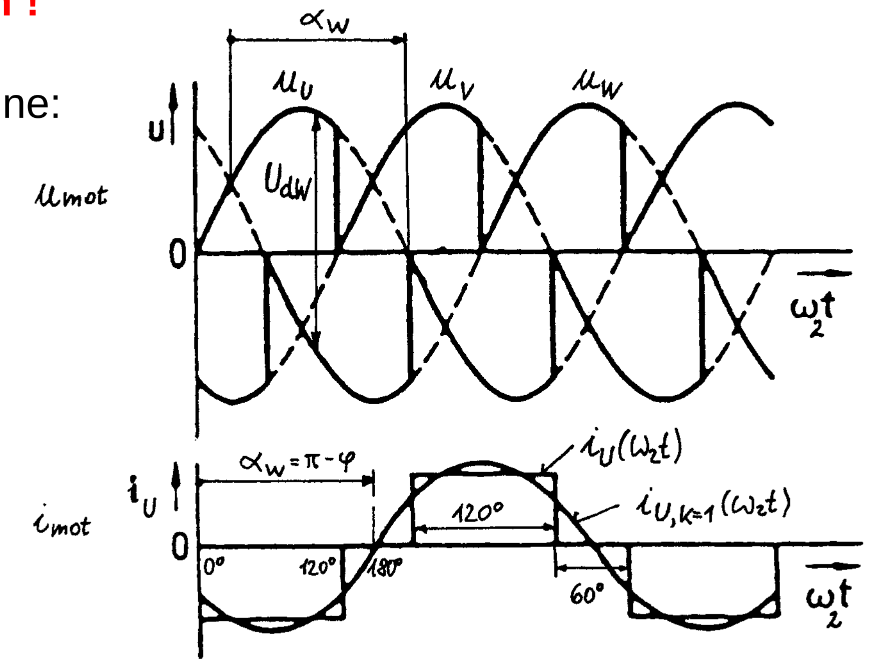
Machine side harmonics in synchronous converter drives

- Only **fundamental of voltage and current** deliver constant torque, thus being responsible for **energy conversion form electric into mechanical system !**

- **Current harmonics** produce **parasitic effects** in the machine:
  - additional losses,
  - pulsating torque components,
  - magnetically excited acoustic noise,
  - radial pulsating forces, causing vibrations !

- By proper design these effects MUST be minimized !

- **FOURIER-analysis** of block shaped current of six-pulse B6C bridge (*P* = 6): Ordinal numbers:



$$k = 1 + P \cdot g = 1 + 6g \qquad g = 0, \pm 1, \pm 2, \pm 3, \ldots$$

$$k = +1, -5, +7, -11, +13, -17, +19, \ldots$$

$$I_{s,k} = \frac{4}{\pi \cdot k} \cdot \sin\left(\frac{k \cdot \pi}{3}\right) \cdot I_d$$

Source: Kleinrath, H.; Springer-Verlag

positive / negative *k*: phase sequence is U, V, W or U, W, V (**inverse fields)**

Inverse air gap fields

Fundamental $|k| = 1$: $i_U = \hat{I}_1 \cos(\omega_s t)$,

$i_V = \hat{I}_1 \cos(\omega_s t - 120°)$, $i_W = \hat{I}_1 \cos(\omega_s t - 240°)$

Harmonic $|k| = 5$: $i_U = \hat{I}_5 \cos(5\omega_s t)$,

$i_V = \hat{I}_5 \cos(5\omega_s t - 5 \cdot 120°) = \hat{I}_5 \cos(5\omega_s t - 240°)$

$i_W = \hat{I}_5 \cos(5\omega_s t - 5 \cdot 240°) = \hat{I}_5 \cos(5\omega_s t - 120°)$

Field wave of ν^{th} order of current harmonic *k* : $\hat{B}_{\nu=1,k=1} \cos(\frac{\nu\pi x}{\tau_p} - k\omega_s t)$

Ordinal number ν of wave harmonic, determined by winding arrangement (phase number *m* = 3): $\nu = 1 + 2mg = 1, -5, +7, ...$

Speed of wave: $\Omega_{\nu,k} = \frac{k \cdot \omega_s}{\nu \cdot p}$ Amplitude of wave: $\hat{B}_{\nu=1,k=1} = \frac{\mu_0}{\delta} \cdot \frac{\sqrt{2} \cdot m \cdot N_s \cdot k_{w\nu} \cdot I_{s,k}}{\pi \cdot p \cdot \nu}$

Positive or negative speed is determined by sign of ν and *k* .

Calculated speed of field harmonics $\Omega_{\nu,k}$ (100% = fundamental)

ν	1	-5	7	-11	13	-17	19	...
k								
1	**+100%**	-20%	+14.3%	-9%	+7.7%	-5.9%	+5.3%	...
-5	-500%	+100%	-71.4%	+45.5%	-38.5%	29.4%	-26.3%	...
7	+700%	-140%	+100%	-63.6%	53.8%	-41.2%	+36.8%	...
-11	-1100%	+220%	-157%	100%	-84.6%	+64.7%	-57.9%	...
...	...	...	...	...	...	...	...	...

Calculated current harmonic amplitudes $I_{s,k}$ (1.0 = fundamental)

k	1	-5	7	-11	13
$I_{s,k} / I_{s,k=1}$	**1.0**	0.2	0.14	0.09	0.08

Magnitude of current and field harmonics

- Amplitude of field harmonics $B_{\nu,k}$ decrease with $k_{w\nu}/\nu < 1/\nu$ due to winding distribution.

- Amplitude of field harmonics $B_{\nu,k}$ is proportional $I_{s,k}$, so they decrease with $1/k$.

Result:
Field amplitudes decrease with $$B_{\nu,k} \sim \frac{1}{\nu \cdot k}$$

- Usually consideration of winding m.m.f. fundamentals $\nu = 1$ is sufficient !

- First (and second) pair of current harmonics has to be considered !

- In $P = 12$ pulse bridge converters the 5th and 7th current harmonic are eliminated: $k = 1 + P \cdot g = 1 + 12g$

$$k = +1, -11, +13, -23, +25, \ldots$$

Eddy current losses in stator winding due to current harmonics

- Increased r.m.s. value of current is only small effect in loss increase: $I_s = \sqrt{\sum_{k=1}^{\infty} I_{s,k}^2} > I_{s,1}$
- Stator frequencies: f_s, $k \cdot f_s$: Small current harmonic amplitudes, but big frequencies, so **increased current displacement effect**, causing additional losses P_{ad} in stator winding.

- Counter-measures:

- Reduced conductor height and reduced height of strands
- Reduction of ESSON´s number = reduced utilization by about 5% ... 10%.

Example:

- Current loading $A \sim I_s$ reduced by 5%, flux density $B_{\delta 1}$ reduced by 5%.
- ESSON´s number C ~ $A \cdot B_{\delta 1}$ reduced by 10% = reduced motor power by 10%
- Reduced fundamental copper losses $P_{Cu} \sim I_s^2$ by 10% and iron losses $P_{Fe} \sim B_{\delta 1}^2$ by 10%.

- Reduced losses $P_{Cu} + P_{Fe}$ at 90% power balance for increased current displacement losses P_{ad} , so winding temperature rise is the same as at sinus operation, 100% power.

Additional rotor losses due to field harmonics

- Current harmonics generate air gap fields ($\nu = 1$) with amplitude $B_{\nu=1,k}$.
- Positive sequence fields: k = 7, 13, ... , inverse fields: k = -5, -11, ...
  Field wave velocity relative to rotor velocity:

$$\Omega_{rel} = \frac{k}{\nu} \cdot \frac{\omega_s}{p} - \Omega_{syn} = \frac{\omega_s}{p} \cdot \left(\frac{k}{\nu} - 1 \right) \quad \Rightarrow \quad \nu = 1: \quad \Omega_{rel} / \Omega_{syn} = k - 1$$

k	1	-5	7	-11	13	-17	19
$k - 1$	0 *)	-6	6	-12	12	-18	18

Waves induce massive rotor surface with frequencies for $k = 1+6g$: $6f_s$, $12f_s$, $18f_s$, ... , causing big eddy current losses.

***) fundamental does not induce rotor**

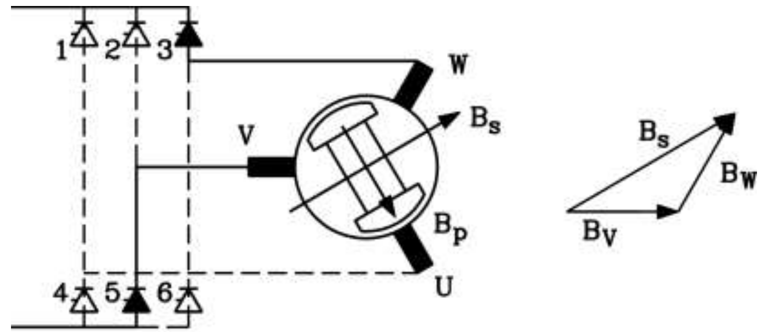
Counter-measures:

- Strong damper winding to be induced by field waves, causing counter fields by damper currents, which nearly eliminate stator harmonic fields. Massive iron is not induced, losses in high conductive damper bars are low.

- Laminated rotor pole shoes or body (if possible due to low centrifugal forces !)

Pulsating torque components in synchronous converter drives

- Block shaped stator current I_s causes six step movement of stator field B_s and stator current loading A_s.
- Continuously rotating rotor flux B_p (sinusoidal distributed) generates with stator current loading A_s a constant torque M_e and **a small loading pulsating torque M_{AC}, which oscillates with mainly $6f_s$, $12f_s$, $18f_s$, ...**

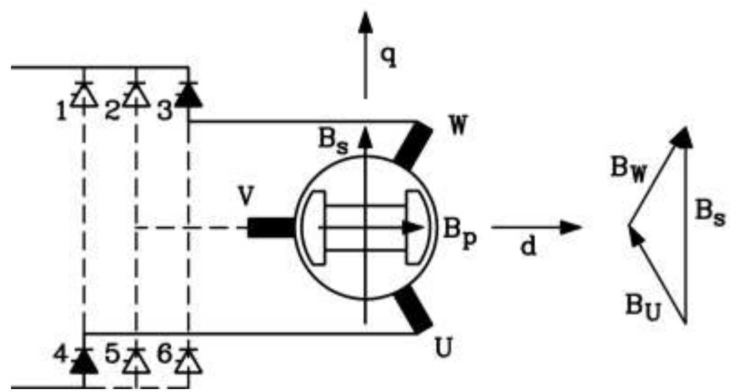


Typical torque AC amplitudes: **$6f_s$**: $\hat{M} / M_N = 0.15$

$12f_s$: $\hat{M} / M_N = 0.05$

- Counter-measures:

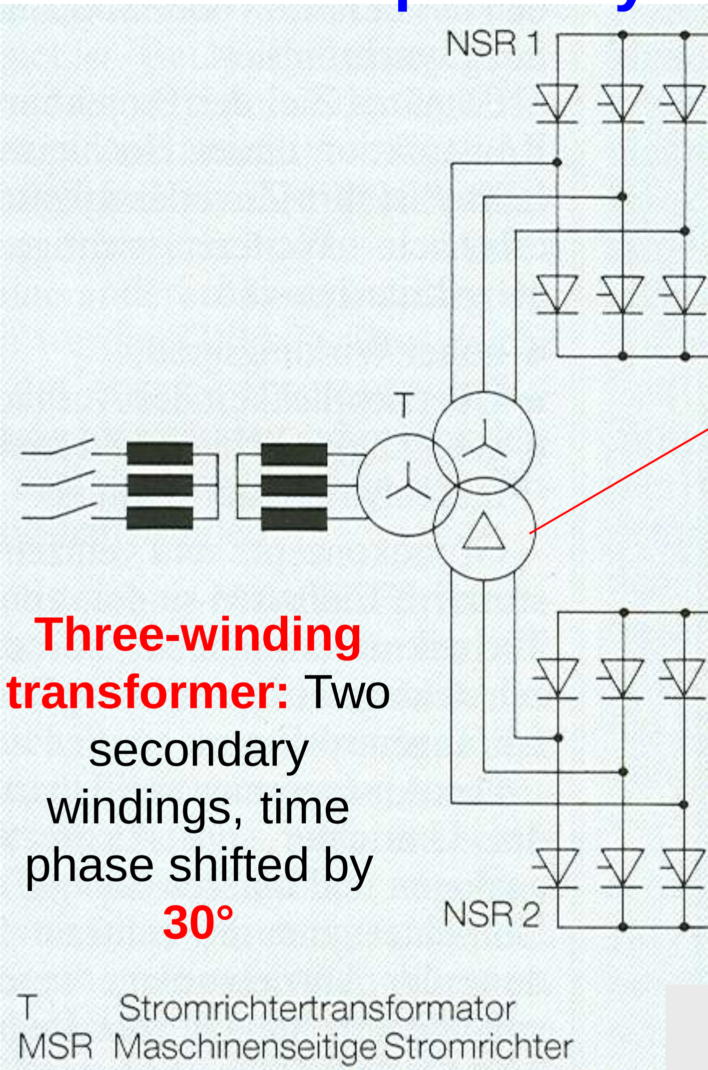
a) 12 pulse bridges eliminate **$6f_s$, $18f_s$, $30f_s$, ...**



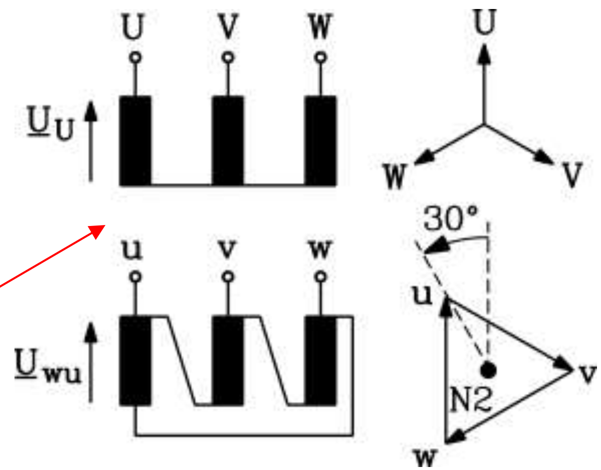
b) Try to put torsion natural frequencies f_d of drive train out of the speed range, where the frequencies **$6f_s$, $18f_s$, $30f_s$, ... = $6n{\cdot}p$, $12n{\cdot}p$, $18n{\cdot}p$, ...** do not hit the natural frequencies = AVOID RESONANCES !

Source: Kleinrath, H.; Springer-Verlag

12-pulse synchronous converter machine



Three-winding transformer: Two secondary windings, time phase shifted by **30°**



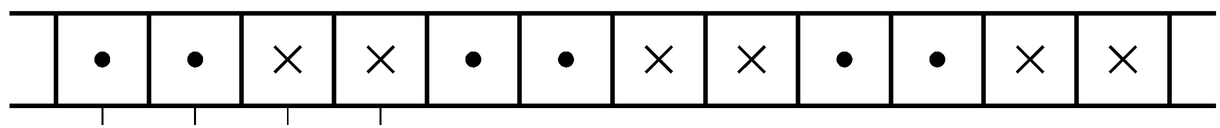
Star-delta-winding transformer:

Time phase of secondary shifted by **30°**

$$\ddot{u} = \frac{U_{1verk}}{U_{2verk}} = \frac{\sqrt{3}U_1}{U_2} = \sqrt{3}\cdot\frac{N_1}{N_2}$$

In the machine: 2 x 3 phases, shifted by $\tau_p/6$ = 30°el :

+U1 +U2 –W1 -W2 +V1 +V2 –U1 –U2 +W1 +W2 –V1 –V2



Source: Siemens AG, Germany

2 x B6C bridges feeding = 12-pulse operation

- **Elimination** of magnetic air gap fields due to -5th, 7th, -17th, 19th, … current harmonics

- *Example:* Fundamental field of 5th current harmonic:

1st 3-phase system: $B_{\nu=1,k=-5}(x,t) = B_{\delta,1,-5} \cdot \cos(x\pi/\tau_p + 5\omega_s t)$

2nd 3-phase system: Space shift by $2\tau_p/12 = \tau_p/6$, time shift by $T/12$

$$B_{\nu=1,k=-5}(x,t) = B_{\delta,1,-5} \cdot \cos((x-\tau_p/6)\cdot\pi/\tau_p + 5\omega_s(t - T/12))$$

$$B_{\nu=1,k=-5}(x,t) = B_{\delta,1,-5} \cdot \cos(x\cdot\pi/\tau_p - \pi/6 + 5\omega_s t - 5\pi/6)$$

$$B_{\nu=1,k=-5}(x,t) = B_{\delta,1,-5} \cdot \cos(x\cdot\pi/\tau_p + 5\omega_s t - \pi)$$

$$B_{\nu=1,k=-5}(x,t) = -B_{\delta,1,-5} \cdot \cos(x\cdot\pi/\tau_p + 5\omega_s t)$$

Sum of fundamental of 1st and 2nd 3-phase system yields ZERO !

Harmonic effects in cyclo-converter drives

- Low speed drives, so stator frequency $f_s = n \cdot p$ and so additional losses are low.

Example: Eddy currents in stator winding

Cyclo-converter: *Sinus operation: 60 Hz*

a) f_s = 5.5 Hz: 100% current

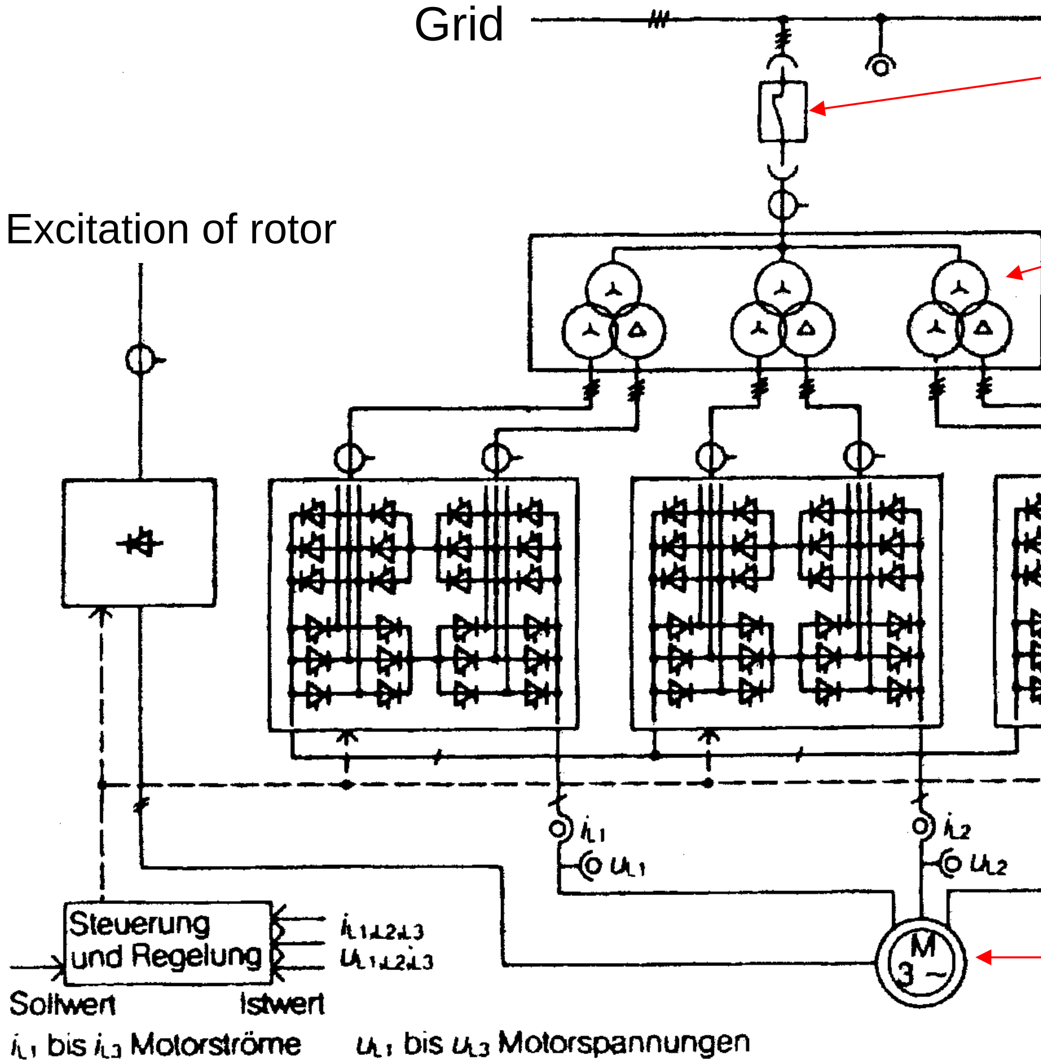
b) $5f_s$ & $7f_s \cong 6f_s$ = 33 Hz: 20% current

c) $11f_s$ & $13f_s \cong 12f_s$ = 66 Hz: 10% current 60 Hz: 100 % current

- Effect is much smaller than for 50/60 Hz machines !
  So ESSON´s number may be increased !

- Often no damper cage, as rotor frequencies $6f_s$, $12f_s$, ..= 33 Hz, 66 Hz, ... are low.
  Missing damper cage:
  Instead of subtransient inductance L''_d the transient inductance $L'_d > L''_d$ acts during commutation, hence smoothing the current = reduces the current harmonics !

12 pulse bridges 2xB6C for cyclo-converter



High voltage switch

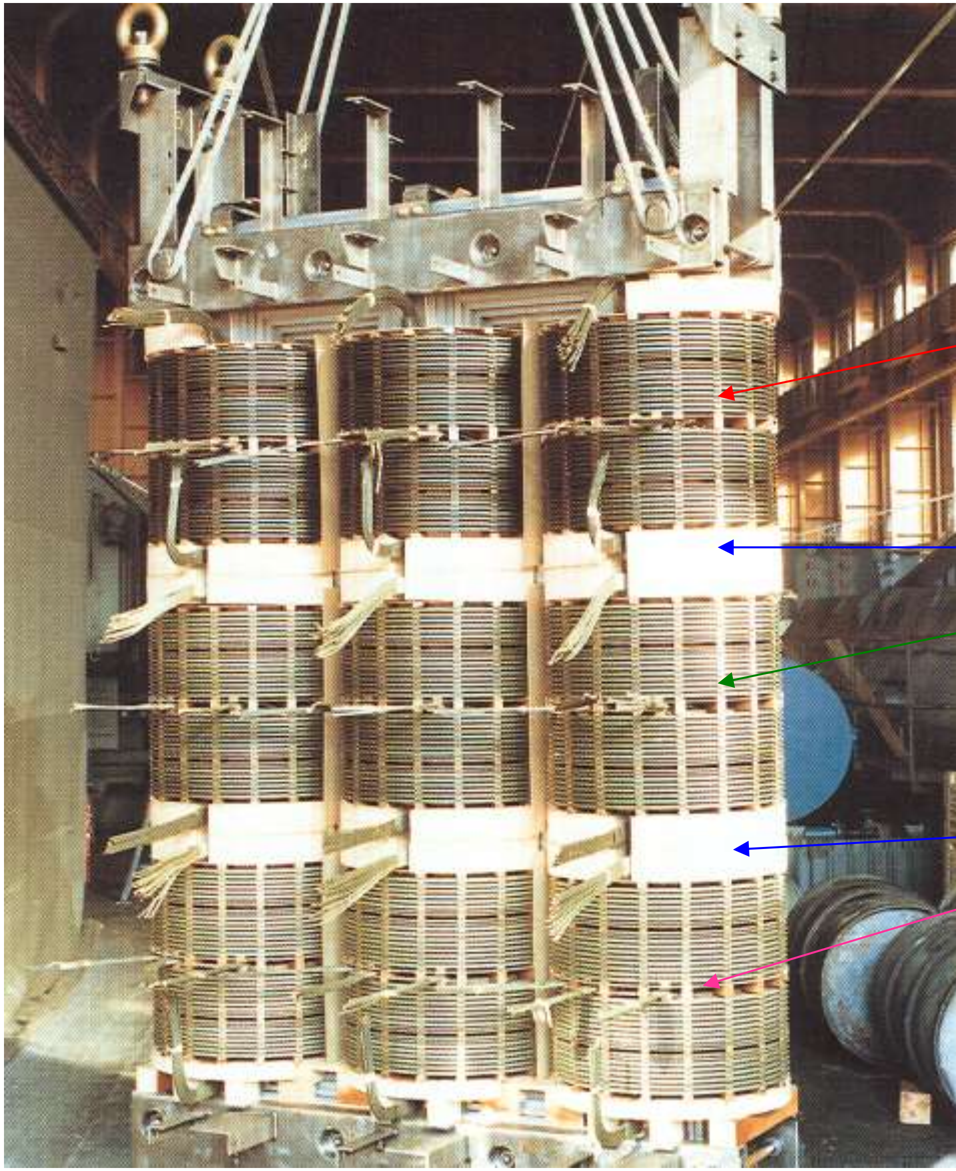
Transformer with 6 secondary windings. Each phase: Y and D secondary, so 30° phase shift between the to series 2xB6C bridges, giving 12 pulse operation !

12 pulse cyclo-converter to reduce voltage and current harmonics

Synchronous machine

Source: Siemens AG

Source: Siemens AG



Transformer with 6 secondary windings for 12-pulse cyclo-converter

21 MW, Drive for wind tunnel

Upper transformer:

Primary star winding 1,
Two secondary windings: a) star, b) delta

Inter-yoke to decouple the three converter phases

Middle transformer:

Primary star winding 2´,
Two secondary windings: a) star, b) delta

Inter-yoke to decouple the three converter phases

Lower transformer:

Primary star winding 3,
Two secondary windings: a) star, b) delta

Primary windings 1, 2, 3 are parallel connected

Summary:

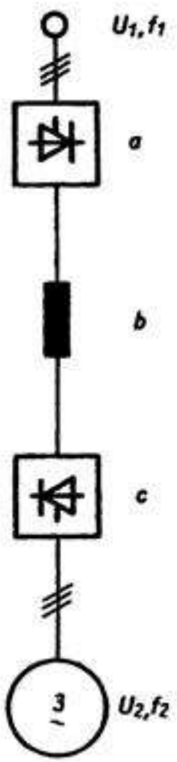
Harmonic effects in inverter-fed synchronous machines

- Grid current harmonics due to block shaped AC current
- Inter-harmonics of machine side current due to finite size of DC link choke
- Parasitic effects in the machine: additional losses, pulsating torque components, magnetically excited acoustic noise, radial pulsating forces
- 12-pulse converters: 5^{th} and 7^{th} current harmonic are eliminated
- Due to harmonic frequencies $\Rightarrow$ increased current displacement effect
  $\Rightarrow$ Reduction of conductor height or of machine utilization necessary
- Additional rotor losses due to eddy currents, induced by field harmonics
  $\Rightarrow$ Counter-measures: strong damper to eliminate stator harmonic field waves; laminated rotor pole shoes if possible
- Cyclo-converter drives: Low stator frequencies $\Rightarrow$ low additional losses; utilization may be increased; often no damper cage necessary

6. Wind generators and high power drives

Source: Vestas, Denmark

6.7 Synchronous generators with high voltage DC link



AC Grid e.g. *Johannesburg*

Inverter station

High voltage DC overhead line (HV DC) e.g. 1400 km

Rectifier station at *Cabora Bassa*

Synchronous hydro generators

Source: Neidhöfer, G.; BBC, Switzerland

- HV DC transmission: Only real power is transmitted, NO reactive power !
- Current harmonics in generators are basically the same as in synchronous converter systems, BUT rectifier and inverter are of high pulse count, so harmonic current content is very low !

Examples:

a) ***Cabora Bassa***
5 x 415 MW,
HV DC via 1400 km to *Johannesburg, South Africa*

b) ***Itaipu***
9 x 700 MW,
HV DC via 800 km from Brazilian border (river *Parana*) to coast !

Summary:

Synchronous generators with high voltage DC link

- DC: Only real power transmission
- Very low harmonic current content due to high pulse count of rectifier and inverter

6. Wind generators and high power drives

Source: Vestas, Denmark

6. Wind generators and high power drives

Variable speed pump storage plants

Variable speed pump storage power plant

- Feeding water into the upper basin (elevation *h* above lower basin) needs to overcome the static pressure $\Delta p = \rho \cdot g \cdot h = \Delta p_N$

- Pump characteristic at rated speed n_N:

  Δp: generated pressure, $\dot{V}$: actual volume flow

  Δp_0: no-load pressure, $\dot{V}_0$: short-circuit volume flow

$$\frac{\Delta p}{\Delta p_0} = 1 - \frac{\dot{V}^2}{\dot{V}_0^2}$$

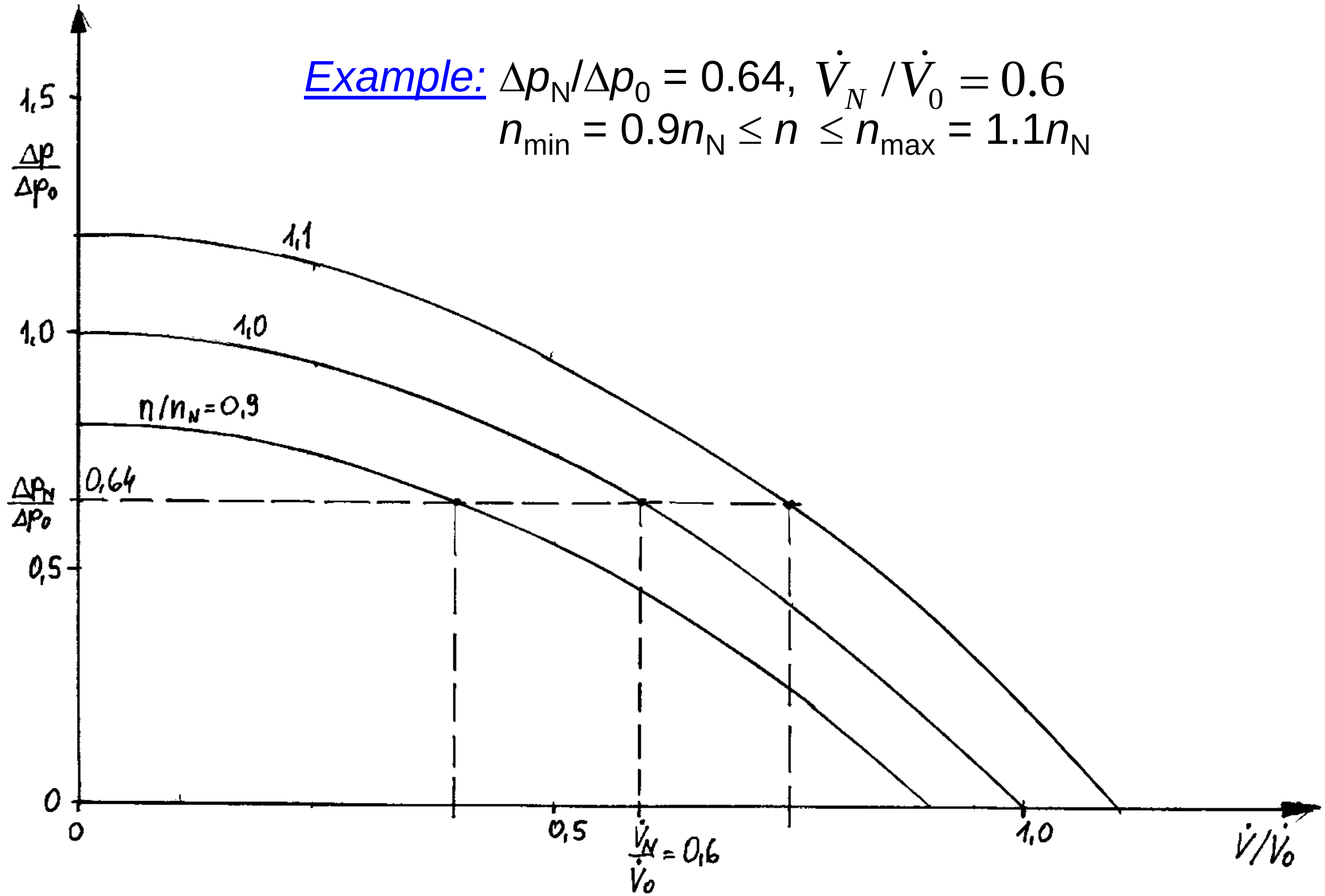
- As $\Delta p \sim n^2$ and $\dot{V} \sim n$, we get the pump characteristic at variable speed *n*:

$$\frac{\Delta p}{\Delta p_0} = \frac{n^2}{n_N^2} - \frac{\dot{V}^2}{\dot{V}_0^2}$$

Fixed and variable speed pump characteristic

Example: $\Delta p_N/\Delta p_0 = 0.64$, $\dot{V}_N/\dot{V}_0 = 0.6$

$n_{min} = 0.9 n_N \le n \le n_{max} = 1.1 n_N$



$$\frac{\Delta p}{\Delta p_0} = 1 - \frac{\dot{V}^2}{\dot{V}_0^2}$$

$$\frac{\Delta p}{\Delta p_0} = \frac{n^2}{n_N^2} - \frac{\dot{V}^2}{\dot{V}_0^2}$$

Fixed and variable speed pumping

In case of a fixed speed pump at rated speed only rated power can be pumped, as the pressure to overcome is fixed as the rated pressure Δp_N.

$$\frac{\Delta p}{\Delta p_0} = 1 - \frac{\dot{V}^2}{\dot{V}_0^2} \qquad \frac{\Delta p_N}{\Delta p_0} = 1 - \frac{\dot{V}_N^2}{\dot{V}_0^2} \qquad P = P_N = \Delta p_N \cdot \dot{V}_N$$

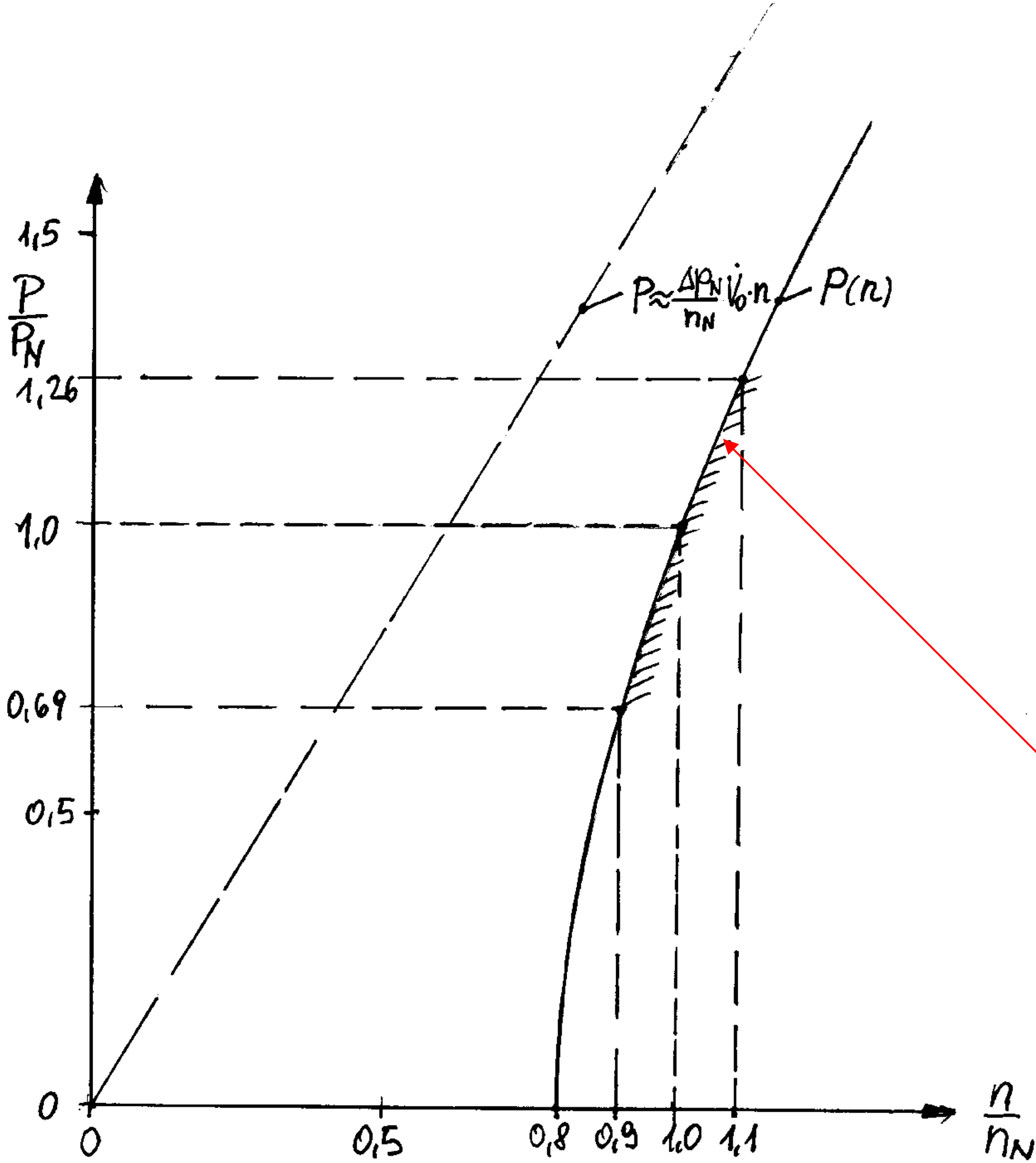
In case of a variable speed pump even at fixed rated pressure Δp_N the volume flow can be varied with speed, so the pump can be operated at variable power.

$$\frac{\Delta p}{\Delta p_0} = \frac{n^2}{n_N^2} - \frac{\dot{V}^2}{\dot{V}_0^2} \qquad \frac{\dot{V}}{\dot{V}_0} = \sqrt{\frac{n^2}{n_N^2} - \frac{\Delta p_N}{\Delta p_0}} \qquad P = \Delta p_N \cdot \dot{V}(n)$$

Example: $\Delta p_N/\Delta p_0 = 0.64$, $\dot{V}_N / \dot{V}_0 = 0.6$ $\qquad n_{min} = 0.9 n_N \le n \le n_{max} = 1.1 n_N$

The power $P = \Delta p_N \cdot \dot{V}$ ranges between $P_{min} = 0.69 P_N \le P \le P_{max} = 1.26 n_N$

Pumping power at variable speed pumping



Example: $\dot{V}_N / \dot{V}_0 = 0.6$

$\Delta p_N / \Delta p_0 = 0.64$,

$n_{min} = 0.9 n_N \le n \le n_{max} = 1.1 n_N$

The power $P = \Delta p_N \cdot \dot{V}$ ranges between:

$P_{min} = 0.69 P_N \le P \le P_{max} = 1.26 P_N$

$$P = \Delta p_N \cdot \dot{V}(n)$$

$$\frac{\dot{V}(n)}{\dot{V}_0} = \sqrt{\frac{n^2}{n_N^2} - \frac{\Delta p_N}{\Delta p_0}}$$

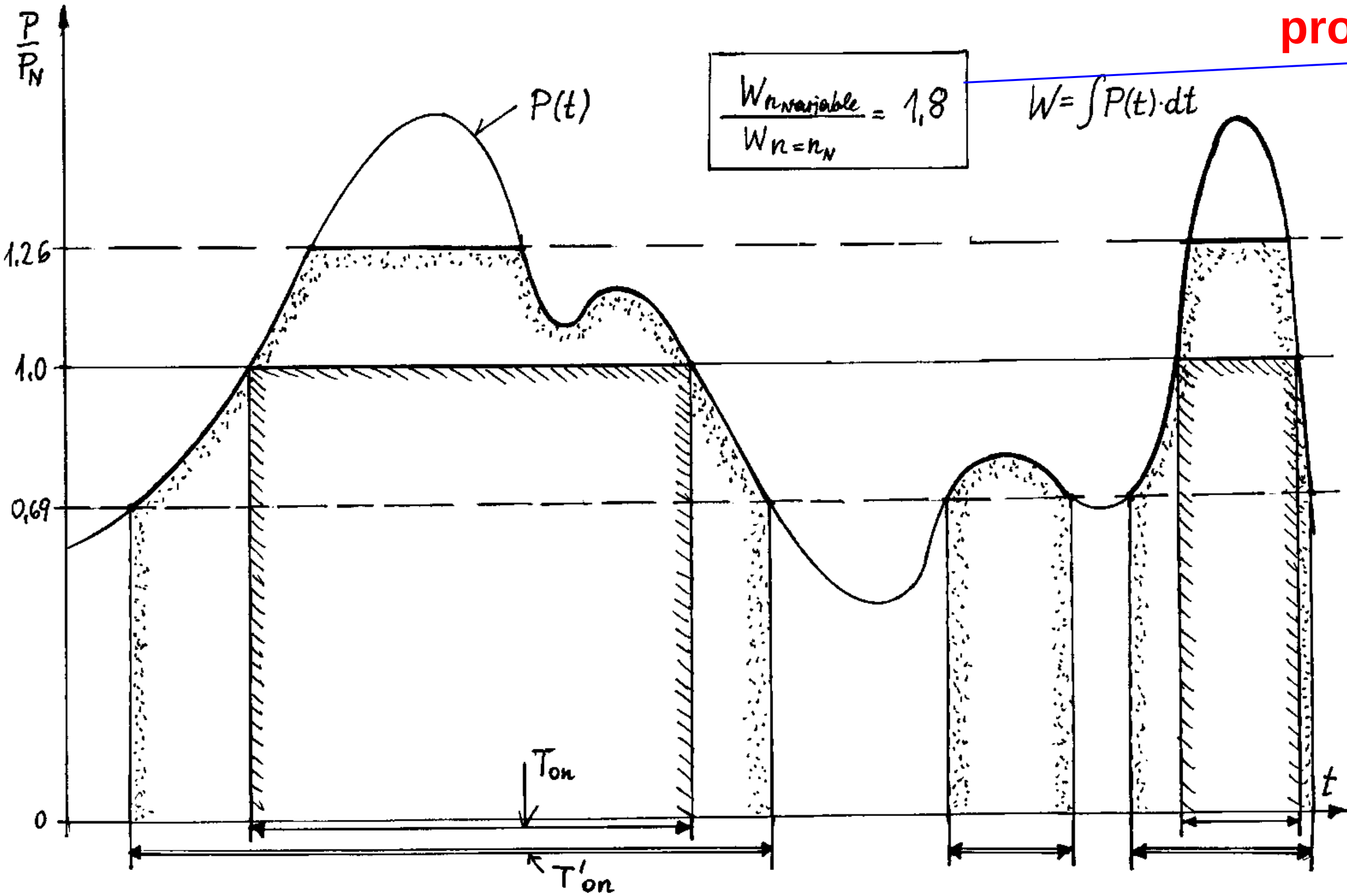
More excess power from the grid can be stored

Example:

$n_{min}/n_{syn} = 0.885$, $n_{max}/n_{syn} = 1.08$

$P_{min} = 0.69 P_N \le P \le P_{max} = 1.26 P_N$

Instead of 100% we can store at the given load profile *P*(*t*) 180% of energy!



Advantages of variable speed pump storage operation

a) Fixed speed pumping: The pump always operates at rated speed and hence with constant rated volume flow $\dot{V}$ at constant pressure head $\gamma g \cdot h$ of the upper basin (at elevation *h*). So it can only stored energy at rated power 100%.

b) Variable speed pumping: The pump operates at e.g. 90 … 105% of rated speed and therefore has a varying volume flow, operating against the pressure head $\gamma g \cdot h$. Hence storage occurs at varying power (ca. 73% … 116% of P_N):

$$\dot{V} = \dot{V}_N \cdot (0.9 \ldots 1.05) \qquad n = n_N \cdot (0.9 \ldots 1.05)$$

$$P \approx P_N \cdot (n / n_N)^3 = P_N \cdot \left(0.9^3 \ldots 1.05^3\right) = P_N \cdot (0.73 \ldots 1.16)$$

$$P_{\min} \approx 0.73 \cdot P_N \qquad P_{\max} = 1.16 \cdot P_N$$

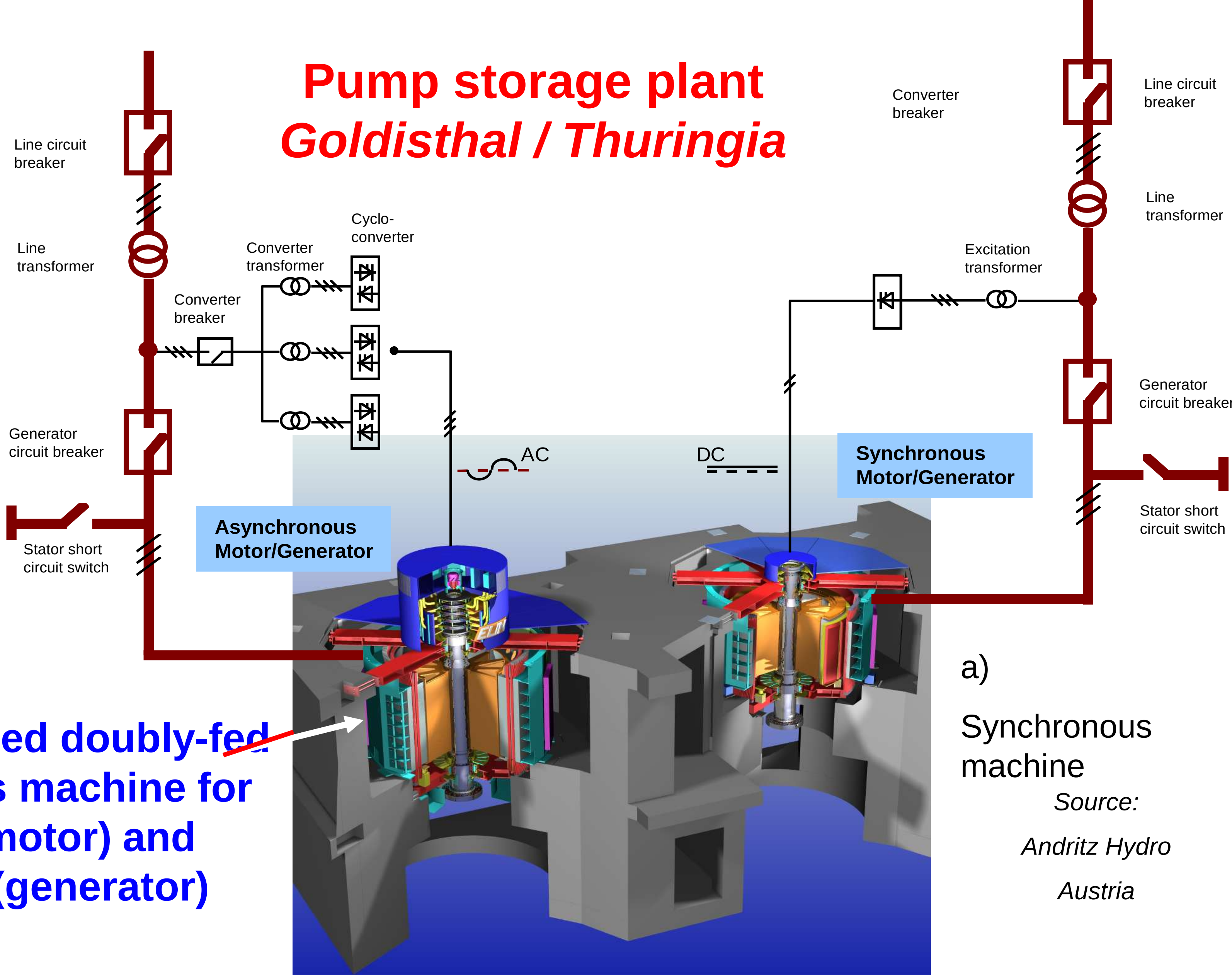
Pump storage plant
Goldisthal / Thuringia

motor-generator:

2 variants:

a) $n = n_{syn}$ = const.
Synchronous machine

b) Variable n :
doubly-fed asynchronous machine



b) Variable speed doubly-fed asynchronous machine for pumping (motor) and generating (generator)

a)

Synchronous machine

Source:

Andritz Hydro

Austria

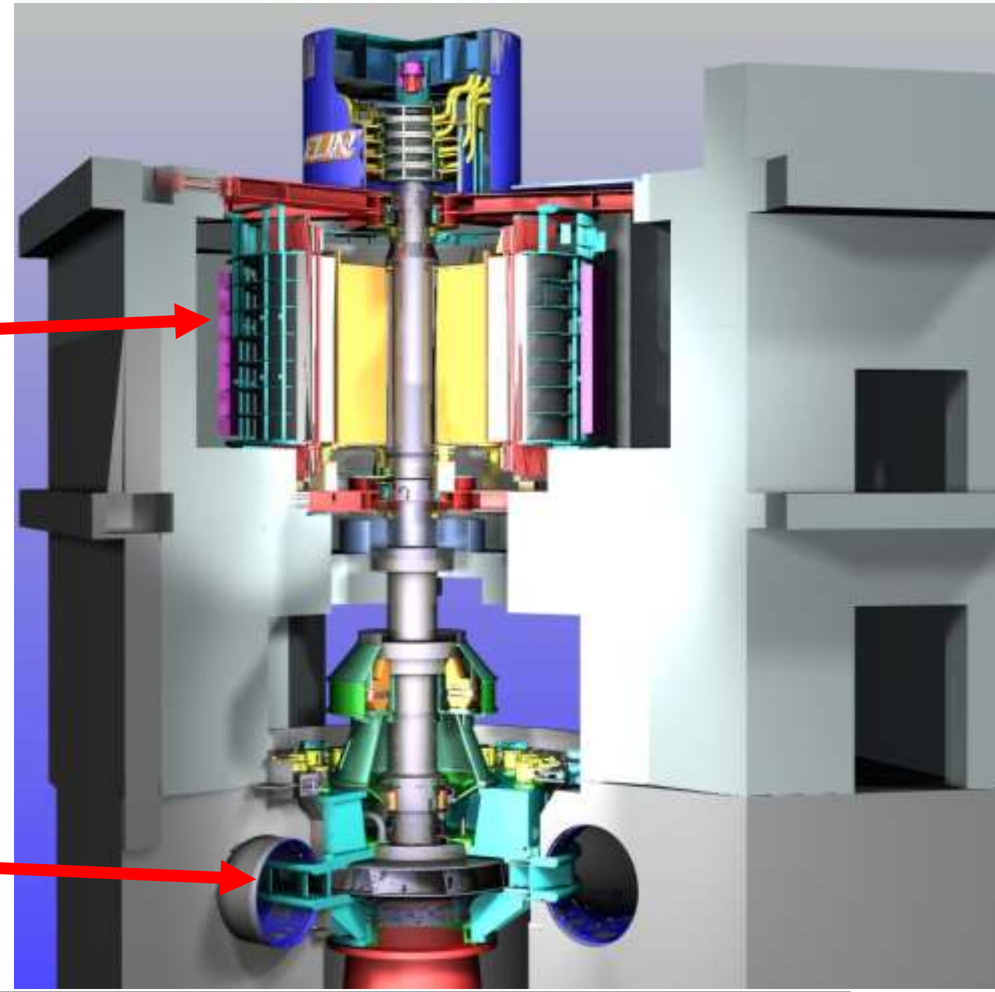
6. Wind generators and high power drives

Pump storage power plant *Goldisthal/Thuringia, Germany*

a) Grid operated synchronous Motor/Generator:
Data:
331 MVA, 333.3/min, 18 poles, 50 Hz

b) Doubly fed induction motor-generator:
Data:
340 MVA, 300 ... 346/min, 18 poles, 50 Hz
Rotor side converter:
Cyclo-converter for low frequency
Rotor slip:
+10% ... 5% slip, so the max. frequency in the rotor is $0.1 \cdot 50 = 5$ Hz

Pump-turbine



Source: Andritz Hydro/Austria

Variable speed induction machines for pump storage plants

$$P_{Pump} \sim n^3$$

Pump storage plant *Goldisthal/Thuringia, Germany*:

a) 2 directly at the grid operating synchronous motor/generator-units: $n = n_{syn}$ = const.
331 MVA, 333.3/min, 18 Pole, 50 Hz, n_{syn} = 333.3/min = f/p = 50/9 = 5.56/s

b) 2 doubly-fed slip-ring induction motor/generator-units: variable n
340 MVA, **300 ... 346/min**, 18 Pole, 50 Hz, n_{syn} = 333.3/min
Rotor-feeding inverter is a thyristor cyclo-converter for low frequencies $f_r \leq 5$ Hz
slip s = +10% ... -5% = max. rotor frequency 5 Hz ($s \cdot f_s = 0.1 \cdot 50 = 5$ Hz)

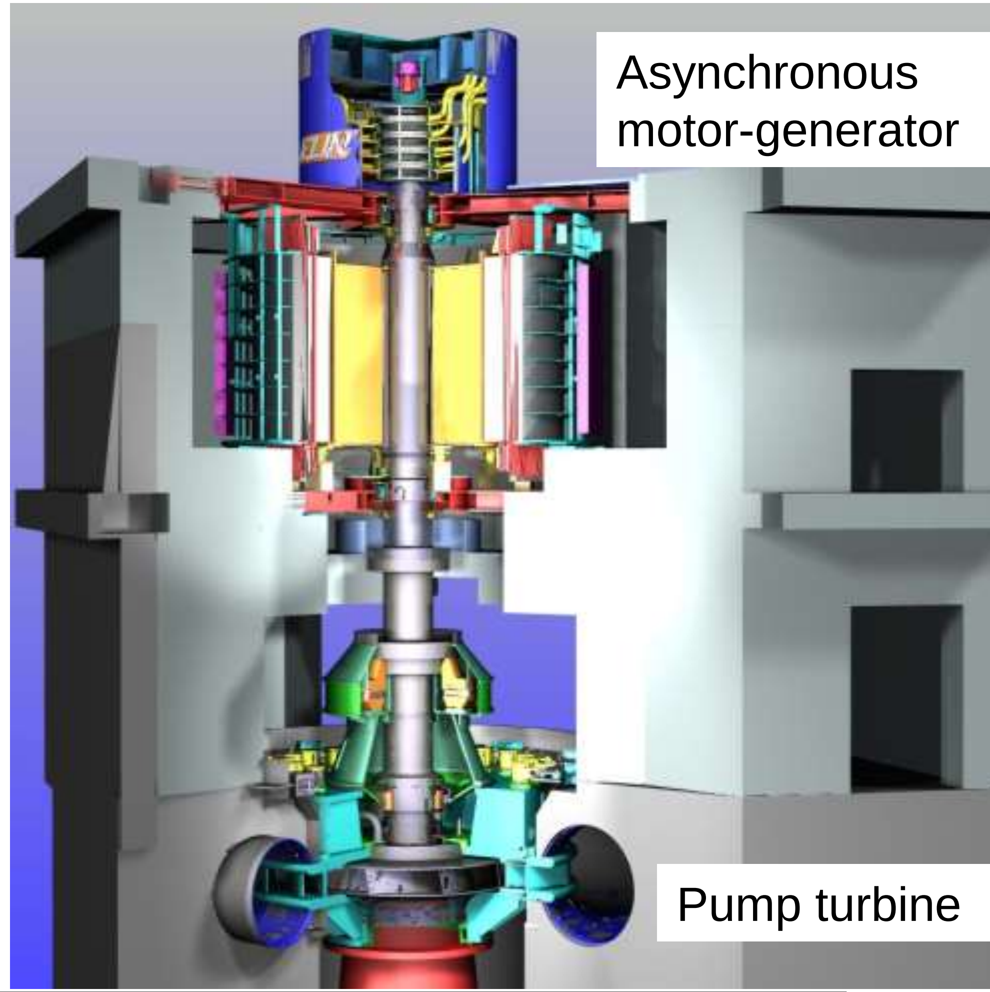
$$\Delta n = s_{\max} \cdot n_{syn} = 0.1 \cdot 333.3 = 33.3/\min \Rightarrow n_{\min} = n_{syn} - \Delta n = 333.3 - 33.3 = 300/\min$$

Pump storage power plant *Goldisthal / Thuringia*

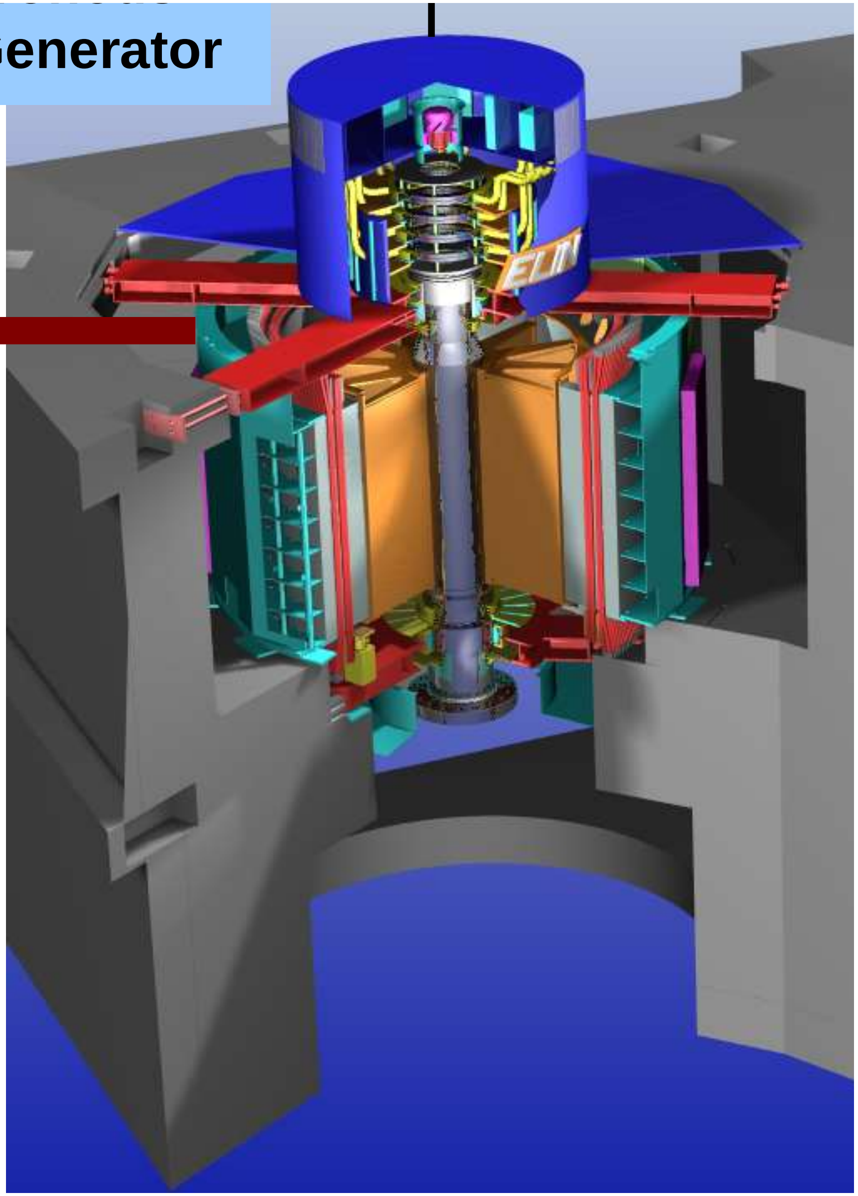
Source: energiewirtschaft 104 (2005), no. 17-18, p. 67

Rotor for 340 MVA, 300 ... 346/min, 18 poles, 50 Hz, at high voltage test 19 kV (r.m.s.), 50 Hz for 1 min.

Source: Andritz Hydro/Austria



Motor/Generator



Variable speed pump storage power plant

Goldisthal/Germany:

pump storage power plant

Slip-ring induction motor/generator
- six slip-rings
- 2 x 3 phases in the rotor

Source: Andritz Hydro/Austria

6. Wind generators and high power drives

Rotors of the asynchronous generator 340.5 MVA/300 MW for the pump storage power plant *Goldisthal/Thuringia, Germany*

Doubly fed induction motor-generator:
340 MVA, 300 ... 346/min, 18 poles, 50 Hz
Rotor voltage at stand still: 9 kV

Left: Rotor iron core

Right: Completed rotor with six-phase winding and steel rings for winding overhang fixation

High voltage testing during manufacturing:
Test voltage 19 kV r.m.s. ($2U_N$ + 1 kV), 50 Hz, 1min

Rotor winding capacitance 5.1 mF per phase

Source: energiewirtschaft 104 (2005), no. 17-18, p. 67

Power plant *Linthal* for variable speed pump storage power plants

Pump storage power plant *Linthal/Glarus, Switzerland*: in operation since 2016

Four doubly fed induction motor-generators with rotor-side voltage source inverters:
4 x 250 MW, driving pump-turbines, Head: 700 m

Rotor-side three-phase system = three slip rings

Already existing pump storage power plant gets INCREASED power at the SAME energy storage. Existing lakes *Muttsee* and *Limmernsee* are used.

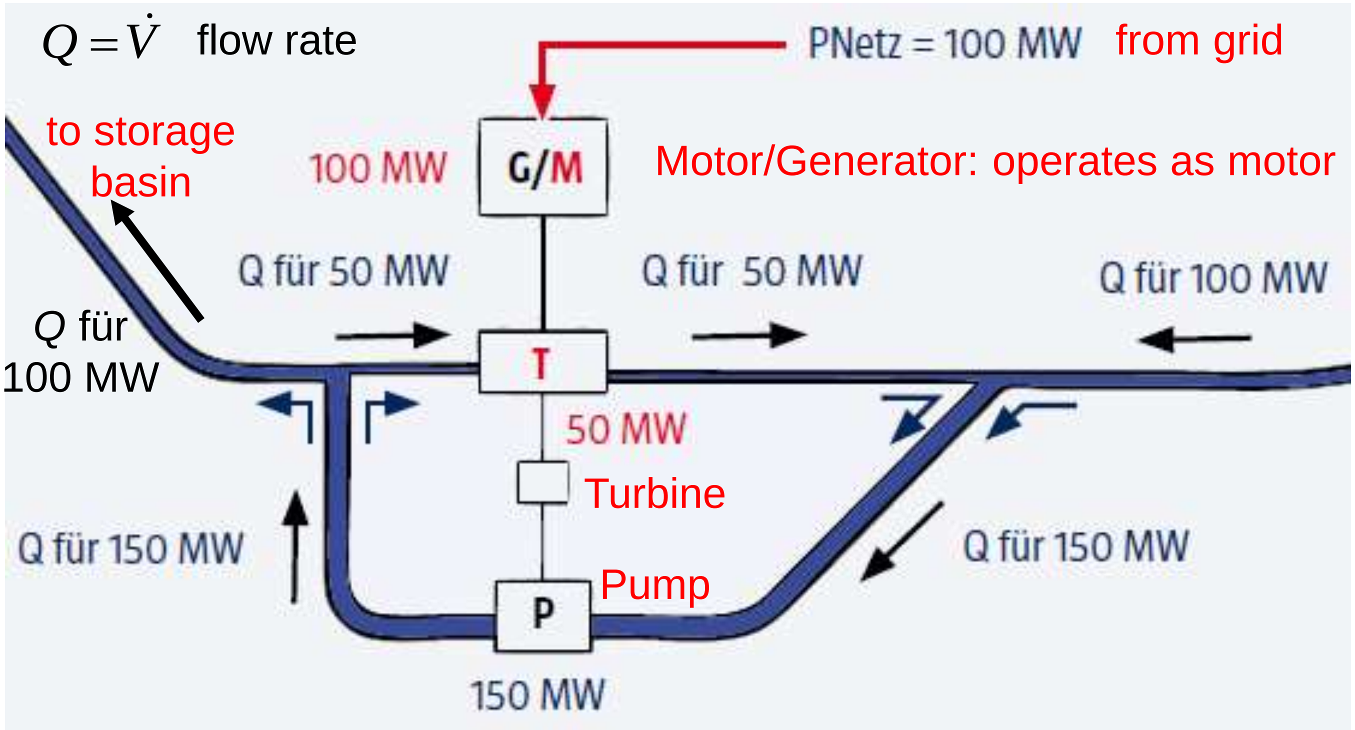
Already existing installed power (1957-1968): 450 MW (synchronous generators !)
Produced electrical energy per year: 460 GWh

New total installed power: 1450 MW
Increased storage capacity (*Muttsee* increased): 350000 $m^3 \rightarrow$ 560000 m^3
Grid voltage must be increased from 220 kV to 380 kV

New project *Linthal* for variable speed pump storage power plant

Source: NOK Newsletter, Switzerland

Alternative to variable speed pumping: “hydraulic short circuit“



- If turbine and pump are separated; the pump power can be held at 100%, whereas the grid input power varies between 0 … 100%.

- The power difference is supplied by the turbine, which is operated by water in “short circuit flow”, driven by the pump.

Source: Vorarlberger Illkraftwerke, Austria

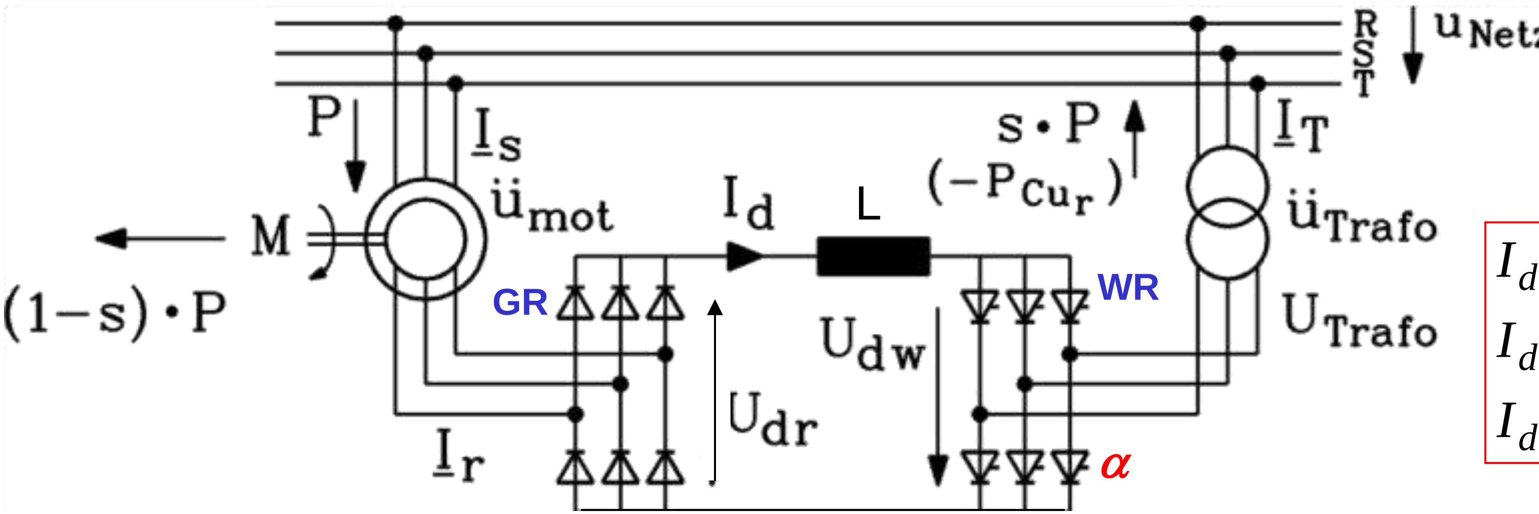
Example: *Kopswerk II* Pump storage plant: 50 Hz, head 800 m, 3 x 150 MW
Rated power of pump, *Pelton* turbine, 12-pole synchr. generator: 150 MW

Grid input power only 100 MW, pump operates at rated 150 MW, feeds turbine with 50 MW

Sub-synchronous converter cascade

Sub-synchronous converter cascade

- **Lower cost alternative** to the doubly-fed induction machine:
  Instead of 4-Q-inverter only a diode rectifier bridge GR is used at the rotor winding:
  Power flow only **from the rotor** via the converter **to the grid is possible.**
- **Power flow:** $sP_\delta - P_{Cu,r} > 0$
  hence we need $s > 0$: so only **sub-synchronous motor operation** ($s > 0$) possible



$I_d = 0 : U_{dr} + U_{dw} = 0$

$I_d > 0 : U_{dr} > -U_{dw}$

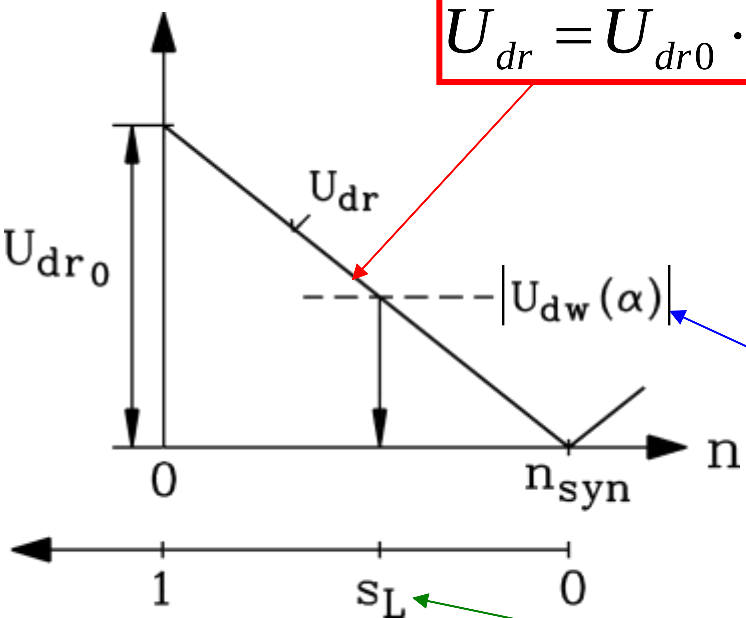
$I_d < 0$ not possible

- Current flow I_r in the rotor winding **only** possible, if $U_{dr} > -U_{dw}$. Current flows as I_d via choke L (smoothes the current ripple) and via the transformer as I_T back to the grid.
- With **controlled converter WR** with U_{dw} the slip s_L is controlled:
  „No-load slip" s_L: $I_d = 0$, $U_{dr} = -U_{dw}$: For $s > s_L$ current may flow = torque is generated

Operating at the no-load slip s_L

- **Induced rotor voltages** $u_{rU}(t), u_{rV}(t), u_{rW}(t)$ increase with increasing rotor frequency $f_r = sf_s$. They rise with decreasing speed $n = (1-s)n_{syn}$.

- Via **rectification** of the rotor voltages we ge the DC voltage $u_{dr}(t)$ with a ripple.
  The average DC voltage U_{dr} is maximum at n = 0: U_{dr0} , and U_{dr} = 0 at n_{syn}!



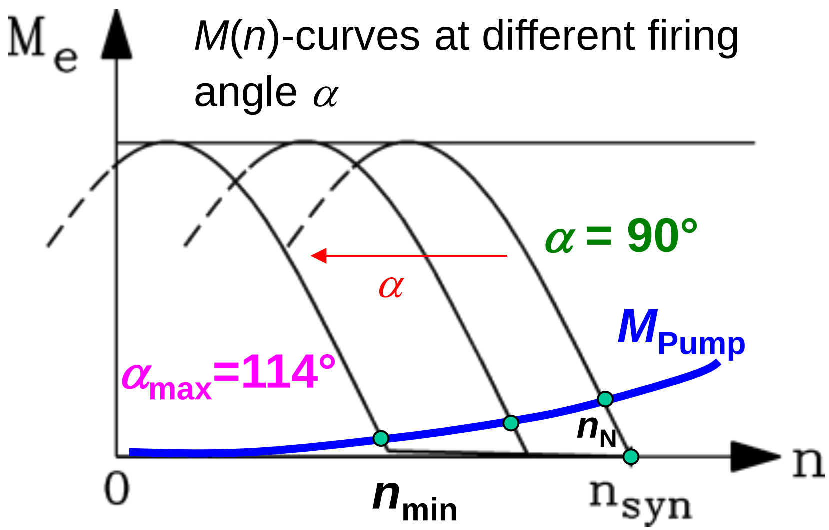
Via **WR** (= fed from the transformer) the fixed transformer voltage $u_{Trafo}(t)$ (with fixed amplitude $\hat{U}_{Trafo}$ and frequency f_{Netz}) is rectified.
Its average value U_{dw} can be changed by the **firing angle** α of the thyristors.

$$-U_{dw}(\alpha) = -\frac{3}{\pi}\sqrt{3} \cdot \hat{U}_{Trafo} \cdot \cos\alpha > 0, \text{ if } \alpha \geq 90°$$

„No-load slip s_L“: $U_{dr} = -U_{dw}$

$$s_L = -3\sqrt{3} \cdot \hat{U}_{Trafo} \cdot \cos\alpha / (U_{dr0} \cdot \pi) \qquad 90° \leq \alpha \leq \alpha_{max}$$

Application: Sub-synchronous converter cascade as pump drive



Example:

12 MW-Water feeder pump drive unit in a thermal power plant (P_N = 12 MW), **variable speed for** adjusting the water flow to the steam generator:

M_{Pump} ~ n^2, transformer voltage: $\hat{U}_{Trafo} / U_{dr0} = \pi / (3\sqrt{3})$

Operation range:

$\alpha = 90° : \cos 90° = 0 : n_{max} = n_N = (1 - s_N) n_{syn} \approx n_{syn}$

up to

$\alpha = 114° : \cos\alpha = -0.4, s_L = 0.4 : n_{min} = (1 - s_L) n_{syn} = 0.6 n_{syn}$

Speed	Volume flow	No-load slip s_L	Power	Feed-back power
n_{max} (100%)	100%	0	12 MW	0 MW
n_{min} (60%)	60%	0.4	2.6 MW	1.73 MW

Min. pump power: $P_m = (n / n_{syn})^3 \cdot P_N = (1 - s)^3 P_N = (1 - s) P_\delta = (1 - 0.4)^3 \cdot 12 = 2.59\,\mathrm{MW}$

Min. air-gap power: $P_\delta = (1 - s)^2 P_N = (1 - 0.4)^2 \cdot 12 = 4.32\,\mathrm{MW}$

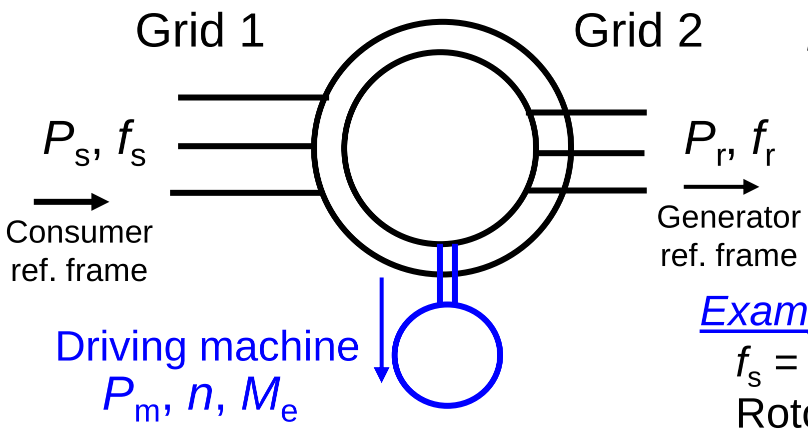
Feed-back power: $P_r \approx s P_\delta = s(1 - s)^2 P_N = 0.4 \cdot 4.32 = 1.73\,\mathrm{MW} = (4.32 - 2.59)\,\mathrm{MW}$

6. Wind generators and high power drives

Rotary frequency converters

Doobly fed slip-ring induction machine as rotary frequency-changing transformer

- Coupling of two asynchronous grids: Grid 1: f_s, Grid 2: f_r



$$f_r = s \cdot f_s \, , n_{syn} = f_s / p \, , 1 - s = n / n_{syn} \rightarrow \boxed{f_s = f_r + n \cdot p}$$

Example:

f_s = 60.1 Hz, f_r = 60.0 Hz, six-pole winding: $2p = 6$

Rotor speed: $n = (f_s - f_r)/p = (60.1 - 60.0)/3 = 0.033/\text{s} = 2/\text{min}$

Speed n VERY small („nearly“ zero!)

Slip $s = f_r/f_s = 60/60.1 = 0.998$ nearly 1, and here POSITIVE!

- Active power flow between Grid 1 and Grid 2:

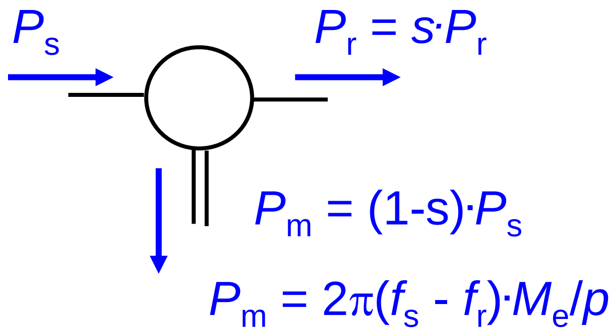
$$P_s = P_\delta = (1-s) \cdot P_\delta + s \cdot P_\delta = P_m + P_r$$

$$M_e = P_\delta \cdot p / \omega_s = P_s \cdot p / \omega_s$$

Torque $M_e > 0 \rightarrow P_s > 0$, $P_r = s \cdot P_s \cong P_s > 0$: active power flow from Grid 1 to Grid 2

Torque $M_e < 0 \rightarrow P_s < 0$, $P_r = s \cdot P_s \cong P_s < 0$: active power flow from Grid 2 to Grid 1

Example: Active power flow ($2p = 6$)



Via the torque of the driving machine we can influence the active power flow between the two grids

$f_s = 60.1$ Hz, $f_r = 60.0$ Hz, $s = f_r/f_s = 60/60.1 = 0.9983 < 1$, $n = 2.04$/min POSITIVE:

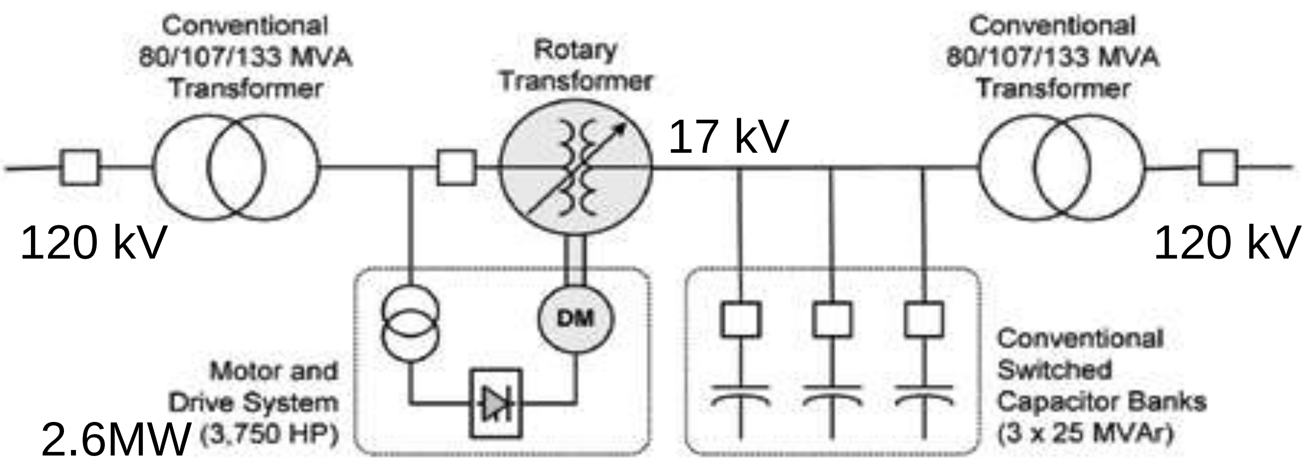
Generator operation	Motor operation
$P_s = 100$ MW	$P_s = 100$ MW
$P_r = 99.83$ MW	$P_r = 99.83$ MW
$P_m = 0.17$ MW	$P_m = 0.17$ MW
$M_e = 811.7$ kNm	$M_e = -811.7$ kNm

$f_s = 60.0$ Hz, $f_r = 60.1$ Hz, $s = f_r/f_s = 60.1/60.0 = 1.0017 > 1$, $n = -2.04$/min NEGATIVE:

Motor operation	Generator operation
$P_s = 100$ MW	$P_s = 100$ MW
$P_r = 100.17$ MW	$P_r = 100.17$ MW
$P_m = 0.17$ MW	$P_m = 0.17$ MW
$M_e = 811.7$ kNm	$M_e = -811.7$ kNm

Rotary frequency converter *Langlois, Canada* (1)

Coupling of eastern grids in *Canada* and *USA* at the station *Langlois* near *Montreal /Quebec*, *Canada*

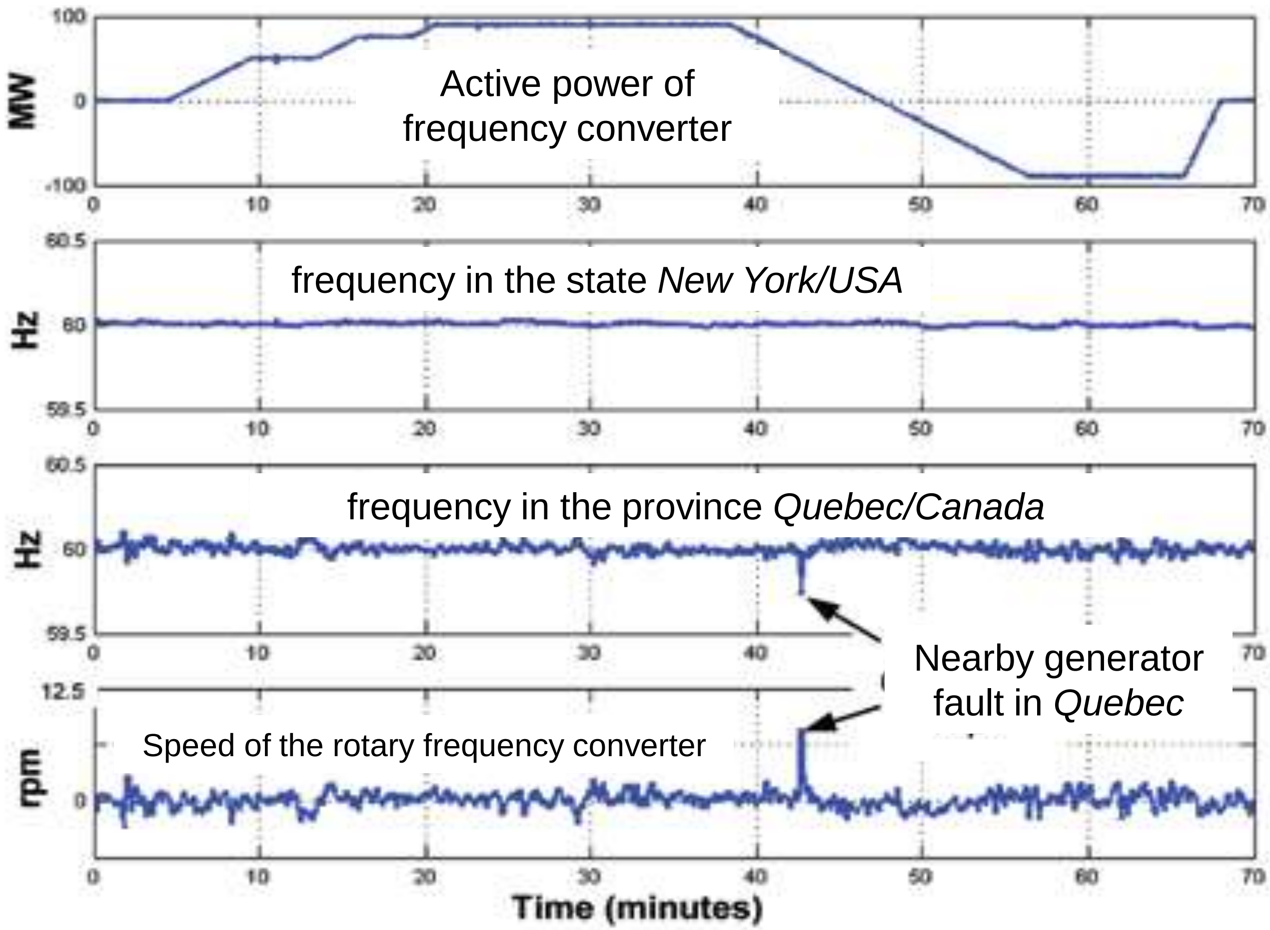


- Converter-fed DC motor 2.6 MW for variable speed
- Switched capacitors for reactive power compensation
- three-leg transformers for adjusting the voltage from 120 kV to 17 kV

- DC motor: relatively low power 2.6 MW << 100 MW, because speed is very low = long bearing and brush life
- Opposite to power electronics frequency converters no current or voltage harmonics are generated

Source: Larsen, E.; Piwko, R.; McLaren, D.: Variable frequency transformers for asynchronous power transfer, energize magazine, June 2009, 34-38

Operation example: Rotary frequency converter *Langlois*



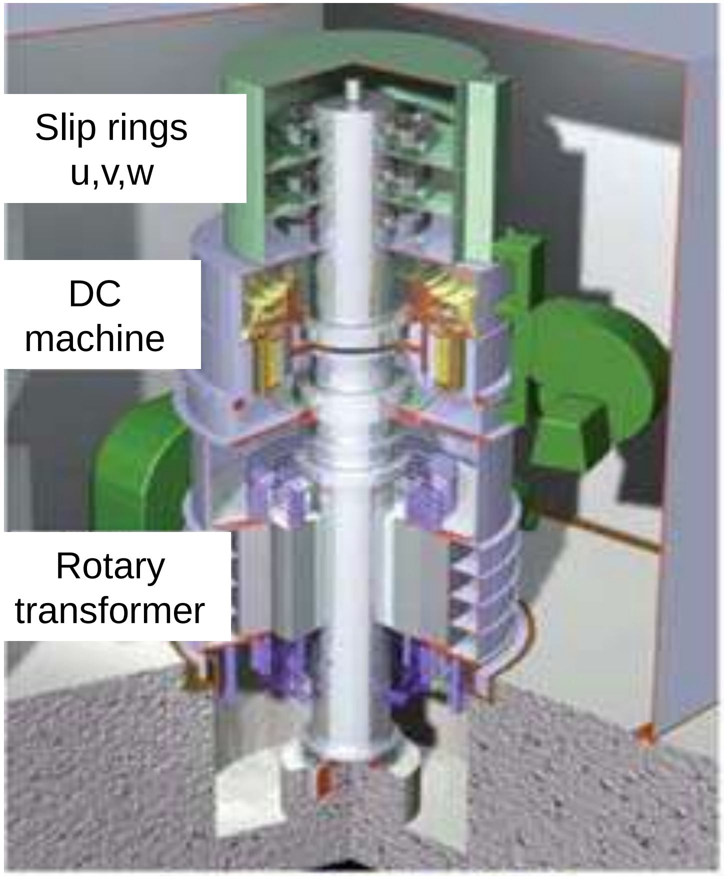
Operation of the frequency converter first with positive, then with negative active power flow

Coupling of the eastern grids of US state *New York/USA* and of the province *Quebec/Canada* in *Langlois*

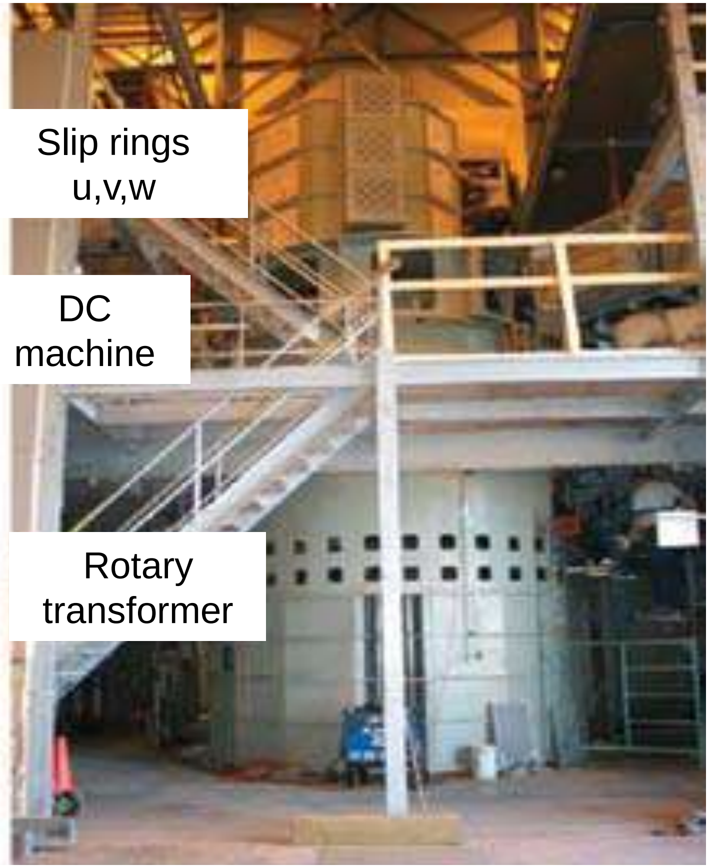
Source: Larsen, E.; Piwko, R.; McLaren, D.: Variable frequency transformers for asynchronous power transfer, energize magazine, June 2009, 34-38

Rotary frequency converter set-up

Coupling of eastern grids in *Canada* and *USA* at the station *Langlois* near *Montreal /Quebec*, *Canada*



Cut-view of the vertical shaft arrangement



100 MW-rotary frequency converter, *Langlois*

Source: Larsen, E.; Piwko, R.; McLaren, D.: Variable frequency transformers for asynchronous power transfer, energize magazine, June 2009, 34-38

Rotor components of the rotary frequency converter

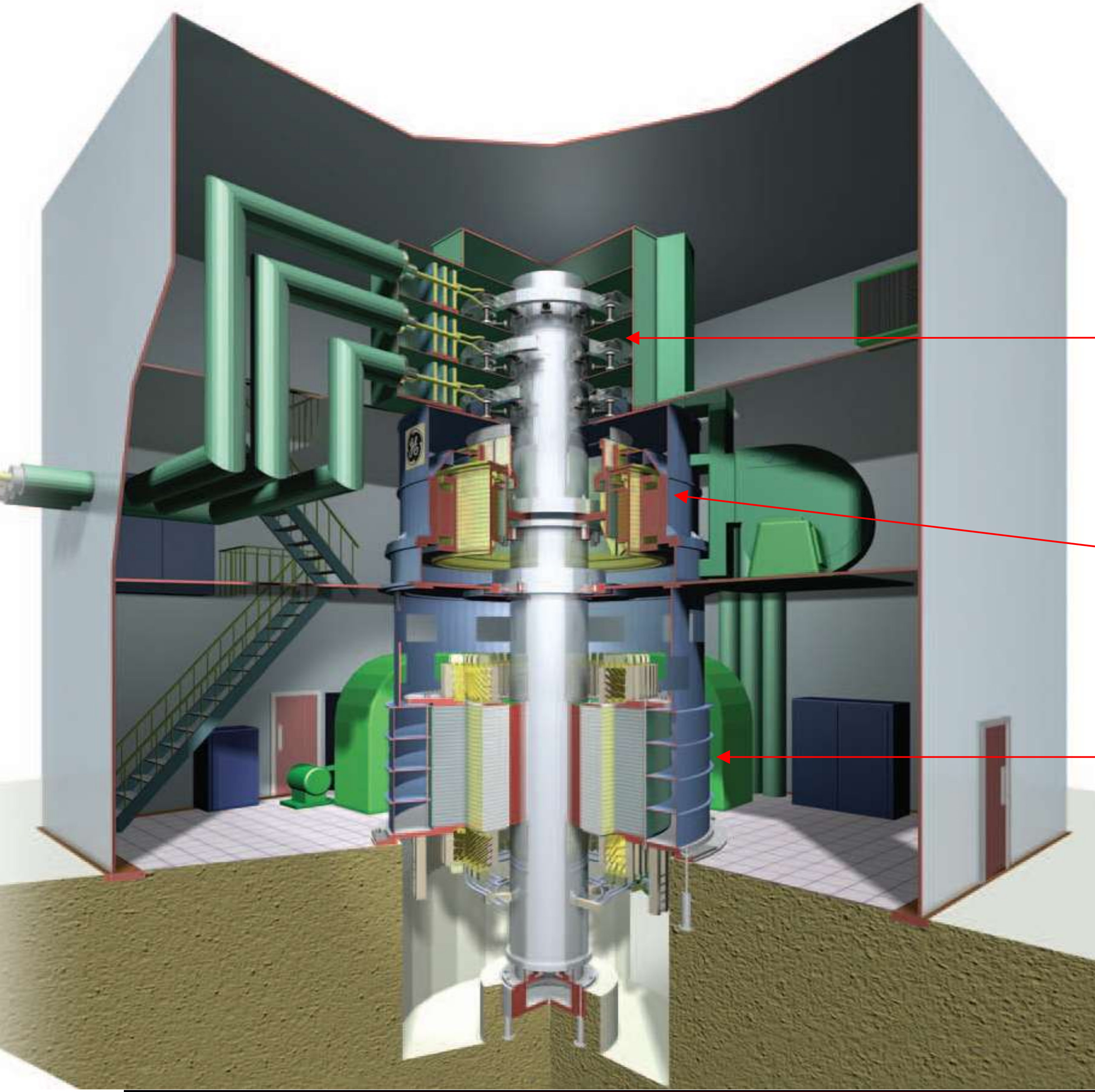
Rotary frequency converter for coupling of eastern grids in *Canada* and *USA* at the station *Langlois* near *Montreal /Quebec*, *Canada*

Manufacturing of slip rings

Source: GE Company, Atlanta, Georgia, USA

Rotor with three-phase star-connected distributed winding in rotor slots

Rotary frequency converter at *Langlois* near *Montreal*, *Canada*



Rotating slip-ring system, three phases = three slip rings

DC machine for driving/braking

Rotary frequency transformer

Source: GE Company, Atlanta, Georgia, USA

Summary:

Applications with big doubly-fed induction machines

- Doubly-fed machines: For pump storage plants a small speed variation is sufficient, so the rotor-side inverter is small = lower cost than full-size stator-side inverter
- But: Slip-ring system with big current flow over brushes demands increased maintenance

- Sub-synchronous converter cascade:
  Only a diode rectifier bridge on the rotor side = very robust and cheap, but only sub-synchronous motor operation
- For pumping units with limited speed range very often sufficient
- Nowadays: Replaced by rotor side voltage-source inverters for 4Q-operation

- Rotary frequency transformers for grid-coupling operate at low speed
- Frequency adjustment via slip (= nearly unity)
- Some applications in northern America