Module 2.2-2
WIND TURBINE TECHNOLOGY
Electrical System
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Contents Module 2.2
- Types of generator systems
- Variable and fixed speed
- Inverter technologies
### Types of generator systems

<table>
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<tr>
<th>Converter type</th>
<th>Application</th>
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<tbody>
<tr>
<td>induction (asynchronous) generator</td>
<td>applied in a large number of turbines (Danish type)</td>
</tr>
<tr>
<td>synchronous generator</td>
<td>only used for a small number of small wind turbines, mainly for stand alone systems</td>
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<tr>
<td>asynchronous or synchronous generator with electronic inverter system</td>
<td>a widely used concept for variable speed machines, increasing applications with growing size of wind turbines</td>
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### Generator concepts of today’s commercially available turbines

![Bar chart showing the number of different types of generator concepts for different power ranges: one speed, two speed, variable speed.]
Wind turbine with Induction Generator, direct coupled to the grid

SG = synchronous generator, ASG = induction generator

Typical induction generator (squirrel-cage)

1. shaft
2. ball bearings
3. rotor
4. aluminium sticks
5. aluminium ring
6. stator nuts with coils
7. stator
8. casing
9. coils of stator
10. ventilator
11. connection box

Squirrel-cage
2 pole and 4 pole generator

Rotating field

4 pole generator

Rotating field
### Synchronous Generator Speeds (rpm)

<table>
<thead>
<tr>
<th>Pole number</th>
<th>50 Hz</th>
<th>60 Hz</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>3000</td>
<td>3600</td>
</tr>
<tr>
<td>4</td>
<td>1500</td>
<td>1800</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>1200</td>
</tr>
<tr>
<td>8</td>
<td>750</td>
<td>900</td>
</tr>
<tr>
<td>10</td>
<td>600</td>
<td>720</td>
</tr>
<tr>
<td>12</td>
<td>500</td>
<td>600</td>
</tr>
</tbody>
</table>

- A larger number of poles means a lower rotational speed and thus lower gear box ratio.
- But it means also a larger dimension of the generator and more weight.

### Synchronisation of a.c. machines

- Synchronous machines can only be connected to the grid, when:
  - Frequency
  - Phase position
  - And voltage
  - Are the same

- Induction generators do not have to be synchronised.
**Induction generator**

- **advantages:**
  - cheap construction, no collector, no brushes
  - very low maintenance
  - no synchronisation

- **disadvantages:**
  - requires an external 3-phase grid, no own grid building capability
  - requires reactive power (usually compensated by capacitor banks)
  - no voltage control

**Wind turbine with induction (asynchronous) generator**

- **rotational speed:** fixed rotational speed plus slip (~ 2 %)
- **grid coupling:** rigid, with low elasticity
- **excitation:** by the grid
- **control:** power control by stall or active stall (also pitch in case of small turbines) speed control by grid frequency

- **advantage:** simple and cheap construction, lower maintenance standard (stall) no synchronisation with the grid required

- **disadvantage:** production of reactive power, generation of power peaks, only low compensation of wind speed fluctuations, power generation not controllable (stall)
Torque diagram – grid connected

\[ M_p: \text{pull-out torque} \]

\[ \text{linear torque function under normal operation range} \]

- \[ M_p \]: pull-out torque

- \[ n/n_s \]: normalized speed

- \[ S > 0 \]: motor mode

- \[ S < 0 \]: generator mode

Induction generator for wind turbines

for a better matching of the torque characteristic of an induction generator to that of a wind turbine (rotor) one can:

- vary the resistance of the rotor windings
- vary applied grid voltage
- use pole changing induction machines (i.e. two speed)
- use a frequency converter with a squirrel-cage induction generator
- use a frequency converter with a slip ring induction generator
- use a double-fed induction generator
Vary resistance of rotor windings

![Graph showing varying resistance of rotor windings](image)

Vary applied grid voltage

![Graph showing varying grid voltage](image)
Pole changing induction machines

Danish concept – direct grid-connection

- stall controlled, three bladed rotor with fixed hub
- wing-tip air brakes for emergency braking
- direct grid connection through thyristors ("soft-starter")
- generally two generators (small ~ .25 of large) or one generator with double windings (4 pole small, 6 pole large)
- induction generators deliberately designed for a larger slip
  - to avoid overload of generator during stall procedure
  - to reduce mechanical stress through high torque gradients during switching on and over the generators
  - to reduce fluctuations of mechanical system and electrical output
Danish concept - schema

**note:** smaller turbines < 100 kW used belt drives

Danish concept – load curve with two induction generators

- From small to large generator
- From large to small generator
Rotor speed – power diagram 600 kW

Switching from lower to higher rotor speed

Example: Stall controlled wind turbine
switching from lower to higher rotor speed (asynchronous generator)
Induction generator with variable slip

rotor speed partly variable (~2 to 10% of nominal speed)
elastic grid coupling through increased slip
reduction of power peaks, no synchronisation needed
generates reactive power, reduced efficiency under part load

Induction generator with variable slip - characteristics
Wind turbine with inverter system in the main power circuit (variable speed)

- **rotational speed**: variable
- **grid coupling**: soft, not coupled to grid frequency, elasticity produced by using the rotational energy
- **storage**: capacity of the rotor at acceleration or deceleration of the rotational speed
- **excitation**: self-excitation (i.e. exciting dynamo)
- **control**: power control by pitch (seldom stall), speed limitation by pitch, speed control by power regulation of the inverter
- **system advantage**: smoothing of power output, compensation of wind speed fluctuations, controllable power generation, controllable production of reactive power, operation at optimal power coefficient $c_p$ due to variable speed, generation of voltage and frequency for autonomous energy systems
- **disadvantage**: expensive construction, generation of harmonics, higher level of maintenance

*SG = synchronous generator, ASG = induction generator*
Wind turbine with variable speed rotor

Power - rotor speed curve = always in aerodynamic optimum

Advantage variable speed

Fluctuations of wind speed converted into torque fluctuations high mechanical strain on the drive train

Fluctuations of wind speed converted into rotor speed increase rotor stores energy smoothen output

source: DEWI
6 pulse rectifier – inverter system

![Diagram of 6 pulse rectifier and inverter system](source: DEWI)

12 pulse rectifier – inverter system

![Diagram of 12 pulse rectifier and inverter system](source: DEWI)
Harmonic distortion

6-pulse inverter with high level of harmonic distortion requires high efforts for filtering.

12-pulse inverter normally two 6-pulse inverter in parallel: one inverter with star-star, the other with star-triangle connection. Special three-winding transformer harmonic distortion greatly reduced.

12-pulse inverter more complex, requires less efforts for filtering.

Inverter with pulse-width-modulation PWM

Rectifier, inverter with IGBT, transformer.

Source: DEWI
Function of PWM inverter

- the condenser between rectifier and PWM inverter acts like an ideal DC voltage source
- Insulated Gate Bipolar Transistors (IGBT) switch at high frequencies (up to 10 kHz) to create a sine wave
- practical no harmonic distortion up to ordinal number 19
- harmonics with higher ordinal numbers exist, but have no effect on the grid, because
  - inductance of the grid blocks higher frequencies
  - capacitance of grid acts like a short-cut for high frequencies
- ideal for modern variable speed wind turbines
  - power output can be controlled (power gradient)
  - no harmonic distortion

Output of a PWM inverter with IGBTs
Power switch cabinet (300 kW) with IGBTs (Enercon)

- IGBT modules
- IGBT control board (MPU)
- AC out
- DC in

Frequency analysis of a wind with pulse width modulated inverter

- Frequency analysis of a wind with pulse width modulated inverter
- Frequency resolution: 6.25 Hz

Sampling frequency of the PWM inverter

- 2. harmonic
- 3. harmonic
Double fed induction generator
variable speed with pulse width modulated inverter

rotational speed: variable
grid coupling: soft, elasticity produced by using the rotational energy storage capacity of the rotor at acceleration or deceleration of the rotational speed
excitation: by the grid
control: power control by stall or pitch speed limitation by pitch speed control by power regulation of the inverter system
advantage: smoothing of power output compensation of wind speed fluctuations controllable power generation operation at optimal power coefficient $c_p$ due to variable speed
disadvantage: expensive construction generation of harmonics

ASG = induction generator
Frequency converter (squirrel-cage a.c.)

Frequency converter (slip ring a.c.)
Double-fed induction generator (DFIG)

Example: Grid connection of a variable speed double fed induction generator
Rotational speed and power against wind velocity

variable rotor speed WT  fixed rotor speed WT, two stage

Typical instantaneous power behaviour

variable rotor speed, pitch controlled WT  constant rotor speed, stall controlled WT
Measured power curve and power curve given by manufacturer

Wind speed at hub height, m/s

Electrical power, kW

Calculated power curve
Measured power curve