Power Electronics – The Key Technology for Renewable Energy System Integration

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Overview of power electronics and renewable energy system
State-of-the-art; Technology overview, global impact

Demands for renewable energy systems
PV; Wind power; Cost of Energy; Reliability, Mission Profiles, Grid Codes

Power converters for renewables
PV inverters at different power; Wind power application; Power semiconductor devices

Control for renewable systems
PV application; Wind power application

Summary
Aalborg University and Department of Energy Technology
Aalborg University - Denmark

Inaugurated in 1974
22,000 students
2,000 faculty

PBL-Aalborg Model
(Project-organised and problem-based)
Aalborg University - Campus
Overview of power electronics technology and renewable energy systems
State of the Art – Renewable Evolution


1. Hydropower also includes pumped storage and mixed plants;
   2. Marine energy covers tide, wave, and ocean energy

Global RES Annual Changes

Global Renewable Energy Annual Changes in Gigawatt (2001-2014)

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy

Share of the Net Total Annual Additions

RES and non-RES as a share of the net total annual additions

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy

Renewable Electricity in Denmark

Proportion of renewable electricity in Denmark (*target value)

<table>
<thead>
<tr>
<th>Key figures</th>
<th>2011</th>
<th>2015</th>
<th>2025</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind share of net generation in year</td>
<td>29.4%</td>
<td>51.0%</td>
<td>58%*</td>
<td></td>
</tr>
<tr>
<td>Wind share of consumption in year</td>
<td>28.3%</td>
<td>42.0%</td>
<td>60%*</td>
<td></td>
</tr>
<tr>
<td>RE share of net generation in year</td>
<td>41.1%</td>
<td>66.9%</td>
<td>82%*</td>
<td>100%*</td>
</tr>
<tr>
<td>RE share of net consumption in year</td>
<td>39.5%</td>
<td>55.2%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Energy and Power Challenge in DK

Very High Coverage of Distributed Generation

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

Global installed wind capacity (until 2015): **433 GW, 2015: 63.5 GW**

- Higher total capacity (55 % non-hydro renewables).
- Larger individual size (average 1.8 MW, up to 6-8 MW).
- More power electronics involved (up to 100 % rating coverage).
## Top 5 Wind Turbine Manufacturers & Technologies

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Concept</th>
<th>Rotor Diameter</th>
<th>Power Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldwind (China)</td>
<td>PMSG</td>
<td>70 – 109 m</td>
<td>1.5 – 2.5 MW</td>
</tr>
<tr>
<td></td>
<td>IG</td>
<td>110 m</td>
<td>3 MW</td>
</tr>
<tr>
<td>Vestas (Denmark)</td>
<td>DFIG</td>
<td>80 – 110 m</td>
<td>1.8 – 2 MW</td>
</tr>
<tr>
<td></td>
<td>PMSG</td>
<td>105 – 164 m</td>
<td>3.3 – 8 MW</td>
</tr>
<tr>
<td>GE Energy (USA)</td>
<td>DFIG</td>
<td>77 – 120 m</td>
<td>1.5 – 2.75 MW</td>
</tr>
<tr>
<td></td>
<td>PMSG</td>
<td>113 m</td>
<td>4.1 MW</td>
</tr>
<tr>
<td>Siemens (Germany)</td>
<td>IG</td>
<td>82 – 120 m</td>
<td>2.3 – 3.6 MW</td>
</tr>
<tr>
<td></td>
<td>PMSG</td>
<td>101 – 154 m</td>
<td>3 – 6 MW</td>
</tr>
<tr>
<td>Gamesa (Spain)</td>
<td>DFIG</td>
<td>52 – 114 m</td>
<td>0.85 – 2 MW</td>
</tr>
<tr>
<td></td>
<td>PMSG</td>
<td>128 m</td>
<td>4.5 MW</td>
</tr>
</tbody>
</table>

DFIG: Doubly-fed induction generator
PMSG: Permanent magnet synchronous generator
IG: Induction generator
SG: Synchronous generator
State of the Art – PV Cell Technologies

Best Research-Cell Efficiencies
### Top 10 PV Cell Manufacturers & Technologies

#### Top Ten PV Cell Technology Focus and Module Assembly Capacity 2015

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Technology</th>
<th>Module Assembly Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trina (CN/NL)</td>
<td>c-Si</td>
<td>510</td>
</tr>
<tr>
<td>JA Solar (CN/MY)</td>
<td>c-Si</td>
<td>400</td>
</tr>
<tr>
<td>Hanwha Q-Cells (CN/DE/MY/KR)</td>
<td>c-Si</td>
<td>430</td>
</tr>
<tr>
<td>Canadian Solar (CN)</td>
<td>c-Si</td>
<td>430</td>
</tr>
<tr>
<td>First Solar (US/MY)</td>
<td>CdTe/c-Si</td>
<td>290</td>
</tr>
<tr>
<td>Jinko Solar (CN/MY)</td>
<td>c-Si</td>
<td>470</td>
</tr>
<tr>
<td>Yingli Solar (CN)</td>
<td>c-Si</td>
<td>245</td>
</tr>
<tr>
<td>Motech Solar (Taiwan/CN)</td>
<td>c-Si</td>
<td>140</td>
</tr>
<tr>
<td>NeoSolar (Taiwan/CN)</td>
<td>c-Si</td>
<td>50</td>
</tr>
<tr>
<td>Shunfeng-Suntech (CN/US)</td>
<td>c-Si</td>
<td>200</td>
</tr>
</tbody>
</table>

c-Si: Crystalline silicon  
CdTe: Cadmium telluride

State of the Art Development – Photovoltaic Power

Global installed solar PV capacity (until 2015): **227 GW**, 2015: **50 GW**

- More significant total capacity (29 % non-hydro renewables).
- Fastest growth rate (42 % between 2010-2015).

Top 5 Global Photovoltaic Inverter Supplier

Global Market Share (% of $M) of Top Five PV Inverter Suppliers (2012-2015)

1. Market share is not shown when less than 2%;
2. Suppliers shown are top five in 2015.

Figure Adapted according to the report by IHS

Demands for renewable energy systems
Requirements for Wind Turbine Systems

General Requirements & Specific Requirements

1. Controllable
2. Variable freq & U

1. Energy balance/storage
2. High power density
3. Strong cooling
4. Reliable

1. Fast/long P response
2. Controllable/large Q
3. Freq & U stabilization
4. Low Voltage Ride Through
Input mission profiles for wind power application

Highly variable wind speed
Different wind classes are defined - turbulence and avg. speed
Large power inertia to wind speed variation – stored energy in rotor.
Large temperature inertia to ambient temp. variation – large nacelle capacity
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.
Power Grid Standards – Frequency/Voltage Support

- Frequency control through active power regulation.
- Reactive power control according to active power generation.
- Voltage support through reactive power control.
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
Requirements for Photovoltaic Systems

General Requirements & Specific Requirements

1. Controllable $I$ / (MPPT)
2. DC voltage / current
...

1. High efficiency
2. Temp. insensitive
3. Reliable
4. Safety
5. Communications

1. Low THD
In case of large scale:
2. $Freq. – P$ control
3. $U – Q$ control
4. Fault ride-through
Input mission profiles for PV power application

- Highly variable solar irradiance
- Small power inertia to solar variation – quick response of PV panel.
- Small temperature inertia to ambient temp. variation – small case capacity.
- Temperature sensitive for the PV panel and power electronics.
Grid Codes for Photovoltaic Systems

Grid-connected PV systems ranging from several kWs to even a few MWs are being developed very fast and will soon take a major part of electricity generation in some areas. PV systems have to comply with much tougher requirements than ever before.

Requirements today

► Maximize active power capture (MPPT)
► Power quality issue
► Ancillary services for grid stability
► Communications
► High efficiency

In case of large-scale adoption of PV systems

► Reactive power control
► Frequency control
► Fault ride-through capability
► …
Cost of Energy (COE)

\[
\text{COE} = \frac{C_{\text{Cap}} + C_{O&M}}{E_{\text{Annual}}}
\]

- \(C_{\text{Cap}}\) – Capital cost
- \(C_{O&M}\) – Operation and main. cost
- \(E_{\text{Annual}}\) – Annual energy production

Determining factors for renewables
- Capacity growth
- Technology development
Approaches to Reduce Cost of Energy

\[ \text{COE} = \frac{C_{\text{Cap}} + C_{O&M}}{E_{\text{Annual}}} \]

- \( C_{\text{Cap}} \) – Capital cost
- \( C_{O&M} \) – Operation and main. cost
- \( E_{\text{Annual}} \) – Annual energy production

<table>
<thead>
<tr>
<th>Approaches</th>
<th>Important and related factors</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower ( C_{\text{Cap}} )</td>
<td>Production / Policy</td>
<td>+</td>
</tr>
<tr>
<td>Lower ( C_{O&amp;M} )</td>
<td>Reliability / Design / Labor</td>
<td>++</td>
</tr>
<tr>
<td>Higher ( E_{\text{Annual}} )</td>
<td>Reliability / Capacity / Efficiency / Location</td>
<td>+++</td>
</tr>
</tbody>
</table>

Reliability is an efficient way to reduce COE – lower \( C_{O&M} \) & higher \( E_{\text{Annual}} \)
# Typical Lifetime Target in PE Applications

<table>
<thead>
<tr>
<th>Applications</th>
<th>Typical design target of Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft</td>
<td>24 years (100,000 hours flight operation)</td>
</tr>
<tr>
<td>Automotive</td>
<td>15 years (10,000 operating hours, 300,000 km)</td>
</tr>
<tr>
<td>Industry motor drives</td>
<td>5-20 years (40,000 hours in at full load)</td>
</tr>
<tr>
<td>Railway</td>
<td>20-30 years (10 hours operation per day)</td>
</tr>
<tr>
<td>Wind turbines</td>
<td>20 years (18-24 hours operation per day) 100000 hours</td>
</tr>
<tr>
<td>Photovoltaic plants</td>
<td>20-30 years (12 hours per day) 100000 hours</td>
</tr>
</tbody>
</table>

**Different O&M programs**
Power converters for renewables application
PV Inverter System Configurations

Source: Infineon, SMA

Module Converters | String Inverter | Multi-String Inverters | Central Inverters
Grid-Connection Configurations

Transformer-based grid-connection

Transformerless grid-connection → Higher efficiency, Smaller volume
AC-Module PV Converters – Single-Stage

~ 300 W (several hundred watts)
High overall efficiency and High power density.

Universal AC-module inverter

Buck-boost integrated full-bridge inverter

String/Multi-String PV Inverters

1 kW ~ 30 kW (tens kilowatts)
High efficiency and also Emerging for modular configuration in medium and high power PV systems.

Bipolar Modulation is used:

- No common mode voltage $\rightarrow$ $V_{PE}$ free for high frequency $\rightarrow$ low leakage current
- Max efficiency 96.5% due to reactive power exchange between the filter and $C_{PV}$ during freewheeling and due to the fact that 2 switches are simultaneously switched every switching
- This topology is not special suited to transformerless PV inverter due to low efficiency!
Transformerless String Inverters

H5 Transformerless Inverter (SMA)

- Efficiency of up to 98%
- Low leakage current and EMI
- Unipolar voltage across the filter, leading to low core losses

H6 Transformerless Inverter (Ingeteam)

- High efficiency
- Low leakage current and EMI
- DC bypass switches rating: $V_{dc}/2$
- Unipolar voltage across the filter

NPC Transformerless String Inverters

Neutral Point Clamped (NPC) converter for PV applications

- Constant voltage-to-ground $\rightarrow$ Low leakage current, suitable for transformerless PV applications.
- High DC-link voltage ($>\text{twice of the grid peak voltage}$)

Central Inverters

~ 30 kW (tens kilowatts to megawatts)
Very high power capacity.

- Large PV power plants (e.g. 750 kW by SMA), rated over tens and even hundreds of MW, adopt many central inverters with the power rating of up to 900 kW.
- DC-DC converters are also used before the central inverters.
- DC voltage become up to 1500 V
- Similar to wind turbine applications → NPC topology might be a promising solution.
Wind turbine concept and configurations

- Variable pitch – variable speed
- Doubly Fed Induction Generator
- Gear box and slip rings
- ±30% slip variation around synchronous speed
- Power converter (back to back / direct AC/AC) in rotor circuit

✓ State-of-the-art solutions

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

✓ State-of-the-art and future solutions
Converter topologies under low voltage (<690V)

**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)
- High dv/dt and bulky filter
- Need for major energy-storage in DC-link
- High power losses at high power (switching and conduction losses) → low efficiency

**Diode rectifier + boost DC/DC + 2L-VSC**

- Suitable for PMSG or SG.
- Lower cost
- Low THD on generator, low frequency torque pulsations in drive train.
- Challenge to design boost converter at MW.
Solution to extend the power capacity

Variant 1 with multi-winding generator.  Variant 2 with normal winding generator

Parallel converter to extend the power capacity

- State-of-the-art solution in industry (>3MW)
- Standard and proven converter cells (2L VSC)
- Redundant and modular characteristics.

- Circulating current under common DC link with extra filter or special PWM
Multi-level converter topology – 3L-NPC

Three-level NPC

- Most commercialized multi-level topology.
- More output voltage levels → Smaller filter
- Higher voltage, and larger output power with the same device rating
- Possible to be configured in parallel to extend power capacity.

- Unequal losses on the inner and outer power devices → derated converter power capacity
- Mid-point balance of DC link – under various operating conditions.
Multi-level converter topology - H-bridge back-to-back

- More equal loss distribution $\rightarrow$ higher output power
- More output voltage levels compared to 2L VSC
- Redundancy if 1 or 2 phases failed.
- Higher controllability coming from zero sequence.

- Open windings for generator and transformer – higher cost
- Hard to be configured in parallel to extend power capacity.
Multi-cells converter topologies in future solution

CHB with medium frequency transformer

- Reduced transformer size for CHB-MFT
- Easily scalable power and voltage level.
- High redundancy and modularity.
- Filter-less design, direct connection to distribution grid.

- Significantly increased components counts
- Still very high cost-of-energy.

Modular multi level converter (MMC)
## Potential power devices for wind power

<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</td>
<td>Westcode, ABB</td>
<td>ABB</td>
<td>Cree, Rohm, Mitsubishi</td>
</tr>
<tr>
<td><strong>Voltage ratings</strong></td>
<td>1.7 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 / 10 kV</td>
</tr>
<tr>
<td><strong>Max. current ratings</strong></td>
<td>1.5 kV - 750 A</td>
<td>2.3 kA / 2.4 kA</td>
<td>3.6 kA / 3.8 kA</td>
<td>180 A / 20 A</td>
</tr>
</tbody>
</table>
Controls for renewable energy systems
General Control Structure for PV Systems

**Basic functions – all grid-tied inverters**
- Grid current control
- DC voltage control
- Grid synchronization

**PV specific functions – common for PV inverters**
- Maximum power point tracking – MPPT
- Anti-Islanding (VDE0126, IEEE1574, etc.)
- Grid monitoring
- Plant monitoring
- Sun tracking (mechanical MPPT)

**Ancillary support – in effectiveness**
- Voltage control
- Fault ride-through
- Power quality
- …
Maximum Power Point Tracking (MPPT)

Role of MPPT - namely to maximize the energy harvesting

- PV array characteristic is non-linear $\rightarrow$ Maximum Power Point (MPP)
- MPP is weather-dependent $\rightarrow$ Maximum Power Point Tracking (MPPT)
## MPPT Algorithms

<table>
<thead>
<tr>
<th>MPPT Methods</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perturb &amp; Observe (P&amp;O) / Incremental Conductance</td>
<td>• Simple</td>
<td>• Tradeoff between speed and accuracy</td>
</tr>
<tr>
<td></td>
<td>• Low computation</td>
<td>• Goes to the wrong way under fast changing conditions</td>
</tr>
<tr>
<td></td>
<td>• Generic</td>
<td></td>
</tr>
<tr>
<td>Constant Voltage (CV)</td>
<td>• Much simple</td>
<td>• Energy is wasted during Voc measurement</td>
</tr>
<tr>
<td></td>
<td>• No ripple due to perturbation</td>
<td>• Inaccuracy</td>
</tr>
<tr>
<td>Short-Current Pulse (SCP, i.e., constant current)</td>
<td>• Simple</td>
<td>• Extra switch needed for short-circuiting</td>
</tr>
<tr>
<td></td>
<td>• No ripple due to perturbation</td>
<td>• Inaccuracy</td>
</tr>
<tr>
<td>Ripple Correlation Control</td>
<td>• Ripple amplitude provides the MPP information</td>
<td>• Tradeoff between efficiency loss due to MPPT or to the ripple</td>
</tr>
<tr>
<td></td>
<td>• Noneed for perturbation</td>
<td></td>
</tr>
</tbody>
</table>

**P&O** – the most commonly used MPPT algorithm!
Example of MPPT Control
Experiments of P&O on a 3-kW double-stage system:

Cloudy Day

Clear Day

Red: theoretical power
Black: MPPT power
Constant Power Generation (CPG) Concept

CPG – one of the Active Power Control (APC) functions

Y. Yang, F. Blaabjerg, and H. Wang, "Constant power generation of photovoltaic systems considering the distributed grid capacity," in Proc. of APEC, pp. 379-385, 16-20 Mar. 2014.

Extend the CPG function for WTS in Denmark to wide-scale PV applications?
Constant Power Generation (CPG) Concept

Implementation of CPG in single-phase PV systems

- Energy “reservoir” – storage elements
- Power management/balancing control
- Modifying the MPPT

![Diagram of power-voltage and current-voltage relationships for CPG implementation in single-phase PV systems.](image)

- $P_{\text{maxn}}$: Rated peak PV power
- $P_{\text{PV}}$: Power output
- $P_{\text{o}}$: Power at point of interest
- $t_0$, $t_1$, $t_2$, $t_3$, $t_4$, $t$: Time points
- $i_{\text{pv1}}$, $i_{\text{pv2}}$: Currents
- $v_{\text{pv1}}$, $v_{\text{pv2}}$: Voltages
- $P_{\text{limit}}$: Limiting power
- $P_{\text{o}} = P_{\text{limit}}$
- $P_{\text{o}} = P_{\text{maxn}}'$
- $P_{\text{PV}}$: Power-time graph
- Energy yield: Graph section I, II, III, IV, V
Constant Power Generation (CPG) Concept

Operation examples of CPG control (experiments)
More Stringent Requirements

Beyond the fundamentals, more stringent are coming:

- New demands for grid integrations, communications, power flow control, and protection are needed to accept more renewables.
- Power electronic converters are important in this technology transformation.

PV system with limited maximum feed-in power control.
(Already in effectiveness in some countries)
General Control structure for Wind Turbine System

**Level I – Power converter**
- Grid synchronization
- Converter current control
- DC voltage control

**Level II – Wind turbine**
- MPPT
- Turbine pitch control
- DC Chopper

**Level III – Grid integration**
- Voltage regulation
- Frequency regulation
- Power quality
MPPT Control for two wind turbine systems

- **DFIG system**

- **PMSG system**
Summary
Summary of presentation

- Cost of Energy more down incl low failure-rate
- Reliability important topic for future
- Control of power electronic system emerging
- Stability in solid state based power grid as well as conventional power system
- More stringent grid codes will still be developed
- Still new technology in renewables (WBG etc..)
- New power converters with new power devices

- And much more..
Acknowledgment

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from Department of Energy Technology
Aalborg University

Look at

www.et.aau.dk
www.corpe.et.aau.dk
www.harmony.et.aau.dk
Thank you for your attention!
References


References

References

37. “Generating plants connected to the medium voltage network - Guideline for generating plants connection to and parallel operation with the medium voltage network”, BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. Reinhardtstraße 32, 10117 Berlin (2008)
38. VDE-AR-N 4105: Generators connected to the low-voltage distribution network - Technical requirements for the connection to and parallel operation with low-voltage distribution network (2010)
44. Y. Yang, H. Wang, and F. Blaabjerg, "Reduced junction temperature control during low-voltage ride-through for single-phase photovoltaic inverters,” IET Power Electronics, pp. 1-10, 2014.
References

