Power Electronics in Renewable Energy Systems

by

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Power Electronics in Renewable Energy Systems

Outline

1. Development in Energy Technology
2. Wind energy systems
3. Solar energy systems
4. Summary
5. Future trends
1. Development in Energy Technology

Where are we from?

- 13000 students
- Founded in 1974
1. Development in Energy Technology

Keywords: Energy production – Energy distribution – Energy consumption – Energy control
1. Development in Energy Technology

**Organisation**

- **Institute of Energy Technology**
- Strategic cooperation:
  - EMSD
  - EDS
  - CEES
  - NEED
  - FACE
- Lab. Facilities:
  - Power electronics Systems
  - Drive Systems Tests
  - Hydraulic
  - Power systems
  - High Voltage
  - DSpace
  - Laser Systems
  - Fuel Cell Systems
  - Proto Type Facilities

- **Power Systems**
- **Power Electronic Systems**
- **Electrical Machines**
- **Fluid Power Systems**
- **Fluid Mechanics and Combustion**
- **Thermal Energy systems**
- **Power Systems**
- **Electrical Machines**
- **Fluid Power Systems**
- **Fluid Mechanics and Combustion**
- **Thermal Energy systems**

- **20 Faculties**
- **15 PhD**
- **10 Guest Researchers**
- **10 Research Assistants**
- **12 TAP**
1. Development in Energy Technology

Electricity production in 2004

Electricity in the world in 2004: 17 400 TWh

- Thermal coal weights more than the total of primary electricity, nuclear, hydro, wind, etc., its market share increases
- The share of thermal gas has increased by 2 points since 2000
- All other electricity sources slowly recede

The share of renewable energy production is still very modest!
1. Development in Energy Technology

Power capacities perspective until 2020

Projections until 2020*: power capacities evolution by energy source

- Gas and coal could cover more than 70% of the power capacity increase worldwide
- Hydro and wind could represent almost 30%
- Nuclear, modest contributor in the capacity increase, would compensate for a decline of oil

*Note: Forecasts extracted from the Enerfuture Forecasts service

- The installed capacity has to increase by over 80%
- New power sources becomes interesting
- More efficient use of the existing sources
  - From production to end user
  - Power balance extremely important
  - New energy storage devices

😄 Distributed Power Generation Systems (DPGS) necessary
1. Development in Energy Technology

Overview of DPGS

- Wind energy – highest development
- Solar energy – next highest development
- Wave energy – largely unexplored
- Tidal energy – largely unexplored
- Small hydro (<10MW), 47GW used, 180 GW untapped (70% in developing countries). Oldest technology (not covered)
- Biomass 18GW used (2000), largely unexplored. Used in CHP. (not covered)

Advantages of DPGS:
- Load management (peak shaving)
- Power quality (required by standards!)
- Enhanced voltage stability
- Reduced transmission losses
- Potential for improving grid reliability/stability
- Load management (peak shaving)
- Power quality (required by standards!)
- Enhanced voltage stability
- Reduced transmission losses
- Potential for improving grid reliability/stability

Disadvantage - high cost!
1. Development in Energy Technology

Classical Power System

Central power plants

September 13, 2006, Gijon, Spain

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1. Development in Energy Technology

Future Power System

Focus in this presentation

Demand

- Stability
- Frequency control
- Voltage control
- Optimized control
- Protection

Less central power plants and more DPGS

September 13, 2006, Gijon, Spain
Outline

1. Development in Energy Technology
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2. Wind Energy Systems

**Actual installed power worldwide**

The annual increase has decreased in 2004!

50 GW installed in 2005!

Predicted for 2010 - 180 GW (source WindForce 10)
2. Wind Energy Systems

Wind Turbine development

- Bigger and more efficient!
- 3.6-6MW prototypes running (Vestas, GE, Siemens Wind, Enercon)
- Danish Vestas and Siemens Wind stand for over 40% of the worldwide market
- 2MW WT are still the "best seller" on the market!
2. Wind Energy Systems

Danish experience – 19% wind power penetration!

- Wind production can vary significantly with respect to the predicted one
- This lead to instant export with low prices or import at high price
- Better wind prediction is needed

### Energy Balance in GWh

<table>
<thead>
<tr>
<th>Year</th>
<th>Primary production</th>
<th>Local production*</th>
<th>Wind production</th>
<th>Total production</th>
<th>Net exports</th>
<th>Consumption incl. losses</th>
<th>Commissioning in 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>11,541.3</td>
<td>6,245.1</td>
<td>3,583.7</td>
<td>20,369.1</td>
<td>299.3</td>
<td>20,669.8</td>
<td>-99.3</td>
</tr>
<tr>
<td>2001</td>
<td>12,865.9</td>
<td>6,811.2</td>
<td>3,895.0</td>
<td>23,562.1</td>
<td>2,186.9</td>
<td>20,376.2</td>
<td>-82.1</td>
</tr>
<tr>
<td>2002</td>
<td>12,938.4</td>
<td>6,723.2</td>
<td>3,823.0</td>
<td>23,484.6</td>
<td>2,610.6</td>
<td>20,858.0</td>
<td>93.7</td>
</tr>
<tr>
<td>2003</td>
<td>16,161.2</td>
<td>6,899.5</td>
<td>4,363.4</td>
<td>27,424.1</td>
<td>3,320.9</td>
<td>21,043.2</td>
<td>72.2</td>
</tr>
<tr>
<td>2004</td>
<td>12,951.2</td>
<td>6,838.9</td>
<td>4,874.8</td>
<td>24,664.9</td>
<td>5,418.9</td>
<td>21,244.0</td>
<td>67.4</td>
</tr>
</tbody>
</table>

(* Includes production at the bioeletor at Unit 3 of the Enerdæktur power station.)

### Meteorological Data

<table>
<thead>
<tr>
<th>Year</th>
<th>Wind relative to normal years in per cent (normal year = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>99.3</td>
</tr>
<tr>
<td>2001</td>
<td>82.1</td>
</tr>
<tr>
<td>2002</td>
<td>85.7</td>
</tr>
<tr>
<td>2003</td>
<td>72.2</td>
</tr>
<tr>
<td>2004</td>
<td>80.4</td>
</tr>
</tbody>
</table>

Source: Energinet.dk
2. Wind Energy Systems

Power Conversion - MPPT

Power curve - Aerodynamic

\[ P_{turb} = \frac{1}{2} C_p \rho A v_{\text{wind}}^3 \]
\[ \lambda = \frac{v_{\text{tip}}}{v_{\text{wind}}} = \frac{r_{rt} \omega_{rt}}{v_{\text{wind}}} \]

- Techniques to limit the produced power
  - Stall control
  - Active stall control
  - Pitch control

For each wind speed, there is a different shaft rotation speed that leads to the extraction of the maximum available power --> MPPT --> variable-speed WT
2. Wind Energy Systems

Power Conversion and control

Basic Topologies
- Fixed speed with capacitor bank (old system, not used today anymore!)
- Two-generator principle - two pole-pairs (exists in many systems)
- Rotor resistance control
- Doubly-fed induction generator DFIG - wounded rotor (very common now!)
- Squirrel cage induction generator SCIG
- Synchronous generator - External magnetized
- Synchronous generator - Permanent magnets
2. Wind Energy Systems

Basic topologies for variable-speed wind turbine

Fixed speed with capacitor bank (Reactive power)
2. Wind Energy Systems

Basic topologies for variable-speed wind turbine

Doubly-fed induction generator - wounded rotor

- Limited speed range (-30% to +20%, typical)
- Small-scale power converter (Less power losses, price)
- Complete control of active $P_{\text{ref}}$ and reactive power $Q_{\text{ref}}$
- Need for slip-rings
- Need for gear
Induction generator - Squirrel cage rotor

- Full speed range
- No brushes on the generator
- Complete control of active and reactive power
- Proven technology
- Full-scale power converter
- Need for a gear
2. Wind Energy Systems

Basic topologies for variable-speed wind turbine

Synchronous generator - Permanent magnets

- Full speed range
- Possible to avoid gear (multi-pole generator)
- Complete control of active and reactive power
- Brushless (reduced maintenance)
- No power converter for field (higher efficiency)
- Full scale power converter
- Multi-pole generator big and heavy
- Permanent magnets needed in large quantities
### 2. Wind Energy Systems

#### Comparison of topologies

<table>
<thead>
<tr>
<th>System</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
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<tbody>
<tr>
<td>Variable speed</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Control active power</td>
<td>Limited</td>
<td>No</td>
<td>Limited</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Control reactive power</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Short circuit (fault-active)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Short circuit power</td>
<td>contribute</td>
<td>contribute</td>
<td>contribute</td>
<td>contribute</td>
<td>limit</td>
<td>limit</td>
<td>limit</td>
<td>limit</td>
<td>limit</td>
</tr>
<tr>
<td>Control bandwidth</td>
<td>1-10 s</td>
<td>1-10 s</td>
<td>100 ms</td>
<td>1 ms</td>
<td>0.5-1 ms</td>
<td>0.5-1 ms</td>
<td>0.5-1 ms</td>
<td>0.5-1 ms</td>
<td>0.5-1 ms</td>
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<tr>
<td>Standby function</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes++</td>
<td>Yes++</td>
</tr>
<tr>
<td>Flicker (sensitive)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Softstarter needed</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Rolling capacity on grid</td>
<td>Yes, partly</td>
<td>No</td>
<td>Yes, partly</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Reactive compensator (C)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Island operation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes/No</td>
<td>Yes/No</td>
<td>Yes/No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Investment</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maintenance</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

- Power electronics now enables wind energy as a power source.
- Power electronics is now in wind turbines
2. Wind Energy Systems

Current developments, Vestas A/S Denmark

Target market: Big off-shore farms

Vestas V120 off-shore turbine
Rated power: 4,500 kW
Rotor diameter: 120 m
Hub height: 90 m
Turbine concept: Gearbox, variable speed, variable pitch control
Generator: HV DFIG

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2. Wind Energy Systems

Current Developments, Enercon GmbH  Germany

Enercon E-112 gearless turbine
Rated power: 4,500 - 6,000 kW
Rotor diameter: 114 m
Hub height: 124 m
Turbine concept: Gearless, variable speed, variable pitch control
Generator: Enercon ring generator

Target market: Big on-shore and off-shore farms.
2. Wind Energy Systems

Current developments - GE-Wind, USA

GE - 3.6 sl - off-shore
Rated power: 3,600 kW
Rotor diameter: 111 m
Turbine concept: Gearbox, variable speed, variable pitch control
Generator: DFIG

25MW off-shore wind farm, 7xGE-3.6 installed in Arklow, Ireland
2. Wind Energy Systems

off-shore wind farms

Doubly-fed induction generator

System A
2. Wind Energy Systems

Current developments – off-shore wind farms

- Rev Horns, Denmark, 80 x 2MW (Vestas V80, pitched, variable-speed, DFIG with gearbox)
- In operation for more than 2 years
- Operated as a conventional power plant
2. Wind Energy Systems

off-shore wind farms

Induction generator

System B

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2. Wind Energy Systems

off-shore wind farms

Common dc-grid

- Park C
- Gear-box
- Induction generator
- Gear-box
- Pitch

System C

- Long distance to PCC
- Grid weak at PCC
Outline

1. Development in Energy Technology
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4. Summary
5. Future trends
3. Solar Energy Systems

Europe Potential

Annual total potential in NW Europe: ca. 1000 kWh/m²/year (ca. 50% direct and 50% diffuse radiation) In southern Europe: ca. 2000 kWh/m²/year
3. Solar Energy Systems

Solar Photovoltaics Energy – developments


- Grid Connected PV System are growing fast
- Japan is the biggest solar panel manufacturer
- Germany is the biggest market in Europe

© 2.5 GW installed until 2004! (Totally installed 3700 GW!)

Source for market data: Paul Maycock, PV News, Volume 23, No. 3 March 2004
3. Solar Energy Systems

Solar Energy – Market development

- Germany and Japan are leaders. USA is expected to grow fast
- Consolidated world production in 2004 – ca 1 GW
- Cumulative world production by 2004 - 2.5 GW
- Expected demand in 2010 – 3.2 GW
  (source: www.solarbuzz.com)
3. Solar Energy Systems

Introducing Photovoltaics

Direct sunlight conversion to electricity using semiconductor materials (ex. Si, Ga-As, etc)

😊 Over 30 years experience
😊 Modular (mW to MW)
😊 Noise and pollution free
😊 No moving parts
😊 Reliable, long life (>20 year)
😊 Low operation cost
😊 Abundant resource (Si)
😊 High manufacturing cost
😊 Typical efficiency 15-18%

Roof-integrated PV system

4.6 MWp, Springfield, Tucson, Arizona, USA,

6.3 MWp, Solar Park Muhlhausen, Germany,
3. Solar Energy Systems

Solar cells technologies. Thin film vs. Crystalline Si

<table>
<thead>
<tr>
<th>Thin Films</th>
<th>Crystalline Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Highest efficiency: 19.2%</td>
<td>• Highest efficiency:</td>
</tr>
<tr>
<td>• Low material costs</td>
<td>24.7% single crystal</td>
</tr>
<tr>
<td>• film thickness &lt; 5μm</td>
<td>19.8% multi-crystalline</td>
</tr>
<tr>
<td>• High utilization</td>
<td>• High materials cost</td>
</tr>
<tr>
<td>• High throughput continuous</td>
<td>• Wafer thickness ≈ 300 μm</td>
</tr>
<tr>
<td>manufacturing</td>
<td>• poor utilization due to sawing</td>
</tr>
<tr>
<td>• Monolithic integration</td>
<td>• Large number of processing steps</td>
</tr>
<tr>
<td>• Stability and reliability</td>
<td>• Wafer binning</td>
</tr>
<tr>
<td></td>
<td>• Module assembly</td>
</tr>
<tr>
<td></td>
<td>• Established market</td>
</tr>
</tbody>
</table>

Obs. – Commercial performances are much lower (typ. 50%)

**Conclusion:**
In the next future, the thin-film PV modules have higher potential for cost reduction than c-Si which is reaching cost saturation. Also due to better building integration possibility!
3. Solar Energy Systems

Efficiency

The thermodynamic ideal limit is ~40%
3. Solar Energy Systems

Photovoltaic Systems - stand-alone

- **Small DC**
  - For telemetry, home and recreational uses

- **Simple DC**
  - Direct powering of the load, no energy storage (water pumping)

- **Hybrid**
  - Supplemental generator supplies additional power as needed

- **AC / DC**
  - Both AC and DC loads can be used

A large variety of applications

- Solar lighting in Mexico
- PV/Wind in Korea
- Mobile Solar, Source Nasa
- Solar/FC Source: IdaTech
- Source: Helios
3. Solar Energy Systems

Photovoltaic Systems - Grid connected

Residential PV is developing very fast in Japan and Germany
3. Solar Energy Systems

Power configuration for grid-connected PV systems

Central inverters
- 10 kW-250kW, three-phase, several strings in parallel
- high efficiency, low cost, low reliability, not optimal MPPT
- Used for power plants

String inverters
- 1.5 - 5 kW, typical residential application
- each string has its own inverter enabling better MPPT
- the strings can have different orientations
- Three-phase inverters for power < 5kW

Module inverters
- 50-180W, each panel has its own inverter enabling optimal MPPT
- lower efficiency, difficult maintenance
- Higher cost/kWp
3. Solar Energy Systems

Converter topologies for PV inverters

- Without boost / with boost of dc voltage
- Galvanic isolation necessary some places
- LF/HF transformer (cost-volume issue)
- A large variety of possibilities
- The optimal topology is not matured yet as for drives
- Transformerless topologies having higher efficiency are emerging
3. Solar Energy Systems

Control of PV inverters

**System control**
- Different control structures
- Current control (THD limits)
- Specific control functions
  - Maximum Power Point Tracking (MPPT)
  - Grid synchronization (PLL)
  - Anti – Islanding detection (standards)
- Ancillary functions (future)
  - Grid control
3. Solar Energy Systems

Example of control for dual-stage full-bridge PWM inverter with LCL filter

- A typical control structure for residential PV inverters up to 5 kW (single-phase)
- Current controller - PI or PR (Prop. Resonant), hysteresis, predictive
- DC voltage controller - P or PI or nonlinear (energy $\sim V_{dc}^2$)
- Isolation trafo is optional and does not influence the control
3. Solar Energy Systems

**MPPT overview**

- Irradiance and temp dependence of MPP
- Tracking of MPP is the challenge
- MPPT - nonlinear and time-varying sys
- Hill climbing method, \( \frac{dP}{dV} = 0 \) at MPP and is either negative or positive in the rest

**The most common methods**

- Perturb & Observe (P&O)
- Incremental Conductance (INC)
- Constant Voltage
- Other methods
- Rapid changing irradiation - dynamic efficiency

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>P&amp;O</th>
<th>INC</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array</td>
<td>96.5%</td>
<td>96.2%</td>
<td>88.1%</td>
</tr>
<tr>
<td>Simulator</td>
<td>97.2%</td>
<td>99.5%</td>
<td>92.7%</td>
</tr>
</tbody>
</table>

**Graphs:**

- Graph showing the dependence of cell current, voltage, and power on temperature and irradiance.
- Graph illustrating the concept of MPPT with dP/dV = 0 at MPP and dP/dV > 0 or < 0 in the rest.
3. Solar Energy Systems

Grid monitoring with PLL. Experimental results

- Both Transport Delay (del) and Inverse Park Transformation (Inv.transf) methods have good results for both amplitude and frequency step changes but the former method is easier to implement.
- More info:

3. Solar Energy Systems

Current control. Experimental results

PI + Voltage-Feed-Forward (Kp=10, Ti=4Ts) THD = 12%,

PR+HC (Kp=10, Ki=1000, K3,5,7=1000) THD = 1.0%.

\[ G_{pi}(s) = K_p + \frac{K_i}{s} \]

\[ G_i(s) = K_p + K_i \frac{s}{s^2 + \omega_n^2} \]

\[ G_{hc}(s) = \sum_{h=3,5,7} K_{ih} \frac{s}{s^2 + (\omega_n h)^2} \]

\[ G_{f}(s) \]
3. Solar Energy Systems

Anti-islanding by harmonic injection

Implemented in software

- A non-characteristic harmonic current is injected in the grid by through the PWM. The resulting harmonic voltage will depend on the grid impedance. The voltage and current at this frequency are computed using DFT. The impedance is calculated by dividing the voltage to the current. The real part is \( R_g \) and the imaginary part is \( L_g \)
- More info:
3. Solar Energy Systems

Anti-islanding by harmonic injection. Experimental results

- Non-continuous injection of the harmonic into the grid.
- Injection is discontinuous to maintain a low current THD
- The detection time is complying with the standards (<5%)
Outline

1. Development in Energy Technology
2. Wind energy systems
3. Solar energy systems
4. **Summary**
5. Future Trends
5. Summary - Power Electronics in RES

- **Power electronics** is an important player enabling better utilization of renewable sources by implementing MPPT function (WT, PV), ride-through capabilities, increase the capacity factor by using low wind/flow range, etc.
- **Power converters** are able to seamless transfer variable frequency power to the fixed frequency grid (ac-dc-ac). Critical for WT, Hydro.
- **Storage solution** could increase the capacity factor of RES like WT and could increase penetration. Europe goal 20% RES by 2020!
- **Distributed Power Generation Systems** (DPGS) will be a solution to avoid energy crisis in the near future. (both conventional and RES)
- It will **increase the power production** close to the consumption place.
- On long-term it will **decrease the power level** in the transmission level and will make the central grid control very complex.
- **Local grid control** will be necessary (ancillary fcn.) in order to avoid grid unstability and blackout.
- The future **RES DPGS should** be able to run in on-grid and off-grid modes
- **Advanced control** of grid converters including grid impedance estimation, adaptive current control are emerging
- **Monitoring and advanced diagnosis** will also be integrated
5. Summary - RES Forecast

- **Required total capacity installed by 2020 - 6TW (2.4 TW new installed)**
- **Wind energy** - very promising RES, huge potential, technology ready
  - 4 Eurocent/kWh (50% more for off-shore)
  - 50 GW installed in 2005 - 1.3% global penetration
  - 400 GW projected in 2020 - 8% global penetration
  - **Higher penetration is possible** if storage solution is found
  - **Large off-shore** is the key but needs more development to take off
- **Solar energy** - very promising RES, huge potential
  - **Concentrated Solar Power (CSP)** - long successful experience
    - Power Towers, trough farms - > 500 MW installed by 2005
      - 12 Eurocent/kWh 2005
      - 7 Eurocent/kWh 2010
    - Dish systems - more development to improve reliability
  - **PV - c-Si** technology > 90% market, residential, plants, stand-alone
    - > 2.5 GW installed by 2004,
    - 20 Eurocent/kWh 2005
    - 4 Eurocent/kWh in 2020
    - New technologies are emerging (CPV, thin-film)
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5. Future Trends - Flexible power systems

Grid scenarios for Denmark

Centralized Energy Production Units with Large Power Plants

- only large units
Better Utilization of Decentralized Power Plants

- expansion of small units up to 80%
- small units must
  - contribute to voltage and frequency control
  - withstand voltage sags
Large Penetration of Large Offshore Wind Farms

- interfacing wind farms with HVDC systems will
  - increase the flexibility of the connection
  - contribute to voltage control
Dispersed Generation in Small Networks

- grid splitted in small cells
- voltage and frequency control both locally and centralized
- high redundancy
- island operation of cells
- etc
5. Future Trends – Intelligent RES

- Each RES unit is an active part of the power system
- Communication to each unit (bi-directional)
- Outstanding monitoring function and control for grid system
- Impedance detection of grid
- Adaptive control
- Flexible frequency/voltage control
- Energy Storage Systems
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12th European Conference on Power Electronics and Applications
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Deadlines:
- Receipt of synopses: 1 November 2006
- Notification of provisional acceptance: 20 February 2007
- Receipt of full manuscript for final review: 1 May 2007

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- Power electronics interface for permanent magnet and field excited synchronous generators connected turbines
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- Fault monitoring and preventive maintenance of power electronic based wind turbine systems
- Protection of power electronic systems for wind turbines
- Planning and protection of wind farm power systems
- Design-through capability of wind turbines with power electronic systems
- Power electronics for integration and control of wind turbines in power systems
- Small wind turbine systems for stand-alone and grid-connected applications
- Future trends of wind energy generation and power electronics applications

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