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Power Electronics in Renewable Energy Systems

Power Electronics in Renewable Energy Systems

by

Prof. Dr. Frede Blaabjerg

Aalborg University
Institute of Energy Technology

fbl@iet.aau.dk

http://www.iet.aau.dk

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

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Power Electronics in Renewable Energy Systems

1. Development in Energy Technology

Where are we from?

- 13000 students
- Founded in 1974

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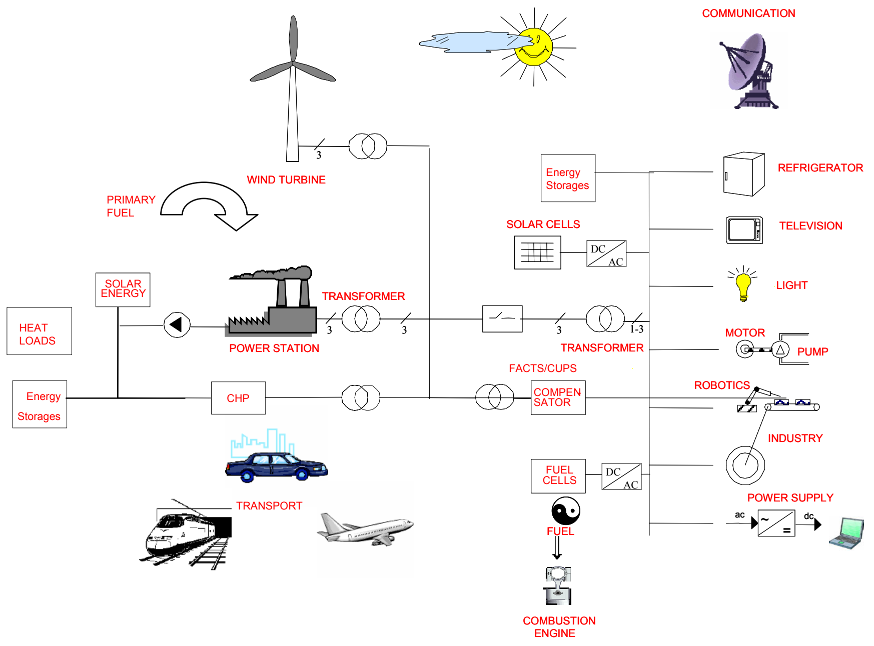
1. Development in Energy Technology



Keywords: Energy production – Energy distribution – Energy consumption – Energy control

1. Development in Energy Technology

Organisation

Institute of Energy Technology

20 Faculties
15 PhD
10 Guest Researchers
10 Research Assistansts
12 TAP

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

Stratetic cooperation:
- EMSD
- EDS
- CEES
- NEED
- FACE

- Fuel cells
- Wind Turbine Systems
- Advanced Combustion and Multiphase Processes
- Modern Power Systems Analysis and Planning
- Green Powers Converters
- Sustainable Transport Systems
- Drive Systems and Motion Control
- Virtual Power Prototyping
- Emergent Projects

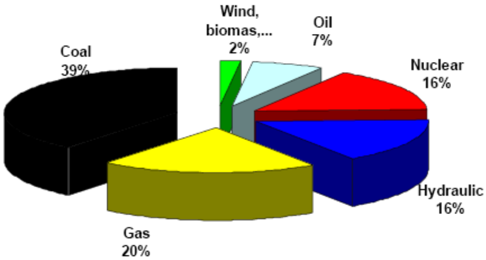
Lab. Facilities:
- Power electronics Systems
- Drive Systems Tests
- Hydraulic
- Power systems
- High Voltage
- DSpace
- Laser Systems
- Fuel Cell Systems
- Proto Type Facilities

1. Development in Energy Technology

Electricity production in 2004

Enerdata

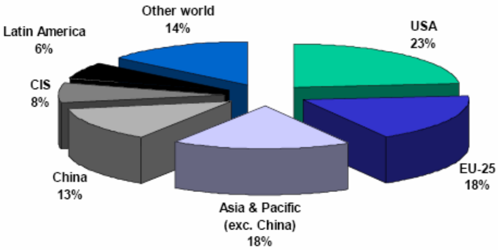
Electricity in the world in 2004: 17 400 TWh



- 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

Enerdata

Electricity in the world in 2004: 17 400 TWh



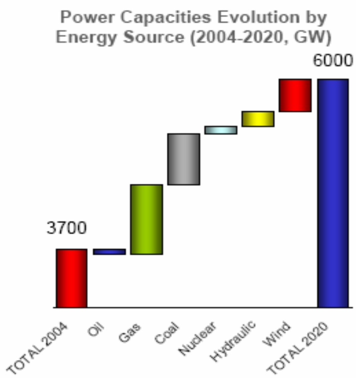
- The OECD weights for 58% of total electricity, OECD + CIS represent 66%
- With 13%, China's weight increases by 1 point every year since 2000

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**

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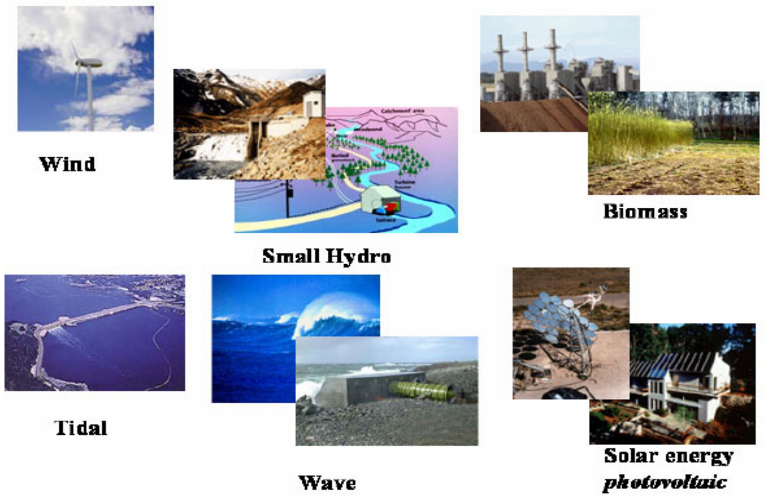
1. Development in Energy Technology

Overview of DPGS



Advantages of DPGS:

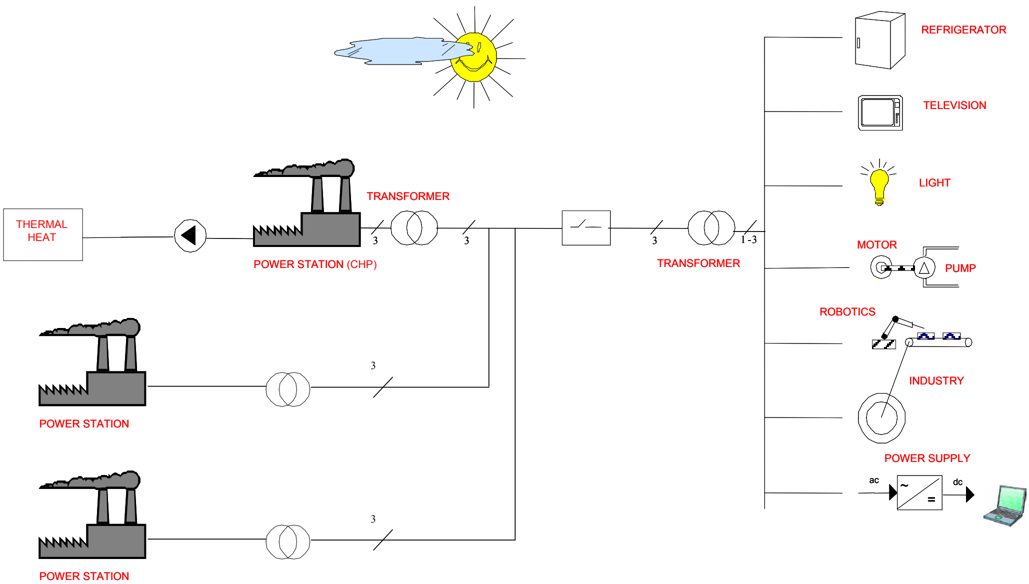
- Load management (peak shaving)
- Power quality (required by standards!)
- Enhanced voltage stabiliity
- Reduced transmission losses
- Potential for improving grid reliability/stability

Disadvantage - high cost!

- 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)

1. Development in Energy Technology

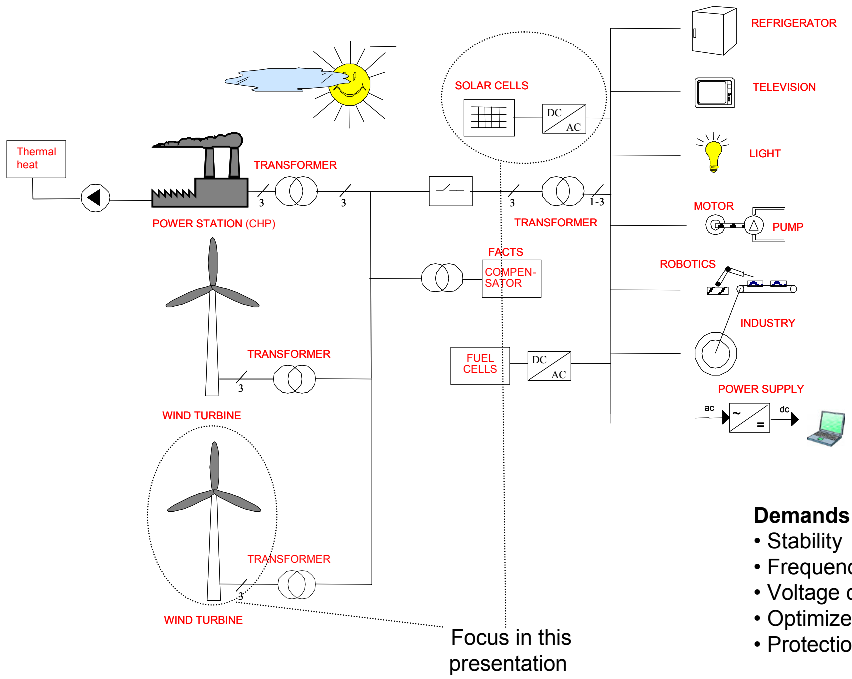
Classical Power System



Central power plants

1. Development in Energy Technology

Future Power System



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

Less central power plants and more DPGS

Outline

1. Development in Energy Technology
2. **Wind energy systems**
3. Solar energy systems
4. Summary
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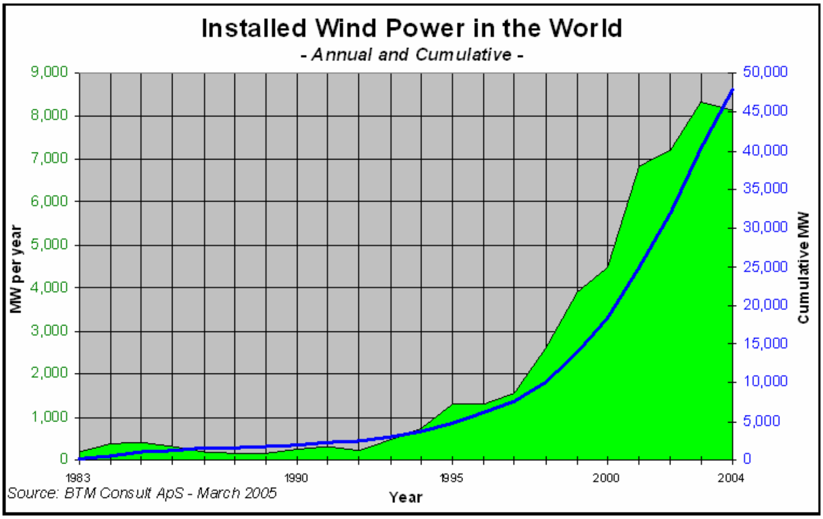
2. Wind Energy Systems

Actual installed power worldwide

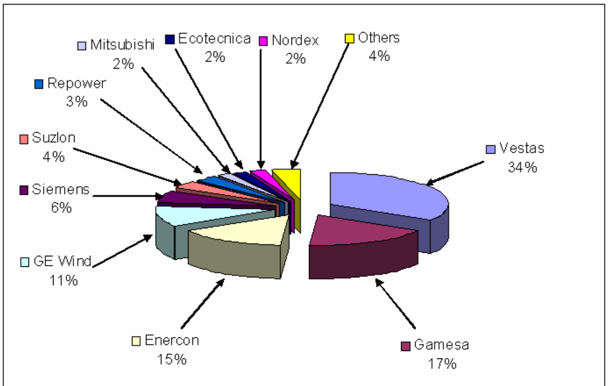


The annual increase has decreased in 2004!

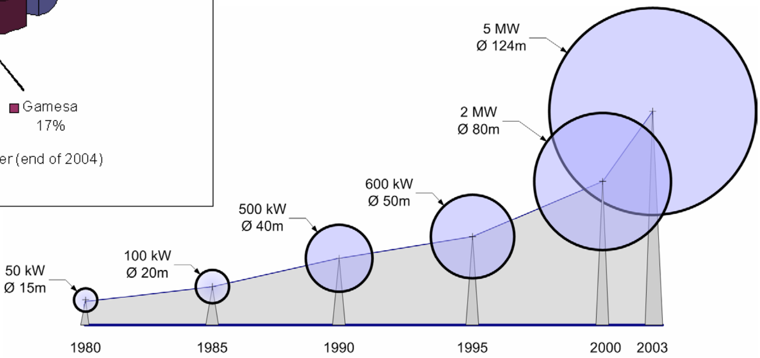
50 GW installed in 2005!
Predicted for 2010 - 180 GW (source WindForce 10)

2. Wind Energy Systems

Wind Turbine development



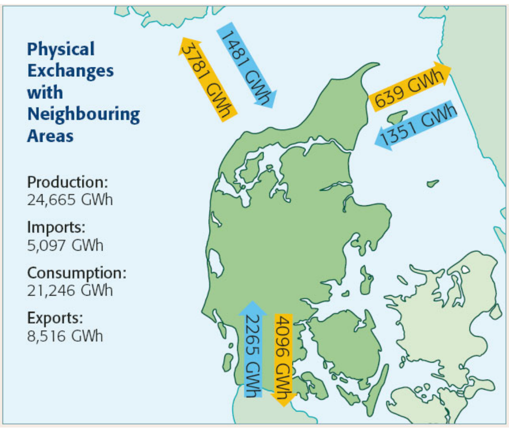
Wind Turbine Market Share by Manufacturer (end of 2004)
source: BTM Consult ApS



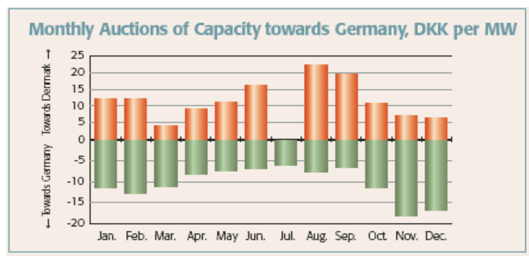
- **Bigger and more efficient !**
- **3.6-6MW prototypes running (Vestas, GE, Siemens Wind,Enercon)**
- **Danish Vestas and Siemens Wind stand for over 40% of the worldwide market**
- **2MW WT are still the "best seller" on the market!**

2. Wind Energy Systems

Danish experience – 19% wind power penetration!



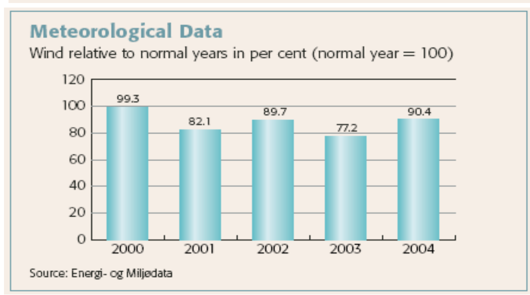
- Wind production can vary significantly with respect to the predicted one
- This lead to instant export with low prices or import at high price
- Better wind prediction is needed



Energy Balance in GWh

	2000	2001	2002	2003	2004
Primary production	11,340.3	12,861.9	12,928.4	16,161.2	12,951.2
Local production*)	6,245.1	6,811.2	6,723.2	6,839.5	6,838.9
Wind production	3,383.7	3,389.9	3,825.0	4,363.4	4,874.8
Total production	20,969.1	23,062.9	23,476.6	27,364.1	24,664.9
Net exports	299.3	2,186.9	2,618.6	6,320.9	3,418.9
Consumption inc. losses	20,669.8	20,876.1	20,858.0	21,043.2	21,246.0
Commissioning in 2004	+ 0.9 %	+ 1.0 %	- 0.1 %	+ 0.9 %	+ 1.0 %

*) Includes production at the bioboiler at Unit 3 of the Enstedværket power station.



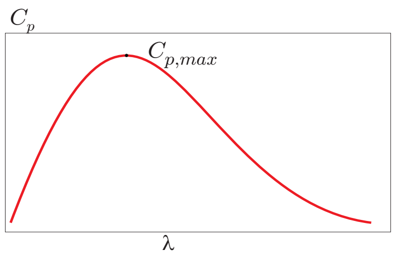
2. Wind Energy Systems

Power Conversion - MPPT

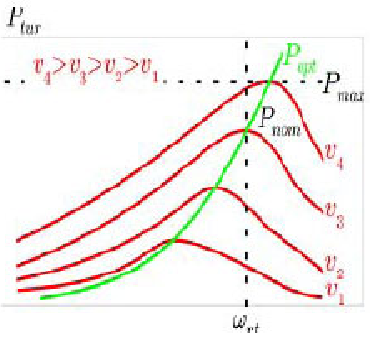
Power curve - Aerodynamic

$$P_{tur} = \frac{1}{2} C_p \rho A_v v_{wind}^3$$

$$\lambda = \frac{v_{tip}}{v_{wind}} = \frac{r_{rt}\omega_{rt}}{v_{wind}}$$



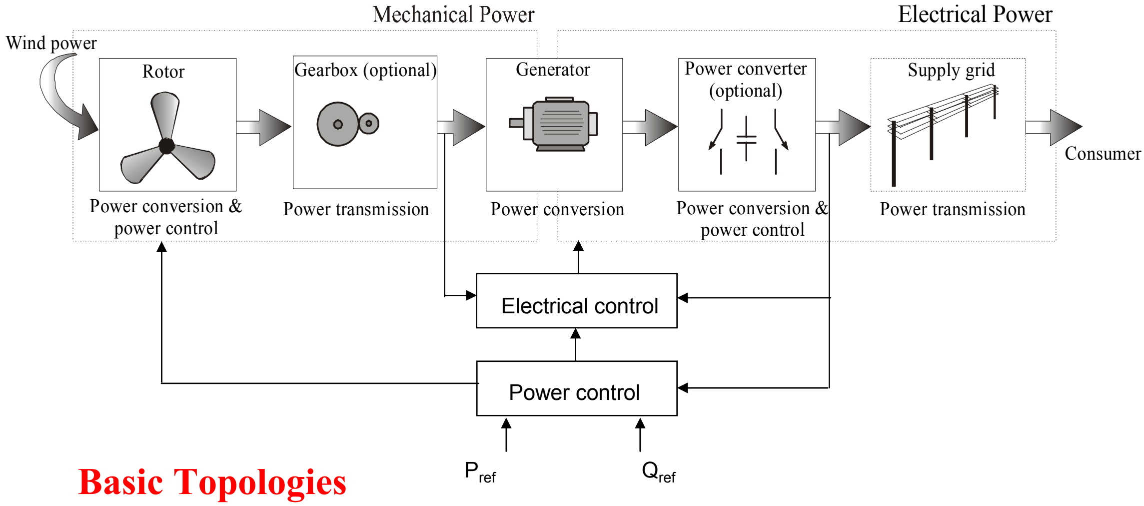
- **Techniques to limit the produced power**
  - Stall control
  - Active stall control
  - Pitch control



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!)

Squirell cage induction generator SCIG

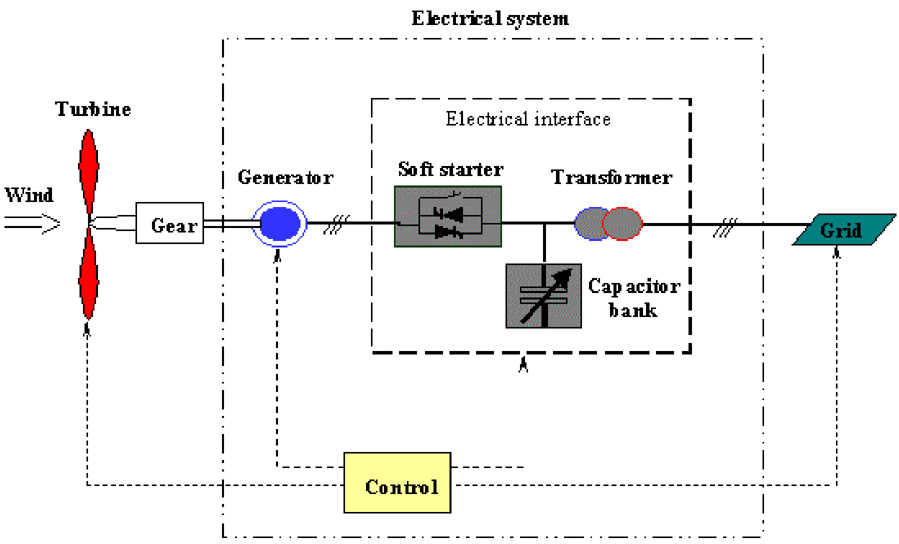
Synchronous generator - External magnetized

Synchronous generator - Permanent magnets

2. Wind Energy Systems

Basic topologies for variable-speed wind turbine

Fixed speed with capacitor bank (Reactive power)

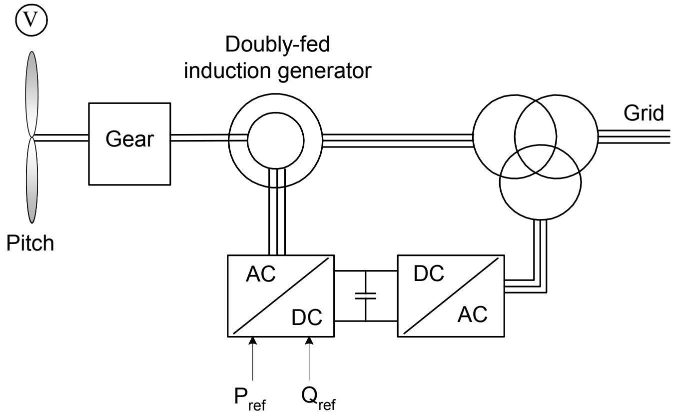


2. Wind Energy Systems

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_{ref} and reactive power Q_{ref}
- Need for slip-rings
- Need for gear

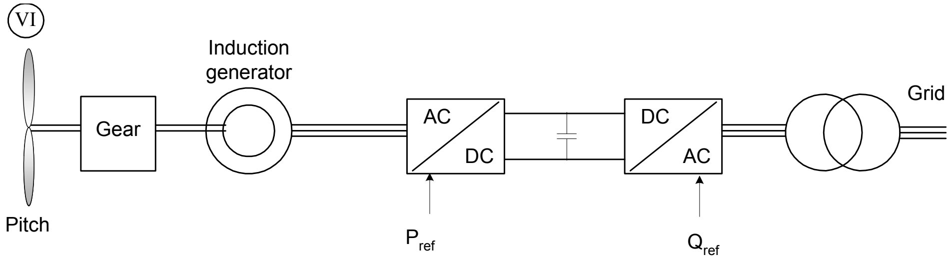


2. Wind Energy Systems

Basic topologies for variable-speed wind turbine

Induction generator - Squirrel cage rotor

- Full speed range
- No brushes on the generator
- Complete control of active og reactive power
- Proven technology
- Full-scale power converter
- Need for a gear

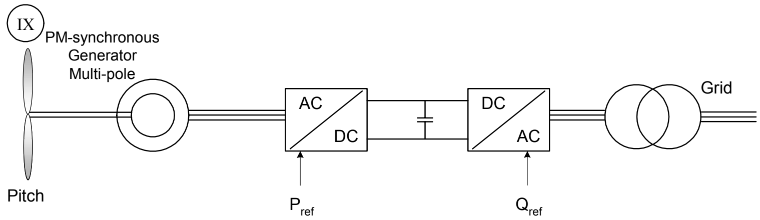


2. Wind Energy Systems

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

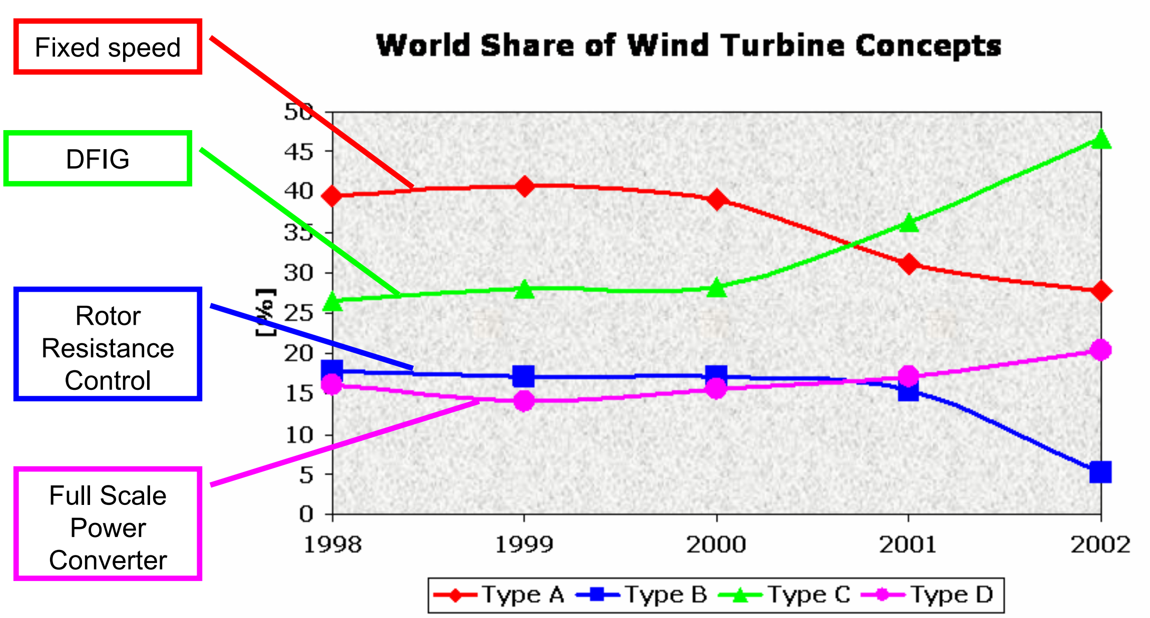
Comparison of topologies

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

- **Power electronics now enables wind energy as a power soource**

2. Wind Energy Systems

Technology comparison

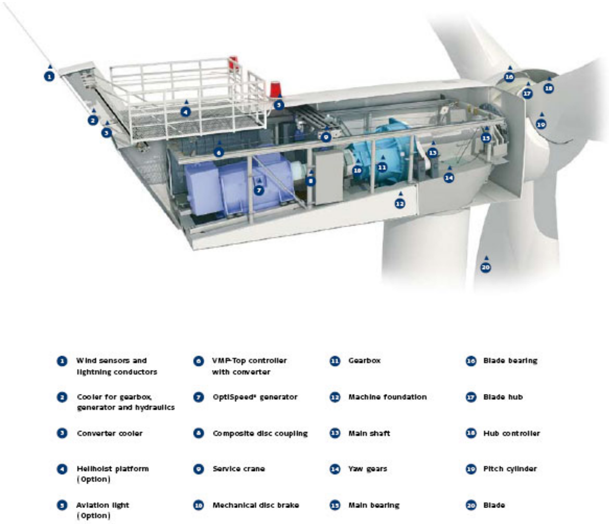


- Power electronics is now in wind turbines

2. Wind Energy Systems

Current developments, Vestas A/S Denmark

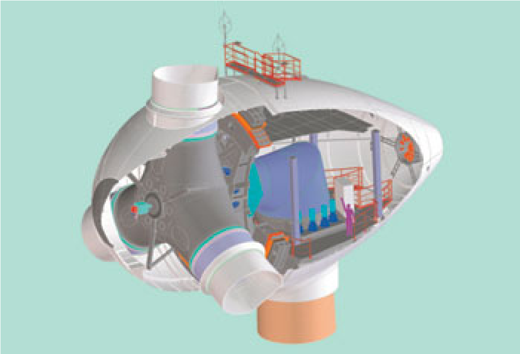
Target market: Big off-shore farms



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

2. Wind Energy Systems

Current Developments, Enercon GmbH Germany

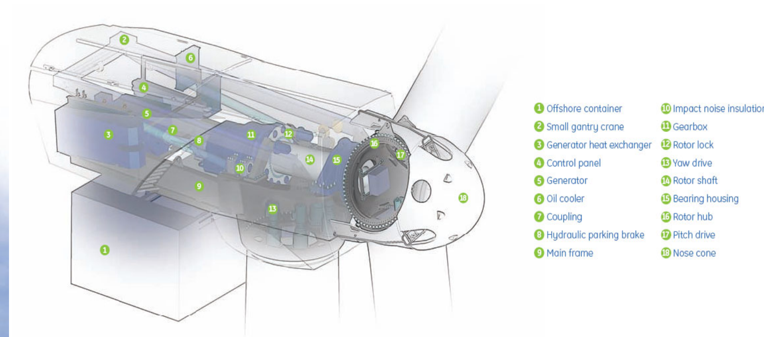


Enercon E-112 gearless turbine
Rated power: 4,500 - 6,000 kW
Rotor diameter: 114 m
Hub height: 124 m
Turbine concept: Gearless, variable speed, variable pitch control
Generator: Enercon ring generator

Target market: Big on-shore and off-shore farms.

2. Wind Energy Systems

Current developments - GE-Wind, USA

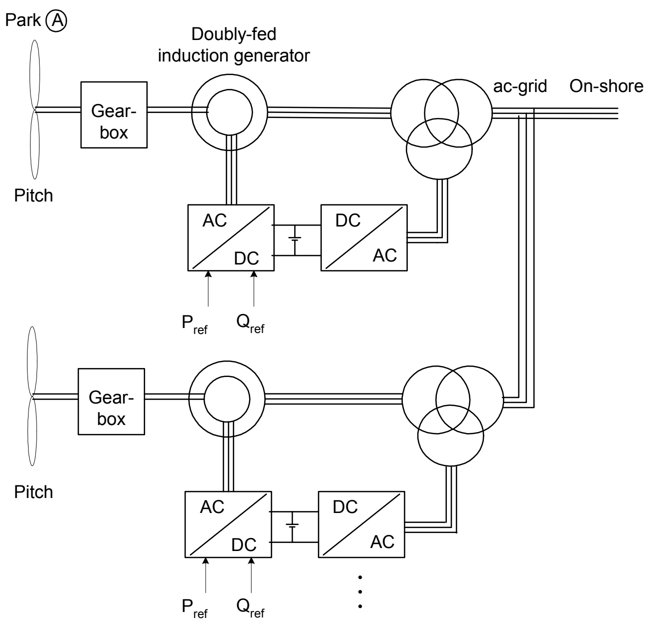


GE - 3.6 sl - off-shore
Rated power: 3,600 kW
Rotor diameter: 111 m
Turbine concept: Gearbox, variable speed, variable pitch control
Generator: DFIG

25MW off-shore wind farm, 7xGE-3.6 installed in Arklow, Ireland

2. Wind Energy Systems

off-shore wind farms



System A

2. Wind Energy Systems

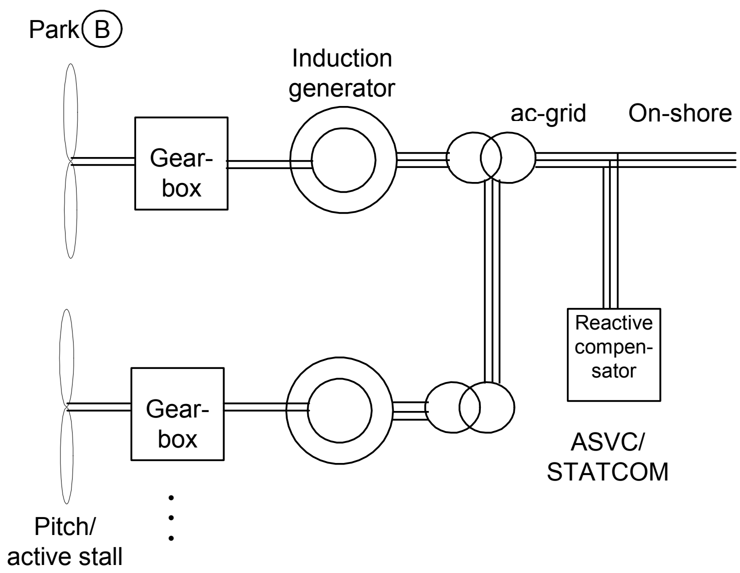
Current developments –off-shore wind farms

- 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

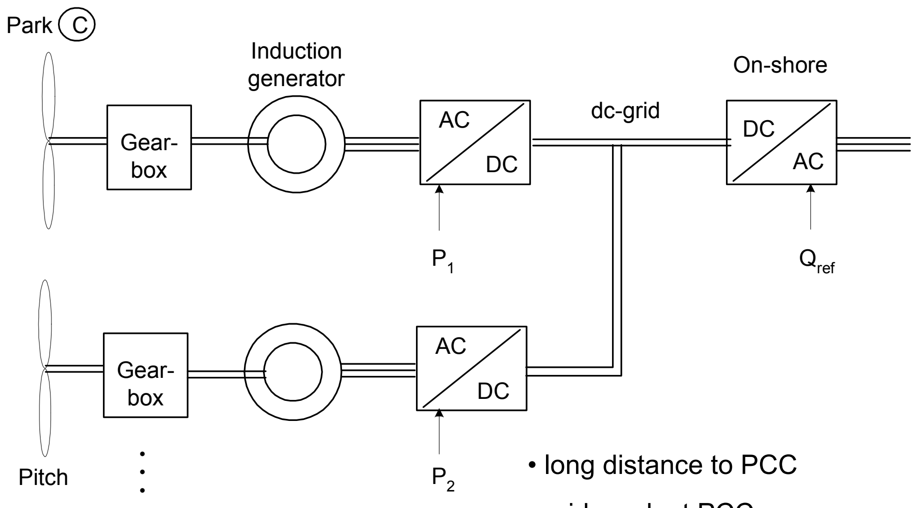


System B

2. Wind Energy Systems

off-shore wind farms

Common dc-grid



• long distance to PCC
• grid weak at PCC

System C

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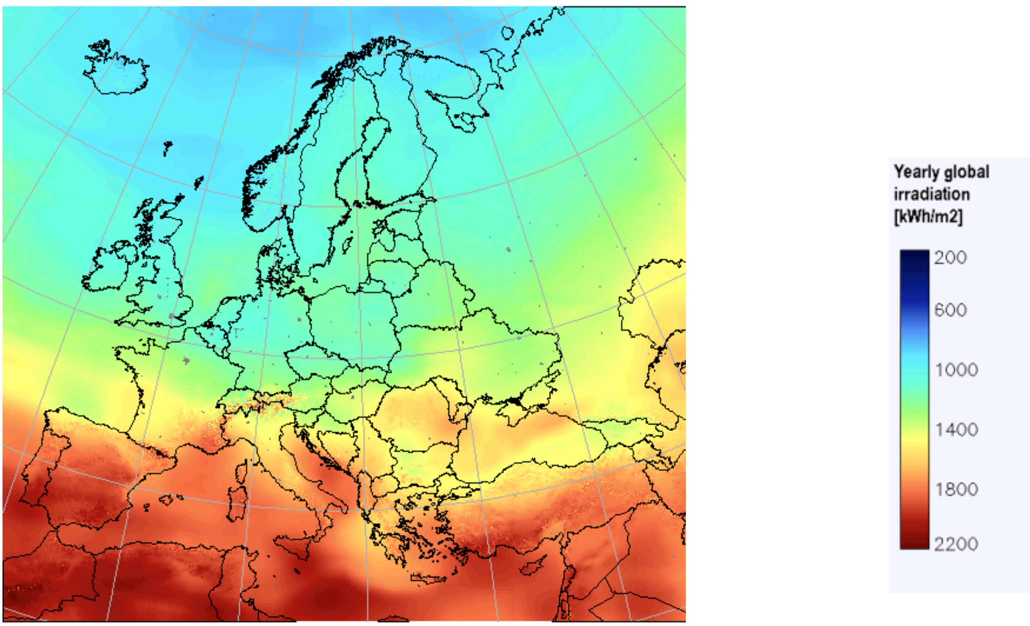
3. Solar Energy Systems

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

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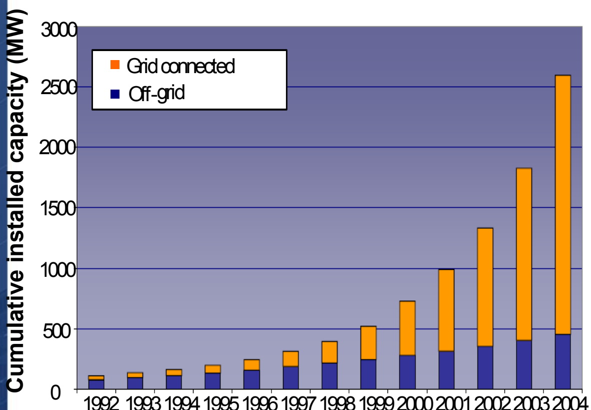
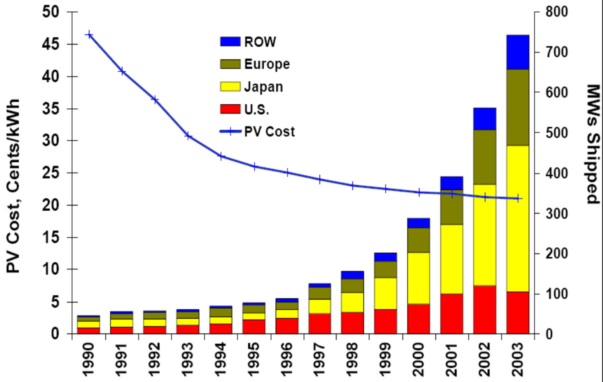
3. Solar Energy Systems

Solar Photovoltaics Energy – developments



Cumulative installed capacity from 1992 to 2004 the IEA-PVPS reporting countries (source: IEA-PVPS, http://www.iea-pvps.org

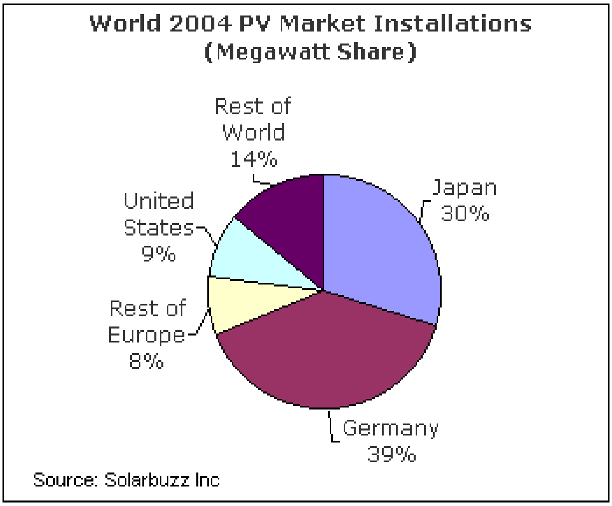


Source for market data: Paul Maycock, PV News, Volume 23, No. 3 March 2004

- ☺ 2.5 GW installed until 2004! (Totally installed 3700 GW!)
- ☺ Grid Connected PV System are growing fast
- ☺ Japan is the biggest solar panel manufacturer
- ☺ Germany is the biggest market in Europe

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
- ☺ Cummulative 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

Skyskrapper on Broadway, New York

4.6 MWp, Springerfield, Tucson, Arizona, USA,

6.3 MWp, Solar Park Muhlhausen, Germany,

3. Solar Energy Systems

Solar cells technologies. Thin film vs. Crystalline Si

Thin Films

- Highest efficiency: 19.2%
- Low material costs
  - film thickness < 5µm
  - high utilization
- High throughput continuous manufacturing
- Monolithic integration
- Stability and reliability

Crystalline Si

- Highest efficiency:
  - 24.7% single crystal
  - 19.8% multi-crystalline
- High materials cost
  - Wafer thickness ≈ 300 µm
  - poor utilization due to sawing
- Large number of processing steps
- Wafer binning
- Module assembly
- Established market

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!

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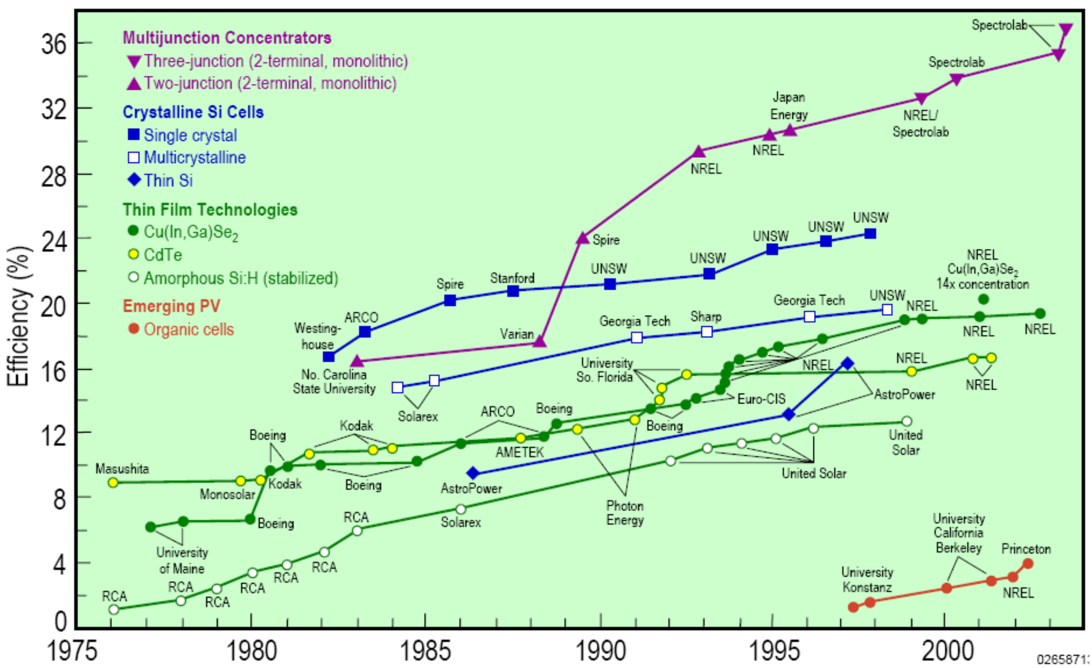
3. Solar Energy Systems

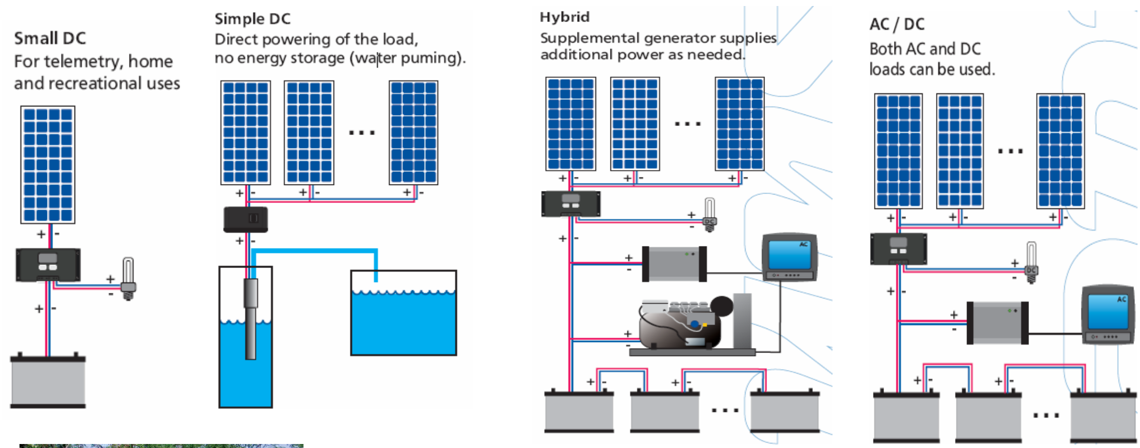
Efficiency

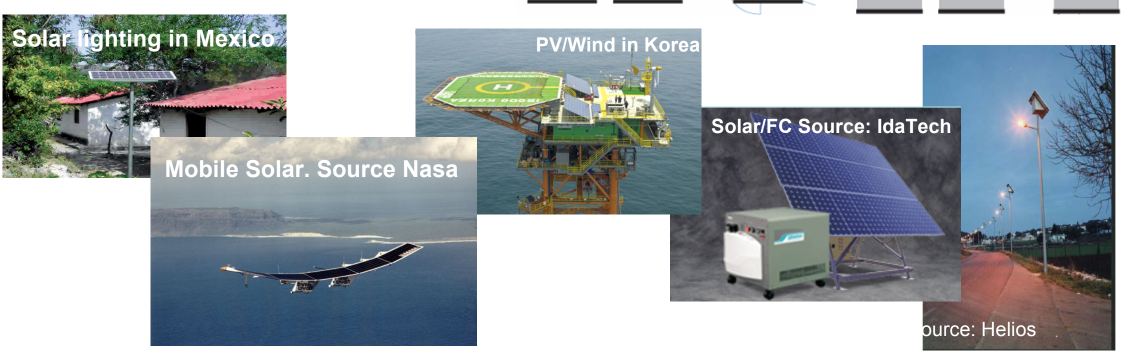


The thermodynamic ideal limit is ~40%

3. Solar Energy Systems

Photovoltaic Systems- stand-alone

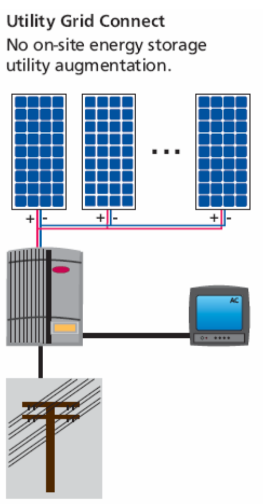




A large variety of applications

3. Solar Energy Systems

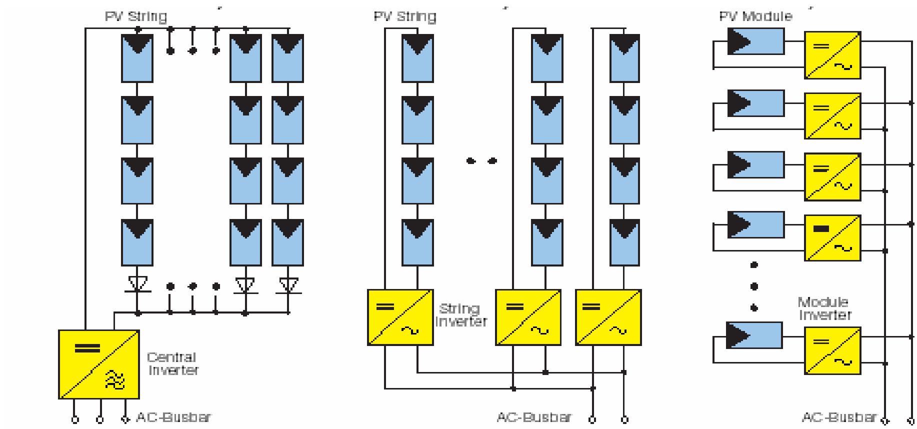
Photovoltaic Systems - Grid connected



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

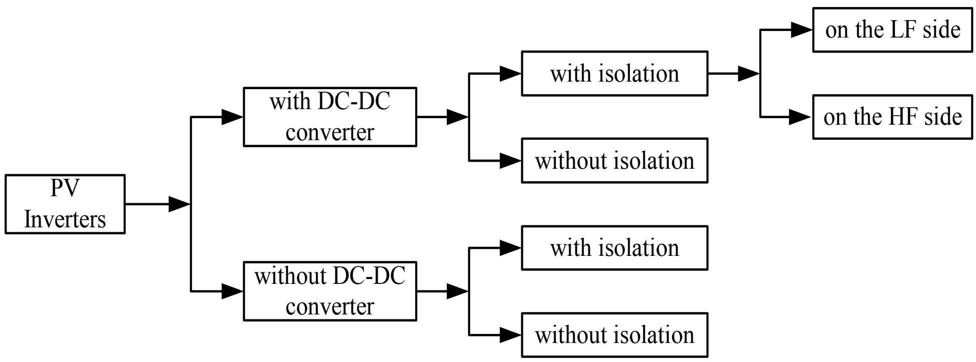
- 1.5 - 5 kW, typical residential application
- each string has its own inverter enabling better MPPT
- the strings can have different orientations
- Three-phase inverters for power < 5kW

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

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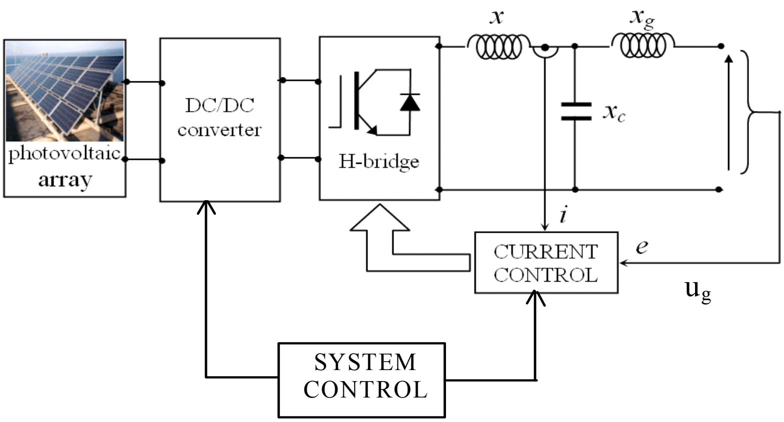
3. Solar Energy Systems

Control of PV inverters

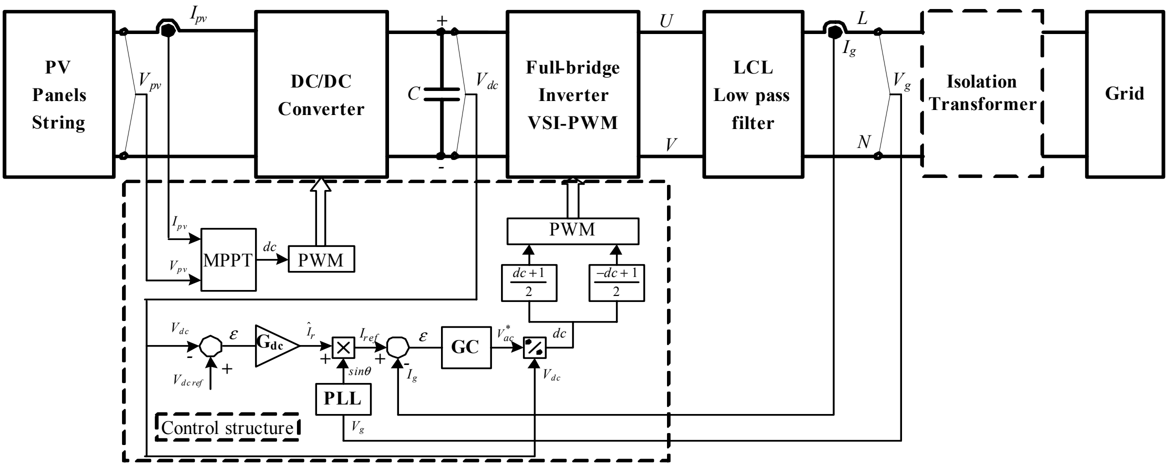


System control

- 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

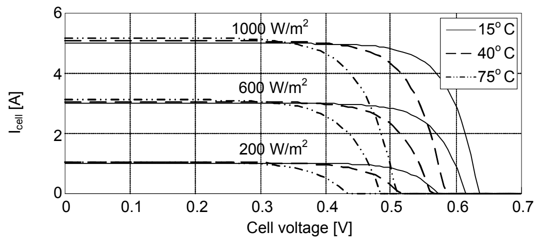
Example of control for dual-stage full-bridge PWM inverter with LCL filter

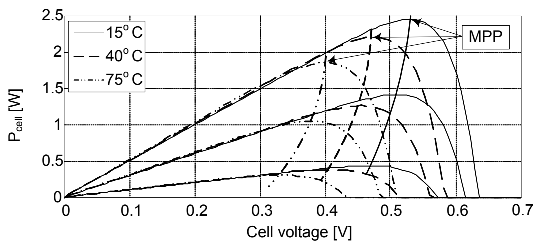


- A typical control structure for residential PV inverters up to 5 kW (single-phase)
- Current controller - PI or PR (Prop. Resonant), hysteresis, predictive
- DC voltage controller - P or PI or nonlinear (energy ~V_{dc}^2)
- Isolation trafo is optional and does not influence the control

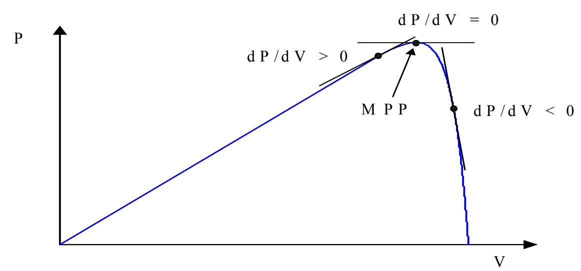
3. Solar Energy Systems

MPPT overview





- Irradiance and temp dependence of MPP
- Tracking of MPP is the challenge
- MPPT - nonlinear and time-varying sys
- Hill climbing method, dP/dV = 0 at MPP and is either negative or postive in the rest



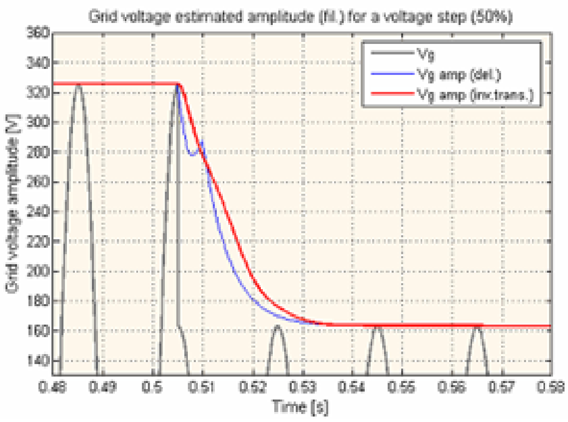
The most common methods

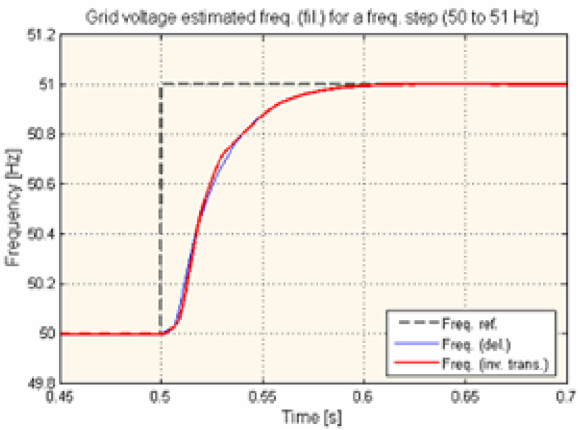
- Perturb & Observe (P&O)
- Incremental Conductance (INC)
- Constant Voltage
- Other methods
- Rapid changing irradiation - dynamic efficiency

	P&O	INC	CV
Array	96.5%	98.2%	88.1%
Simulator	97.2%	98.5%	92.7%

3. Solar Energy Systems

Grid monitoring with PLL. Experimental results





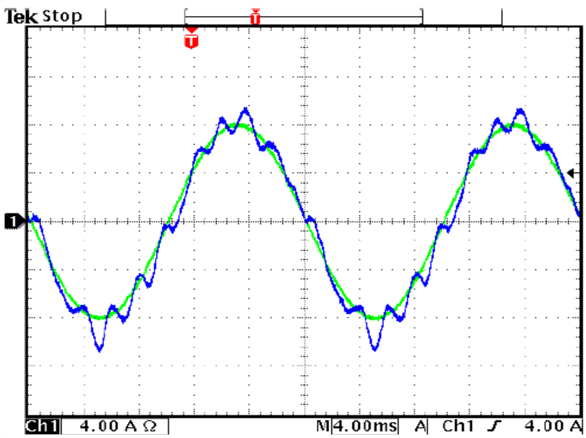
- Both Transport Delay (del) and Inverse Park Transformation (Inv.transf) methods have good results for both amplitude and frequency step changes but the former method is easier to implement
- More info:

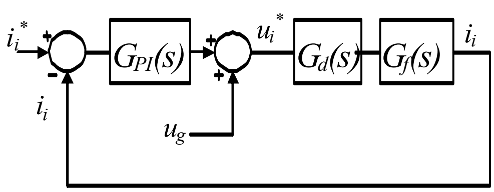
[Ciubotaru, M, Teodorescu, R., Blaabjerg, F., "Improved PLL Structures for Single-Phase Grid Inverters" – Proceedings of International Conference on Poer Electronics and Intelligent Control for Energy Conservation, PELINCEC'05, Warsaw, 16-19 October 2005]

3. Solar Energy Systems

Current control. Experimental results

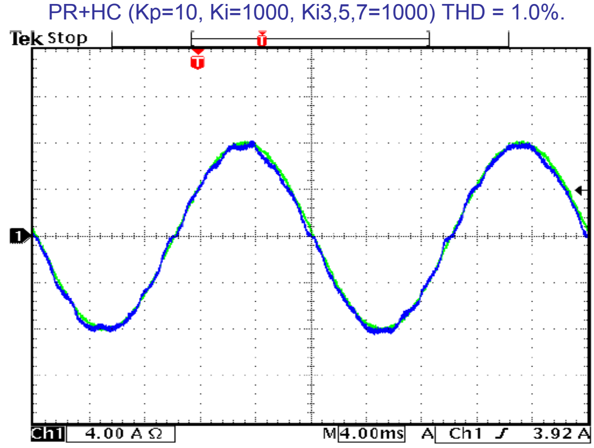
PI + Voltage-Feed-Forward (Kp=10, Ti=4Ts) THD = 12%,

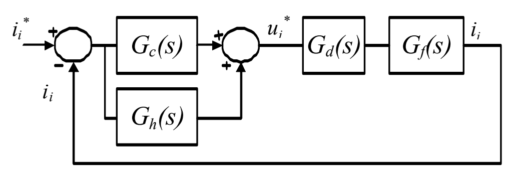




$$G_{PI}(s) = K_P + \frac{K_I}{s}$$

PR+HC (Kp=10, Ki=1000, Ki3,5,7=1000) THD = 1.0%.



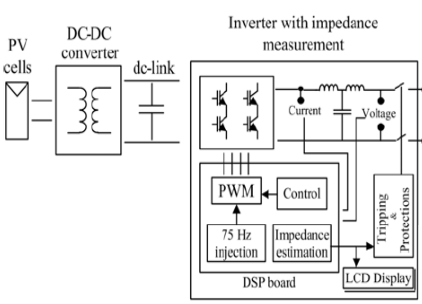


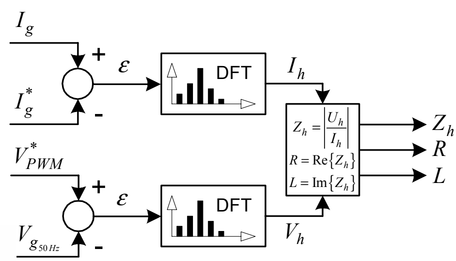
$$G_c(s) = K_P + K_I \frac{s}{s^2 + \omega_o^2} \qquad G_h(s) = \sum_{h=3,5,7} K_{Ih} \frac{s}{s^2 + (\omega_o h)^2}$$

3. Solar Energy Systems

Anti-islanding by harmonic injection

Implemented in software





$$\underline{Z}(h) = \frac{\underline{V}(h)}{\underline{I}(h)}$$

$$\underline{Z}(h) = \frac{V \cdot e^{j\varphi_V}}{I \cdot e^{j\varphi_I}} = Z \cdot e^{j\varphi_Z}$$

$$\underline{Z}(h) = R_g + j \cdot \omega_h \cdot L_g$$

$$\underline{Z}(50Hz) = R_g + j \cdot \omega_{50} \cdot L_g$$

- 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 calulated by dividing the voltage to the current. The real part is Rg and the imaginary part is Lg
- More info:
  [Asiminoaie L.,Teodorescu,R., Blaabjerg,F., Borup,U. – "A Digital Controlled PV-Inverter with Grid Impedance Estimation for ENS Detection " IEEE Trans on PE 2005.]

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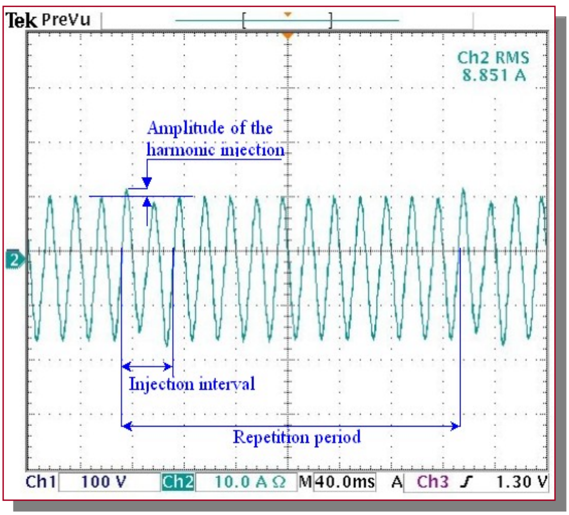
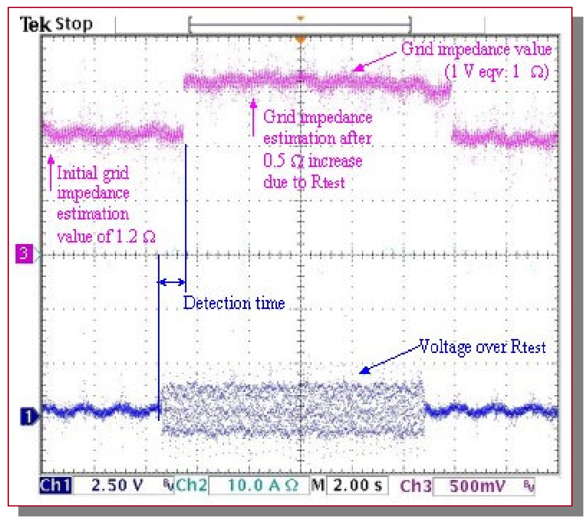
3. Solar Energy Systems

Anti-islanding by harmonic injection. Experimental results



Non-continuous injection of the harmonic into the grid.



Dynamic response of the method detecting 0.5 Ω resistive increase.

- Injection is discontinuos 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 necessarry (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 promissing 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 promissing RES, huge potential
  - **Concentrated Solar Power (CSP)** -long succesfull 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)

Outline

1. Development in Energy Technology
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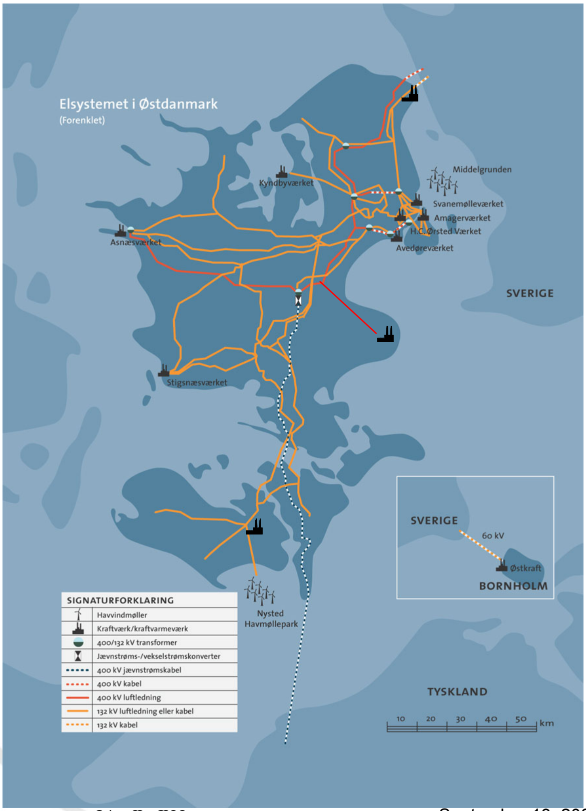
5. **Future Trends**

5. Future Trends- Flexible power systems

Grid scenarios for Denmark



Centralized Energy Production Units with Large Power Plants

- only large units

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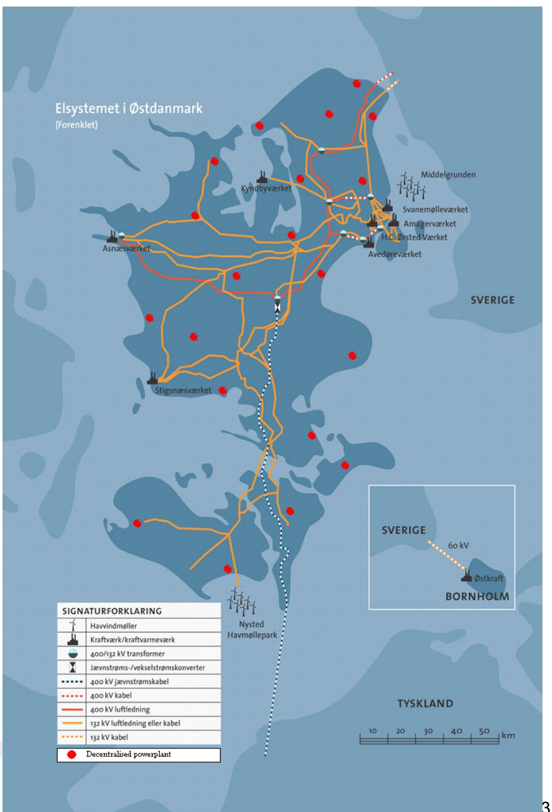
5. Future Trends- Flexible power systems

Grid scenarios for Denmark

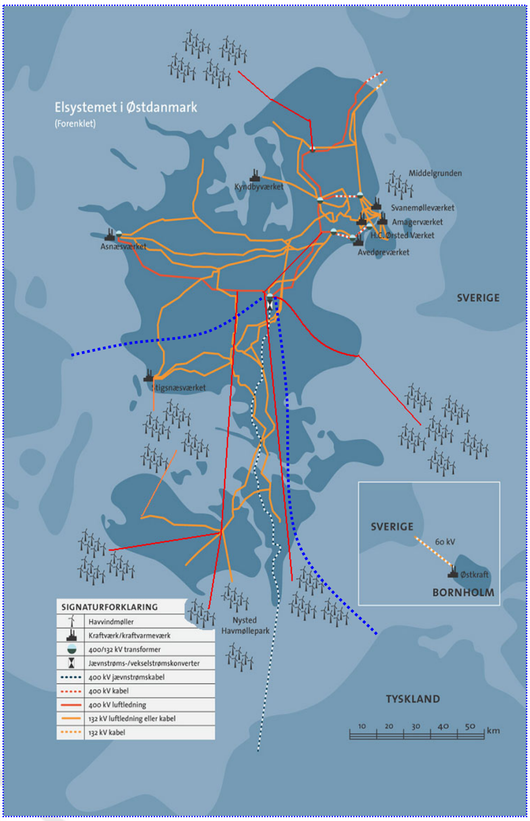


Better Utilization of Decentralized Power Plants

- expansion of small units up to 80%
- small units must
  - contribute to voltage and frequency control
  - withstand voltage sags

5. Future Trends- Flexible power systems

Grid scenarios for Denmark

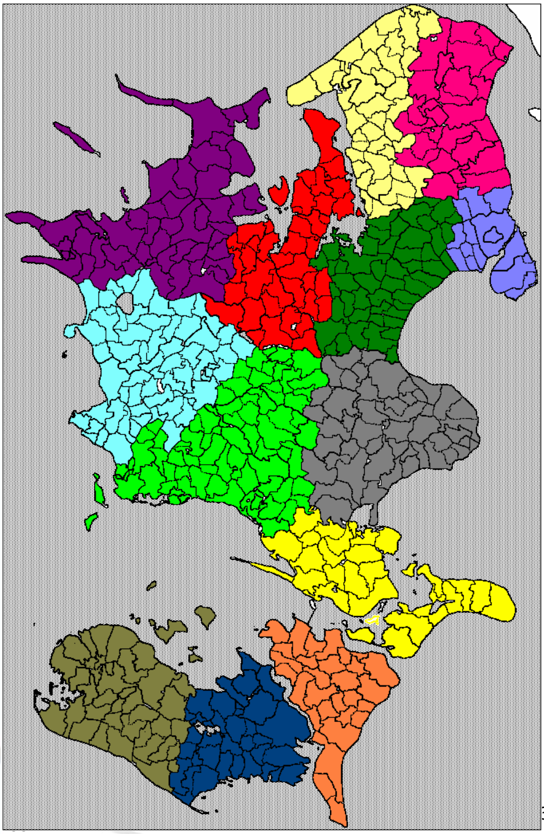


Large Penetration of Large Offshore Wind Farms

- interfacing wind farms with HVDC systems will
  - increase the flexibility of the connection
  - contribute to voltage control

5. Future Trends- Flexible power systems

Grid scenarios for Denmark



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 – Inteligent 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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Power Electronics in Renewable Energy Systems

IEEE TRANSACTIONS ON POWER ELECTRONICS

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- Power electronic interface for permanent-magnetic and field excited synchronous generators based wind turbines
- Modelling and simulation of power electronic systems with wind turbines and windfarms
- Fault monitoring and predictive maintenance of power electronic based wind turbine systems
- Protection of power electronic systems for wind turbines
- Planning and configuration of wind farm power systems
- Ride-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 standalone and grid-connected applications
- Future trends of wind energy conversion and power electronic applications

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