Wind Power - A Technology enabled by power electronics

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Outline

Wind Power -
A Technology enabled by power electronics

- Aalborg University and Department of Energy Technology
- Power Electronics for Wind Turbines
- Reliability Challenge of Power Electronics
- Power Converter Operation in Wind Turbines
- Conclusions
Aalborg University and Department of Energy Technology, Denmark
Aalborg University - Denmark

Inaugurated in 1974
19,000 students
2,500 faculty

PBL-Aalborg Model
(Project-organised and problem-based)
Aalborg University - Campus
Energy production - distribution - consumption - control
Department of Energy Technology

Strategic Networks
- EMSD
- CEES
- ECPE
- VE-NET
- DUFRET
- WEST
- VPP
- REN-DK
- HUB NORTH
- Energy Sponsor Programme

Multi-disciplinary Research Programmes
- Wind Turbine Systems
- Fluid Power in Wind and Wave Energy
- Biomass
- Photovoltaic Systems and Microgrids
- Modern Power Transmission Systems
- Smart Grids and Active Networks
- Fuel Cell and Battery Systems
- Automotive and Industrial Drives
- Efficient and Reliable Power Electronics
- Thermoelectrics
- Green Buildings

Lab. Facilities
- Power Electronics Systems
- Drive Systems Tests
- Fluid Power
- Power Systems & RTDS
- Micro Grid
- High Voltage
- DSpace
- PV Converter & Systems
- Laser Systems
- Fuel Cell Systems
- Battery Test
- EMC
- Vehicles Test Lab
- Biomass Conversion Facilities
- Proto Type Facilities

Center of Reliable Power Electronics
Power Electronics for Wind Turbines
Energy and Power Challenge

Four main challenges in energy
Sustainable energy production (backbone, weather based, storage)
Energy efficiency
Mobility
Infrastructure

Different initiatives
EU Set-plan (20-20-20) and beyond
Danish Climate Commision – Independent in 2050 of fossil fuel
Germany – no nuclear in the future
Globally large activity
Renewable Electricity in Denmark

Key figures for proportion of renewable electricity (Data source: Energinet.dk) (*target value)

<table>
<thead>
<tr>
<th>Key figures</th>
<th>2010</th>
<th>2011</th>
<th>2020</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind share of net generation in year</td>
<td>21.3%</td>
<td>29.4%</td>
<td>50%*</td>
<td></td>
</tr>
<tr>
<td>Wind share of consumption in year</td>
<td>22.0%</td>
<td>28.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RE share of net generation in year</td>
<td>32.8%</td>
<td>41.1%</td>
<td></td>
<td>100%*</td>
</tr>
<tr>
<td>RE share of net consumption in year</td>
<td>33.8%</td>
<td>39.0%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Energy and Power Challenge in DK

Very high coverage of distributed generation.
Development of Electric Power System in Denmark

From **Central** to **De-central** Power Generation

(Picture Source: Danish Energy Agency)

(Picture Source: Danish Energy Agency)

**Electric power infrastructure 1985**
- Centralized CHP
- Decentralized CHP
- Wind turbine
- Interconnector (AC)
- Interconnector (DC)

**Electric power infrastructure 2009**
- Centralized CHP
- Decentralized CHP
- Wind turbine
- Offshore wind turbine
- Interconnector (AC)
- Interconnector (DC)

CHP = Combined Heat and Power

Only CHP plants with capacity over 0.5 MW are shown.
Renewable Energy System

Important issues for power converters

- Reliability/security of supply
- Efficiency, cost, volume, protection
- Control active and reactive power
- Ride-through operation and monitoring
- Power electronics enabling technology
Global Wind Turbine Capacity

Globally it changes from country to country annually

Large investment a critical factor
New wind turbines development cost is expensive

Worldwide wind power capacity (Giga Watts)

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>13.6</td>
</tr>
<tr>
<td>2000</td>
<td>17.4</td>
</tr>
<tr>
<td>2001</td>
<td>24</td>
</tr>
<tr>
<td>2002</td>
<td>31</td>
</tr>
<tr>
<td>2003</td>
<td>39</td>
</tr>
<tr>
<td>2004</td>
<td>48</td>
</tr>
<tr>
<td>2005</td>
<td>59</td>
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<tr>
<td>2006</td>
<td>74</td>
</tr>
<tr>
<td>2007</td>
<td>94</td>
</tr>
<tr>
<td>2008</td>
<td>121</td>
</tr>
<tr>
<td>2009</td>
<td>159</td>
</tr>
<tr>
<td>2010</td>
<td>198</td>
</tr>
<tr>
<td>2011</td>
<td>238</td>
</tr>
<tr>
<td>2012</td>
<td>282</td>
</tr>
<tr>
<td>2020</td>
<td>760 (E)</td>
</tr>
</tbody>
</table>
Wind Turbine Development

Global installed wind capacity (up to 2012): **282 GW, 2012: 44 GW**

Bigger, cheaper and more efficient

3.6-7 MW prototypes running (Vestas, GE, Siemens Wind, Enercon)

2-3 MW WT are still the “best seller” on the market
Grid Codes for Wind Turbines

**Conventional power plants** provide active and reactive power, inertia response, synchronizing power, oscillation damping, short-circuit capability and voltage backup during faults.

**Wind turbine technology** differs from conventional power plants regarding the converter-based grid interface and asynchronous operation.

**Grid code requirements today**
- Active power control
- Reactive power control
- Frequency control
- Steady-state operating range
- Fault ride-through capability

**Wind turbines are active power plants**
Requirements to be a power station

- Designed for all ratings
- Set-point may be given by power system operator
Power Grid Standards – Ride-Through Operation

Requirements during grid faults

Grid voltage dips vs. withstand time

- Withstand extreme grid voltage dips.
- Contribute to grid recovery by injecting $I_q$.
- Higher power controllability of converter.

Reactive current vs. Grid voltage dips
Wind Turbine Concepts

- **Wound-rotor induction generator**
- **Variable pitch – variable speed**
- **±30% slip variation around synchronous speed**
- **Power converter** (back to back/direct AC/AC) in rotor circuit

- **Variable pitch – variable speed**
- **With/without gearbox**
- **Generator**
  - Synchronous generator
  - Permanent magnet generator
  - Squirrel-cage induction generator
- **Power converter**
  - Diode rectifier+boost DC/DC+inverter
  - Back-to-back converter
  - Direct AC/AC (e.g. matrix, cycloconverters)
Back-to-back two-level voltage source converter

- Proven technology
- Standard power devices (integrated)
- Decoupling between grid and generator (compensation for non-symmetry and other power quality issues)

- Need for major energy-storage in DC-link (reduced life-time and increased expenses)
- Power losses (switching and conduction losses)
Power Electronic Converters

Boost and Voltage Source Converter to grid

Current Source Inverter to grid

Power converters

➢ Proven technologies today
Parallel of low voltage power converters

Multi-winding low voltage

➢ Also proven technologies today
Multi-level topologies +6 MW

Three-level NPC

Half-bridge and open-winded transformer
Multi-level topologies +6 MW

Half-bridge, five-level

Three-level and five-level
Multi-level topologies +6 MW

Medium frequency transformer

Stacked output converter

To grid

DC
DC
DC
AC
DC
DC
DC
AC

Rectifier

MVDC

To generator

Center of Reliable Power Electronics
Power has to be controlled by means of the aerodynamic system and has to react based on a set-point given by a dispatched center or locally with the goal to maximize the power production based on the available wind power.
Current Development Example

Vestas Wind Systems A/S Denmark

Vestas V164 offshore turbine

- Rated power: 8,000 kW
- Rotor diameter: 164 m
- Hub height: min. 105 m
- Turbine concept: medium-speed gearbox, variable speed, variable pitch, full-scale power converter
- Generator: permanent magnet

Target market: Big offshore farms
Horns Reef I 160 MW, Horns Reef II 209.3 MW

- 80 x 2MW (Vestas V80, in operation Dec 11, 2002)
- 91 x 2.3MW (Siemens SWT-2.3-93, in operation Sep 17, 2009)

**Vestas V80–2.0 MW**

- Rotor Diameter: 80 m
- Hub Height: 60-100 m
- Weight: 227-303 tons
- Min/Max rotation speed: 9/19 rounds/minute
- Min/Nom/Max Wind: 4/16/25 m/s
- Gear box: Yes (1:100.5)
- Generator: DFIG (4 pole – slip rings)
Improved performance of Wind Turbines

Integration with a battery storage system
Take part in primary and secondary control
Wide-Band-Gap Devices: Ways to Higher Power Density

January 27, 2012

DB-4

WBG devices

≤ 200
400 ~ 600
≥ 1200

Power (W)

Source D, Boroyevich - CPES

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SiC Devices

Blocking Voltage

<table>
<thead>
<tr>
<th>600 V</th>
<th>1200 V</th>
<th>1700 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schottky diode</td>
<td>MOSFET</td>
<td>Schottky diode</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Super-junction BJT</td>
<td>Thyristor 6.5 kV</td>
</tr>
<tr>
<td>Schottky diode</td>
<td>JFET Normally-on</td>
<td>Schottky diode</td>
</tr>
<tr>
<td>MOSFET</td>
<td>JFET Normally-on/off</td>
<td>JFET Normally-off</td>
</tr>
<tr>
<td>BJT</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A lot of research going on for high-voltage SiC devices

Source D, Boroyevich - CPES

Mainstream: 1.2 kV switches

A lot of research going on for high-voltage SiC devices
## Wind Turbine – power electronic components

<table>
<thead>
<tr>
<th></th>
<th>IGBT module</th>
<th>IGBT Press-pack</th>
<th>IGCT Press-pack</th>
<th>SiC MOSFET module</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Density</strong></td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td></td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td><strong>Failure mode</strong></td>
<td>Open circuit</td>
<td>Short circuit</td>
<td>Short circuit</td>
<td>Open circuit</td>
</tr>
<tr>
<td><strong>Easy maintenance</strong></td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td><strong>Insulation of heat sink</strong></td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td><strong>Snubber requirement</strong></td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Thermal resistance</strong></td>
<td>Large</td>
<td>Small</td>
<td>Small</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>Switching loss</strong></td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Conduction loss</strong></td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Large</td>
</tr>
<tr>
<td><strong>Gate driver</strong></td>
<td>Moderate</td>
<td>Moderate</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td><strong>Major manufacturers</strong></td>
<td>Infineon, Semikron, Mitsubishi, ABB, Fuji</td>
<td>Westcode, ABB</td>
<td>ABB</td>
<td>Cree, Rohm, Mitsubishi</td>
</tr>
<tr>
<td><strong>Medium voltage ratings</strong></td>
<td>3.3 kV / 4.5 kV / 6.5 kV</td>
<td>2.5 kV / 4.5 kV</td>
<td>4.5 kV / 6.5 kV</td>
<td>1.2 kV</td>
</tr>
<tr>
<td><strong>Max. current ratings</strong></td>
<td>1.5 kV / 1.2 kA / 750 A</td>
<td>2.3 kA / 2.4 kA</td>
<td>3.6 kA / 3.8 kA</td>
<td>100 A-180 A</td>
</tr>
</tbody>
</table>

Emerging devices soon ready for wind power processing
Wind Turbine system cost – Off-shore

Not only Wind turbine cost
Wind Turbine system cost – before and future

Different trends
But the Cost of Energy will be reduced
Reliability Challenge of Power Electronics in Renewable Energy Systems
Failures of Power Electronic Systems

Field Experience of Wind Turbines – Normalized Failure Rate

(Source: Reliawind, Report on Wind Turbine Reliability Profiles – Field Data Reliability Analysis, 2011.)
Critical Components in Power Electronic Systems


Failure root causes distribution for power electronic systems* (% may vary for different applications and designs)
**Availability Impact on Cost-of-Energy (COE)**

\[
\text{COE} = \frac{\text{CAPEX} + \text{OPEX}}{\text{AEP}}
\]

- **CAPEX** – Capital cost
- **OPEX** – Operation and maintenance cost
- **AEP** – Annual energy production

Higher reliability and better maintenance

↓

Lower downtime

↓

Lower OPEX and higher AEP

↓

Lower COE

(source: MAKE Consulting A/S)
Reliability basics

Life time models for switching devices

Thermal cycling parameters $\Delta T_j$ and $T_m$ are important for device life time.
Thermal models for switching devices

IGCT  
\[ Z_{T(j-c)} \]  
\[ T_j \]  
\[ T_A \]  
\[ T_C \]  
\[ Z_{T(c-h)} \]  
\[ T_H \]  
\[ Z_{(h-a)} \]  
\[ T_A \]

Diode  
\[ Z_{D(j-c)} \]  
\[ T_j \]  
\[ T_A \]  
\[ T_C \]  
\[ Z_{D(c-h)} \]  
\[ T_H \]  
\[ Z_{(h-a)} \]  
\[ T_A \]

Switch

Clamped Diode

Diode  
\[ Z_{D(j-c)} \]  
\[ T_j \]  
\[ T_A \]  
\[ T_C \]  
\[ Z_{D(c-h)} \]  
\[ T_H \]  
\[ Z_{(h-a)} \]  
\[ T_A \]

Thermal model of the impedance \( Z_{T(j-c)} \) or \( Z_{D(j-c)} \) from junction to case.

Note:
\( T_j \): junction temperature, \( T_C \): case temperature, \( T_H \): heat sink temperature, \( T_A \): ambient temperature
\( Z_{T(j-c)} \): thermal impedance from junction to case, \( Z_{(c-h)} \): thermal impedance from case to heat sink, \( Z_{(h-a)} \): thermal impedance from heat sink to ambient

(Source: ABB)

Thermal models are important for \( \Delta T_j \) and \( T_m \).
Reliability basics

Reliability evaluation tools for converter

Wind Profiles $v_w$ → Turbine-Generator Models $I_G$, $V_G$ → Loss Model $L_{loss}$ → Thermal Model $\Delta T_j$, $T_m$ → Life time Model $MTTF$

$turbine, drive, generator$ $device$ $topology$ $thermal$ $impedance$

Mission Profiles

From mission profiles to Life time

Wind Profiles $v_w$ → Turbine-Generator Models $I_G$, $V_G$ → Loss Model $L_{loss}$ → Thermal Model $R_{therm}$, $C_{therm}$ → Chip Size Model $Cost$ $\Delta T_j$, $T_m$ → Life time Model $MTTF$ $Wind$ $speed$

$turbine, drive, generator$ $topology, devices$

Mission Profiles

From life time to cost
Power Converter Operation in Wind Turbines
Promising LV configurations

2L DFIG

2L PMSG
Power loss profile

Grid-side Converter

Generator-side Converter

2L DFIG

2L PMSG
Normal operation

Thermal cycling

- Mean junction temperature (°C)
  - IGBT DFIG
  - IGBT PMSG
  - Diode DFIG
  - Diode PMSG

- Temperature fluctuation (°C)
  - IGBT DFIG
  - IGBT PMSG
  - Diode DFIG
  - Diode PMSG

Generate-side converter

Grid-side converter
Grid faults operation

Operation status under balanced LVRT

P/Q power vs. Grid voltage

- When \( V_g < 0.5 \) p.u. is regardless of wind speeds (100% \( I_q \), no \( I_p \)).
- When \( V_g > 0.5 \) p.u. is referring to the generated power/wind speeds (some room for \( I_p \)).

Current amplitude & position vs. Grid voltage
Grid faults operation

Thermal optimized modulation under LVRT
(for 3L-NPC grid inverter)

With normal modulation

With optimized modulation

Junction temperature dynamic response
(wind speed 8 m/s, 0.05 p.u. LVRT, dip time 500 ms)
Summary

**Power Electronics for Wind Power**

- A solution for the long term future in society
- Smart grid also pushed by renewable
- Coordinated control of production and consumption – better integration
- Systems should be able to run in on-grid and off-grid modes
- Wind turbines have been the fastest growing but PV will come
- Wind turbine technology – better performance
  - Full scale power electronics
  - New generator concepts (e.g. PM, gearless)
  - Larger size – lower cost per kWh
  - Reliability – a key to lower Cost of Energy
enabling wind power into an intelligent grid
References