# Green energy conversion

Prof. Dr.-Ing. habil. Andreas Binder

Department of Electrical Energy Conversion

Darmstadt University of Technology

abinder@ew.tu-darmstadt.de

# Contents of lecture

# 1. Green energy conversion systems

## 1.1 Wind energy converters

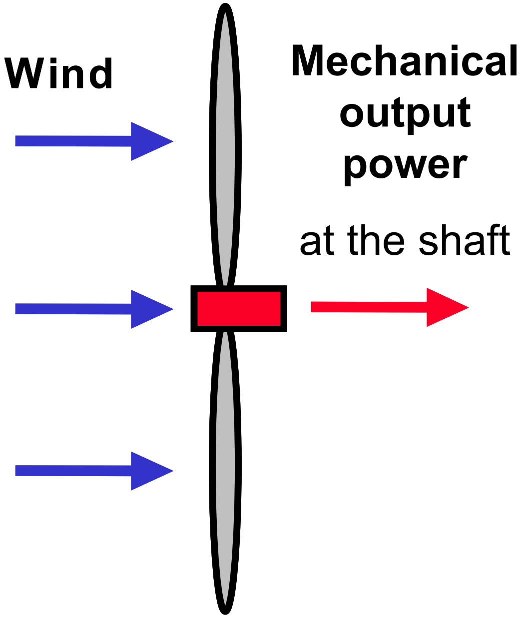
Source:

Winergy, Germany

# Wind energy conversion

**Rotor**

Fixed or variable speed, stall or pitch control




Source: S. Joeckel, Innowind, Germany

**Long term wind power fluctuation (weeks/months)**

→ Problem of prediction, reserve energy of grid

→ Surviving "50 years storm weather"

**Medium term wind power fluctuation (days/weeks)**

→ Usually partial load operation

→ Aerodynamic limiting of power by pitch or stall control of blades

**Short term torque pulsations (0.05 ... 2 Hz)**

→ "Shadow" effect of centre pole - torsion oscillations of shaft

→ Direct grid connection of synchronous generators: big "flicker"

→ Smaller "flicker"-effect also with cage induction generators

**Extremely low speed of 1 ... 5 MW-wind turbines (10 ... 40 /min)**

→ Grid-operated low pole count generators need gear

→ Directly driven generators: high pole count = big diameter

**Low wind energy density W/m$^2$: modular wind farm design needed**

→ Upper per-unit power of wind converter < 10 MW

# Wind energy conversion

- **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

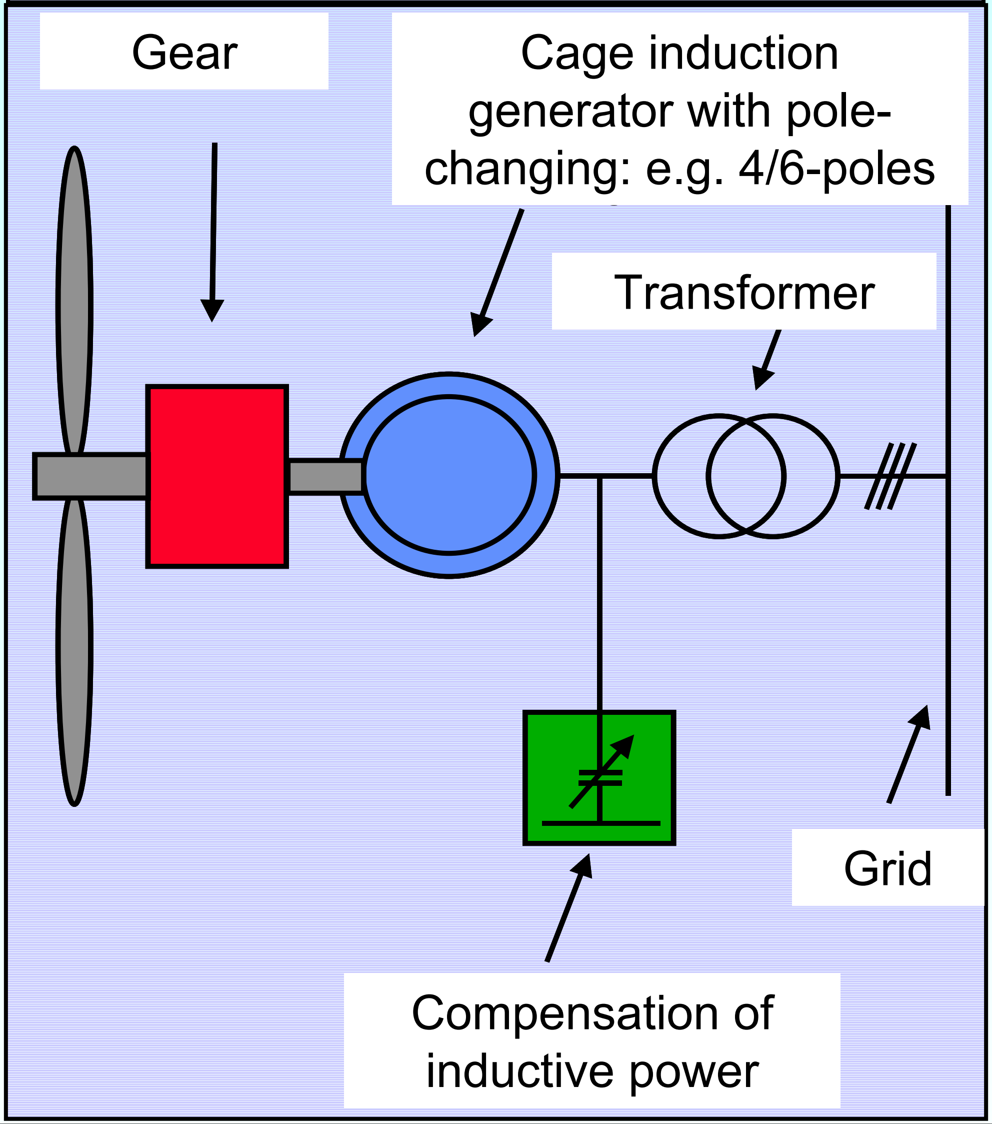
# Fixed speed wind energy conversion

- 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.

# Fixed speed wind energy conversion

Speed nearly constant: $f_s/p\cdot(1 - s)$

$s$ = -0.005 ... -0.01




- **Power typically up to 1 MW**
- **stall power control**

Source: S. Joeckel, Innowind, Germany

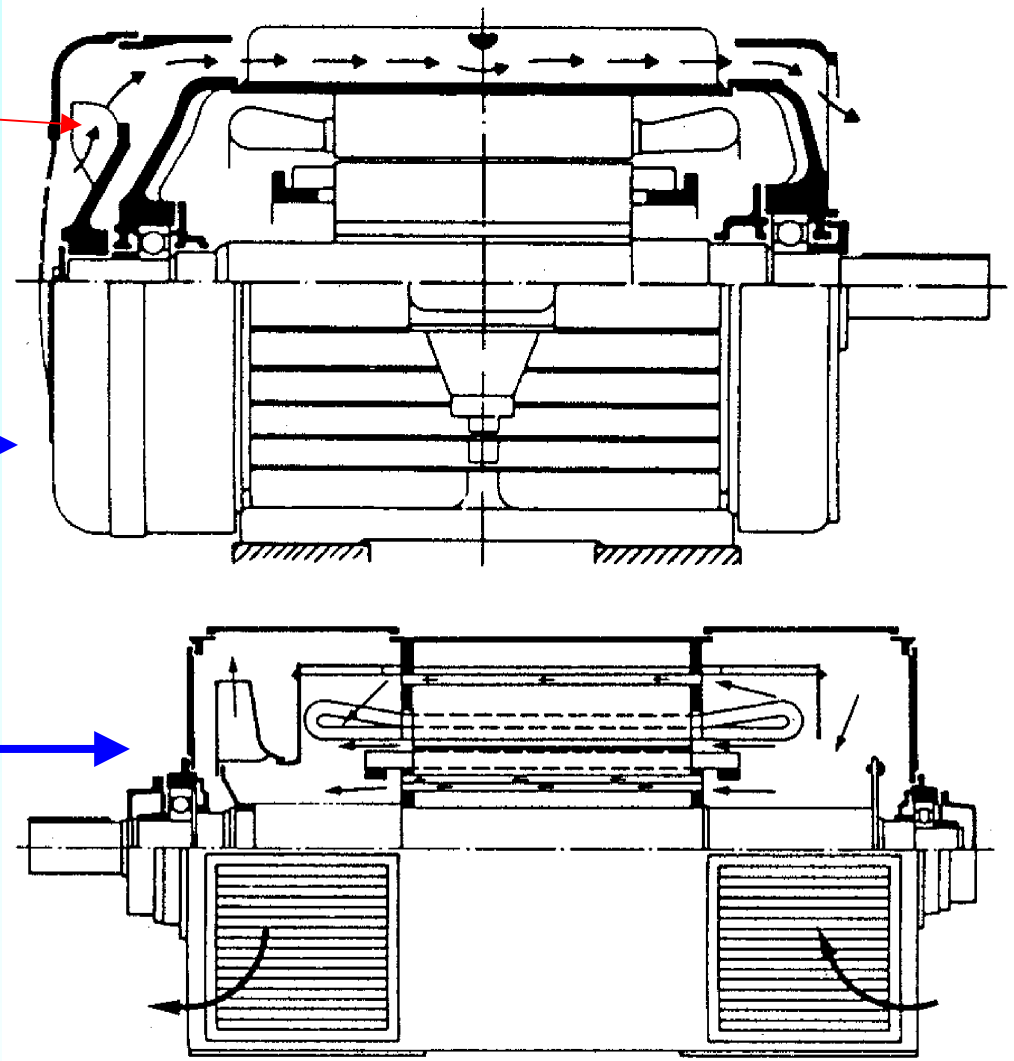
# Air cooling variants of cage induction machine

**Shaft mounted fan:**

**Well suited for fixed speed operation to ensure full air flow**

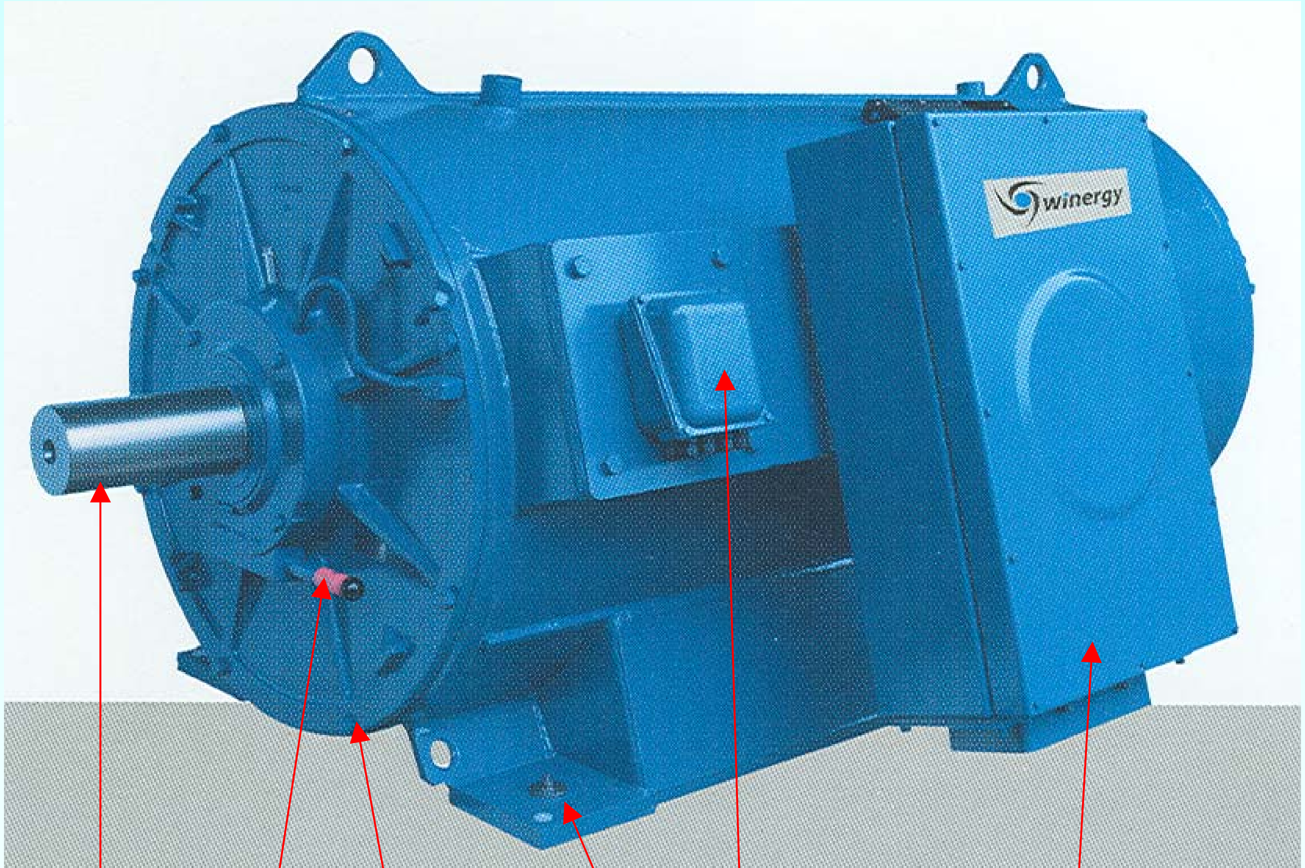
**Totally enclosed machine,** cooling fins on housing, no contamination of inner machine parts by salty air etc.

**Open ventilated cage induction** generator increases thermal utilization, but not well suited for outdoor application. Needs high performance winding insulation.



Source: ABB, Switzerland

# Pole changing cage induction generator




Shaft end Housing feet terminal box Power terminal box

Bearing with lubrication opening

Rated power: 1.3 MW

4-pole winding:

1500/min at 50 Hz

1800/min at 60 Hz

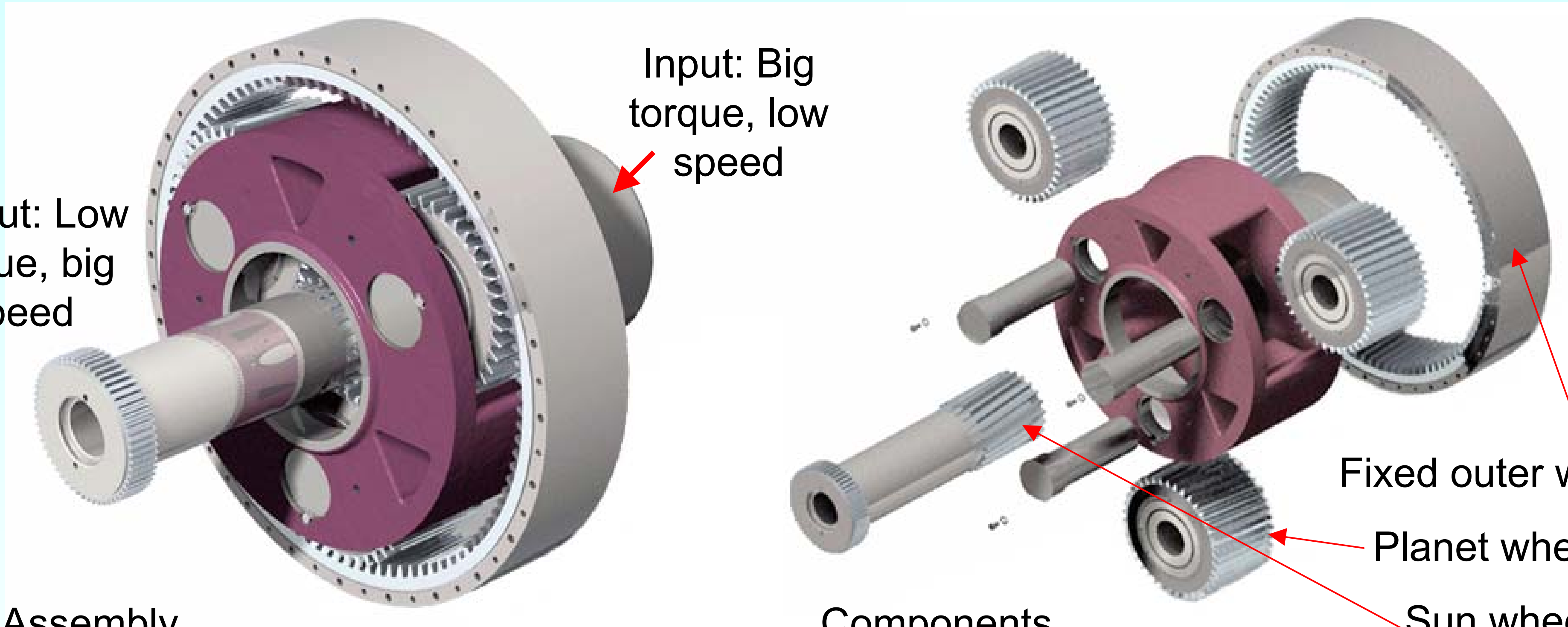
**Water jacket cooling stator housing allows closed generator operation for outdoor use**

Source:

Winergy, Germany

# 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: $M_{out} = M_{in}/i$, $n_{out} = i \cdot n_{in}$

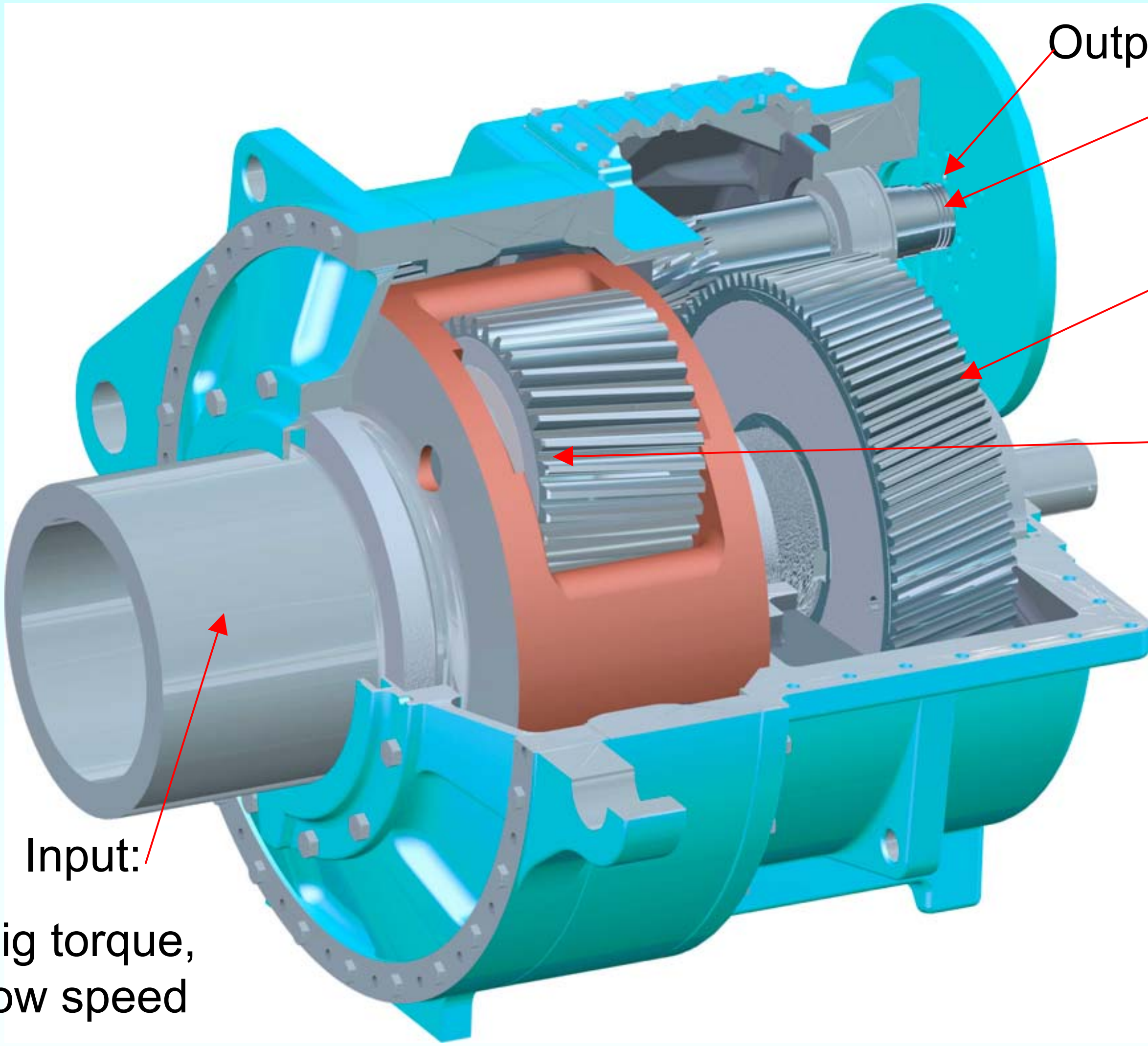



Assembly

Components

Source: GE Wind, Germany

# Principle of 3 stage gear with planetary gear as $1^{st}$ stage



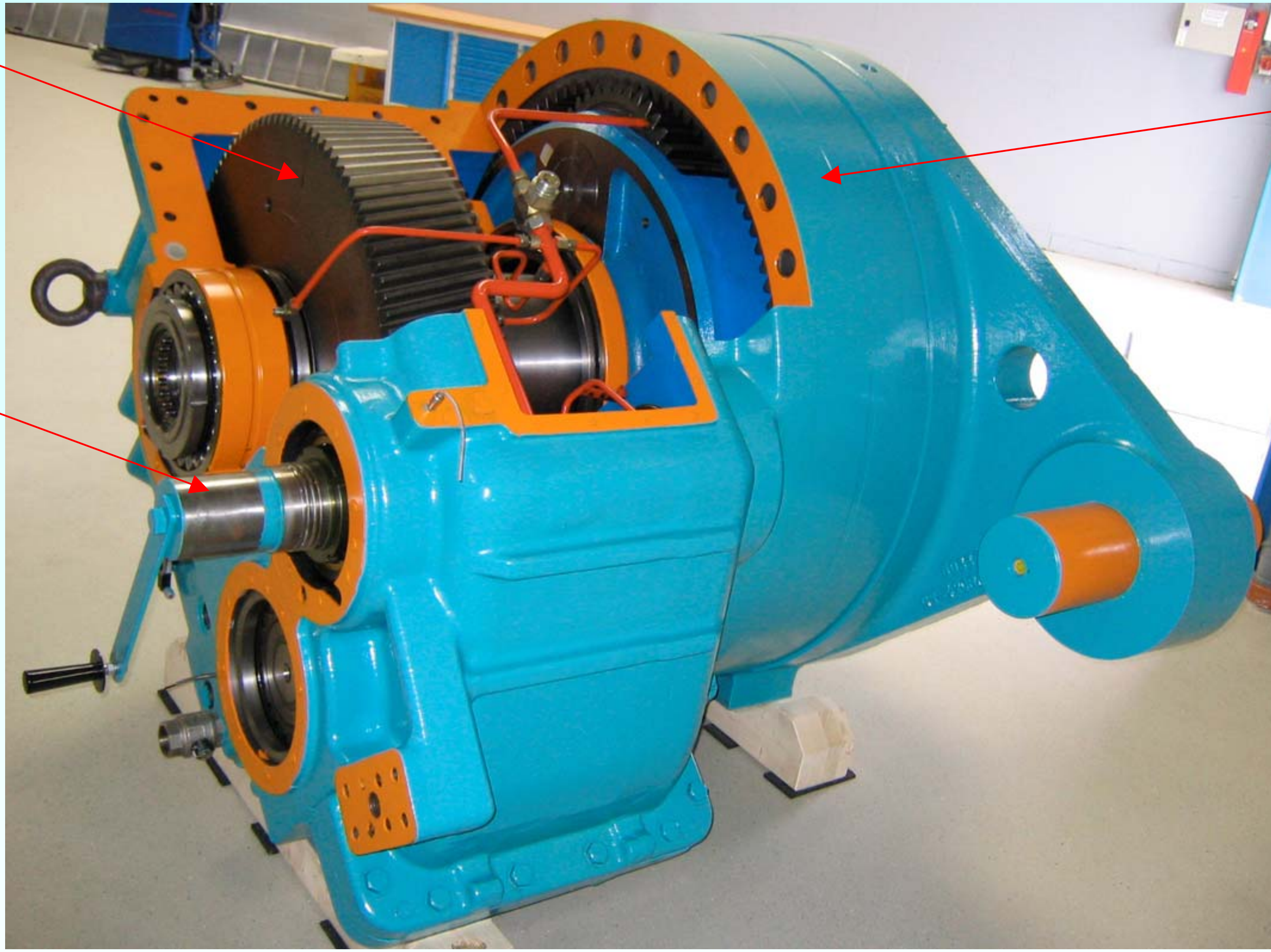

Source: GE Wind, Germany

# 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

Cut-view demonstration object



First stage:

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

Source:

GE Wind,

Germany

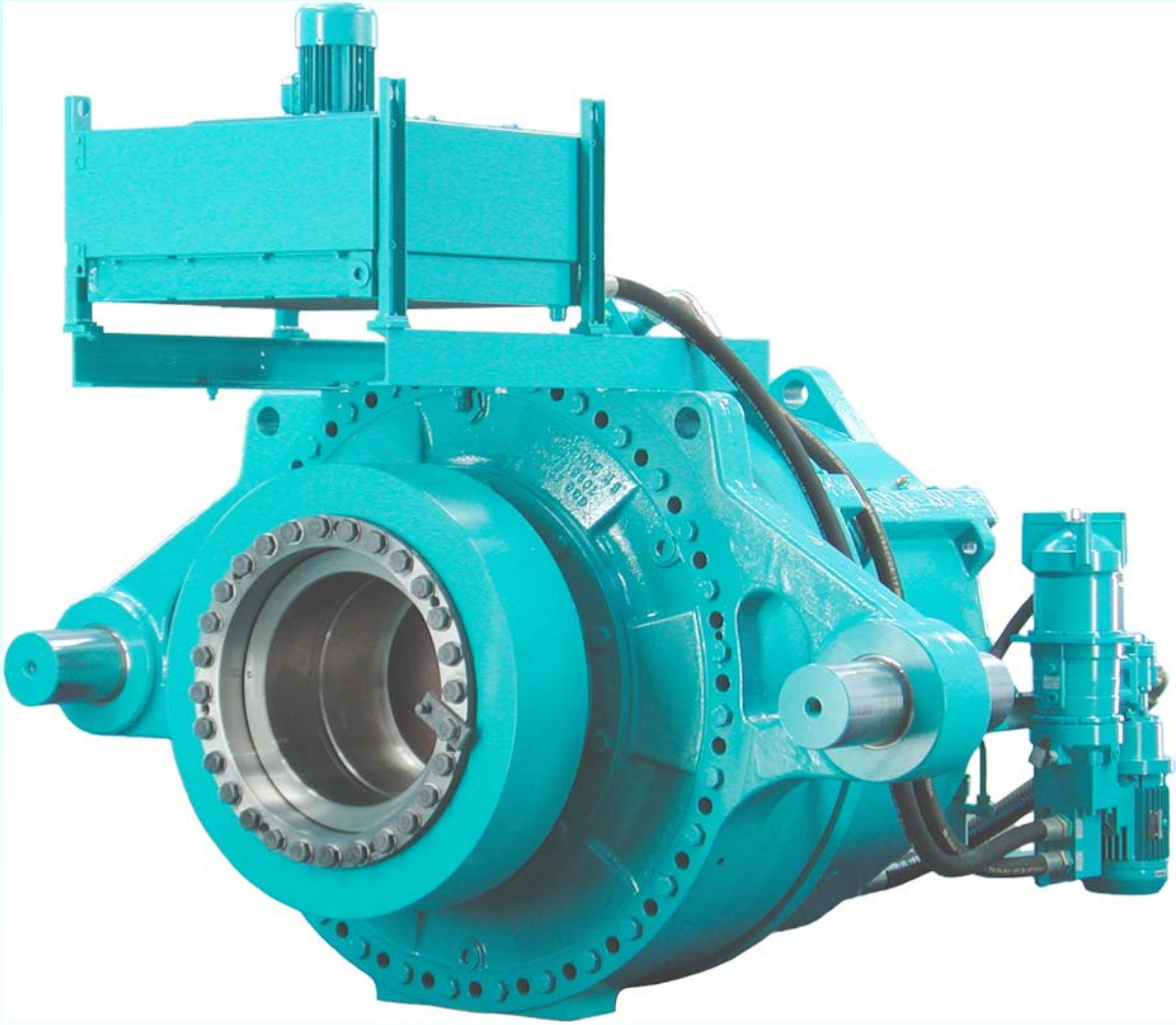
# Three stage gear before assembly in wind converter

Source:

GE Wind,

Germany

# 3 stage gear for 1.5 MW



Source:

GE Wind,

Germany

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


Source:

Vestas, Denmark

# Variable speed wind energy conversion

- 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

# Typical rated data of variable speed wind converters

| $P$ / MW | $D_R$ / m | $n_R$ / min$^{-1}$ | Company | Generator | $v_{Rmax}$ /km/h | $v$, $v_N$ /m/s | Gear $i$ |
|---|---|---|---|---|---|---|---|
| 1.5 | 70<br>77 | 10...19<br>9...17 | *Repower*<br>*Südwind* | DS-ASM<br>DS-ASM | 251<br>247 | No data<br>3...20, 11.1 | No data<br>104 |
| 2.0 | 80<br><br>90 | 9...19<br><br>7.4...14.8 | *Vestas*<br><br>*Made* | DS-ASM<br>Optispeed<br>Syn-G RG | 287<br><br>251 | 4...25, 15<br><br>3...25 | No data<br><br>101 |
| 2.7<br>2.75 | 84<br>92 | 6.5...18<br>$n_{RN}$ = 15.6 | *GE Wind*<br>*NEG Micon* | DS-ASM<br>DS-ASM | 285 | 4.5...25<br>4...25, 14 | No data<br>70.65 |
| 3.0 | 90 | 10...20 | *Scan Wind* | PM-Syn | 339 | No data | gearless |
| 3.6 | 104 | 8.5...115.3 | *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 |

Pitch controlled variable speed wind energy converters up to 5 MW for on- and off-shore application (Source: Hannover Fair “Industrie”, Germany, 2004)

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

| 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<br>14 t (300 l Oil)<br>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<br>65 t<br>Shaft + Bearing: 35 t | Total nacelle mass: 240 t<br>*Length* x *Height*: 23 m x 6 m | Total mass: 350 t |

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

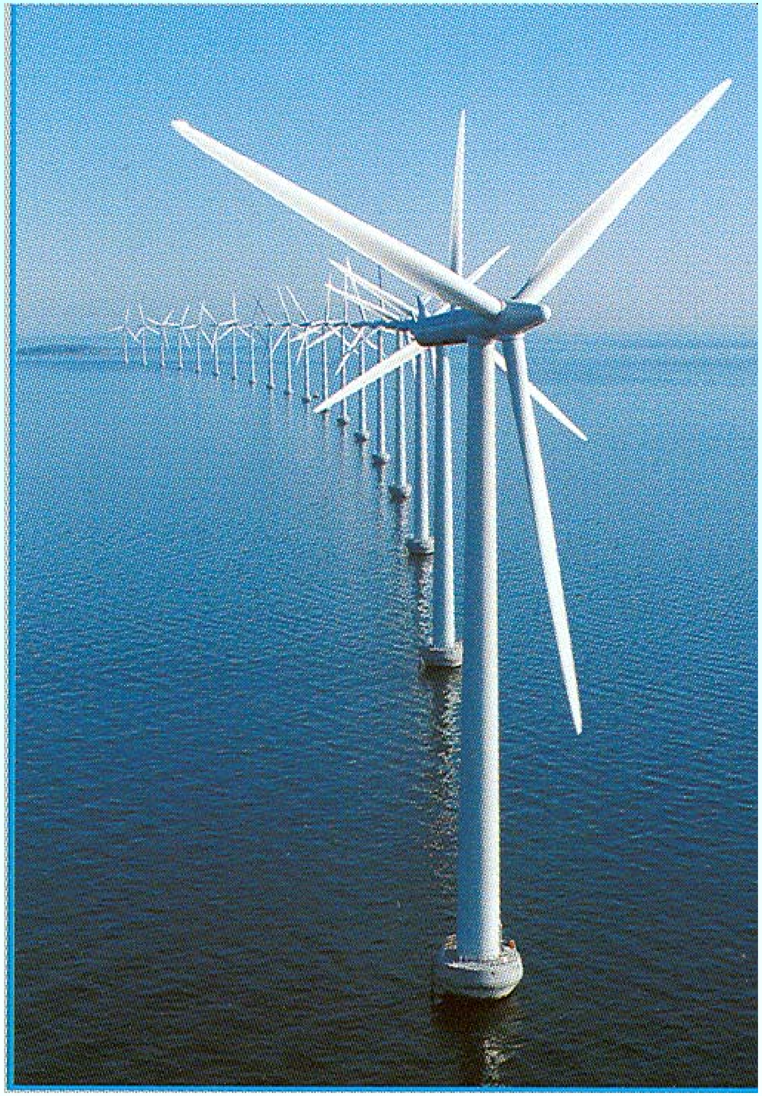
# Off-shore wind park near *Denmark*

Variable speed wind turbines

Pitch control

Doubly-fed induction generators

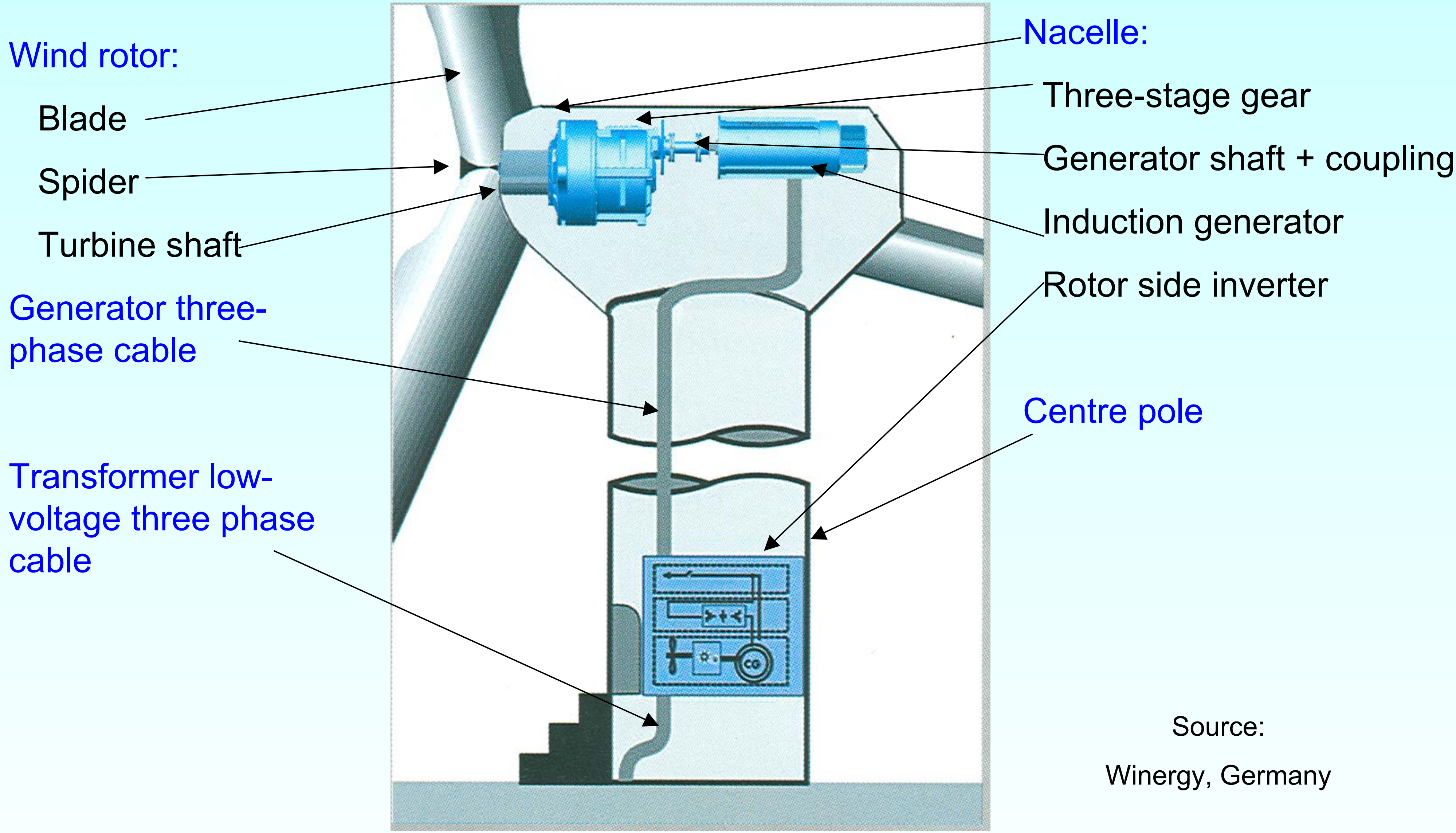
Yaw control to align wind direction



Source:

Winergy, Germany

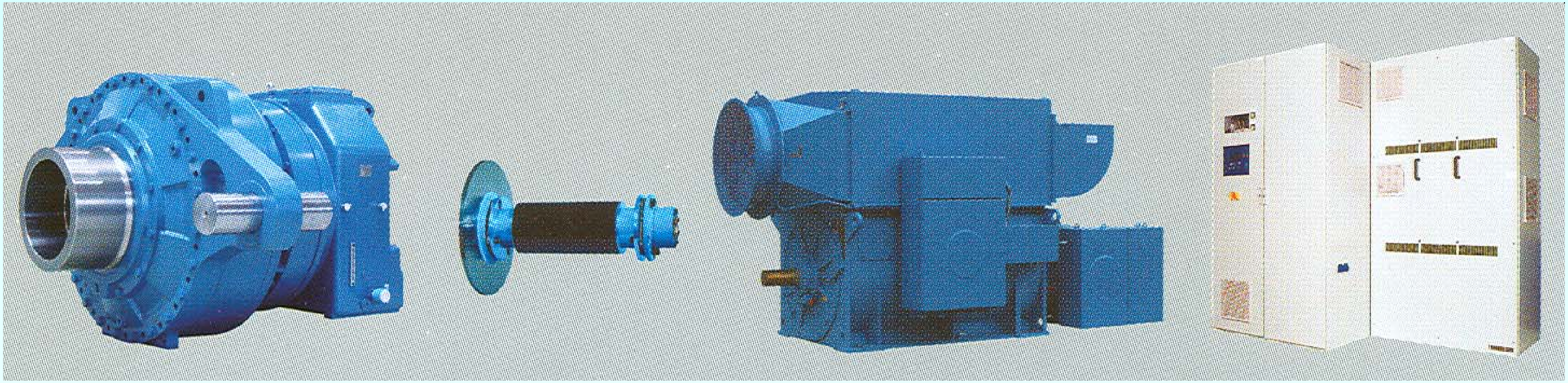
# Components of variable speed wind converter systems




Source:

Winergy, Germany

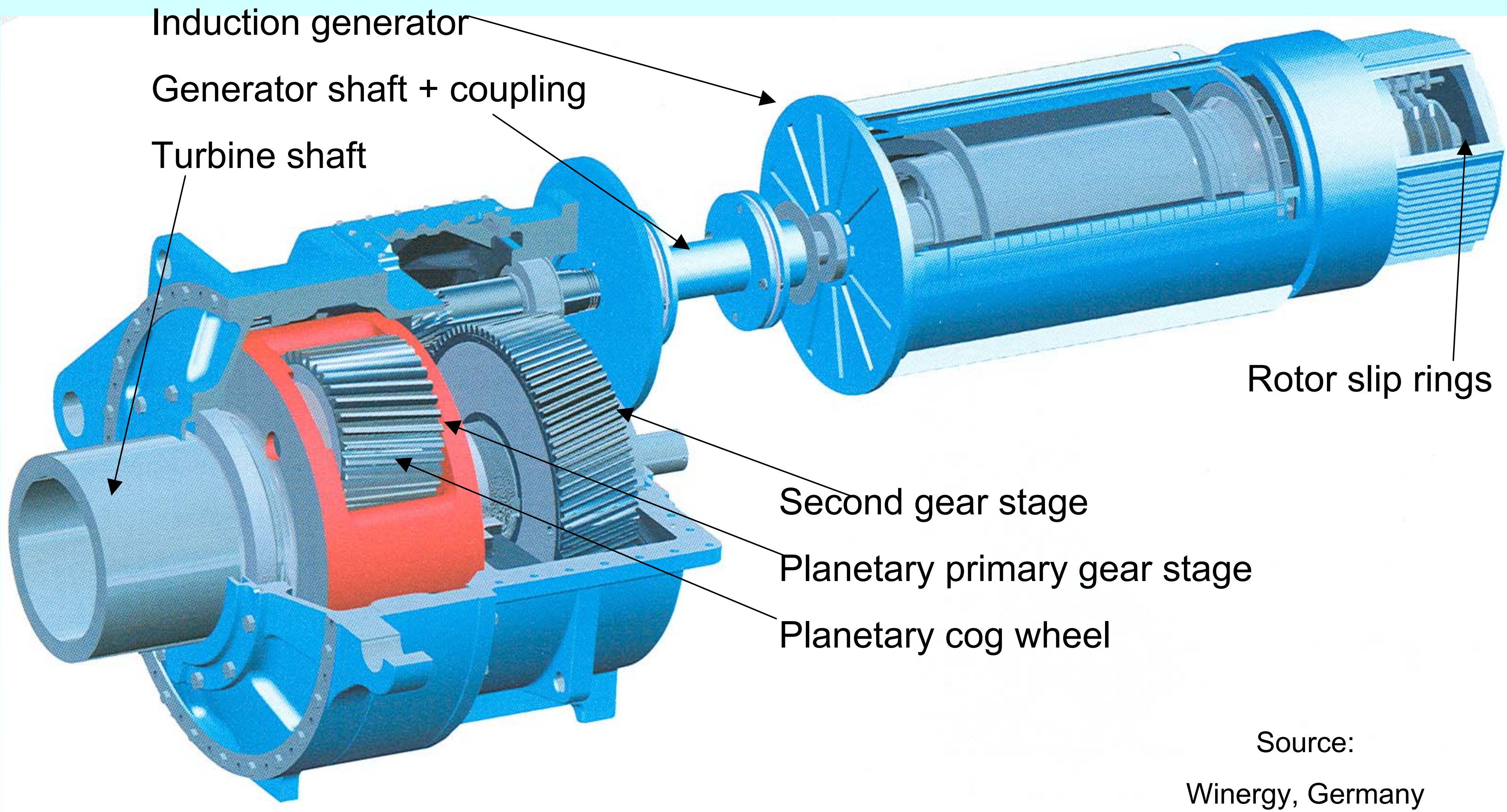
# Components of doubly-fed induction generator system 2 MW



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

Source: Winergy, Germany

# Geared doubly-fed induction wind generator

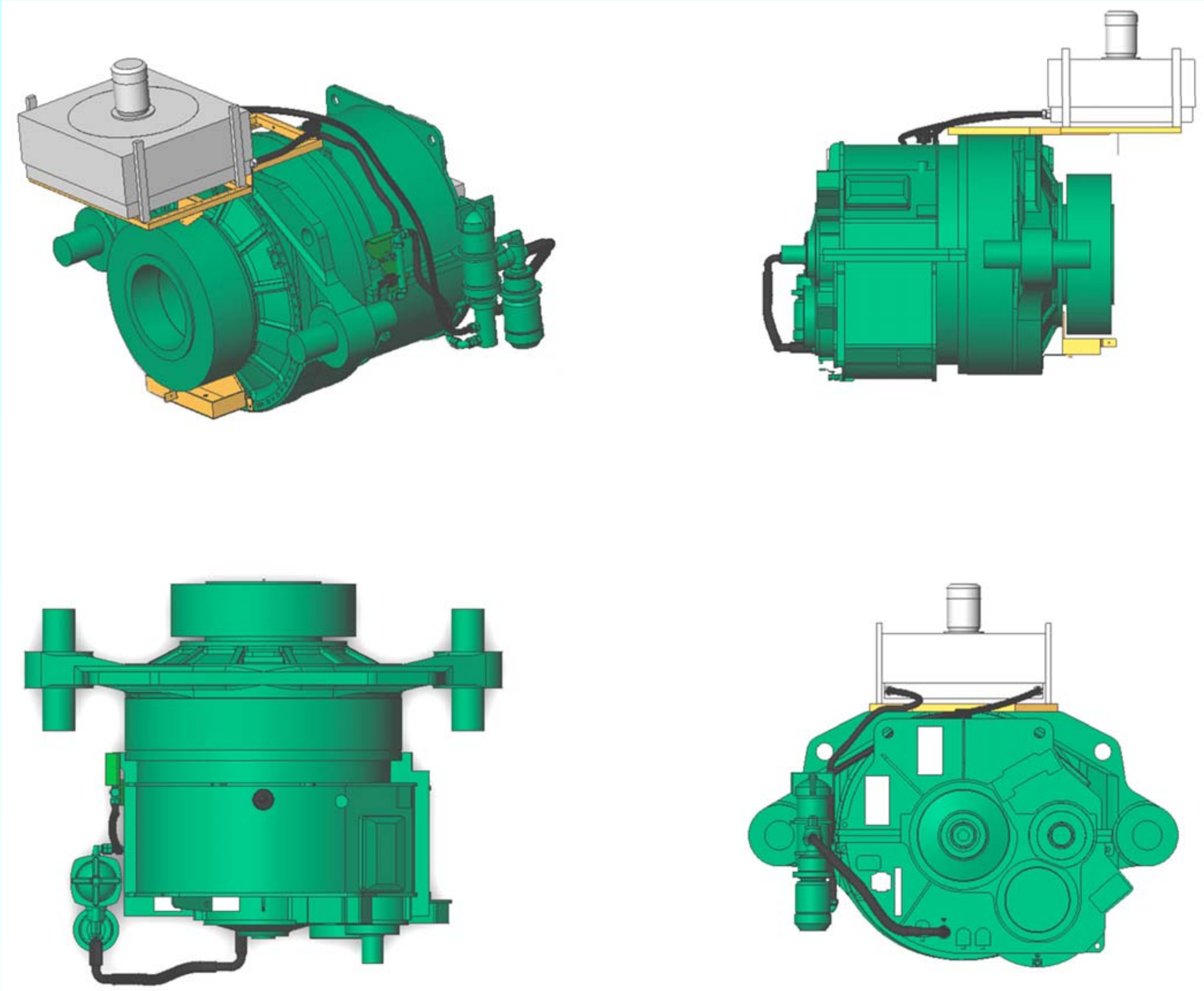


# Planetary gears for 600 kW ... 2750 kW


Source:

Winergy, Germany

# 1.5 MW three-stage gear unit: front and side view



Source:

GE Wind, Germany

# Testing of two 5 MW 3-stage gears back-to-back in the test field

Air-cooler

Air-cooled wind generator for driving the gear

Gear no.1

Gear no.2

Source:

Winergy

Germany

# Masses of three-stage gears

| | Stage 1 | Stage 2 | Stage 3 | Gear in total |
|---|---|---|---|---|
| | Planetary gear | Helical stage 1 | Helical stage 2 | |
| Transmission *i* | 8 | 4 | 3 | 96 |
| Torque | 100 % | 12.5 % | 3.1 % | |
| Mass | 86.5 % | 10.8 % | 2.7 % | 100 % |

Mass is determined by the first stage, which is designed for full turbine torque, demanding big diameter of cog wheels.

| | | |
|---|---|---|
| Rated power | 1.5 MW | 5 MW |
| Wind rotor rated speed | 16 /min | 11.5 /min |
| Torque | 895.2 kNm | 4151.2 kNm |
| Gear mass ratio | 100 % | 464 % |
| Gear mass | 14 t = 100 % *Südwind* | 65 t = 464 % *Repower* |

# Gear losses and efficiency

- Gear losses $P_d$ consist of no-load losses $P_{d0}$ (e.g. oil flow losses) and load-dependent losses $P_{d1}$ (e.g. contact friction force).

- No-load losses depend on square of speed, load losses linear of load torque.

$$\boxed{P_d = P_{d0N} \cdot \left( \frac{n_R}{n_{RN}} \right)^2 + P_{d1N} \cdot \left( \frac{M_R}{M_{RN}} \right)}$$

*Example:*

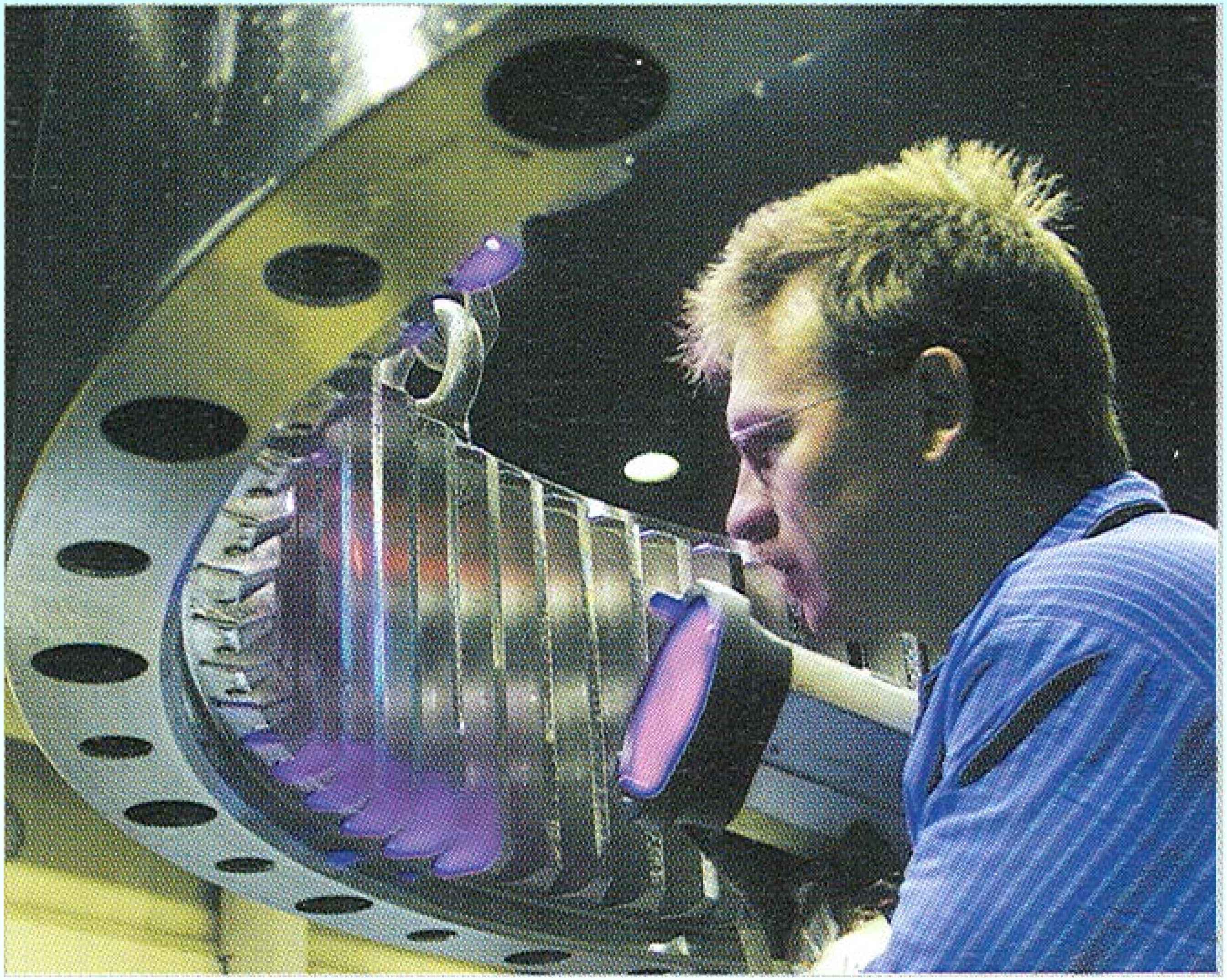
$P$ = 600 kW, $i$ = 45, no-load losses $P_{d0}$ = 8 kW, load losses $P_{d1}$ 10 kW,

- Total losses 18 kW, full load efficiency = 600 / 618 = **97.09 %.**
- Efficiency at 60 % of rated load: 360 kW: $P_{d1}$ = 6 kW, total: 14 kW, partial load efficiency = 360 / 374 = **96.3 %**

*Example:* $P$ = 3000 kW, $i$ = 90:

| | Full load | 60% load | 25% load |
|---|---|---|---|
| Efficiency | 98 % | 97 % | 93.65 % |

# Inspection of inner teeth row of planetary gear stage during production

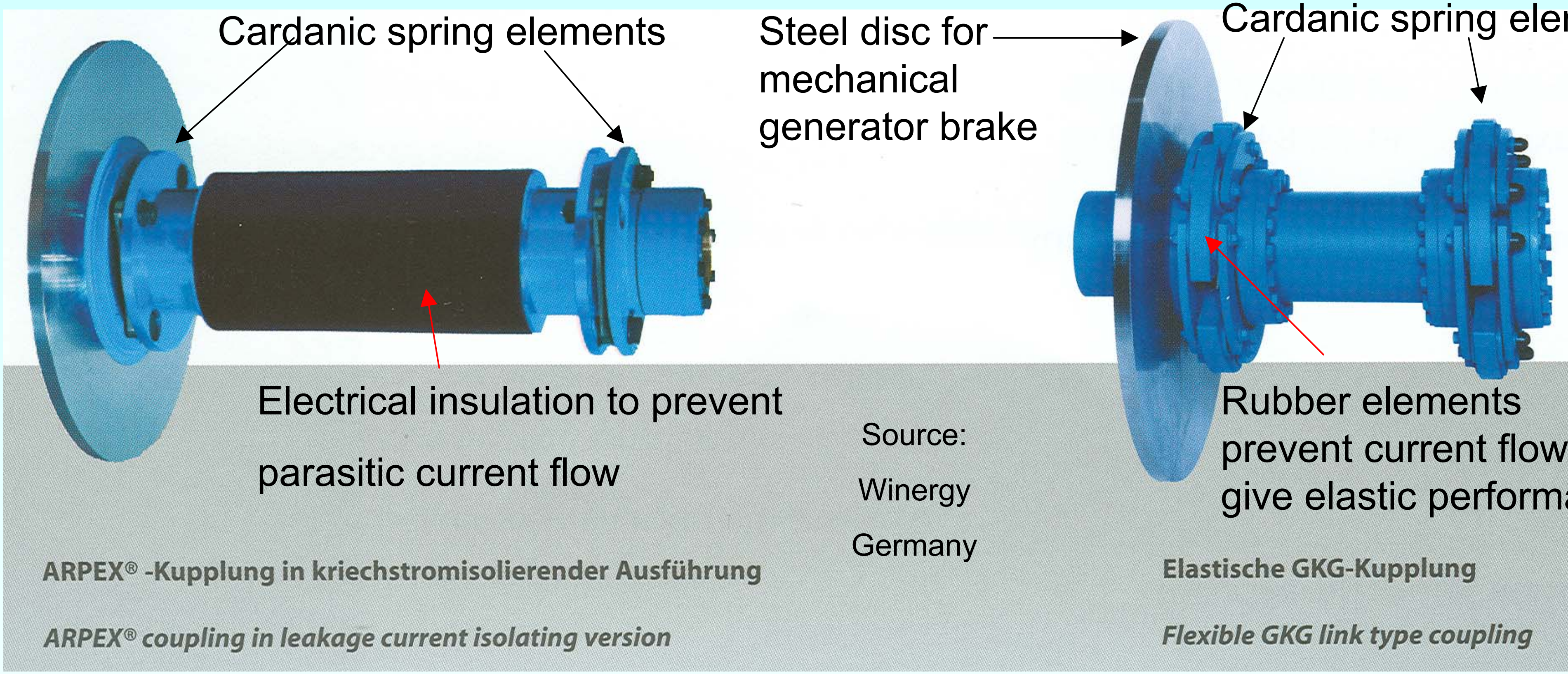


Source:

Winergy

Germany

# Cardanic generator coupling, electrically insulating




Electrically insulating coupling

Glass fibre reinforced shaft element

Elastic coupling steel coupling

with rubber elements

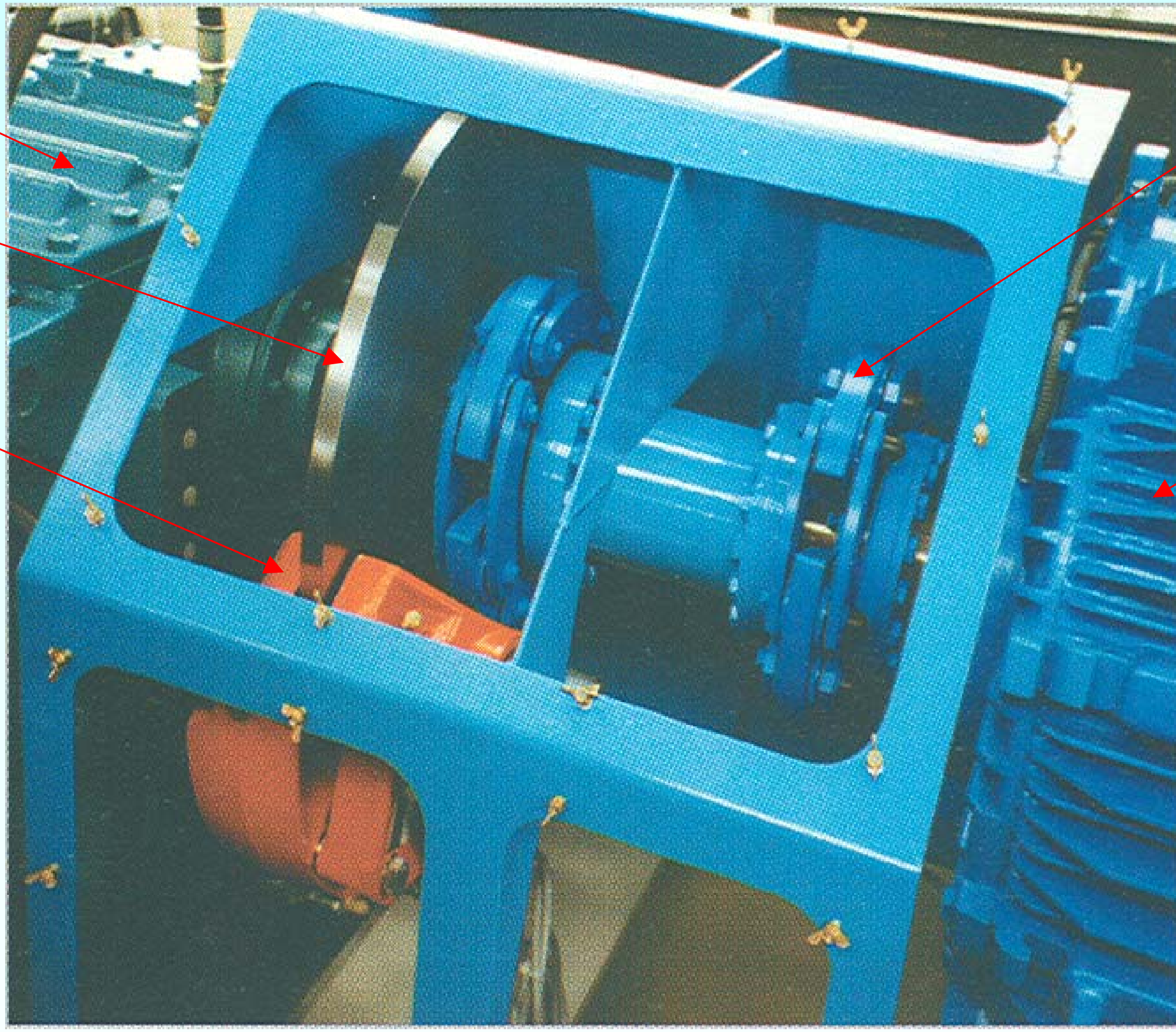
3° shaft misalignment admissible, often with slipping hub as torque-limiting component

# Coupling between gear and generator

Gear

Braking disk

Brake



Elastic coupling with rubber elements

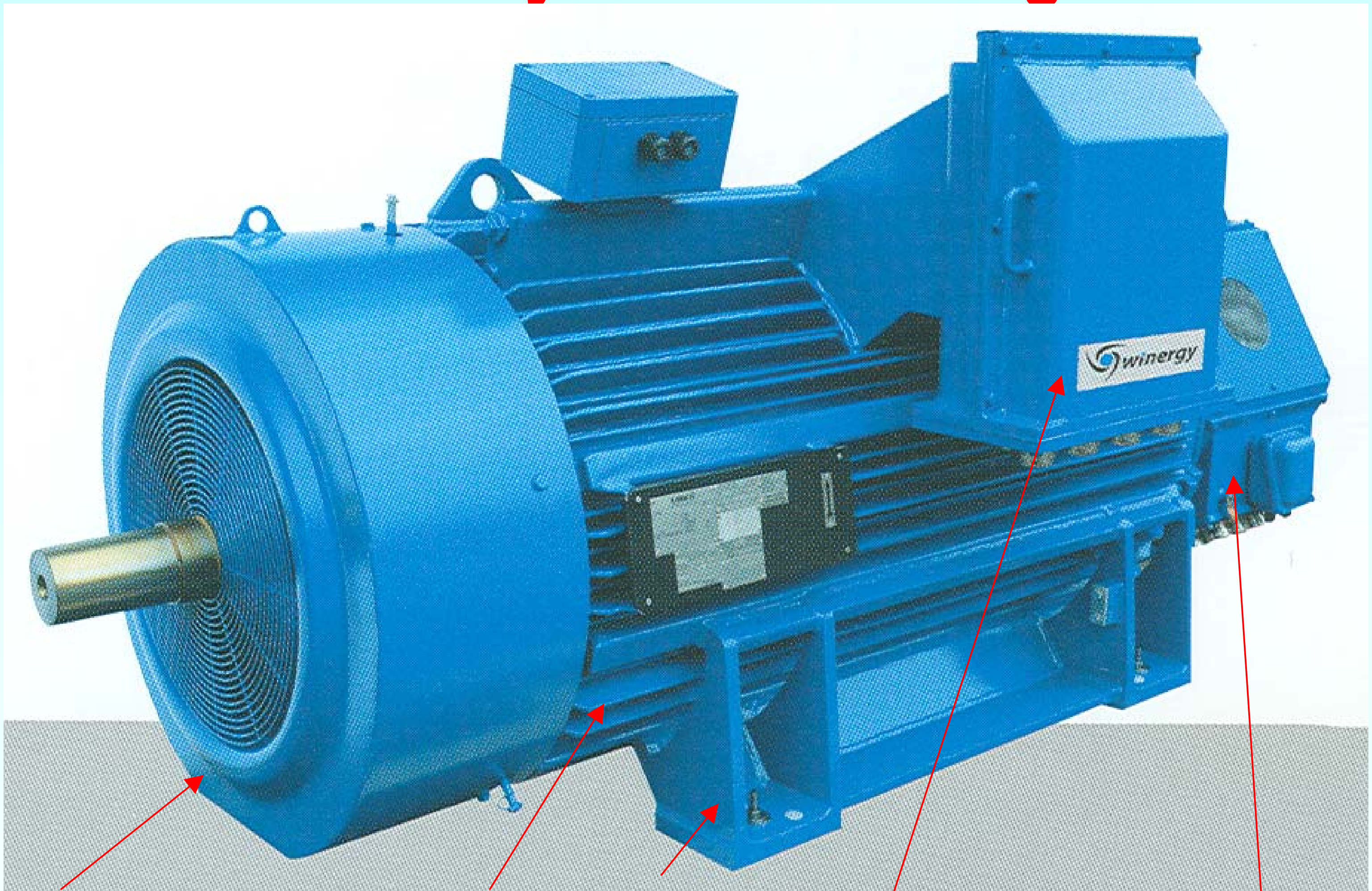
Generator housing with cooling fins

Source:

Winergy

Germany

# Doubly-fed induction generator




Totally enclosed doubly-fed induction generator

Air-cooled with iron-cast cooling fin housing

600 kW at 1155/min

Source:

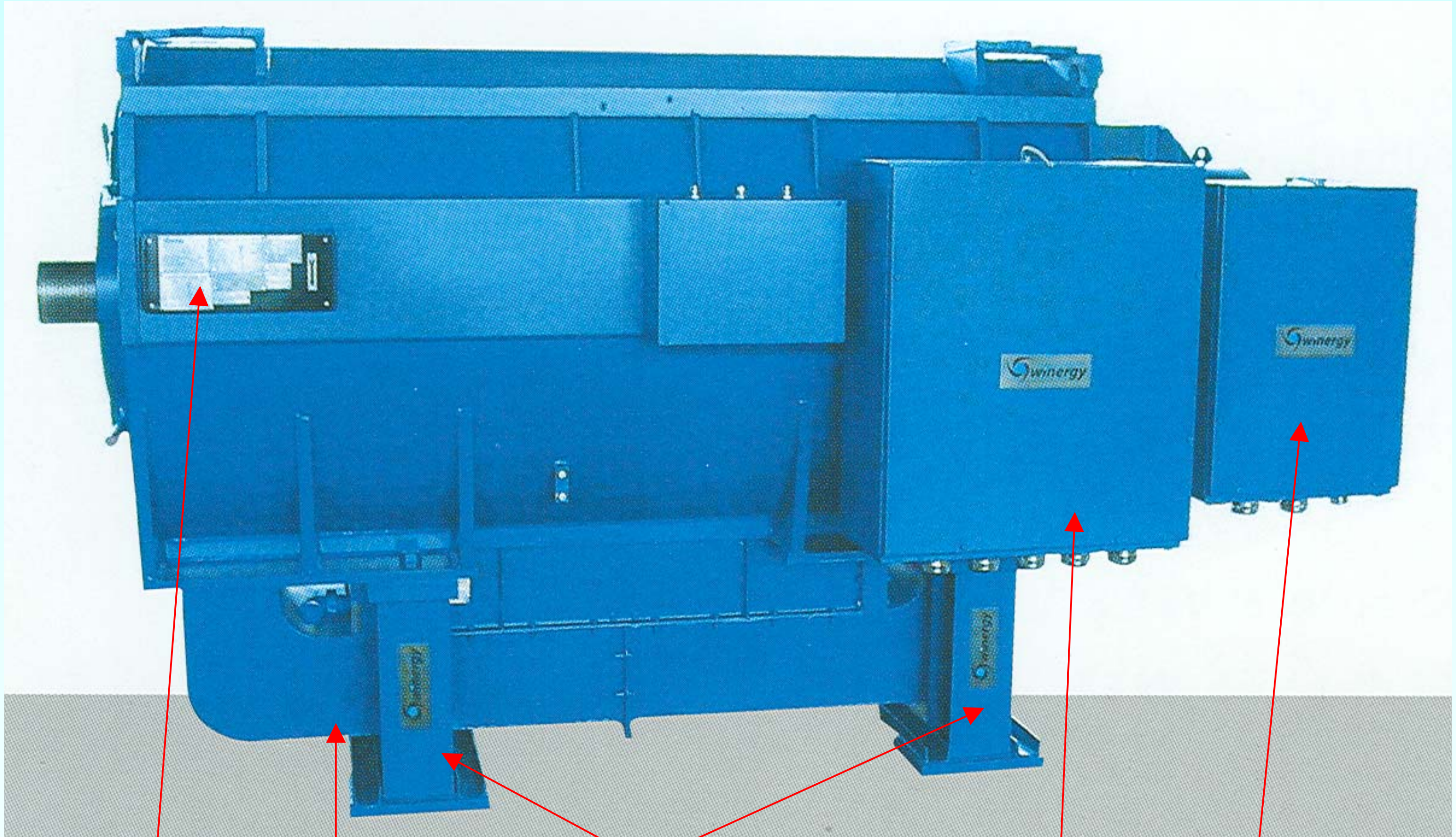
Winergy

Germany

Fan hood Cooling fins Feet Power terminal box Slip ring

Shaft mounted fan inside terminal box

# Doubly-fed induction generator with heat exchanger




Doubly-fed induction generator

2750 kW at 1100/min

Source:

Winergy

Germany

Name plate

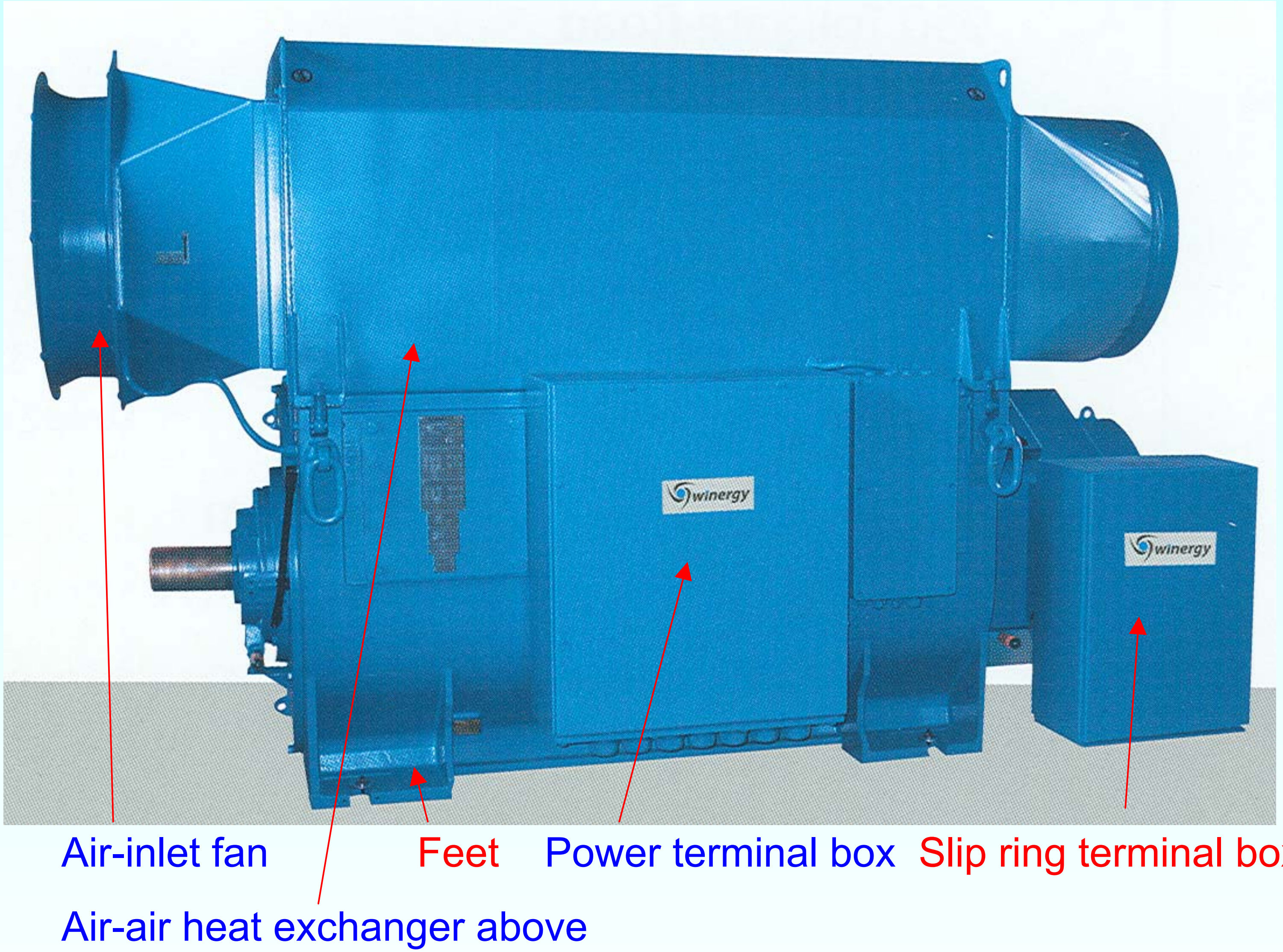
Feet

Power terminal box

Slip ring terminal box

Air-water heat exchanger beneath

# Doubly-fed induction generator with heat exchanger




Doubly-fed induction generator

4 poles

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

Rotor frequency 10 Hz

Source:

Winergy

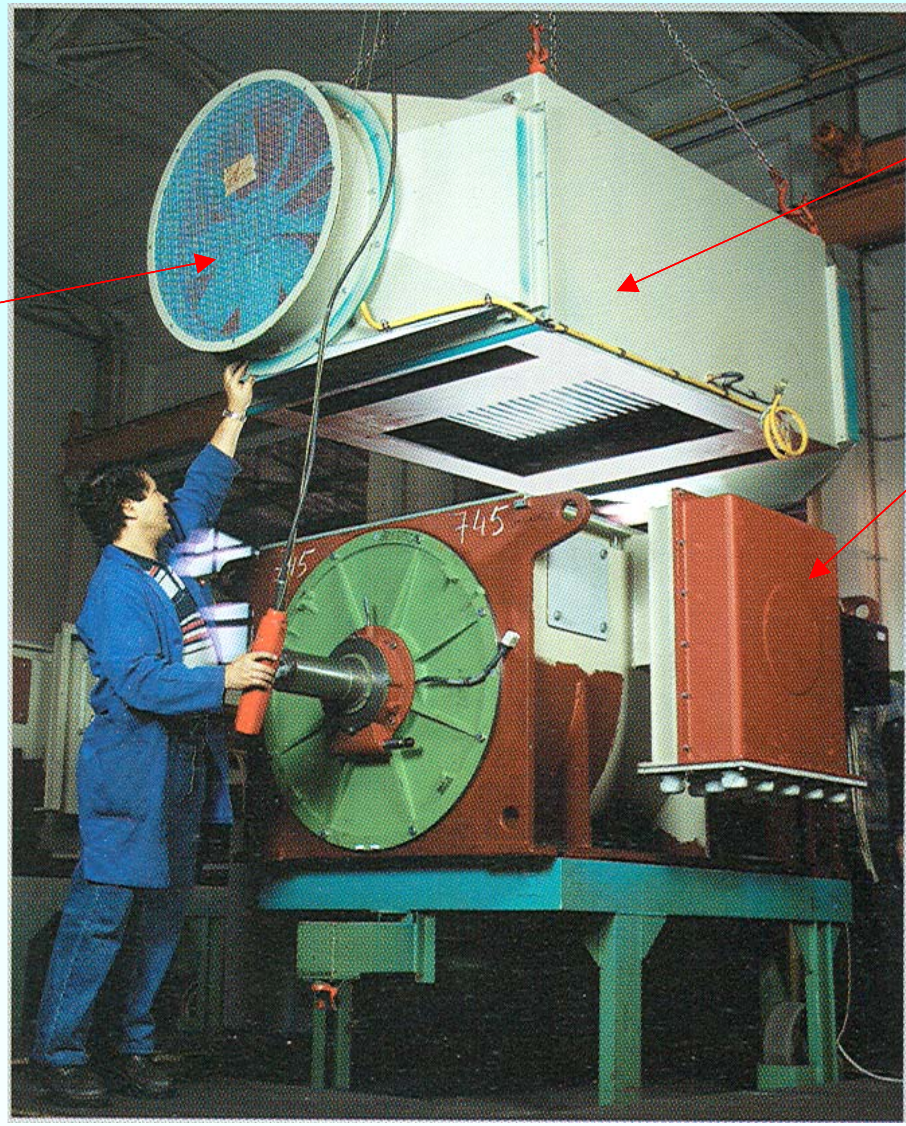
Germany

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

Doubly-fed induction generator

1500 kW at 1800/min

Air inlet fan




Air-air heat exchanger

Generator terminal box

Source:

Winergy

Germany

# *Example:* Rating for doubly-fed generators

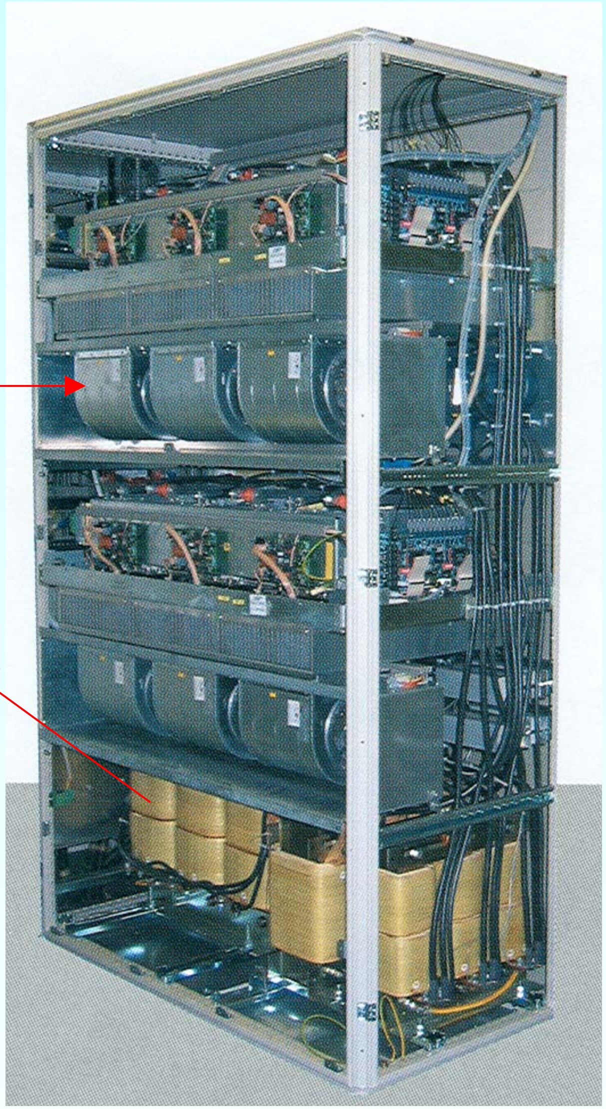
a

| | |
|---|---|
| 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 |

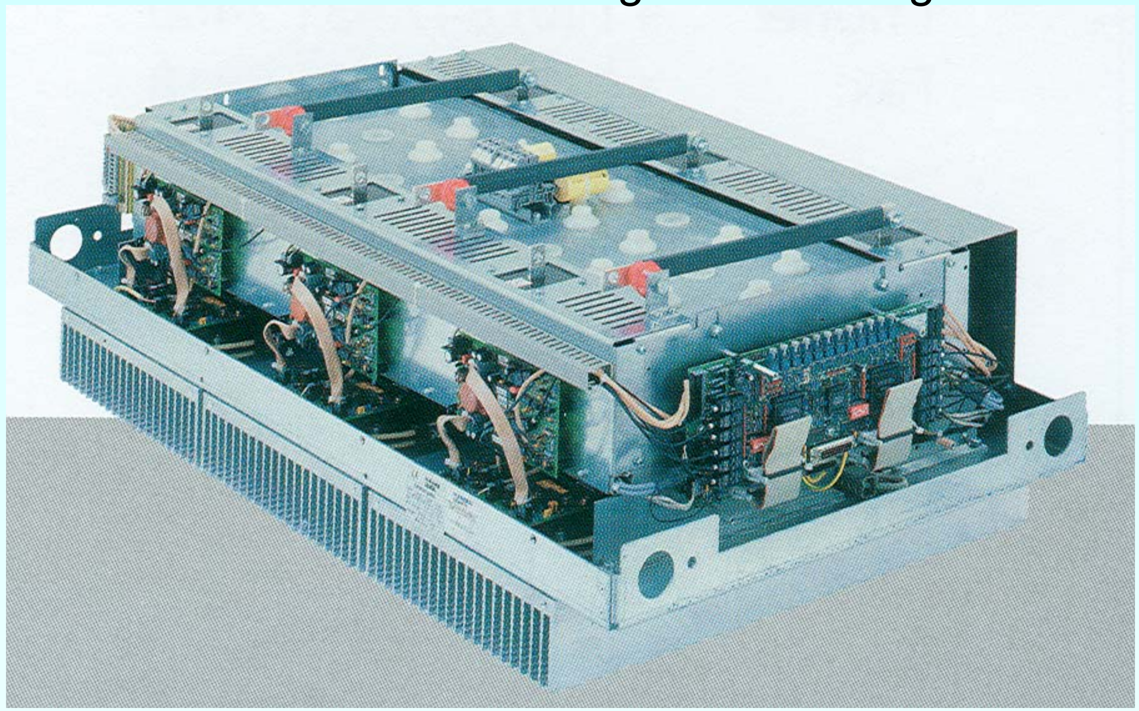
# Rotor side PWM voltage source inverters

Fan units

Filter chokes



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

# Inverter rating for doubly-fed generators

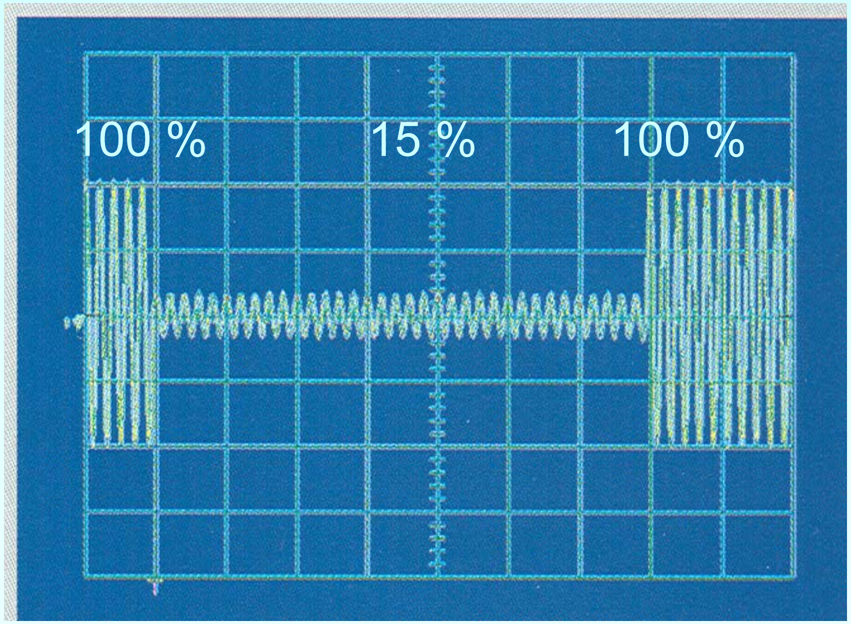
| | |
|---|---|
| Rated power of wind converter | 3 MW |
| Rated voltage / Current / Frequency | 732 V / 748 A / <15 Hz; 50 Hz |
| Rated apparent power | 950 kVA |
| Inverter unit / full-load efficiency | 800 kW / 820 A / 97 % |
| Dimensions *LxBxH* / Mass | 0.9x0.6x2.45 = 1.3 $m^3$ / 1045 kg |
| Crowbar: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

# 15% voltage break-down during 0.7 s

Generator terminal voltage




Generator transient currents

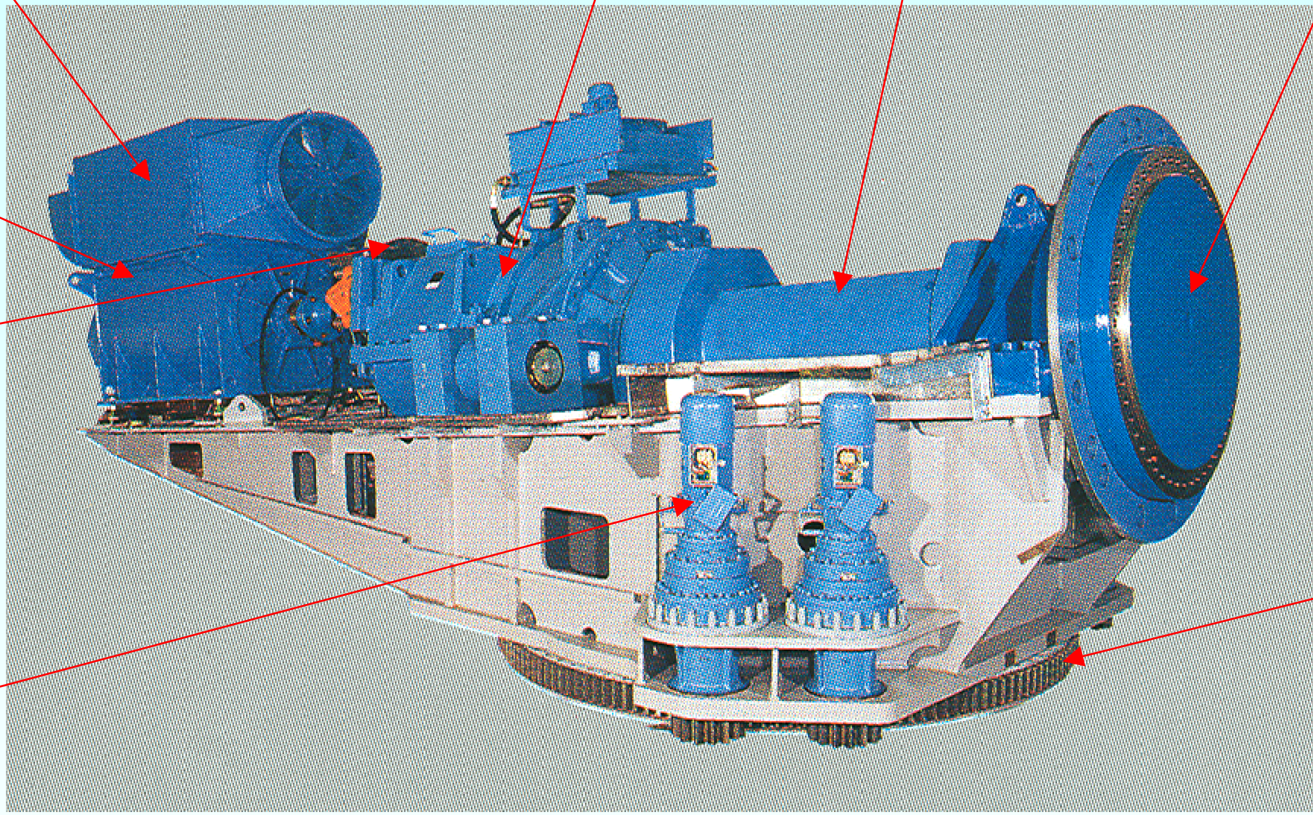

0.1 s/div. Measured voltage break-down response in test lab

**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

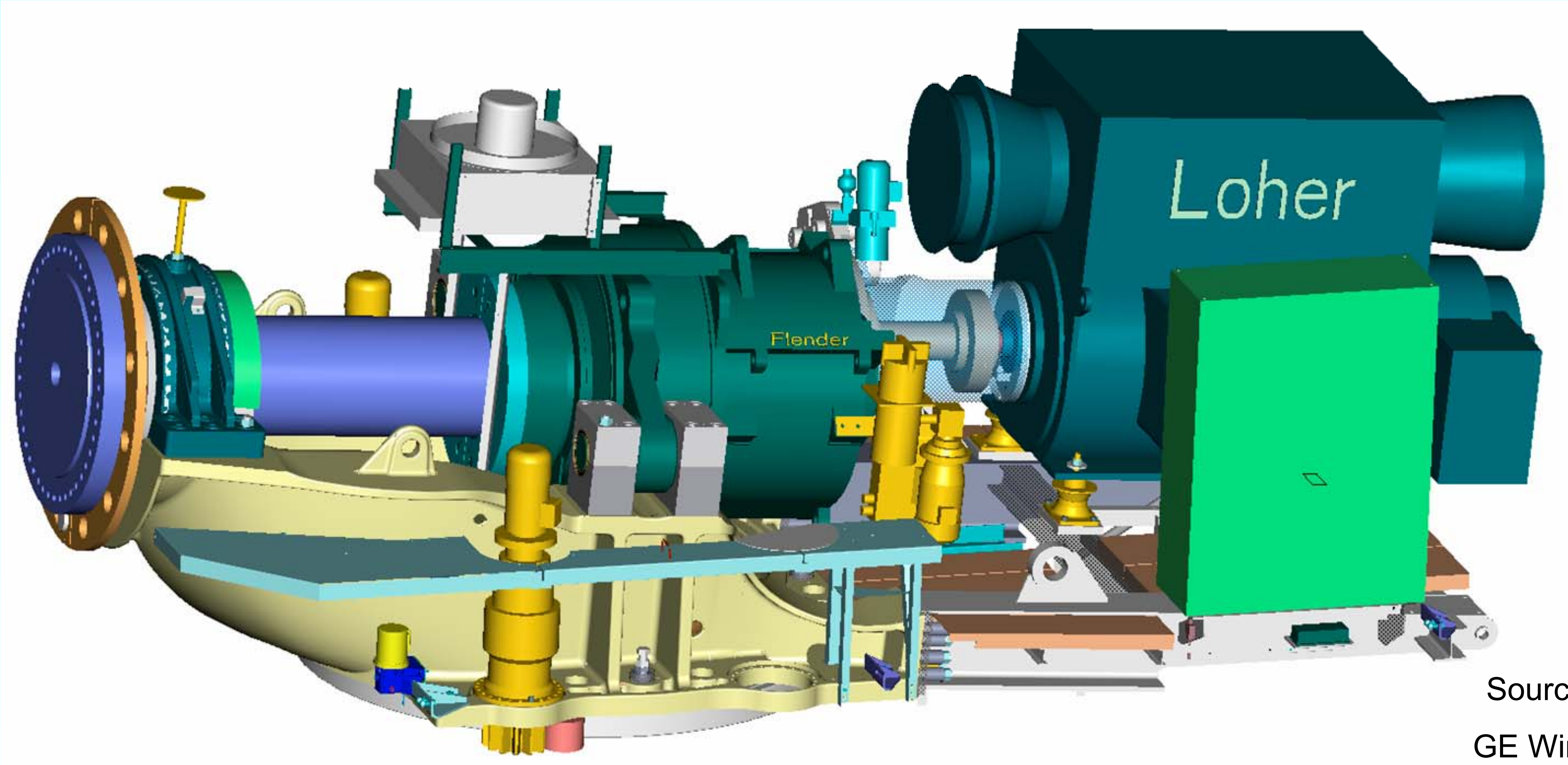



Source:

Winergy

Germany

# Electro-mechanical drive train of 2.1 MW variable speed wind converter unit with doubly-fed induction generator




Source:

GE Wind, Germany

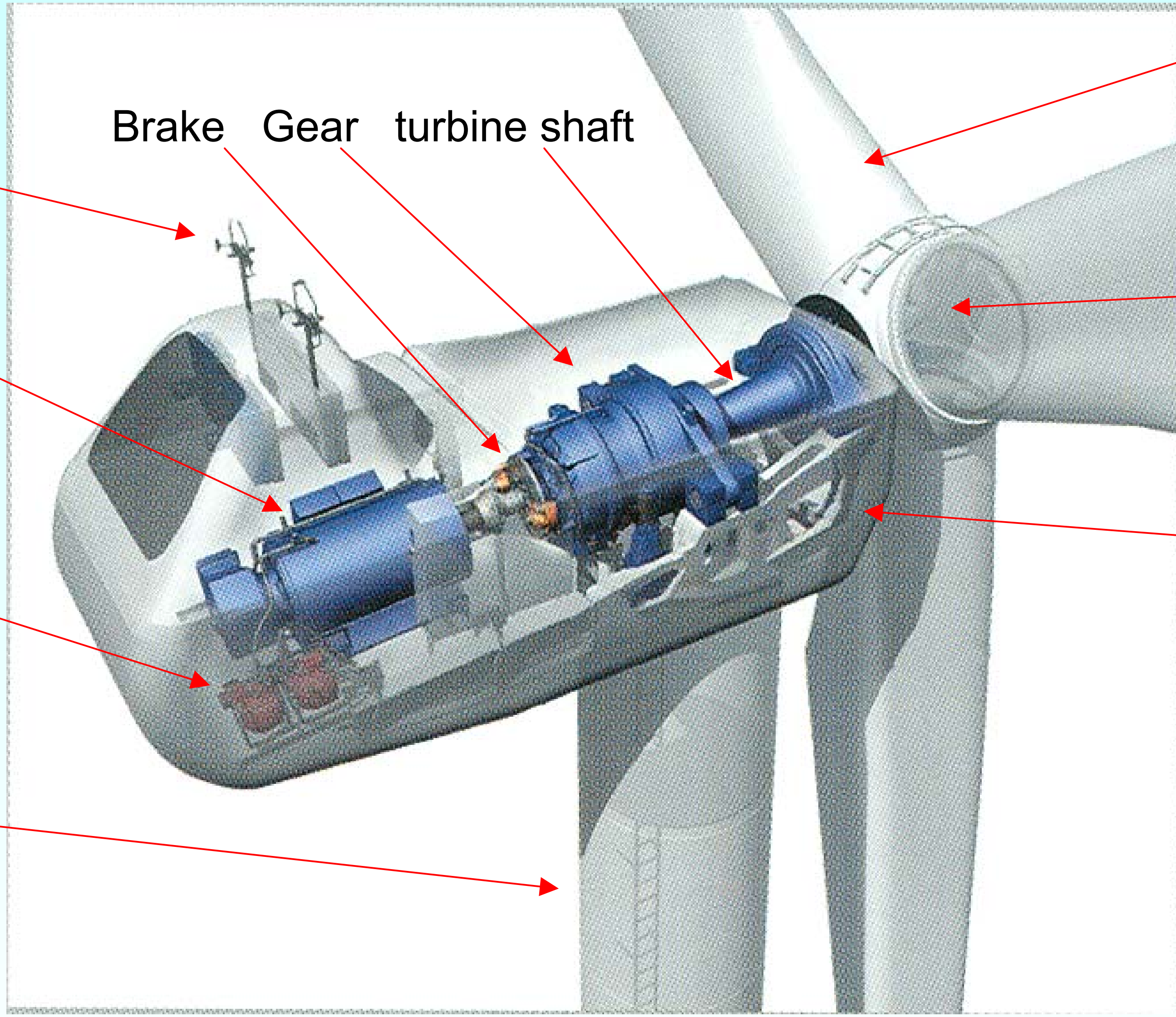
# Wind converter assembly

Wind speed & direction sensors

Water-jacket cooled induction generator

Water pump system

Pole




Blades

Spider

Nacelle

Source:

Winergy

Germany

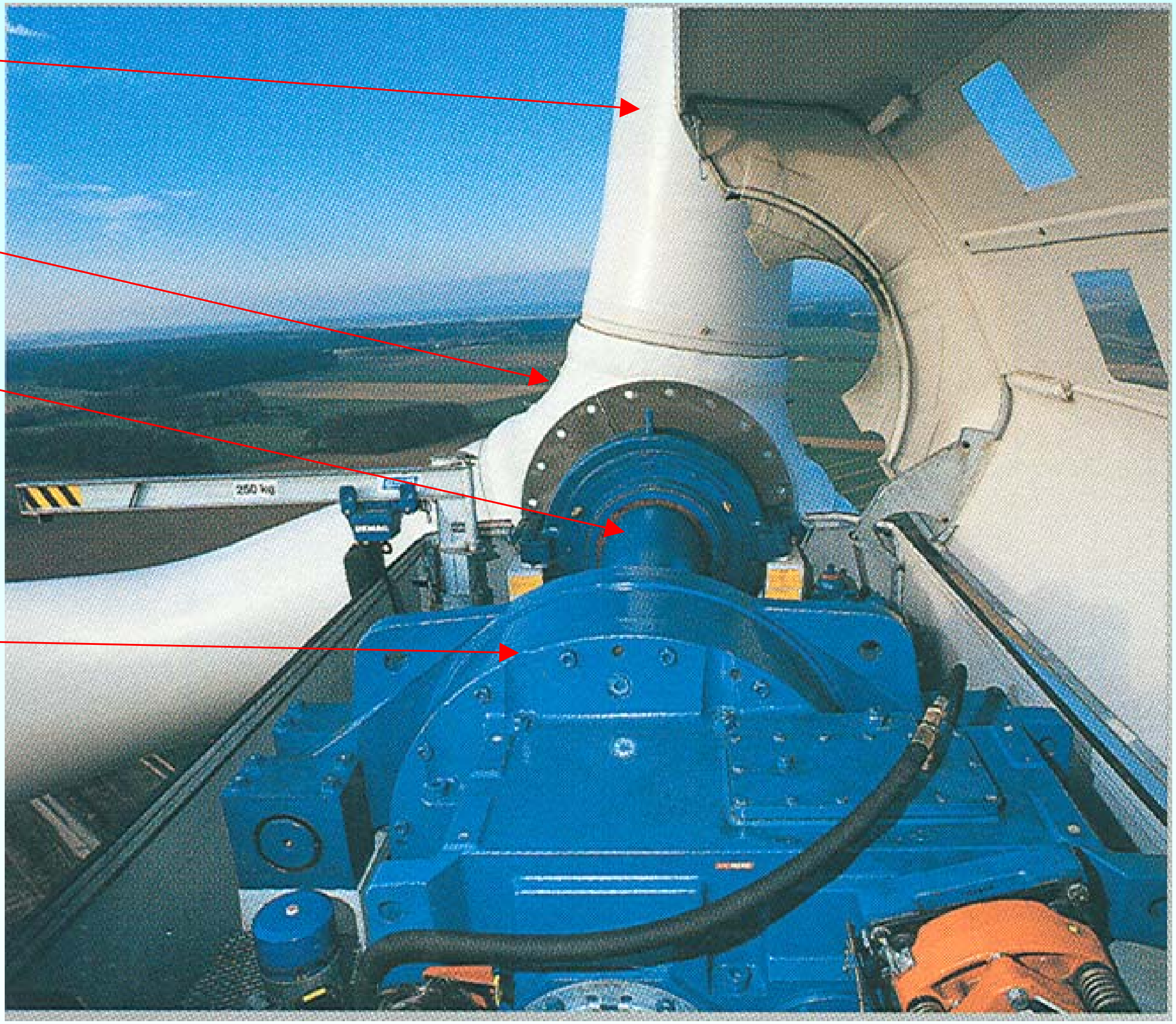
# Mounting of drive assembly in nacelle

Blade

Spider

Turbine shaft

Gear




Source:

Winergy

Germany

# Installation of monitoring system for generator unit

Totally enclosed induction generator with shaft mounted fan

Generator coupling

Gear

Source:

Winergy

Germany

# Gearless wind turbines

Typical data of gearless permanent magnet synchronous wind generator:

3 MW, 606 V, 3360 A, frequency 13.6 Hz (via inverter feeding)

cos phi = 0.85 under-excited, speed 17 / min, efficiency 95.5%

Rated torque: 1685 k Nm (!)

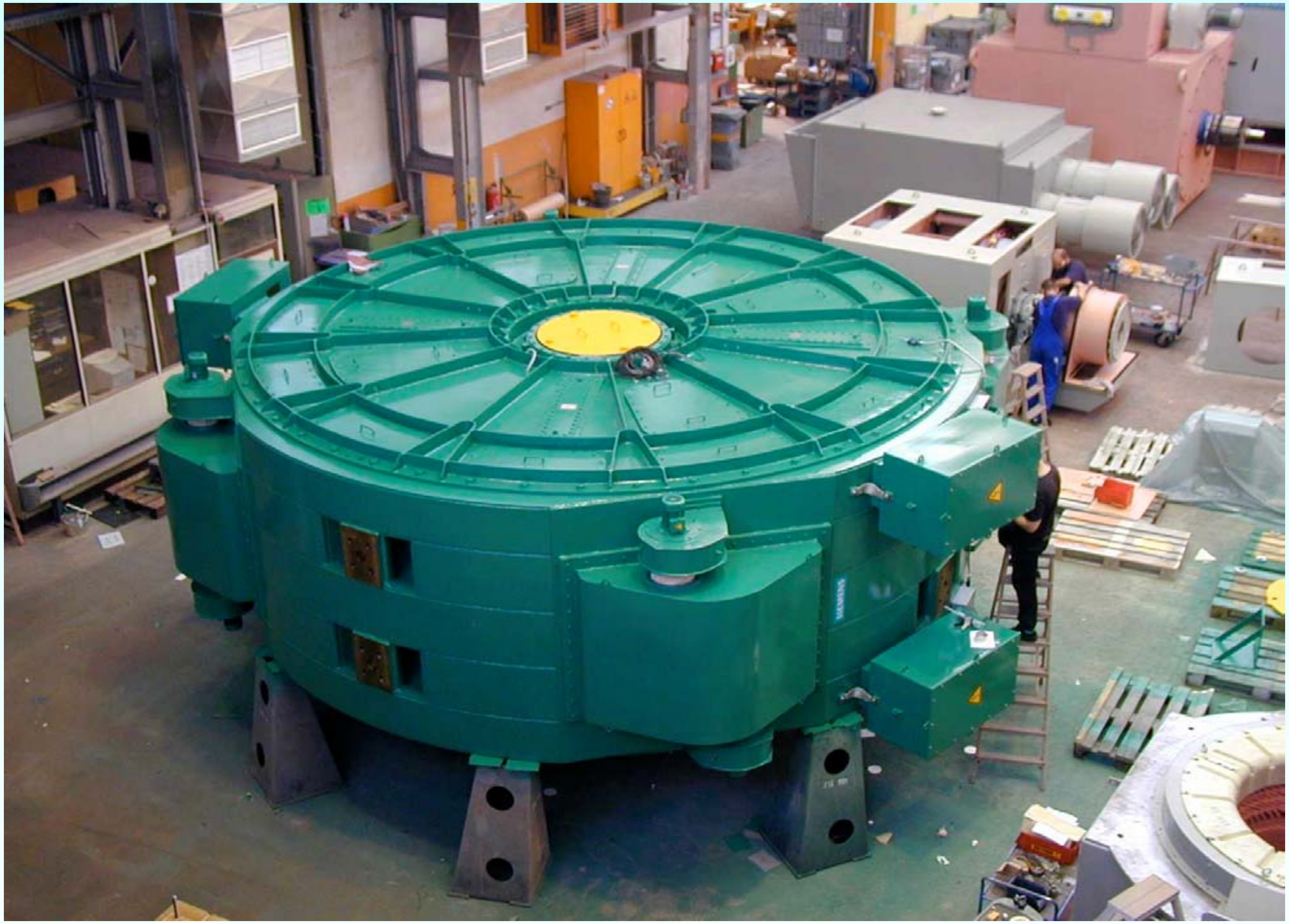
Outer diameter of generators: ca. 5.8 m, axial length: ca. 2.3 m

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

***Note:*** An induction generator with that small pole pitch and that relatively big air gap would need a big magnetizing current. So power factor would be very poor (below 0.6), leading to lower efficiency !

*Source: Siemens AG, Germany*

# Gearless permanent magnet wind generator
# *Scanwind/Norwegian* coast 3 MW, 17/min



Wind rotor diameter 90 m

Three-blade rotor

Pitch control

Variable speed operation

10 ... 20/min

Gearless drive

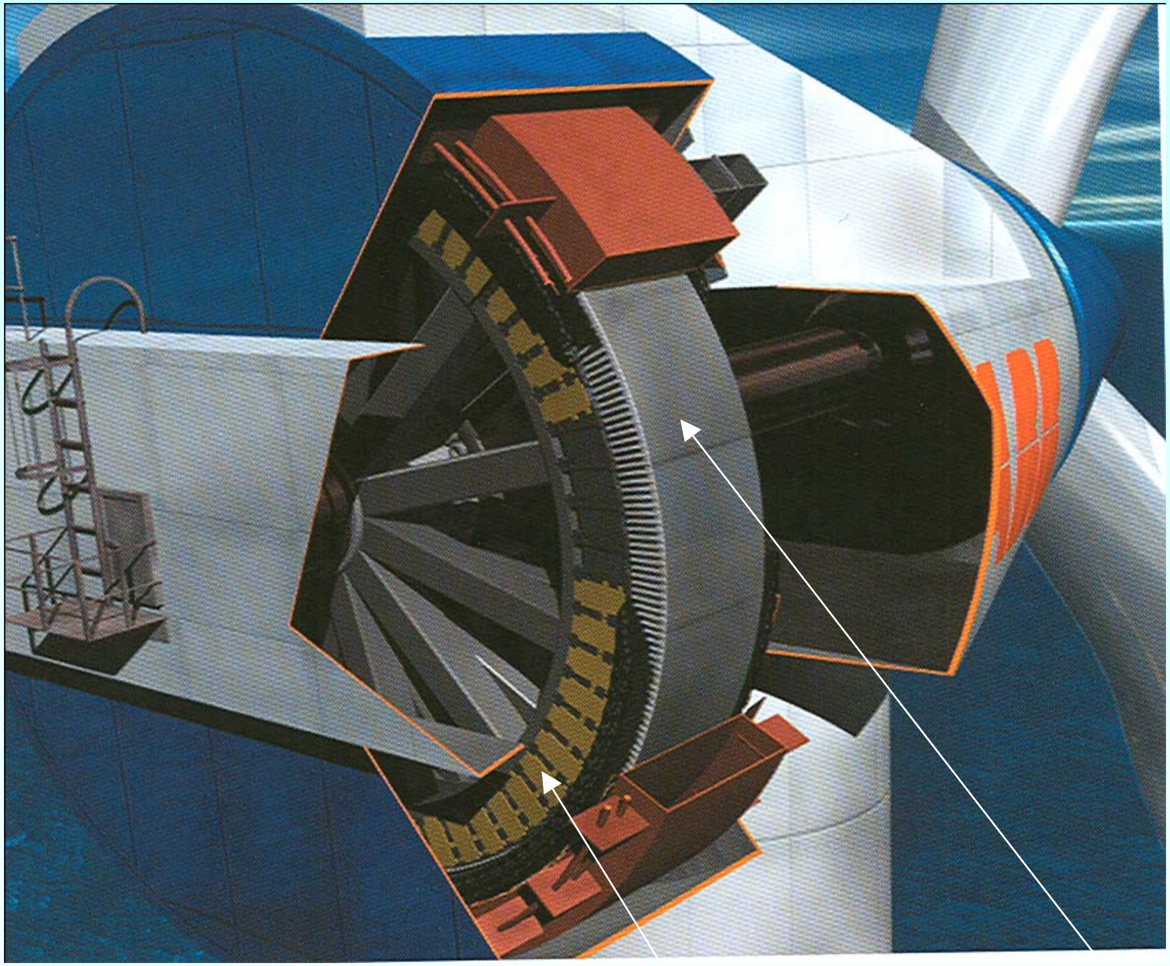
IGBT inverter 690 V

*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

Magnet rotor high voltage stator with winding

*Source: ABB, Sweden*

# Permanent magnet wind generator: gearless inner stator / outer 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

Centre pole mass: 96 t

PM generator

Source:

Innowind, Germany

Goldwind, Urumqi, Xinjiang, China