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
2. Electromagnetic fundamentals
3. Three phase winding technology
4. Electrically excited synchronous machines
5. Induction machines with wound rotor
6. Induction machines with cage rotor
7. Inverter operated induction machines
8. Permanent magnet synchronous machines
9. Examples of hydro energy conversion
1. Green energy conversion systems

1.1 Wind energy converters

Source: Winergy, Germany
Wind energy conversion

- **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/m²: modular wind farm design needed**
  - Upper per-unit power of wind converter < 10 MW

Source: S. Joeckel, Innowind, Germany
Wind energy conversion

- Fixed speed drives: super-synchronous speed \( n_{\text{Gen}} = (1-s) \cdot \frac{f_s}{p} \), \( s \sim -0.5 \ldots -1 \% \)
  Cage induction generators, directly grid operated, super-synchronous speed
  geared wind turbines \( n_T = n_{\text{Gen}} / i \) (\( i \): gear ratio, typically 50 \ldots 100)
  stall turbine power control
  Rated unit power up to 1 MW

- Variable speed drives: speed varies typically \( n_T 50\% \ldots 100\% \)
  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 \ldots 5 MW
Fixed speed wind energy conversion

- **Generator speed**: super-synchronous speed $n_{Gen} = (1-s)f_s/p$, $s \sim -0.5 \ldots -1\%$

  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: $2p = 6$: $n_{syn} = f_s/p = 1000/\text{min at } 50\text{ Hz}$

  Big 4-pole winding: $2p = 4$: $n_{syn} = f_s/p = 1500/\text{min at } 50\text{ Hz}$

- **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

Power typically up to 1 MW

stall power control

Source: S. Joeckel, Innowind, Germany

Speed nearly constant: \( f_s/p \cdot (1 - s) \)
\( s = -0.005 \ldots -0.01 \)

Gear

Cage induction generator with pole-changing: e.g. 4/6-poles

Transformer

Grid

Compensation of inductive power

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

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 $i < 8 \ldots 9$: $M_{\text{out}} = M_{\text{in}} / i$, $n_{\text{out}} = i \cdot n_{\text{in}}$

Source: GE Wind, Germany
Principle of 3 stage gear with planetary gear as 1st stage

Input: Big torque, low speed

Output: high speed, low torque

- Helical gear as 3rd stage
- Helical gear as 2nd stage
- Planetary gear as 1st stage

Source: GE Wind, Germany
Planetary gear with two helical stages = 3 stage gear  
\[ i = 100 \]

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

Second stage  
= helical gear

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

Cut-view demonstration object

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: \( n_{Gen} = (1-s) \cdot f_s / p \), \( s \sim -0.5 \ldots -1 \% \)
  - Cage induction generators: Big variation of torque with slip (\textit{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” \textit{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

<table>
<thead>
<tr>
<th>$P$ / MW</th>
<th>$D_R$ / m</th>
<th>$n_R$ / min$^{-1}$</th>
<th>Company</th>
<th>Generator</th>
<th>$v_{R\text{max}}$ / km/h</th>
<th>$v_{N}$ / m/s</th>
<th>Gear $i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>70</td>
<td>10...19</td>
<td>Repower</td>
<td>DS-ASM</td>
<td>251</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>9...17</td>
<td>Südwind</td>
<td>DS-ASM</td>
<td>247</td>
<td>3...20, 11.1</td>
<td>104</td>
</tr>
<tr>
<td>2.0</td>
<td>80</td>
<td>9...19</td>
<td>Vestas</td>
<td>DS-ASM</td>
<td>287</td>
<td>4...25, 15</td>
<td>No data</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>7.4...14.8</td>
<td>Made</td>
<td>Optispeed</td>
<td>251</td>
<td>3...25</td>
<td>101</td>
</tr>
<tr>
<td>2.7</td>
<td>84</td>
<td>6.5...18</td>
<td>GE Wind</td>
<td>DS-ASM</td>
<td>285</td>
<td>4.5...25</td>
<td>No data</td>
</tr>
<tr>
<td>2.75</td>
<td>92</td>
<td>$n_{RN} = 15.6$</td>
<td>NEG Micon</td>
<td>DS-ASM</td>
<td>285</td>
<td>4.25, 14</td>
<td>70.65</td>
</tr>
<tr>
<td>3.0</td>
<td>90</td>
<td>10...20</td>
<td>Scan Wind</td>
<td>PM-Syn</td>
<td>339</td>
<td>No data</td>
<td>gearless</td>
</tr>
<tr>
<td>3.6</td>
<td>104</td>
<td>8.5...115.3</td>
<td>GE Wind</td>
<td>DS-ASM</td>
<td>300</td>
<td>3.5...25</td>
<td>No data</td>
</tr>
<tr>
<td>4.5</td>
<td>104</td>
<td>No data</td>
<td>Enercon</td>
<td>Syn-G SL</td>
<td>No data</td>
<td>No data</td>
<td>gearless</td>
</tr>
<tr>
<td>5.0</td>
<td>125</td>
<td>7...13</td>
<td>Repower</td>
<td>DS-ASM</td>
<td>306</td>
<td>4...30, 12</td>
<td>98.3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>3 MW</th>
<th>5 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>3 MW</td>
<td>5 MW</td>
</tr>
<tr>
<td>Wind turbine rotor diameter</td>
<td>104 m</td>
<td>125 m</td>
</tr>
<tr>
<td>Speed range 1/min</td>
<td>8.5 ... 13 (Rated) ... 15.3</td>
<td>7 ... 11 (Rated) ... 13</td>
</tr>
<tr>
<td>Wind velocity m/s</td>
<td>3.5 ... 25</td>
<td>3 ... 25</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Rated power</th>
<th>3-blade wind rotor</th>
<th>Generator system: Doubly fed induction gen.</th>
<th>Nacelle</th>
<th>Wind rotor + Nacelle</th>
</tr>
</thead>
</table>
| 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 |

<table>
<thead>
<tr>
<th>Rated power</th>
<th>3-Blatt-Windrotor</th>
<th>Generator system: synchronous gen.</th>
<th>Nacelle</th>
<th>Wind rotor + Nacelle</th>
</tr>
</thead>
</table>
| 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 Pfleiderer  | In total with spider: $100$ t | Gear: $i = ca.14$  
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:
Winery, Germany
Components of variable speed wind converter systems

Wind rotor:
- Blade
- Spider
- Turbine shaft
- Generator three-phase cable

Nacelle:
- Three-stage gear
- Generator shaft + coupling
- Induction generator
- Rotor side inverter
- Centre pole

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

- Induction generator
- Generator shaft + coupling
- Turbine shaft

- Second gear stage
- Planetary primary gear stage
- Planetary cog wheel
- Rotor slip rings

Source:
Winery, Germany
Planetary gears for 600 kW ... 2750 kW

Winergy series products from 600 – 2,750 kW

Planeten-Stirnradgetriebe PEAS 4280 / 600 kW
Planetary helical gear unit PEAS 4280 / 600 kW

Planeten-Stirnradgetriebe PEAS 4390 / 1,500 kW
Planetary helical gear unit PEAS 4390 / 1,500 kW

Zweistufiges Planetengetriebe PZAB 3450 / 2,500 kW
Planetary gear unit (2 stages) PZAB 3450 / 2,500 kW

Planeten-Stirnradgetriebe PEB 4500 / 2,750 kW
Planetary helical gear unit PEB 4500 / 2,750 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

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Gear in total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission $i$</td>
<td>8</td>
<td>4</td>
<td>3</td>
<td>96</td>
</tr>
<tr>
<td>Torque</td>
<td>100 %</td>
<td>12.5 %</td>
<td>3.1 %</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>86.5 %</td>
<td>10.8 %</td>
<td>2.7 %</td>
<td>100 %</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>1.5 MW</th>
<th>5 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind rotor rated speed</td>
<td>16 /min</td>
<td>11.5 /min</td>
</tr>
<tr>
<td>Torque</td>
<td>895.2 kNm</td>
<td>4151.2 kNm</td>
</tr>
<tr>
<td>Gear mass ratio</td>
<td>100 %</td>
<td>464 %</td>
</tr>
<tr>
<td>Gear mass</td>
<td>14 t = 100 % Südwind</td>
<td>65 t = 464 % Repower</td>
</tr>
</tbody>
</table>
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.

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

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, $i = 90$:

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Full load</th>
<th>60% load</th>
<th>25% load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>98 %</td>
<td>97 %</td>
<td>93.65 %</td>
</tr>
</tbody>
</table>
Inspection of inner teeth row of planetary gear stage during production

Source: Winergy
Germany
Cardanic generator coupling, electrically insulating

Cardanic spring elements
Steel disc for mechanical generator brake
Cardanic spring elements

Electrical insulation to prevent parasitic current flow
Source: Winergy Germany

Steel coupling
Rubber elements prevent current flow and give elastic performance

ARPEX®-Kupplung in kriechstromisoliierender Ausführung
ARPEX® coupling in leakage current isolating version
Elastische GKG-Kupplung Flexible GKG link type coupling

Electrically insulating coupling
Glass fibre reinforced shaft element

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

Source: Winergy Germany
Coupling between gear and generator

Source: Winergy Germany

- Elastic coupling with rubber elements
- Generator housing with cooling fins

Gear
Braking disk
Brake
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
Doubly-fed induction generator with heat exchanger

- Source: Winergy
- Germany

Doubly-fed induction generator
- 2750 kW at 1100/min

Components:
- 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind power rating</td>
<td>3 MW</td>
</tr>
<tr>
<td>Generator cooling / Thermal class</td>
<td>Air-Air heat exchanger / Class F</td>
</tr>
<tr>
<td>Generator rating</td>
<td>3.3 kV / 616 A / 50 Hz</td>
</tr>
<tr>
<td>Apparent power / power factor</td>
<td>3.5 MVA / 0.88 inductive load</td>
</tr>
<tr>
<td>Real power / Generator mass</td>
<td>3.1 MW / 14.6 t</td>
</tr>
<tr>
<td>Slip range / Rotor voltage at stand still</td>
<td>+/- 30 % / 2443 V at 50 Hz</td>
</tr>
<tr>
<td>Rotor: rated current / apparent power</td>
<td>748 A / 950 kVA</td>
</tr>
<tr>
<td>Generator frame size / dimensions LxBxH</td>
<td>630 mm / 3.8x2.6x1.7 m³</td>
</tr>
<tr>
<td>Full load efficiency</td>
<td>97.1 %</td>
</tr>
<tr>
<td>Turbine speed / Gear transmission ratio</td>
<td>11.9 rpm / 990/11.9 = 83.2</td>
</tr>
</tbody>
</table>
Rotor side PWM voltage source inverters

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power of wind converter</td>
<td>3 MW</td>
</tr>
<tr>
<td>Rated voltage / Current / Frequency</td>
<td>732 V / 748 A / &lt;15 Hz; 50 Hz</td>
</tr>
<tr>
<td>Rated apparent power</td>
<td>950 kVA</td>
</tr>
<tr>
<td>Inverter unit / full-load efficiency</td>
<td>800 kW / 820 A / 97 %</td>
</tr>
<tr>
<td>Dimensions $L \times B \times H$ / Mass</td>
<td>$0.9 \times 0.6 \times 2.45 = 1.3 \text{ m}^3 / 1045 \text{ kg}$</td>
</tr>
<tr>
<td>Crowbar:</td>
<td>ca. $1.3 \text{ m}^3$, ca. 1 t</td>
</tr>
<tr>
<td>Control unit for grid voltage break down 15 %</td>
<td>ca. $1.3 \text{ m}^3$, ca. 1 t</td>
</tr>
</tbody>
</table>

**Crowbar:** 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

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
- Inverter-fed induction motors for yaw positioning
- Cog wheel for yaw positioning

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
- Brake
- Gear
- Turbine shaft
- 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

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

Source:
Innowind, Germany
Goldwind, Urumqi, Xinjiang, China