Power electronics as efficient interface in dispersed power generation systems.

by
Frede Blaabjerg
Institute of Energy Technology
Aalborg University
www. iet.aau.dk
E-mail: fbl@iet.aau.dk

Institute of ENERGY TECHNOLOGY

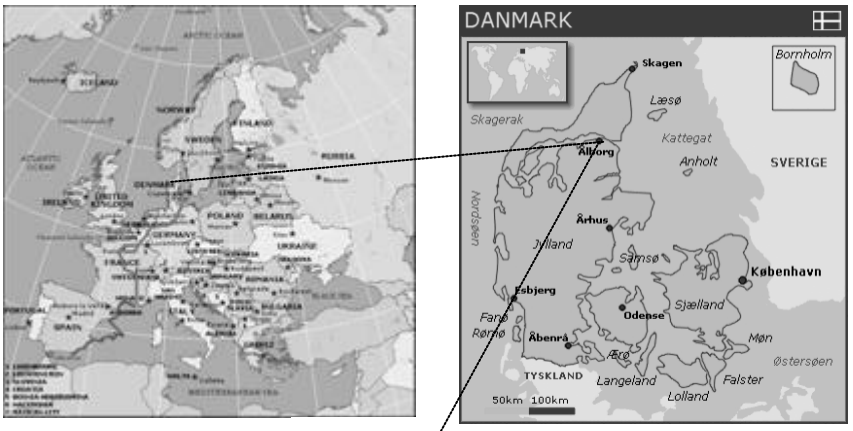
Power electronics as efficient interface in dispersed power generation systems.

Outline

1. Institute of Energy Technology
2. DPGS in Denmark
3. System demands
4. Grid connection requirements
5. New issues in Denmark
6. Basic Principle of Wind Energy Conversion
7. Wind Turbine Configurations
8. Wind Turbine Control
9. Conclusion

3

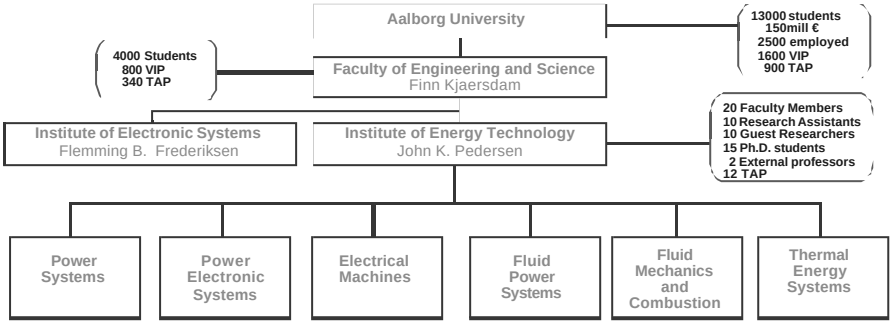
Where are we from?



AALBORG UNIVERSITY DENMARK

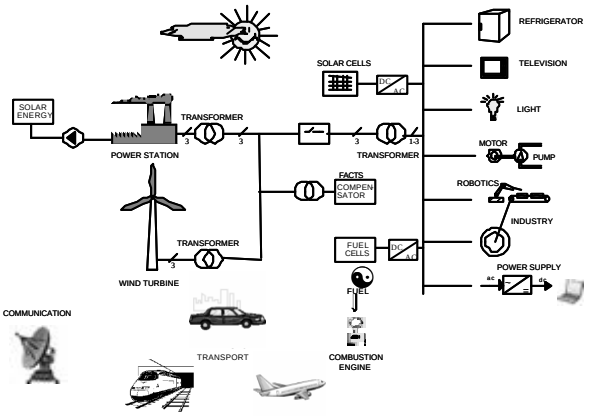
- 13000 students
- Founded in 1974

4



- Founded 1974
- Project-oriented and problem-based

Energy System



- Only full Energy Institute in Denmark

Organisation

Institute of Energy Technology

20 VIP
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

Research Programme

Stratetic cooperation:
- **EMSD**
- **EDS**
- **CEES**
- **NEED**
- **FACE**
- **WEST**
- **DFV**

- **Fuel cells**
- **Integrated energy systems**
- **Wind Turbines**
- **Industrial drive systems**
- **Traction and automotive**
- **Modern Power Systems**
- **Advanced Combustion and Multiphase Processes**
- **..**
- **Actuators and Motion Control**

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

7

Power systems

- Power Quality in the network grid
- Transient stability
- Network planning methods
- Relay protection
- Distributed Power Connection
- Simulation of the network grid
- High voltage Measurements
- Modelling of partial discharges
- Test of Insolation

- Lightning protection
- Diagnostic methods
- Modelling of high voltage components
- Conducted interference
- Over voltage protection

Institute of ENERGY TECHNOLOGY
1. Institute of Energy Technology

8

Power Electronic Systems

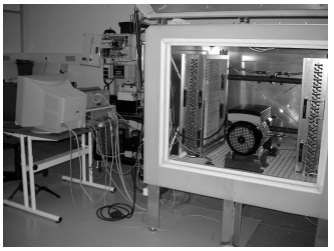
- Power Electronic Components
- AC/DC – DC/AC Converters Topologies
- DC/DC Converter Topologies
- AC/AC Converter Topologies
- PFC and Active Filters
- PWM and Resonans Control
- Random Modulation

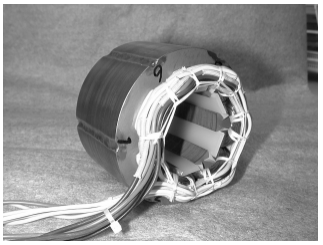
- Modelling and simulation
- Optimized Design
- FACTS – Converters for Power Systems
- Electrical Drive Systems
- DSP / 💻-controllers
- Test of Components and Systems

9

Electrical Machines

- Modern Machines (SR, PM)
- Classical Machines (IM, DC)
- Electromagnetic Components
- Modelling for Design, Simulation and Control



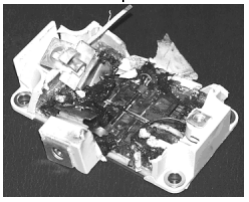


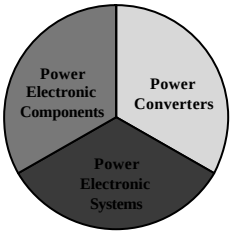
- FEM and MEC Analysis
- Advanced Optimised Design
- Design Software
- Power Electronic/Machine interaction
- Test and Monitoring of Machines, Drive and Materials

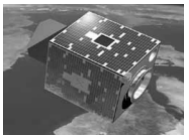
10

Section of Power Electronic Systems

Basic competences







11

Section of Power Electronic Systems (Systems)

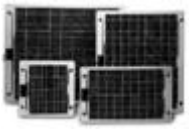
- Danish Academy of Wind Energy (DAWE)
- Simulation platform for wind turbines
- Advanced modelling and control of doubly-fed induction generator system
- Stand-alone concepts for small wind turbines
- Simulation of wind farms
- Model for the interaction of distributed power systems
- Optimization of Electrical System for off-shore wind farms by a genetic algorithm approach
- Power Quality of Grid Connected Wind Turbines and their interaction with the grid
- Power converters for wind turbines

12

Section of Power Electronic Systems (Systems)

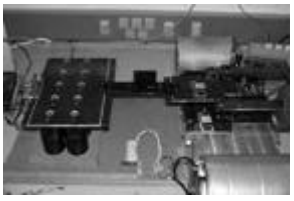
- Direct Power Electronic Conversion for ASD
- Segmented Electronic Motors
- Harmonic calculation on ASD
- Solution to reduce harmonics from power converters and grid at equipment and distribution level
- Single-phase motor control
- Low-cost and low-power motor drives
- EMC output filters for Adjustable Speed Drives

Section of Power Electronic Systems (Converters)



- Matrix-converter for ASD
- 3-level resonant converter for UPS
- Dynamic Voltage Restorer (10 kV)
- AC-module for PV
- Development of Product Platform of PV (1.5 kW)
- Optimized Design of PV-inverters (DC/DC/AC)
- Multilevel converters
- Sensorless control of active rectifiers

Power Electronic Systems (Components)



- IGBT-fuses
- Advanced cooling systems
- Life-time prediction of IGBT-modules
- Advanced modelling of IGBT's and diodes

15

Power Electronic Systems

Test Facilities

- Calorimetric measuring system (1,5 kW, 50 W)
- Advanced grid simulator / power supply(30 kVA)
- Power semiconductor test facilities (1,2 kV, 400 A)
- Acoustic and vibrational test room
- Advanced drives test system (up to 50 kW)
- High speed drive test system (up to 50000 rpm)
- Test system for iron losses (up to 20 kHz)
- Characterization system for PM and switched reluctance drives
- Test system for line conducted noise
- Dynamic Voltage Restorer (400 kVA, 10 kV)
- DSPACE drives lab.
- Fuel Cell Systems
- Renewable Energy Lab (PV)

16

Power Electronic Systems

- 2.75 MW DFIG
- Access to system
- Equipped with sensing equipment
- 6 km from Campus

1. Institute of Energy Technology

Danfoss A/S
Danfoss Drives A/S

Grundfos A/S

Axel Åkerman A/S

Elfor

Nesa A/S

Vestas Wind Systems A/S

Logimatic A/S

Mita-Teknik a/s

Cooper Bussmann

Eltra

Nordex

Sauer Danfoss

DEFU

B&O

APC

ABB Motors

Migatronic

Thrige Electric

Electrolux

PowerLynx

E2

Bonus Energy

2. DPGS in Denmark

- Wind power penetration increases
- Wind power replaces conventional power plants
- Power system operators issue new Grid Connection Requirements (GCR) for wind turbines
  - ? Grid control tasks
  - ? Ride through transient faults

2. DPGS in Denmark

- Production capacity in Denmark 2002
  - Central power plants: 7816 MW
  - Decentral power plants: 1769 MW
    - Owned by power plants: 749 MW
    - Not owned by power plants: 1020 MW
  - Windturbines: 2886 MW
    - Owned by power plants: 544 MW
    - Not owned by power plants: 2342 MW
  - Hydro power plants: 11 MW
    - Owned by power plants: 9 MW
    - Not owned by power plants: 2 MW
  - Other primary industry 397 MW
  - Total: 12.879 MW

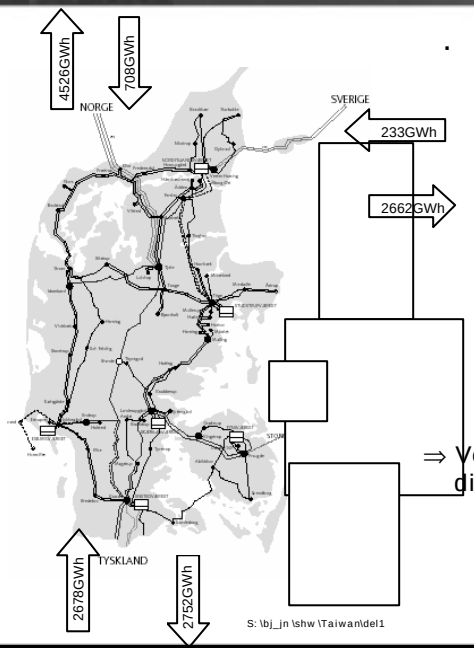
2. DPGS in Denmark

- The capacity of dispersed production units owned by the power plants 2002

2. DPGS in Denmark

- Production capacity and the production in the Eltra area ultimo 2003 (Jutland + Fyn)
  - Central power plants: 3.516 GW/16.161GWh
  - Decentral power plants: 1.567 GW/6.840GWh
  - Wind power: 2.374 GW/4.363GWh
  - Consumption: 21.043GWh
  - Export: 6.321GWh

2. DPGS in Denmark

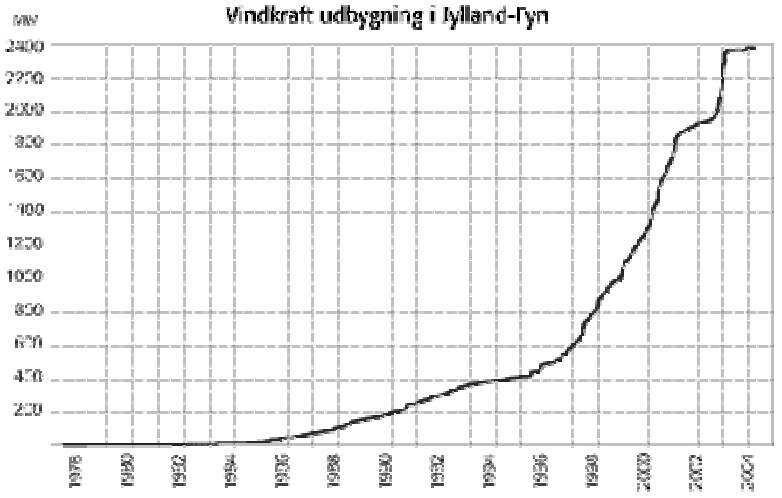


- Import export and max and minimum load (Eltra area)
  - Max load 3780 MW
  - Min load 1246 MW
  - Central power plants 3516 MW
  - Decental power plants 1567 MW
  - Wind power 2374 MW

⇒ Very high coverage of dispersed generation

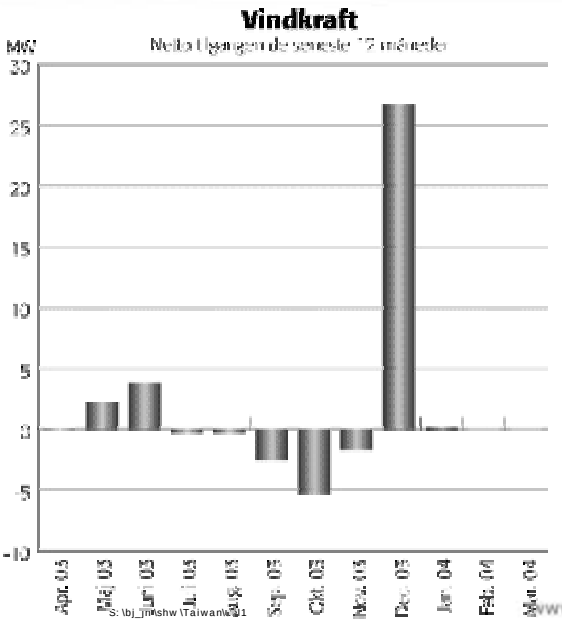
2. DPGS in Denmark

- Wind power development in Eltra area



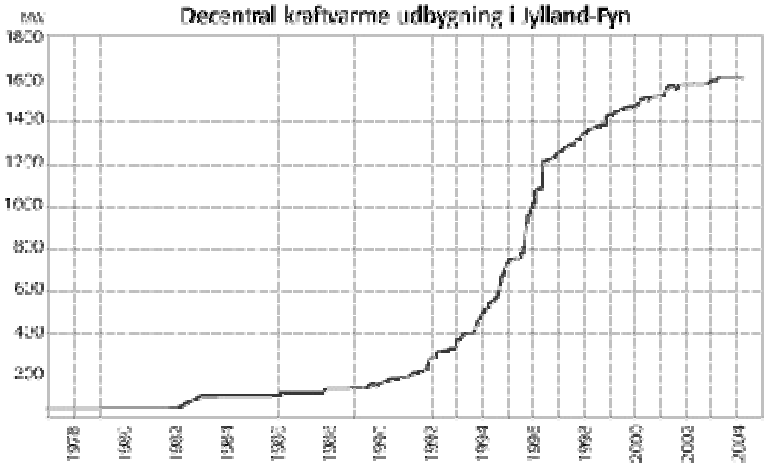
2. DPGS in Denmark

- Wind power development the last 12 months in the Eltra area



2. DPGS in Denmark

- Development in decentralized power plants in the Eltra area



- Now saturated (combined Heat Power)

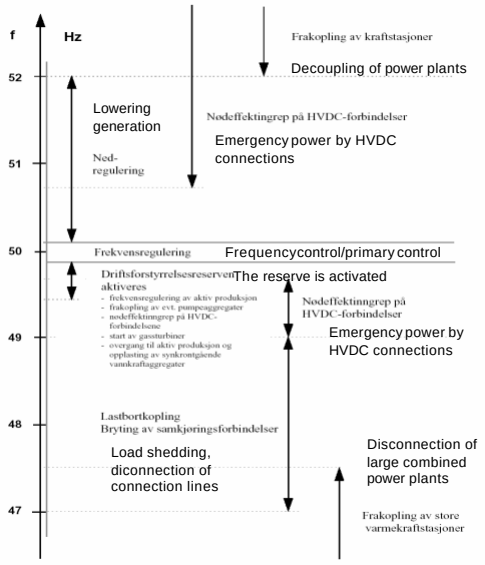
3. System demands

- Primary control:
  - Maintain the balance between generation and demand in the network using turbine speed governors
  - Automatic control to regulate the frequency within seconds
- Secondary control:
  - Secure import/export balancing with neighbouring areas with reserve generating capacities. Control within minutes
  - In case of a major frequency deviation in the control area to restore the frequency and to free capacity for the primary control
  - Can be manual or automatic
- Tertiary control:
  - Is automatic or manual change in the working points of generators in order to restore adequate secondary control reserve at the right time

3. System demands

- UCTE:
- Primary control
  - Maximum dead band ±10 mHz
  - 35-40 MW, ±200 mHz (30 sek)
  - Droop 2-8%
  - Re-established within 15 min.
- Secondary control
  - Start within 30 sec. Fully activated within 15 min.
- N-1 network security
- Ability to re-establish supply after black out

3. System demands



- NORDEL (Nordic countries)
  - Primary control
    - 0 MW in frequency control reserve (50,1 -49,9 Hz)
    - 192 MW in momentarily disturbance reserve (49,9 -49,5 Hz) 50% (5sek),100 % (30sek), HVDC emergency power,
    - Re-established within15 min.
  - Secondary control
    - Fast reserve 600 MW within 15 min

4. Grid connection requirements

- Purpose:
  - To ensure the properties essential for the power system operation as regards:
    - Security of supply
    - Reliability
    - Power quality
  - In the short as well as in the long run
- Two specifications:
  - Connection of wind turbines to the low-voltage and medium voltage network grid: DEFU KR-111 (recommendation). New hearing version is made as a draft (GCR for Wind turbines on a voltage level below 100 kV, Eltra 2003). The latter is only used here.
  - Specifications for connecting wind farms to the transmission network Eltra doc 74174 (in English translation Eltra doc 74557)

4. Grid connection requirements

- Specifications for connecting wind farms to the transmission network
- Topics:
  - Power and power control
    - Production control
    - Start up
  - Frequencies
  - Voltages
    - Reactive power compensation
    - Voltage quality
    - Temporary overvoltages
  - Interaction between power system and wind farm in case of faults in the power system
  - Protection
  - Communication to/from the wind farm
  - Verification and tests

4. Grid connection requirements

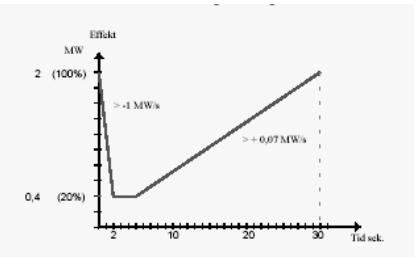
- Conditions at network grid faults:
  - The voltage at the wind turbines disappears
  - The reactive power increases drastically
  - The magnetisation cannot be kept
  - No electrical counter torque
  - Constant pitch angle turbines: the rotor accelerates and the wind turbine decouples due to over speed
  - Pitch angle controlled turbines: The rotor speed is controlled and the turbines is kept connected to the network grid
  - Setup, synchronization and MW-ramping
  - Time to discharge the capacitor banks before reconnection
  - Insurance of enough self supply to more following faults

4. Grid connection requirements

- Stability requirements:
- In all operational situations the wind farm shall be able to withstand the following fault sequences without being disconnected (does not apply to radial connected wind turbines):
  - Three-phase fault on a random line or transformer with definitive disconnection without any attempt at reclosing.
    - T=0 3-phase short circuit
    - T=100 ms typical disconnection of the fault
  - Two-phase fault on a random line with unsuccessful reclosing
    - T=0 2-phase short circuit
    - T=100-150 ms Typical disconnection of fault and the line
    - T=400-450 ms automatic reclosing
    - T=500-950 ms disconnection of the fault
  - Withstand 3 faults within 2 minutes
  - Withstand 6 faults if delay between faults are 5 minutes

4. Grid connection requirements

- Power control
  - Production limit control both on transmission and distribution
    - Controlled by one single setpoint signal
    - 1 minutes average should not exceed setpoint more than 5% of wind farm power rating
    - For passive stall turbines on the distribution level, the power can be controlled cut in and cut out of single turbines
  - Reduction below 20% of maximum power in less than 2s on transmission level
  - Automatic power control after faults up to full power reduction or increase within 30s on transmission level



4. Grid connection requirements

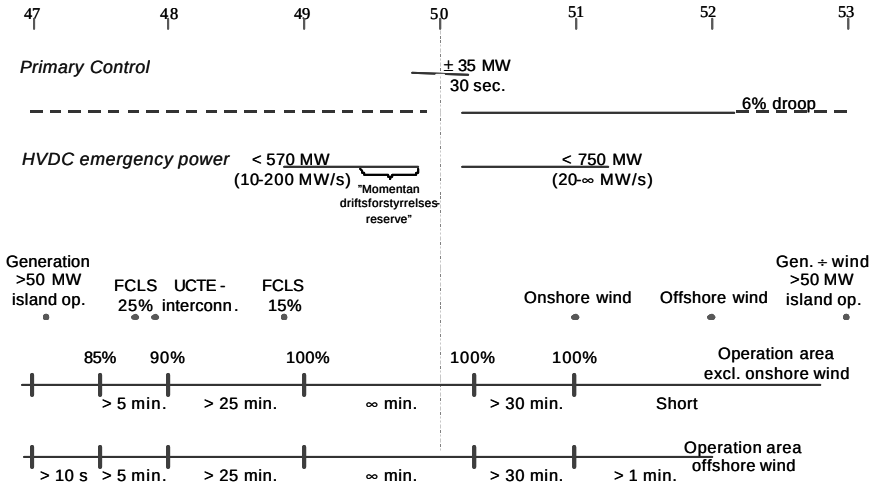
- Frequency at transmission level :

Underfrequencies	At frequencies below 47 Hz disconnection must take place after 0.3 s At frequencies below 47.5 Hz disconnection is allowed after 10 s At least 5 min opration at frequencies between 47.5 and 48 Hz At least 25 min operation at frequencies between 48 and 49 Hz No constraints at underfrequencies above 49 Hz
Overfrequencies	At frequencies above 53 Hz disconnection must take place after 0.3s At least 1 min operation between 51 and 53 Hz At least 30 min operation between 50.3 and 51 Hz No constraints at overfrequencies below 50.3 Hz

- Frequency at distribution level
  - No frequency control
  - Wind turbine shall disconnect if system frequency is below 47 Hz or above 51 Hz, with a delay time of 200 ms

4. Grid connection requirements

System response at frequency deviations



4. Grid connection requirements

- Reactive power compensation transmission level:
  - ? $Q_{diff} \leq 10\% P_{max}$
  - ? If over dimensioned compensation units or the windfarm is connected through an HVDC-link, the reactive power control should be made available for the grid operator for central voltage control.
- Voltages:
  - ? Transmission network

Voltage	Max voltage	Variations	Normal voltages	Full load area
150 kV	170 kV	122-170 kV	165-169 kV	146-170 kV
400 kV	420 kV	360-420 kV	415-420 kV	360-420 kV

  - ? If voltage is above 1.2 p.u., voltage reduction should start within 100 ms.

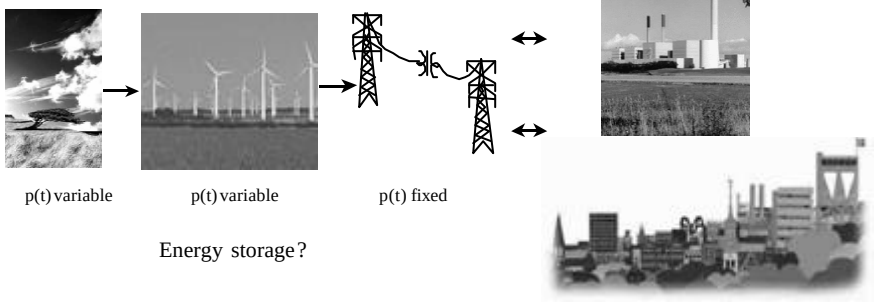
5. New issues in Denmark

- Large scale integration been possible by
  - Strong grid
  - Strong interconnection
  - Demands to DPGS
- 17% of all electricity covered by wind (2004)
- Much higher % covered by dispersed generation (small CHP)
- Two new 200 MW off-shore wind farms being planned (2006, 2007)
- Even more ambitious discussions (>50% from renewable)
- Dispersed generation system may become upgraded
- Wind turbine technology even more efficient + new methods for interconnections
- New transmission + line utility (National)
- Projects are initiated to determine maximum possible wind energy penetration in Danish System
- Projects initiated with cell – like structure of the grid (bi-directional)

6. Basic Principle of Wind Energy Conversion

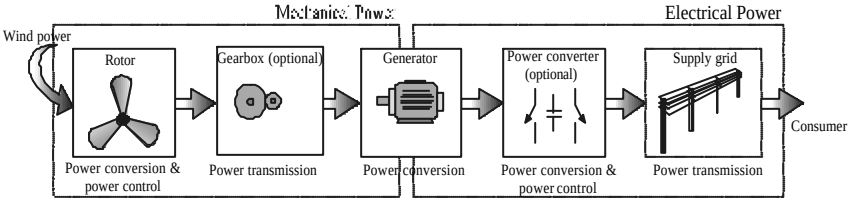
Basic Energy System:

Problems to be solved



Short-term solution - Long-term solution

Wind power conversion:



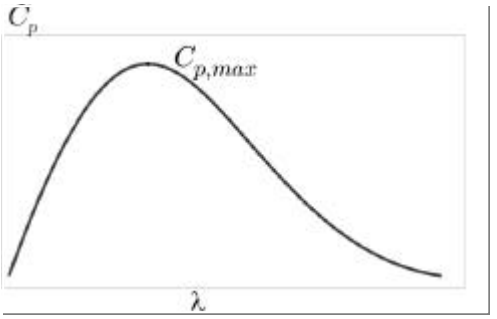
Key technology

Power curve - Aerodynamic

➢Power to the generator- shaft is given by:

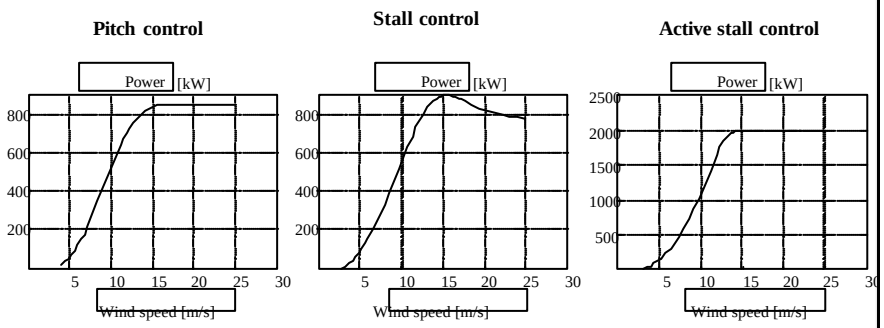
$$P_{tur} = \frac{1}{2} C_p \rho A_v v_{wind}^3$$

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



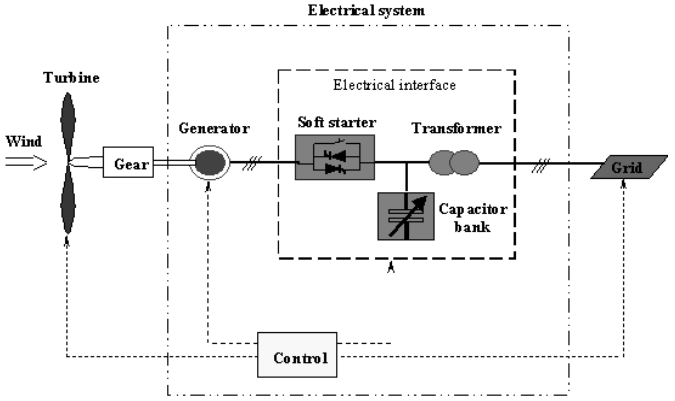
= ratio between tip-speed and wind speed

Power Control



Power curves from different wind turbines

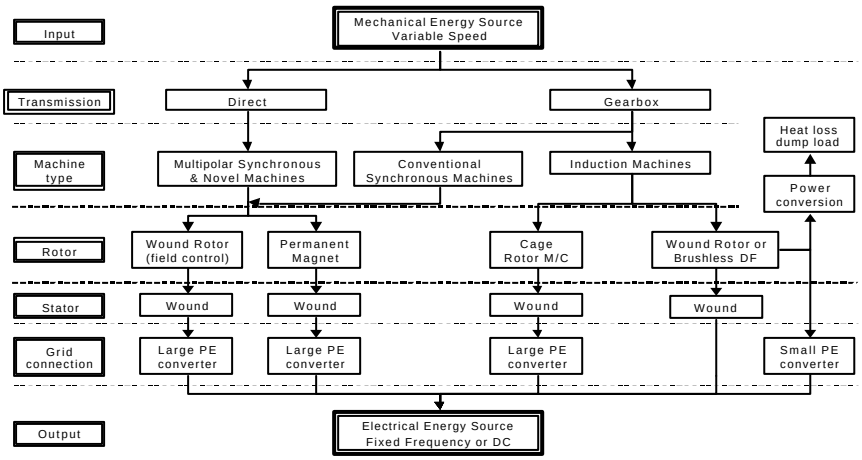
Topology for wind turbine (Danish Concept)



- **Fixed speed with capacitor bank**

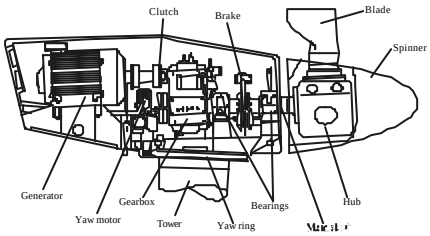
6. Basic Principle Wind Energy Conversion

Variable speed (Road map)



6. Basic Principle Wind Energy Conversion

Nacelle in wind turbine



Vestas V80-2 MW

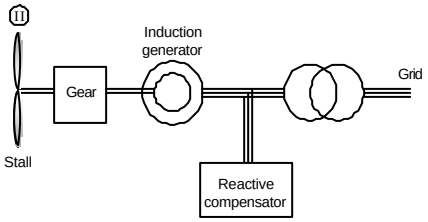
- **Example of technology**

7. Wind Turbine Configurations

Two-generator principle (exists in many systems): (System II)

- **Shift between number of poles**
  - **"Variable speed with 1 bit resolution"**
  - **No reduction in mechanical load**
  - **No reduction in power pulsations to the grid**

Poles	50 Hz grid (rpm)
2	3000
4	1500
6	1000
8	750
10	600
12	500

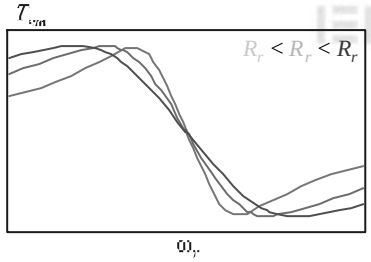


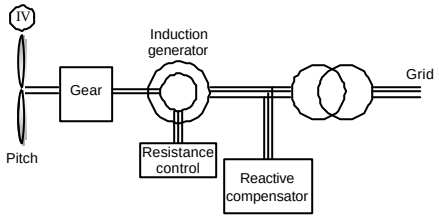
Institute of ENERGY TECHNOLOGY

7. Wind Turbine Configurations

Rotor resistance control (System IV):

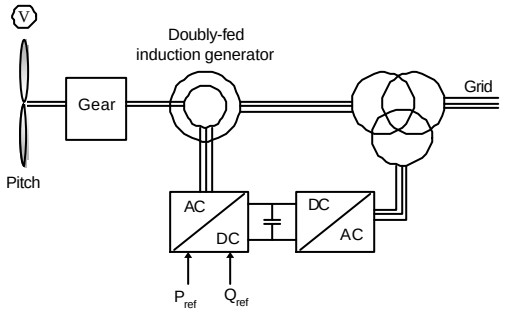
- **Higher speed range**
- **Lower mechanical stress**
- **Less grid pulsations**
- **Improvement in Optislip (no rings)**
- **Still reactive power compensation**
- **Use basically slip-rings**
- **Speed range still limited to 5-10 % of nominal speed (above synchronous speed)**
- **Higher power losses in the rotor**





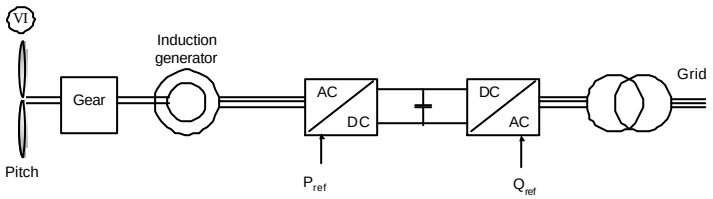
Doubly-fed induction generator - wounded rotor (System V)

- Limited speed range (-20% 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



Induction generator - Squirrel cage rotor (System VI)

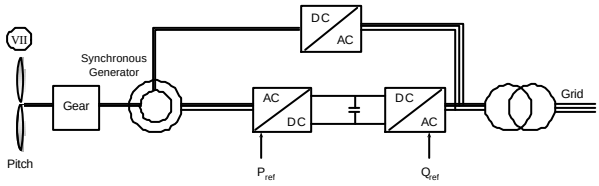
- Full speed range
- No brushes on the generator
- Complete control of active og reactive power
- Proven technology
- Full-scale power converter
- Need for a gear



49

Synchronous generator - External magnetized (System VII)

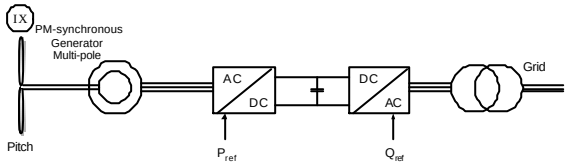
- Full speed range
- Possible to avoid gear (multi-pole generator)
- Complete control of active and reactive power
- Small converter for field
- Need of slip-rings
- Full scale power converter
- Multi-pole generator may be big and heavy



50

Synchronous generator - Permanent magnets (System IX)

- 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



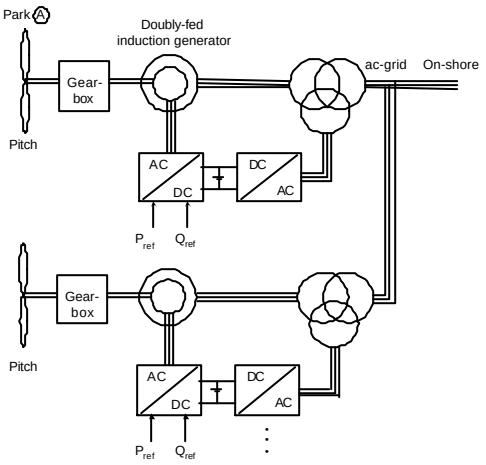
7. Wind Turbine Configuration

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**

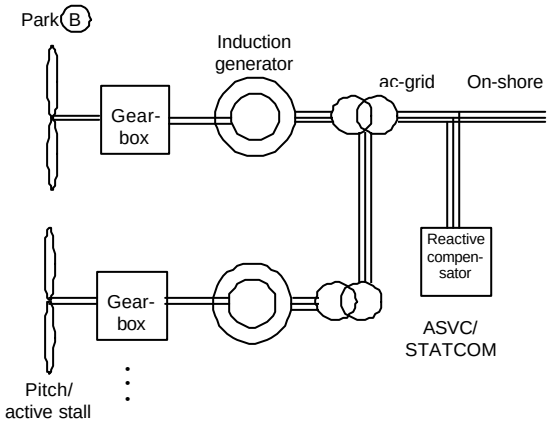
7. Wind Turbine Configuration

Doubly-fed System Park



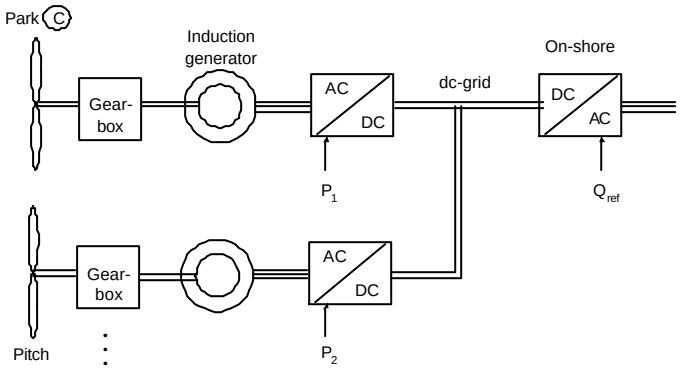
System A

Induction generator Park



System B

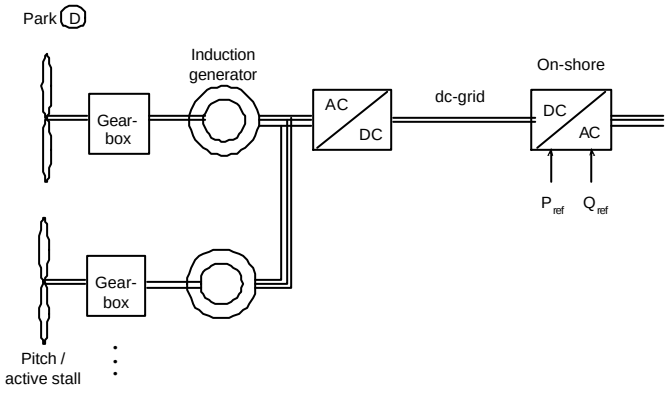
Common dc-grid Park



System C

7. Wind Turbine Configuration

Common dc-grid Park



System D

7. Wind Turbine Configuration

Comparison Park Systems

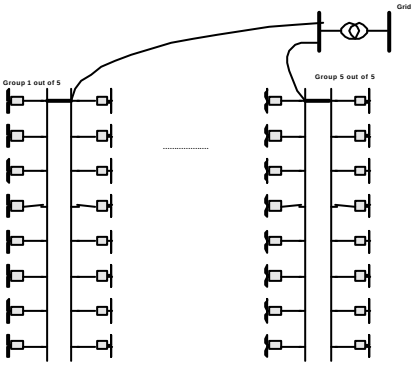
Comparison of Wind Farms

Farm configuration (Fig. 12)	A	B	C	D
Individual speed control	Yes	No	Yes	No
Control active power electronically	Yes	No	Yes	Yes
Control reactive power	Yes	Centralized	Yes	Yes
Short circuit (active)	Partly	Partly	Yes	Yes
Short circuit power	Contribute	Contribute	No	No
Control bandwidth	10-100 ms	200ms - 2s	10 -100 ms	10 ms – 10 s
Standby-function	Yes	No	Yes	Yes
Softstarter needed	No	Yes	No	No
Rolling capacity on grid	Yes	Partly	Yes	Yes
Redundancy	Yes	Yes	No	No
Investment	+	++	+	+
Maintenance	+	++	+	+

7. Wind Turbine Configuration

Wind Power station example

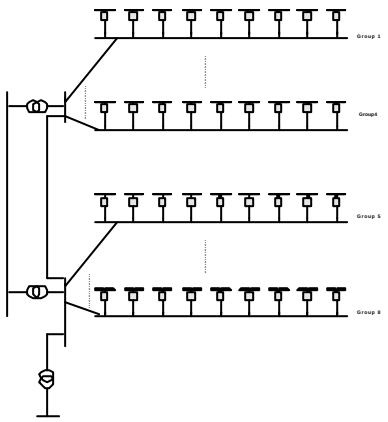
160 MW Windfarm (in operation)



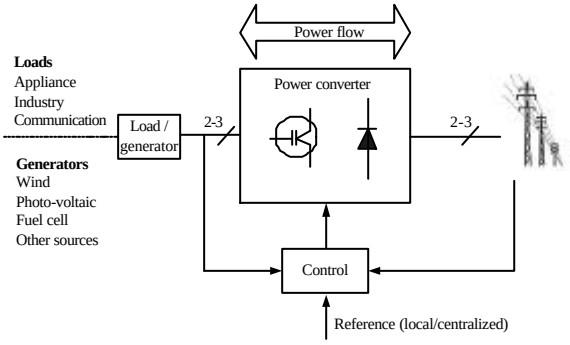
- Doubly-fed induction generator system with pitch
- Horns Rev, Denmark

7. Wind Turbine Configuration

Wind Power Station **160 MW Windfarm (in operation)**

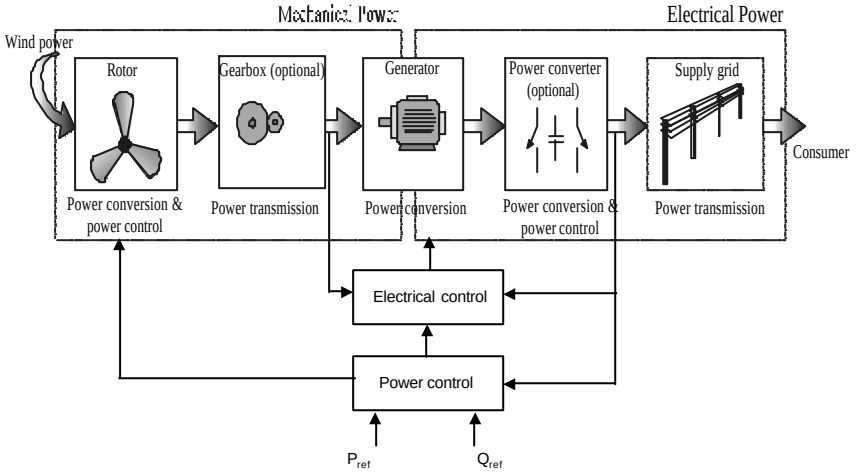


- Two-speed wind turbine system with Active stall
- Rødsand, Denmark



- **Control active and reactive power (frequency and voltage)**
- **Smooth connection to grid**
- **Ride-through during voltage dips**
- **Robustness in general**

Control of wind turbine :



Demands to wind turbine:

Electrical:

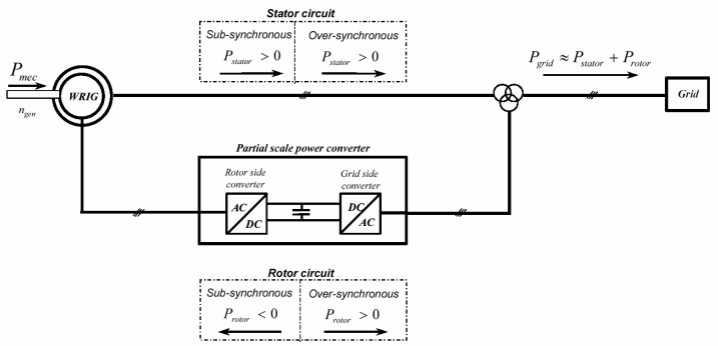
- Interconnection (conversion, synchronization)
- Overload protection
- Active and reactive power control

Mechanical:

- Power limitation (pitch)
- Maximum energy capture
- Speed limitation/control
- Reduce acoustical noise

Control loops with different bandwidth

Basic power flow



$$s = \frac{n_{syn} - n_{gen}}{n_{syn}}$$

$$P_{rotor} \approx -s\, P_{stator}$$

$$P_{stator} \approx P_{grid} / (1 - s)$$

8. Wind Turbine Control

Control structure

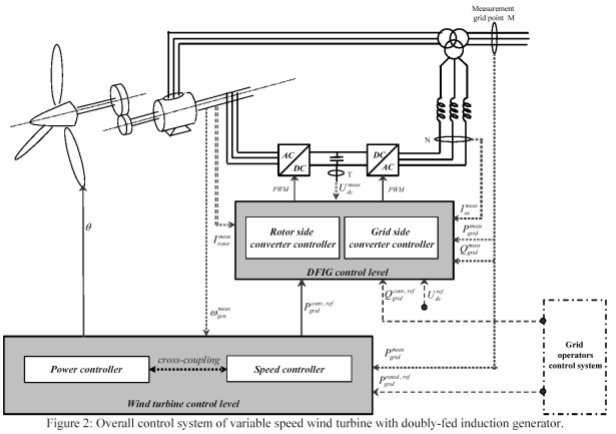
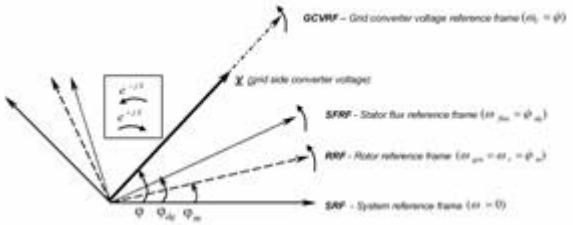
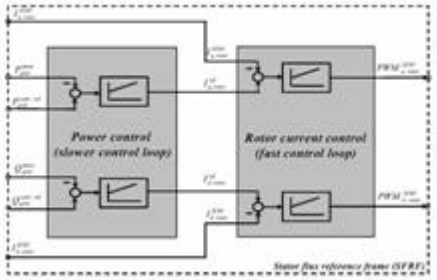


Figure 2: Overall control system of variable speed wind turbine with doubly-fed induction generator.

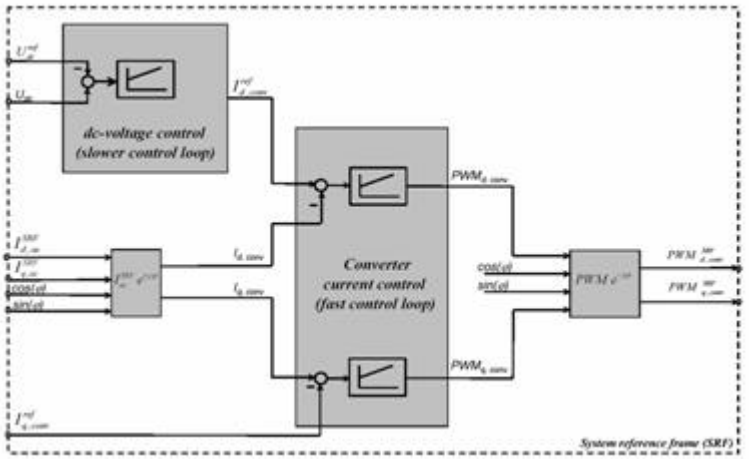
8. Wind Turbine Control

Generator control



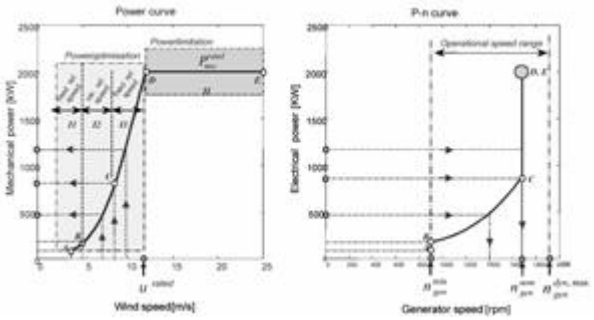


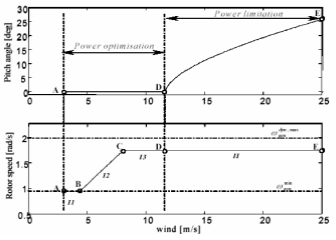
8. Wind Turbine Control



8. Wind Turbine Control

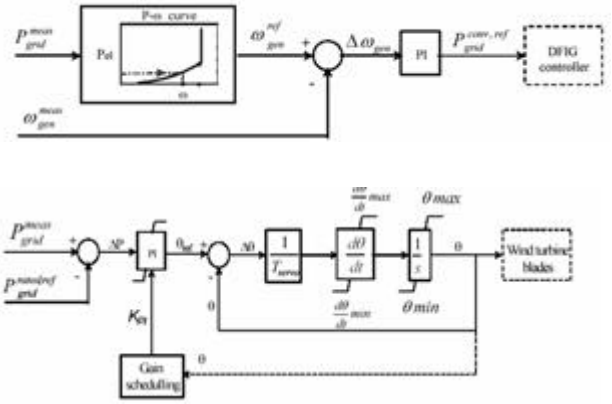
Operation





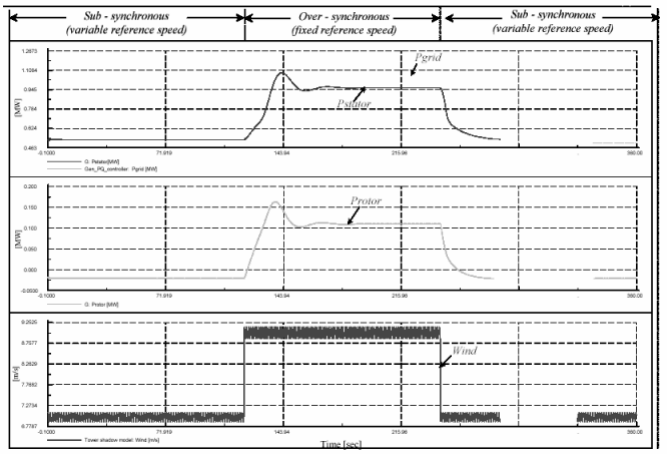
8. Wind Turbine Control

Pitch control



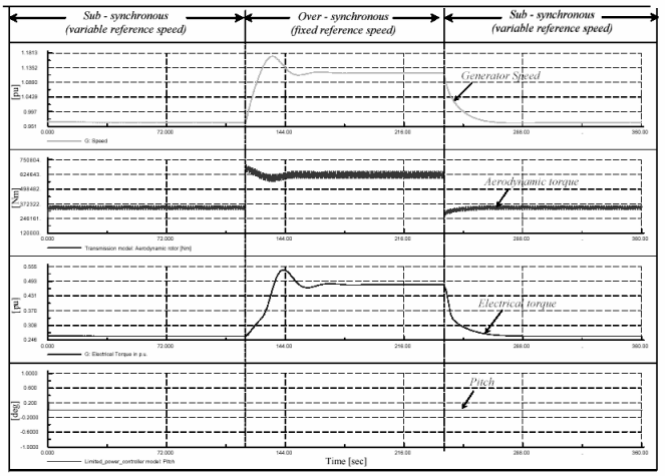
8. Wind Turbine Control

Simulation results



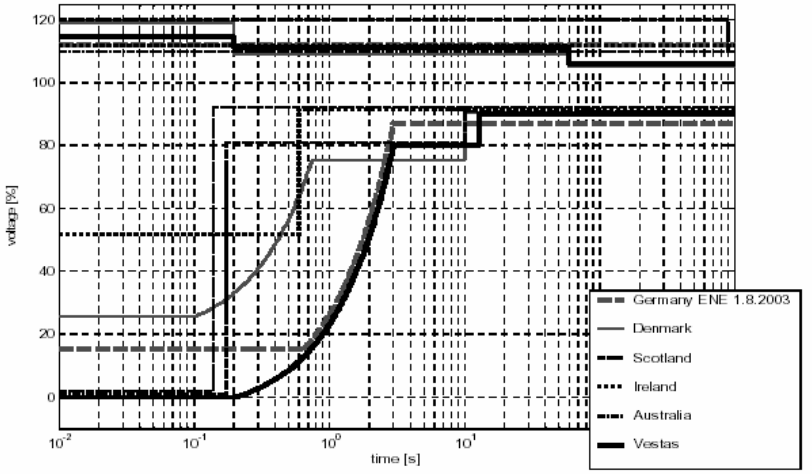
8. Wind Turbine Control

Simulation results



8. Wind Turbine Control

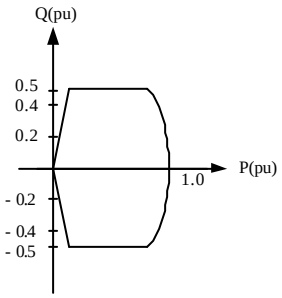
Grid codes for different countries

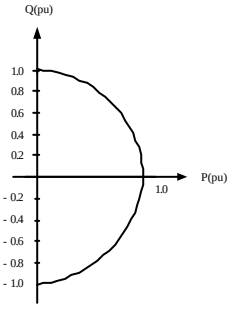


- **Sustain serious voltage dips**
- **Protection**

8. Wind Turbine Control

Static PQ-curves





- Doubly-fed induction generator system

- Full-scale power converter

- **Act as an active part in power system**
- **Idealized curves (dependent on voltage)**

9. Conclusion

- **Wind Turbine technology steadily more efficient**
- **Key-drivers**
  - **Turbine cost**
  - **Maintenance**
  - **Availability/reliability**
  - **Energy production**
- **Power electronics now a key technology (interconnection mechanical/electrical)**
  - **From energy to power source**
- **New concepts can come**
- **Still grow in size**
- **Many challenging research topics**
- **The technology can be used in all kind of dispersed generation systems**