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INTERNATIONAL ENERGY AGENCY

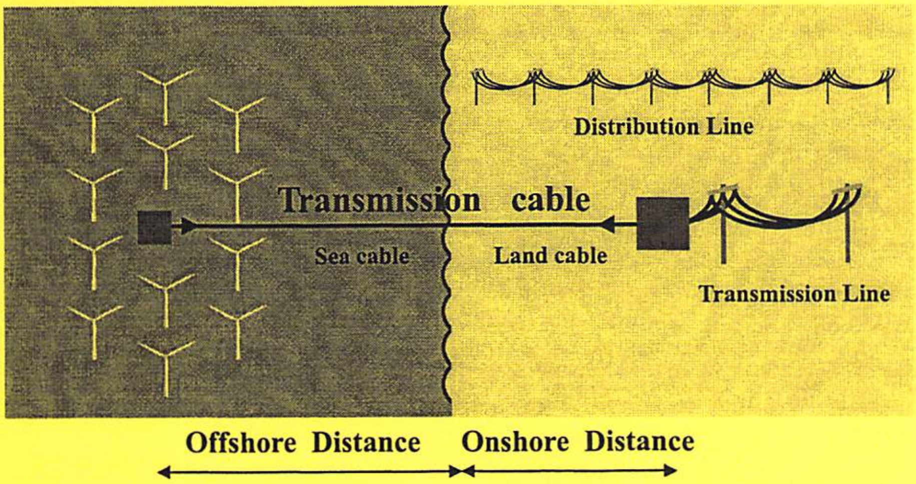
Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems
ANNEX XI

36th IEA Topical Expert Meeting

Large Scale Integration into the Grid

Newcastle, November 2001

Organised by: ETSU



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CONTENT

Annex XI

IEA SYMPOSIUM ON LARGE SCALE INTEGRATION INTO THE GRID

INTRODUCTORY NOTE

Guy Nicholson, Econnect
With comments from Thomas Ackermann and John Olav Giæver Tande

Wind power penetration is increasing in many grid systems world-wide. In some areas in Europe, e.g. Northern Germany or Denmark, wind power supplies already more than 10 % of the yearly average demand. Hence, during times with high wind speeds and low loads (night), the wind power penetration can be well above 50 % in some network areas.

As wind power penetration increases also in other areas of the world, e.g. Spain, Texas or California, the influence of large wind power penetration becomes more and more of an international interest. The Danish and German experiences thereby provide valuable information, however, it has to be discusses how those experiences can be transferred to other network configurations.

In addition, a new challenge is the integration of large wind farms into the grid. At present, the largest wind farms have a power output of 50 MW to about 150 MW. In the U.S. and Europe wind farms with a power output of well over 150 MW are currently planned. In Europe, for example, large offshore wind farms with a total installed capacity of up to 1000 MW are investigated and in the US, particularly on the West Cost and along the Great Plains, project of more than 500 MW will soon be installed.

The issues that lie ahead are:

Technical aspects:

- How can high capacity links (500 MW to 1000 MW) from wind farms to the grid be created?
- Under what circumstances are high voltage DC links needed?
- How can the varying output power be taken into the grid?
- What are the limits with short term forecasting techniques?
- Is load management a possibility to match supply and demand?
- Is it possible to make grids more intelligent?
- What IT solutions already exist to operate grids more intelligent?
- What is the state of the art of HVDC links and how will it develop in the future?

Economic aspects:

- What are the interconnection line costs, e.g. what is the (future) cost per km of a 500 MW HV AC line, likewise for a 1000 MW HVDC line?
- How will program responsibility affect the structure and price of power purchase contracts?
- How to integrate wind power into competitive market structure, e.g. how to design a balance market with a large about of wind power in the system?
- Who will bear the costs of interconnection lines. Is there a regulatory framework for the attribution of costs?

Target audience: utilities that connect and/or generate, IPP's that generate, big developers wind turbine manufacturers. It is the suggested intention of this meeting to:

- clarify the status of large-scale integration techniques and assessment methods
- identify need for future R&D and appropriate scope for IEA action

E-connect

There are significant differences between the many grid systems including: the overall size of the total interconnected a.c. system, the size and penetration within different interconnected regions of the network (e.g. Denmark); the mix, types and flexibility of other plant on the network; and (of increasing significance) the organisational and market structure of the system, especially with growing liberalisation of markets.

The wind power contribution in a regional grid can comprise many small projects at one extreme, to one very large project at the other. There are also different wind turbine generation technologies, which impact on grids: e.g. generator types (induction, inverter and doubly fed) and turbine type (stall / pitch regulated & variable / fixed speed). There are questions of how, when and whether to model these variations and sometimes how the confidential data for the accurate modelling can be accessed.

The effects of any wind project will comprise those on the local network and those on the larger region or total system. The local issues are typically: thermal issues from reversing normal power flows, steady state voltage regulation; step voltage changes and flicker; prospective short circuit current and equipment ratings and protection system and settings. The system issues are generally scheduling and despatch, system security, frequency and voltage response.

The approach to protection settings and islanding are vary different for operators with a very small amount of wind power who want the plant off for virtually any fault, compared to those with significant wind penetration who must ensure that the wind plant can ride through faults and operate in an island with other plant. Concern is rising with regard voltage recovery of large numbers of induction machines following a fault on the grid causing a significant voltage dip.

As wind power penetrations rise, its role in the provision of services such as frequency response and voltage control are being debated. In some networks these roles are simply imposed on or allocated to other plant. In some networks the wind plant operators must seek a derogation from supplying these services, particularly for larger projects. In other networks ancillary services markets are being set up and wind plant operators must ask if they should participate and if so when and how often and decide on the turbines and /or ancillary equipment to make this cost effective.

Large scale integration of wind power

John Olav Giæver Tande
SINTEF Energy Research, Norway

What is large scale integration?

- Grid connection of large wind farms ranging from some tens to hundreds of MW
- Wind farms supplying a significant portion of the area load

Topics of large scale integration

- Assessment methods
  - voltage quality (load-flow, dynamic, IEC61400-21)
  - stability (contingencies)
  - grid losses
  - reliability
  - system operation
- Integration techniques
  - grid connection (AC/DC, SVC, FACTS, VCU etc)
  - system operation (forecast, AGC, IEC61400-25)
- Isolated systems?
- Regulatory framework?

IRISH ENERGY CENTRE
RENEWABLE ENERGY INFORMATION OFFICE

Large Scale Penetration of Wind Energy : The Challenges in Ireland

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IEA R&D Wind Annex XI

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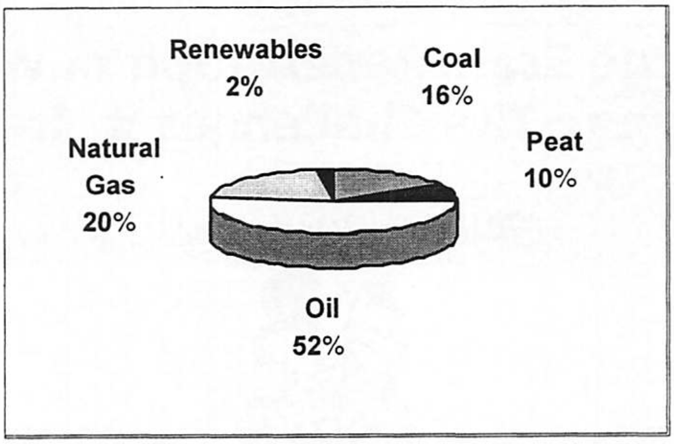
November 6/7 2001

Challenges to Increasing Wind Energy Penetration

- Geographic Concentration
- The Electrical Grid Infrastructure
- Technical Compliance of Wind Farms with Grid Code
- The Costs (Controllability, HVDC Links, Constraining Off)

Ireland's Energy Supply Situation - Only 2 % Renewable



Ireland spends some £ 5,000 Million every year on energy

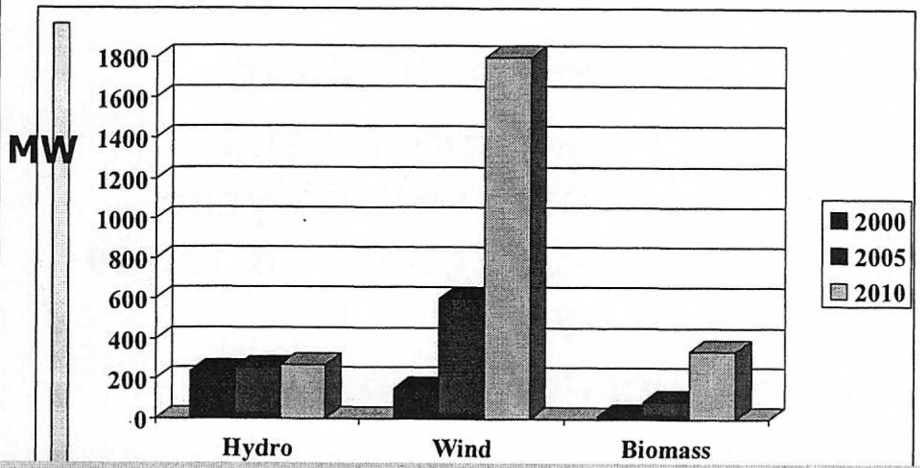
% of Energy Produced from Renewables in the EU

		1990	1995
Above EU Average	Sweden	24.7	25.4
	Austria	22.1	24.3
	Finland	18.9	21.3
	Portugal	17.6	15.7
	Greece	7.1	7.3
	Denmark	6.3	7.3
	France	6.4	7.1
	Spain	6.7	5.7
	Italy	5.3	5.5
Below EU Average	Ireland	1.6	2.0
	Germany	1.7	1.8
	Luxembourg	1.3	1.4
	Netherlands	1.3	1.4
	Belgium	1.0	1.0
	United Kingdom	0.5	0.7
[Average for]	**European Union**	**5.0**	**5.3**

Source: EUROSTAT

Ireland - well below the EU average

Irish RE Electricity Targets to 2005 & Projections to 2010



12 % of Irish Electricity from Renewables by 2005
25 to 30% Possible by 2010

Large Practical Wind Energy Resource

Wind	Resource MW	Resource TWh	Developed MW	Developed TWh	Cost Pence/kWh
Onshore	1,500	*4*	125	*0.4*	2 - 5
Offshore	3,000	*9*			4 - 12
Total	**4,500**	***13***	**125**	***0.4***	**2 – 12**
Coal/Gas					2 – 4

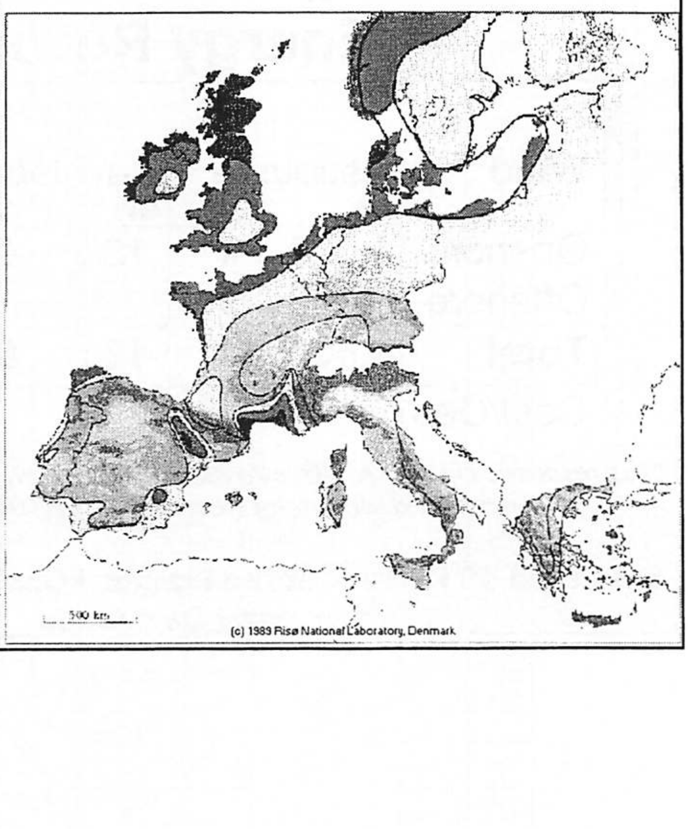
This resource is large relative to our total Irish electrical capacity, and our projected electricity needs of 35 TWh/year by 2010.

Less than 10 Percent of the Practical Onshore Resource is Currently Developed

Challenge 1: Lack of Geographic Dispersion of Wind Farms

- Nature: On and Offshore
- Policy: Competitive Tender Based System with 15 year PPAs - AER 5 Tender Currently Under Way
- Planning Permissions

Ireland's Vast Wind Energy Resource - the Best in Europe

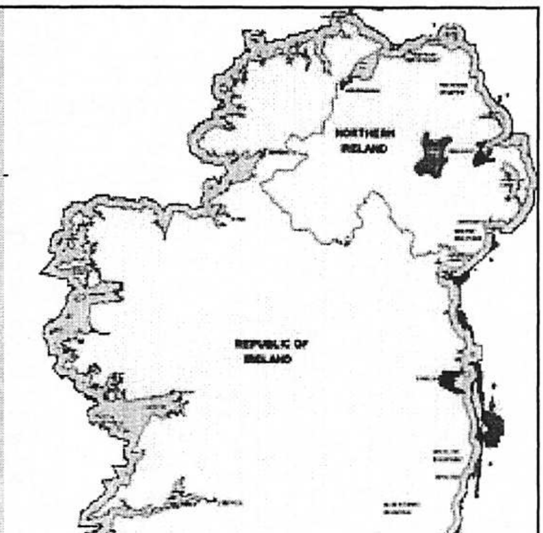


21 Wind Farms Now Operational in Ireland

125 MW

Producing 0.4 TWh/yr

Offshore Wind Farms: Areas of Interest (>2,000 MW) Shallow Sand Banks off the East Coast



Latest Government Support Scheme (AER 5, 2001)

- Competitive Tender System – 240 MW on offer
- Price Cap 4.8 ?c/kWh based on AER 3 pricing
- Only Viable for the Very Best, Most Exposed, Sites - Wind speed must be above 8.75 m/s at 50m to achieve a viable project
- 'Fortunate sites' e.g. very close to the grid, may be possible at 8.5 m/s
- Generally – Western, Coastal Regions

Feed In Prices Vs Tenders

	Country	Installed end of 2000 (MW)	Expansion in 2000 (MW)
Countries with Feed in Prices	Germany	5,432	989
	Spain	2,099	557
	Denmark	2,016	245
	Total	**9,547**	**1,791**
Countries with Tenders	UK	391	38
	Ireland	105	32
	France	41	19
	Total	**525**	**89**

The UK & France Have Now Abandoned the Tender System for Onshore Wind Energy

Analysis of The Current Wind Energy Situation

With Planning	379
In Planning	569
Under Appeal	102
Potential AER 5	1050
Free Market Share	310

Operational	125
In Construction	15

Government Targets of 600 MW by 2005 Could be Exceeded by 2003

Challenge 2: Electrical Grid Infrastructure

- **Ireland is relatively sparsely populated with population concentrated in East and South**
- **Many remote areas with potential for wind farms have relatively weak grid**
- **Capacity on East coast for generation from Large Wind Farms?**
- **Plan for Large or Small wind farms**
- **An Island (with interconnectors)**

Some Help?

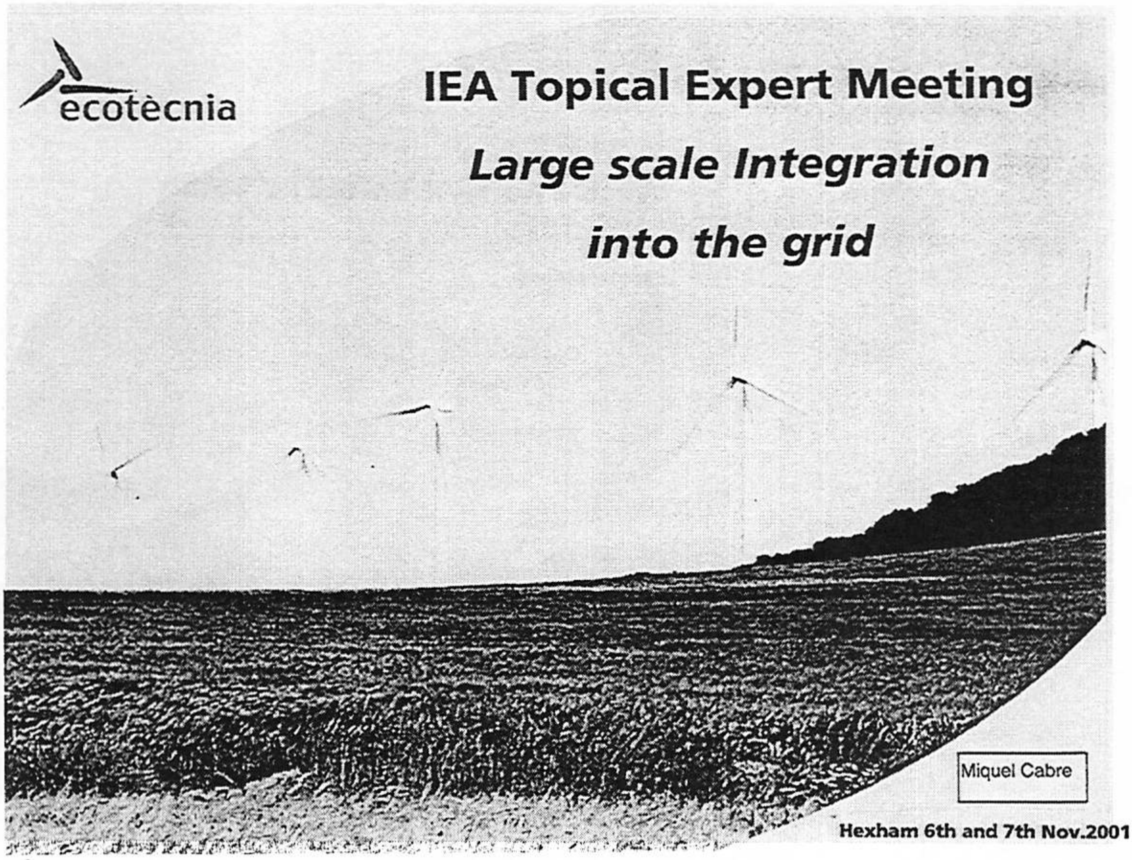
- 2.5 Billion Euro Grid Infrastructure Upgrade underway
- £ 40 Million for Small Scale RES Grid Access Support Proposed
- Study on Wind Energy Penetration
- Wind Forecasting
- Increased Controllability and Dispatching of Wind Farms

Challenge 3: Connection to the Grid

- Technical requirements for a single wind farm: Grid Code Compliance
- Effect of increasing penetration –more stringent code, or compliance
- Fault Ride-through capability of Wind Turbines/Farms
- New Technology – and its cost

Challenge 4: Economics of Increasing Penetration

- **HVDC Links for connection of remote/offshore areas**
- **Increasing sophistication of technology for control, generation, switching or protection**
- **Constraining off – Idle Wind Turbines?**
- **As penetration levels and installed capacity increases – incremental costs (or all costs) may rise.**
- **Export?**



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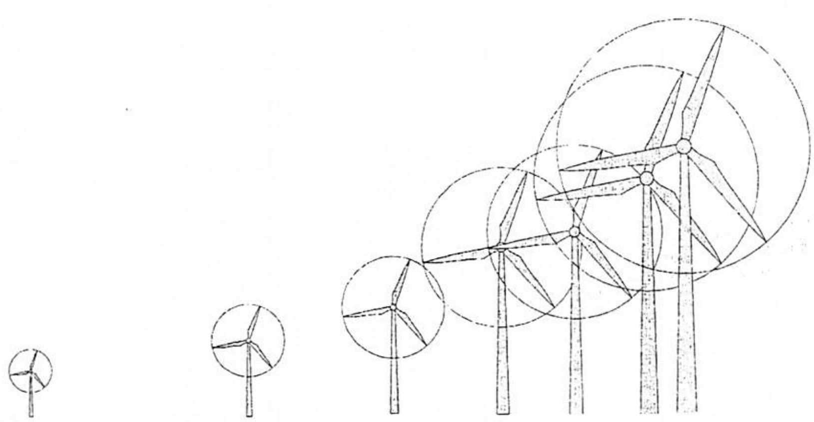
Technology developments



Year	1984	1989	1993	1996	1998	2001	2002
Power (kW)	30	150	225	640	750	1250	1600

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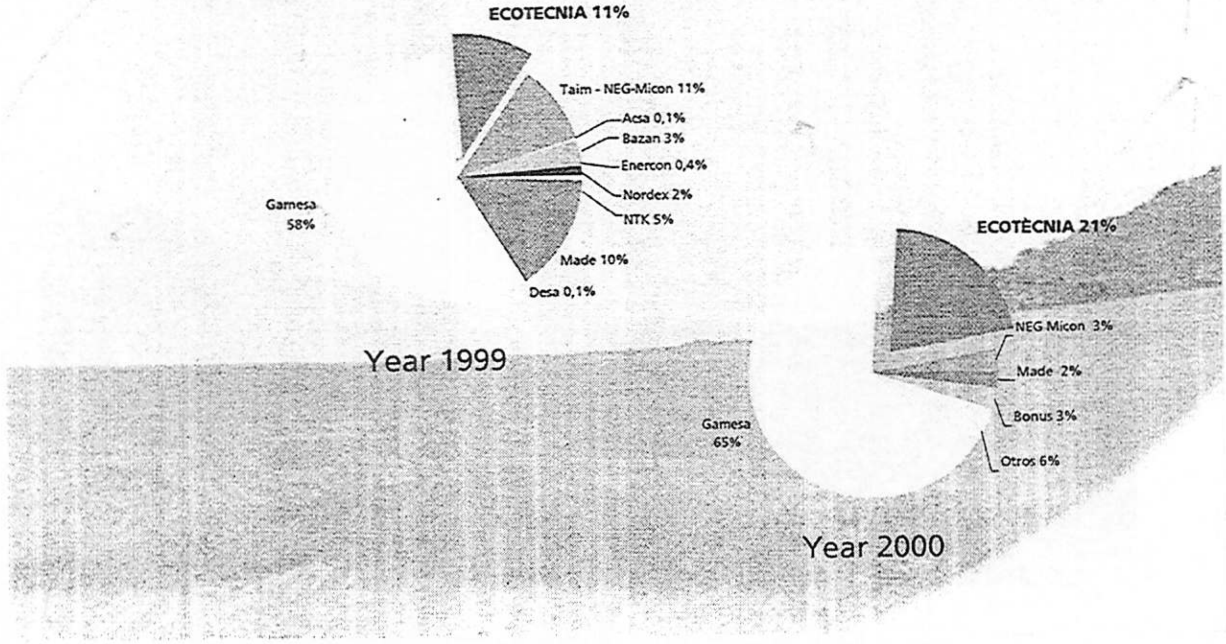
Wind Energy Market in Spain



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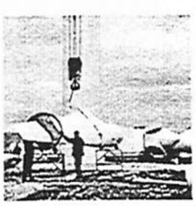
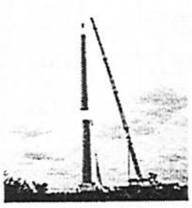
ECOTÈCNIA's Wind Energy in Spain

	Units	MW
ECOTECNIA 150	79	12
ECOTECNIA 225	146	33
ECOTECNIA 640	181	116
ECOTECNIA 750	395	297
ECOTECNIA 1250	1	1
	802	459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Integration into the grid

Aspects to take into account

1. Energy Quality
    - Harmonics
    - Flicker

2. Energy Control
    - Active power limitation
    - Control of reactive power

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Optimising the integration into the grid

The Wind Farm as an unit of energy generation and control

1. NOVOgrid Project

    Demonstrate the wind energy capacity for participating in grid control.

Key aspects:

- Optimise cos φ required by the utility, using the wind turbines capabilities and controlling the capacitor banks.
- To develop the capability of controlling the generated power of the wind farm in emergency cases.

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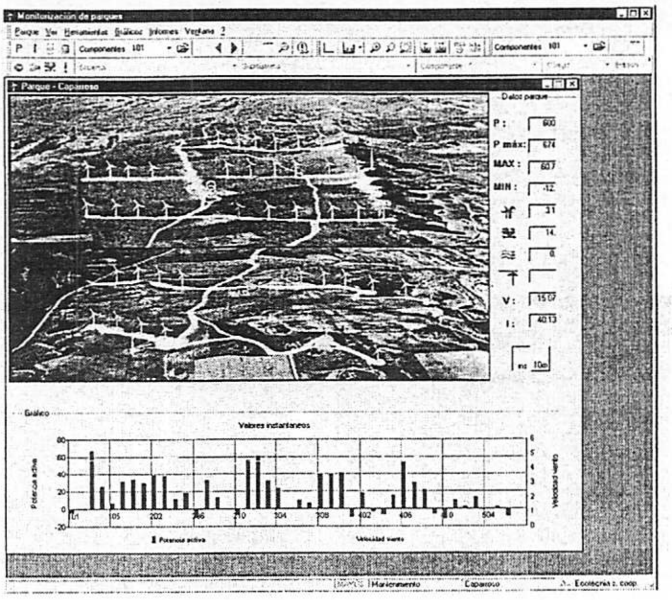
ARGOS: Monitoring the Wind Farm and optimising the integration into the grid



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Integration into the grid: the Spanish case

First Step Penetration limits

- 50 % of Transformer Nominal Power when connecting to a Substation
- 50 % of the capacity when connecting to a High Voltage line

Attribution of costs

- 100 % of the total costs are assumed by the wind farm promoters

The future: Working on developing new techniques for short term forecast

Large scale wind power in the Nordic electricity system

Hannele Holttinen, VTT Energy, Finland

- Results of simulations for the Nordic countries:
  - 4...25 % wind in the hydro-thermal electricity system of Scandinavia
  - What does wind power production replace in the system? CO_2 abatement of wind power?
  - Value of wind power to the electricity market
  - Effects to the system in weekly level: hydro, exchange between the areas
- First results of hourly time series analysis
  - Hourly time series for year 2000
  - How much variations smooth out?
  - How much wind power increase the variations seen by the rest of the electricity system (net load variations vs load variations) ?

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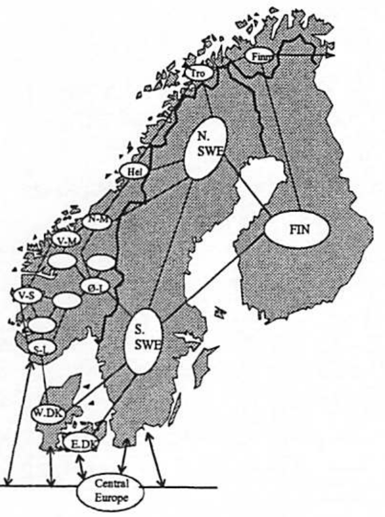
EMPS input for the areas



- Weekly electricity consumption:
  - Division of the week into 4 stages with high/low consumption
- Thermal system:
  - maximum production capacity (MW or GWh/week), operating costs and availability.
- Hydro power:
  - inflow series (30 years of weekly data), also wind production series
  - max power, reservoir size, coupling between the power stations, restrictions.
- Transmission between the areas:
  - MW, price difference before use, losses

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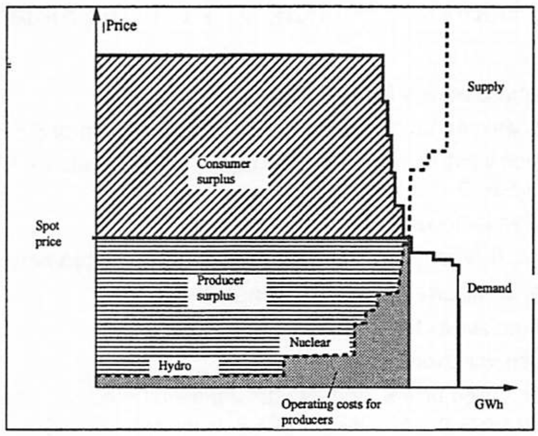
Spot price formation. Market cross.



- Wind will come to the market as a price taker, with 0 marginal cost

Simulated cases

- Reference simulations “ref2000” and “ref2010”:
  - today's electricity system “ref2000”
  - a scenario for 2010 electricity system with CO_2 tax and reduced power surplus (consumption added more than production capacity)“ref2010”
- Increasing wind production in the system, cases “wind1-2-3”:
  - 16-31-46 TWh/a, 4-8-12 % of electricity consumption. Wind1 corresponds to existing targets for 2010, Wind3 is near possible targets for 2030

	Ref.	Wind1			Wind2			Wind3		
	TWh/a	MW	TWh/a	%*	MW	TWh/a	%*	MW	TWh/a	%*
Norge	0	1000	3	2.5 %	2000	6	5.0 %	3000	9	7.5 %
Sverige	0	1500	4	2.8 %	3500	9	6.3 %	5300	14	9.9 %
Finland	0	450	1	1.3 %	1800	4	5.1 %	3100	7	8.9 %
Denmark	3.5	3900	8	22.9 %	5200	12	34.3 %	6500	16	45.7 %
TOTAL	3.5	6750	16	4.3 %	12500	31	8.2 %	17900	46	12.2 %

*Wind production as % of consumption today

Input to EMPS model

	Fin	Swe	Den	Nor	Eur
Consumption	78800	142400	34900	120000	567100
[GWh/a]	**90500**	**152300**	**37000**	**121900**	
Nuclear	21800	70800			152900
[GWh/a]		**67000**			
CHP	24800	8700	27000		196600
[GWh/a]	**28600**	**15000**	**44000**		
Condense	3000	400	1800	280	42500
[MW]	**4000**	**1200**		**680**	
Gas turbines [MW]	975	195	70		
Hydro* [GWh/a]	13000	63000	3500*	115000	

*wind in DK

Table 1: *Maximum production capacity and electricity consumption (ref2000 plain* ***ref2010 bold****). CHP= Combined heat and power.*

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Transmission between the areas

- Wind is added as an extra production to a reference system
  - an amount corresponding to 30...40 % of the wind production is exported from Nordic countries to Central Europe
  - Sweden, Norway and Denmark increase exports
  - Imports increased to Finland, Central Europe and Denmark
- Indications of bottlenecks in transmission with large amounts of wind
  - lines to Central Europe, especially West Denmark to Germany
  - lines within and out of Norway: during wet years more profound bottlenecks, during dry years wind helps out the situation

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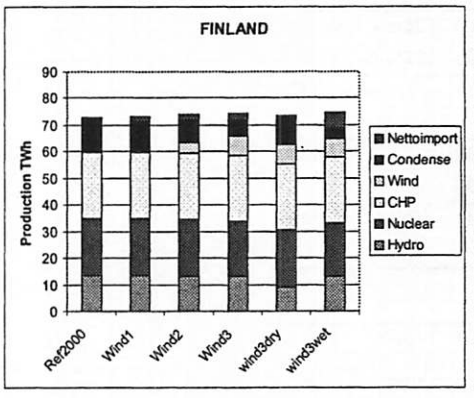
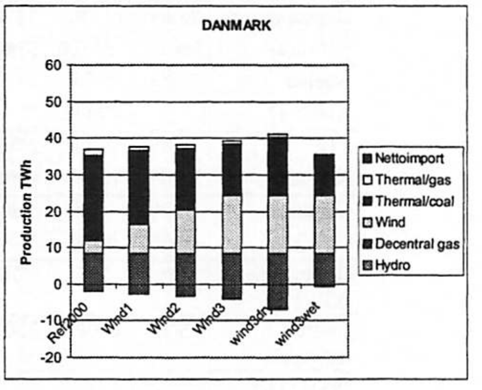
Simulation results for 16…46 TWh/a wind in Nordel





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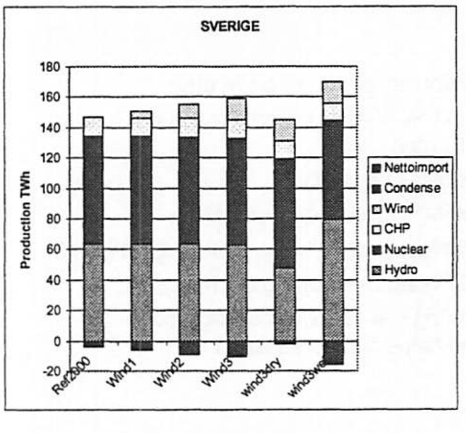

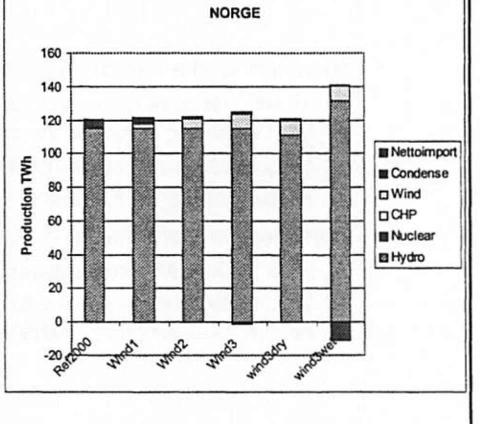

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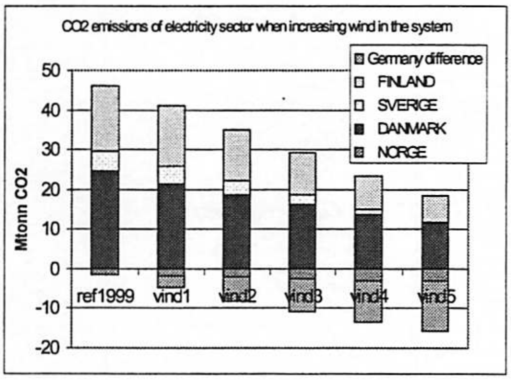
CO_2 abatement from Nordic simulations



- CO_2 abatement, when increasing wind in the system 16…72 TWh/a (4…25 %)
  - for today's system 680…580 gCO_2/kWh
  - for scenario year 2010 700…650 gCO_2/kWh
  - a large share of emissions reduced out of Nordic countries

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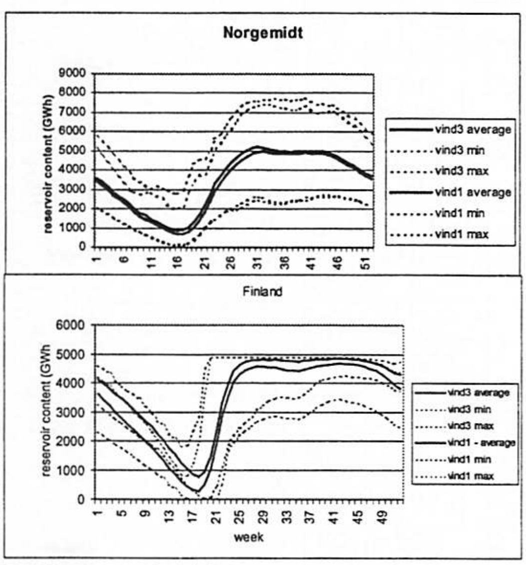
Effects to hydro power production



- Increased floodwater for 46 TWh/a wind:
  - average 0.5 TWh/a for ref2000
  - average 1 TWh/a for ref2010

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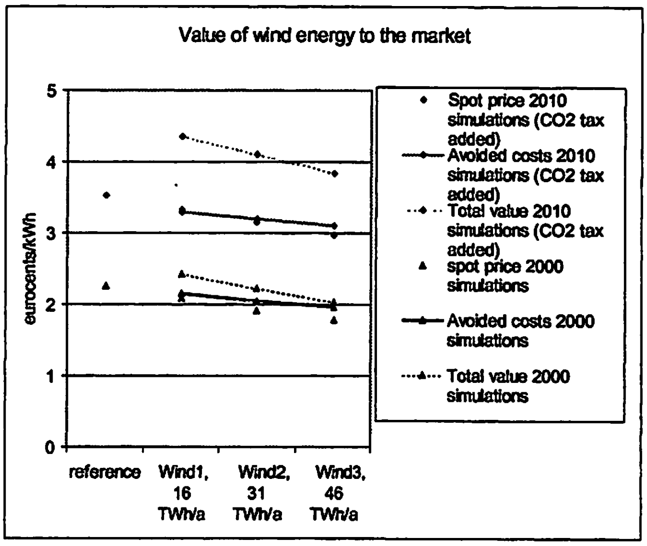
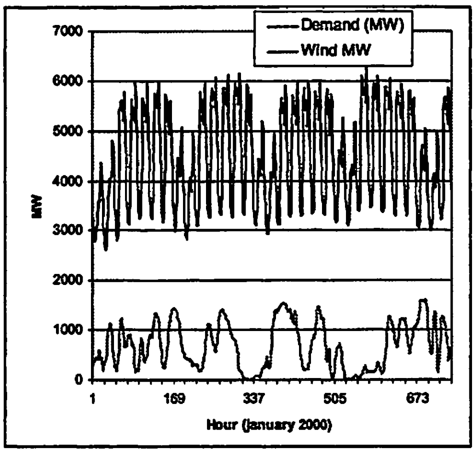
Spot market price. Value of wind.



Conclusions and discussion of EMPS simulations

- Large scale wind power in the Nordic electricity market will
  - replace mainly coal and oil and to some extent gas and nuclear power
  - result in CO_2 emission reduction of 680...620 gCO_2/kWh.
  - lower the market spot price : average yearly price 0.2 eurocents/kWh for 10 TWh/a if wind is added to existing system
  - result in avoided costs of 2.1...2.0 (3.3...3.1) eurocents/kWh with 16...46 TWh/a wind in today's (2010) system, slightly higher than spot price
  - have a socio-economic value 15 % (30 %) higher than the average spot price in today's (2010) electricity system
- Results based on input of marginal/operating costs of thermal power
- Results based on simulations with weekly resolution
  - assumption: all the wind production will be available in the system
  - assumption: hydro power handles in-week variations, no restrictions on thermal power use (start-ups, regulation)
  - hourly simulations will be a subject for further study

Large scale production of wind power



- Fluctuating power production
  - min-hours-days-months-years
  - average production of 100 MW, varies between 0...400 MW
- Many scattered wind parks
  - smoothing out the variations when large geographical distribution
- Production 2...40 hours ahead can be forecasted
  - for scheduling and exchange (market)
  - forecasting errors => regulating market
- In-hour variations have to be absorbed by the system
  - max ± 20 % of wind capacity

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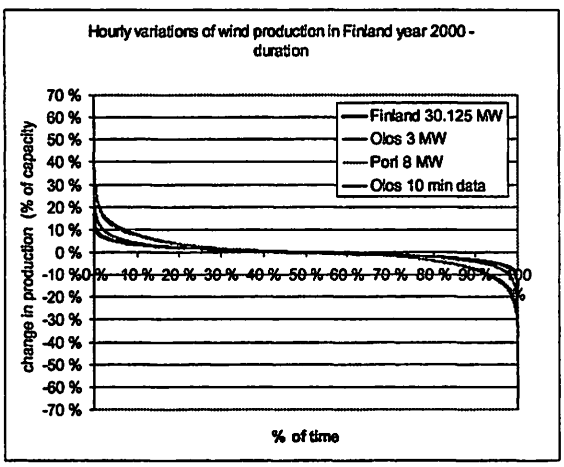
Variations of large scale wind power production



- Hourly variations:
  - max ± 20 % of nameplate capacity (Germany, Denmark, Finland)
- 12 h variations:
  - max ± 95 % of nameplate capacity (Germany, ISET)
  - max ± 84..92 % of capacity (Finland)
- 15 min variations:
  - 8.4 % of of nameplate capacity 6 times per month, max 11 % (Denmark)

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How much wind power can electricity system absorb?

- => "How much does the integration of large scale wind energy cost?"
  - Not so much a technical than an economical question
- The extra costs of integration depend on the electricity system and wind penetration:
  - X % without operational changes or extra costs:
    - Variations of load will absorb the variations of wind (wind is seen as a negative load by the system). UK: max hourly change 3 % of peak load => X= 4-5 % of yearly consumption
  - XX % with prediction tools and exchange possibilities:
    - Changes in scheduling, changes in export/import, negligible extra costs. DK, Eltra, up to 2000 => XX = 10-15 % of yearly electric consumption
  - YY % need with extra integration costs:
    - The larger the wind penetration the more flexibility in the system needed: reserves/transmission/DSM
    - Electricity surplus at certain hours, how much flexibility inside a country vs agreements with neighbouring countries

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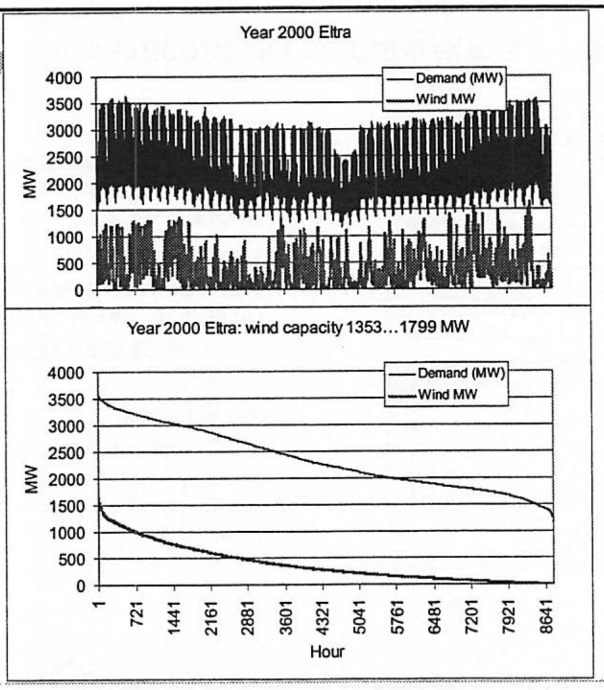

Data for year 2000

- geographically well dispersed for Denmark and Finland
  - a real large scale production data for Denmark
  - data from 30 turbines, upscaled for Finland
- only 4 sites in Southern Sweden --> upscaling overestimates the variations

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Wind data for countries - statistics

- Correlation of wind data:

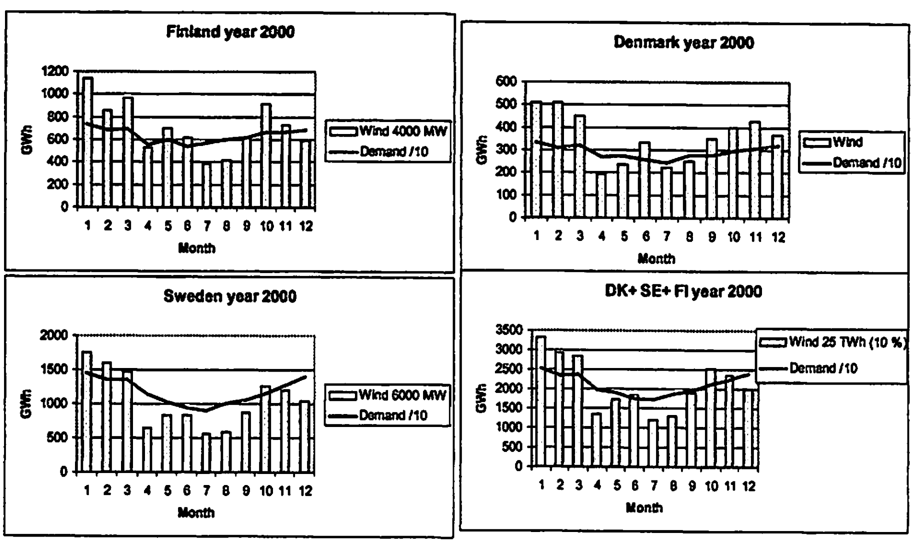
	Finland Mv	Sweden MW	Denmark N	DK-SE-FI à :
Finland MW	1.00			
Sweden MW	0.48	1.00		
Denmark MW 2C	0.33	0.76	1.00	
DK-SE-FI à 200C	0.70	0.91	0.86	1.00

- Descriptive statistics:

Finland MW		Sweden MW		Denmark MW 2000		DK-SE-FI à 2000 MW	
Mean	474.7	Mean	479.3	Mean	484.5	Mean	1438.5
Standard Err	3.9	Standard Err	4.7	Standard Err	4.7	Standard Err	11.1
Median	384.5	Median	335.7	Median	335.6	Median	1173.0
Standard De\	366.1	Standard De\	438.8	Standard De	440.1	Standard De	1035.7
Range	1780.0	Range	1878.1	Range	2050.3	Range	5216.0
Minimum	2.5	Minimum	-1.0	Minimum	-0.7	Minimum	29.0
Maximum	1782.5	Maximum	1877.2	Maximum	2049.6	Maximum	5245.0
Largest(24)	1646.7	Largest(24)	1828.2	Largest(24)	1885.1	Largest(24)	4770.1
Smallest(24)	10.4	Smallest(24)	-0.5	Smallest(24)	0.4	Smallest(24)	70.4
Sum	4169721	Sum	4209983	Sum	4255993	Sum	12635697
Count	8784	Count	8784	Count	8784	Count	8784
Confidence L	7.657559	Confidence L	9.17727	Confidence I	9.20553	Confidence L	21.66224

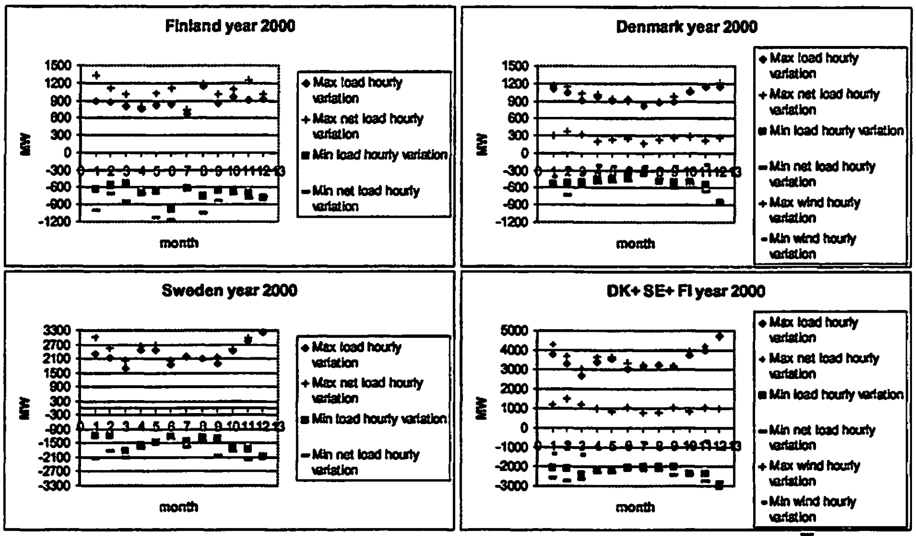
VTT ENERGY

Monthly production of wind vs consumption

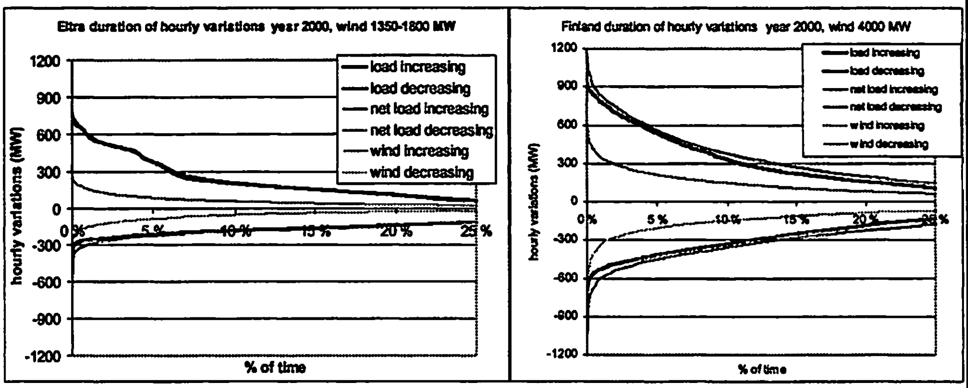


VTT ENERGY

Maximum hourly variations of load and net load



Hourly variations of wind vs variations of load



- Large amount of turbines in small geographic area (Eltra)
- Larger geographic area with a small number of turbines (Finland), data upscaled to make 10 % energy penetration
- Wind has considerably less effect on net load variations when using real data with large amount of turbines

Conclusions from first results of hourly data analysis

- An effort to estimate the reserve needs for large scale wind power production:
  - Comparing the hourly load variations without wind to the variations after large scale wind production: hourly variations of net load vs load
  - Wind production data upscaled --> can over estimate the variations of wind
  - Only one year of data
- If wind is well dispersed, increase in the hourly variations that one country's electricity system has to deal with, first after about 10 % energy penetration of wind

Connecting New Generation to the Irish Transmission System

Presented by the

Transmission System Operator
ESB National Grid/EirGrid

Cormac Mac Donnachadha

November 2001

EIRGRID

The Transmission System Operator TSO

- Required by **European Directive 96/92/EC**
  - required the establishment of a framework for independent management of the transmission system.
- Defined by **Statutory Instrument 445 December 2000**
  - To be a separate legal entity called **EirGrid.**
- EirGrid will not legally take over the role of TSO until:
  - 1. **INFRASTRUCTURE AGREEMENT** is in place.
    - Relationship between EirGrid(TSO) and ESB(TAO)
  - **2. TRANSFER AGREEMENT** is in place.
    - relates to the transfer of resources from ESB to Eirgrid

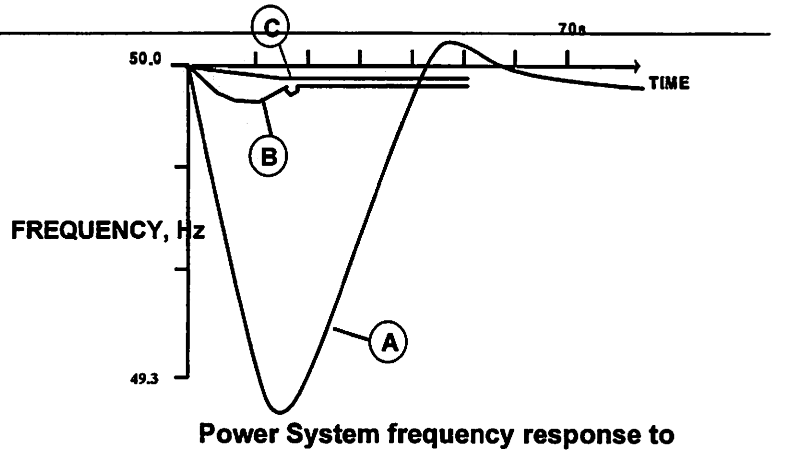
EIRGRID

Overview of the Irish Transmission System

- System is planned in line with International Standards.
- Small, sparse, island system.
- Ireland's load density is the second lowest in the EU.
- Sparse => thermal and voltage issues.
- Island => Frequency control and Reserve issues.
- 6% growth rate year on year for 6 years

EIRGRID

SECURITY OF SUPPLY

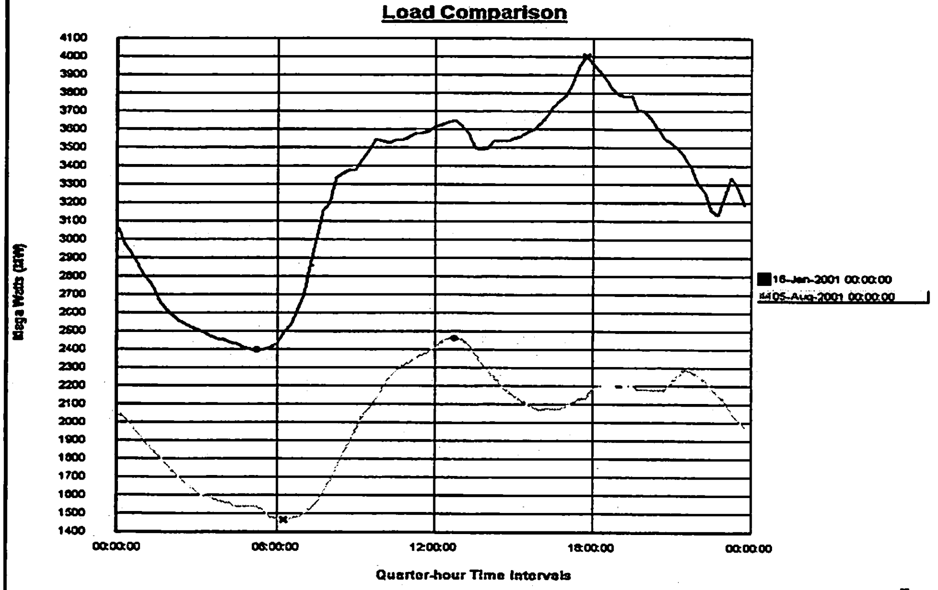


Power System frequency response to loss of generation

A: Irish, loss of 300 MW
B: European, loss of 2500 MW
C: European, loss of 1200 MW

EIRGRID

Daily Load Curves

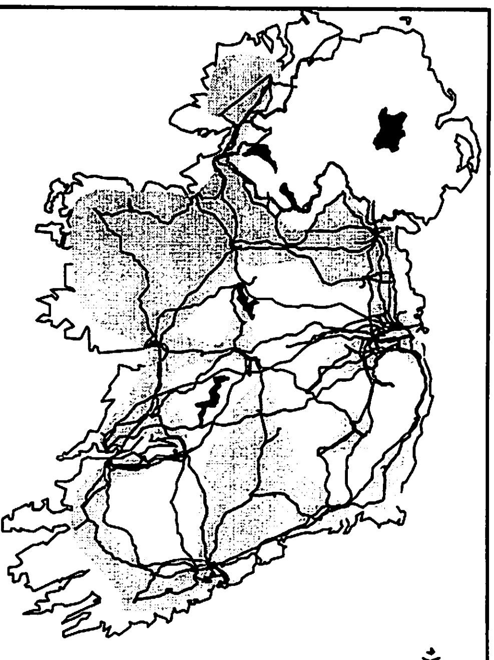


EIRGRID

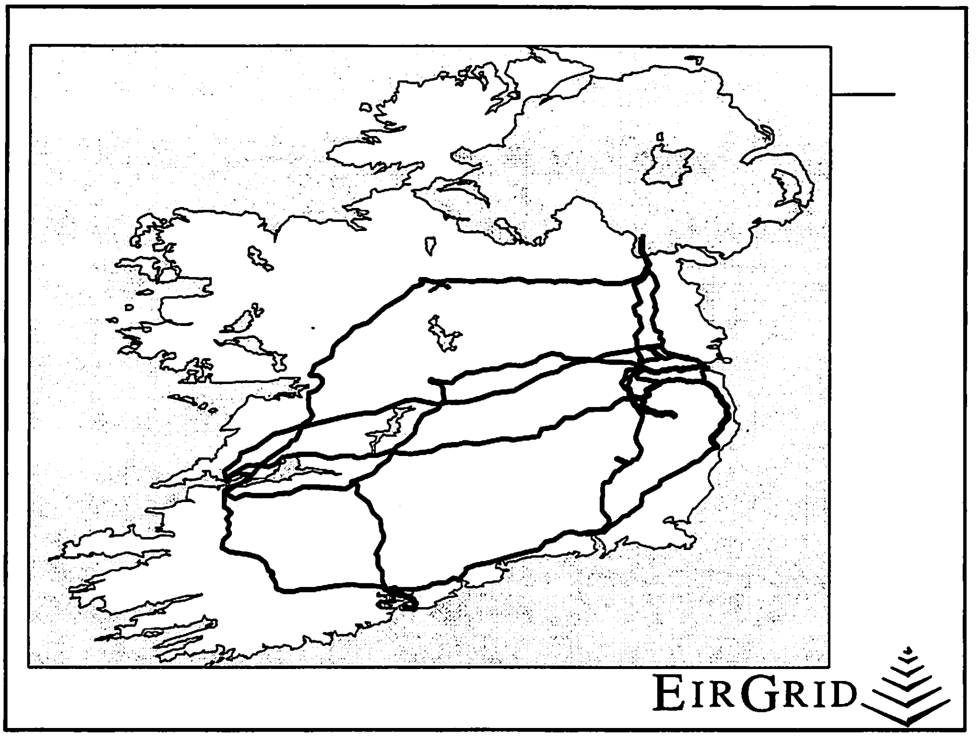
Problem Areas Over Next Few Years

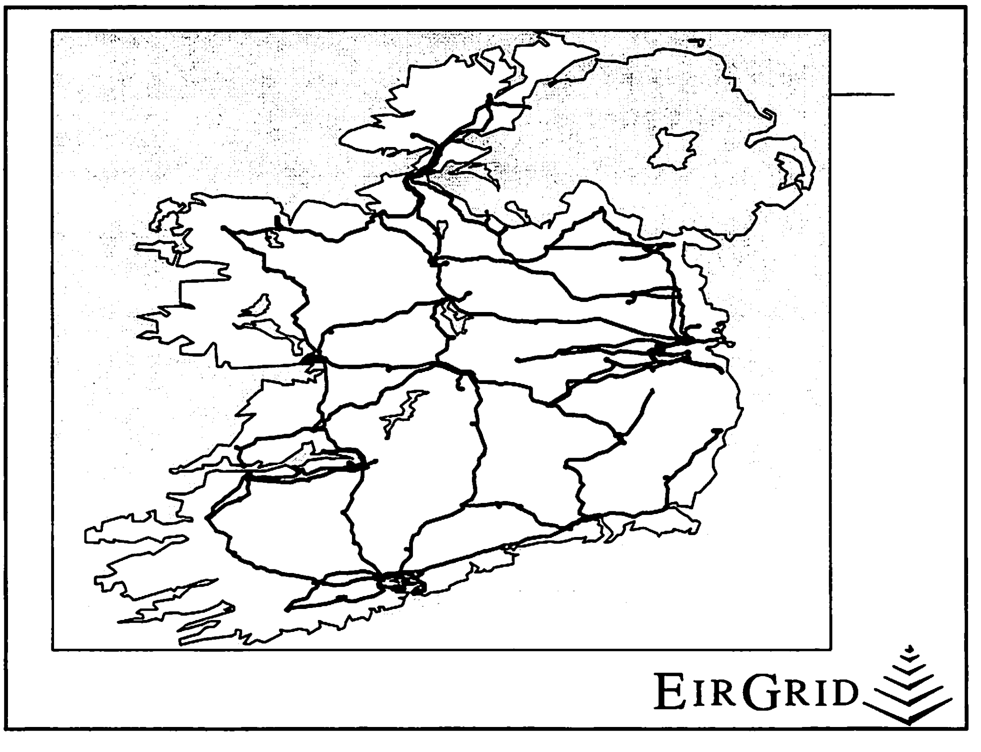
Very substantial areas of the network will remain outside our desired transmission planning standards, over the coming years

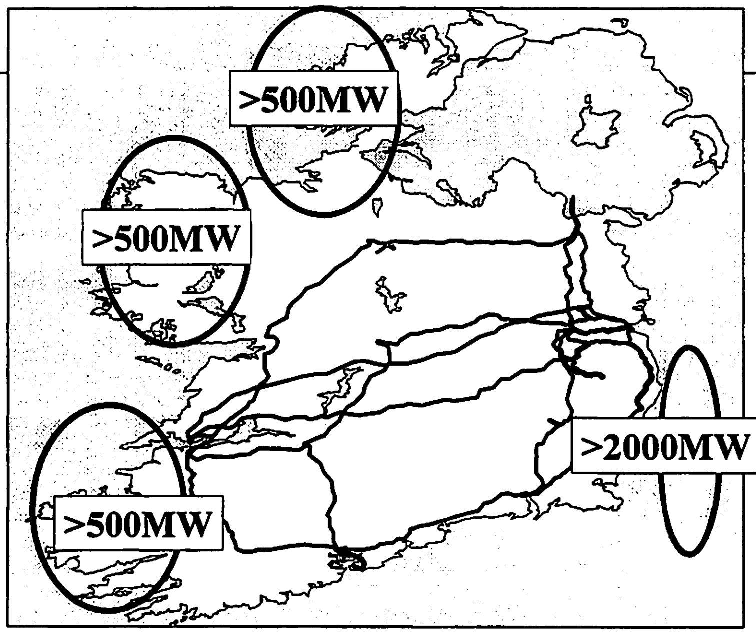
(refer to Forecast Statement)



EIRGRID


EIRGRID


EIRGRID



EIRGRID

Wind Generation in Ireland

- Plenty of wind resource potential in Ireland
- Growing interest,
  - 120 MW mainly connected at Distribution voltages (38kV and below) approx. 2% of annual demand
  - high appetite for more as a further 240MW in AER V
- New trend towards large sites and offshore sites.
  - Offshore have greater potential
  - Predominately on the east coast

EIRGRID

<u>Grid Code</u> issues arising for wind generators connecting to the Irish Transmission System

Because we have small island system must consider:

- Frequency Regulation
- Active Power Control
- Reactive Power Control
- Fault Ride Through Capability
- Predictability
- Power Quality
- Novelty & Rapid Development

EIRGRID

In Summary

- We are seeing a growing interest in connecting large wind generation to the Irish Transmission System.
- Connecting large amounts of wind to the Irish Transmission system requires careful consideration by the TSO to ensure a secure and reliable supply for all users of the system.

  A MAJOR TECHNICAL CHALLENGE !

EIRGRID

The End ! Thank you for your attention

Contact details:
Cormac MacDonnchadha;
ESB Natioanl Grid
email: cormac.macdonnchadha@ngrid.ie
Ph (353 1) 7027907

EIRGRID

IEA expert meeting on large scale integration into the grid,
Hexham, 6th-7th November 2001

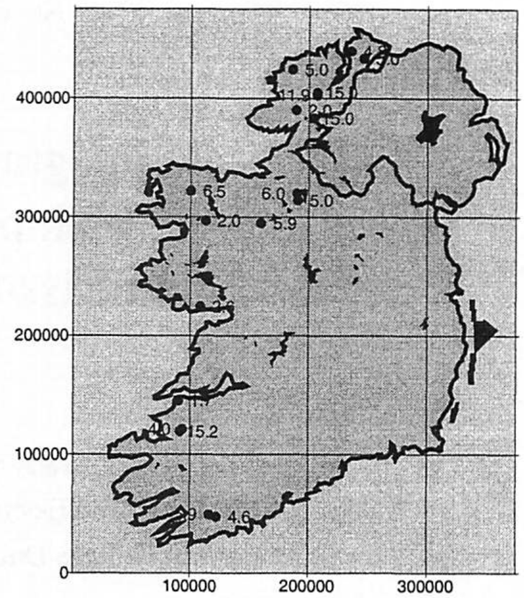
Large scale integration of wind power into the Irish power system – some issues

Rick Watson
Dept.of Electronic and Electrical Engineering
University College Dublin, Ireland

Large scale integration of wind power

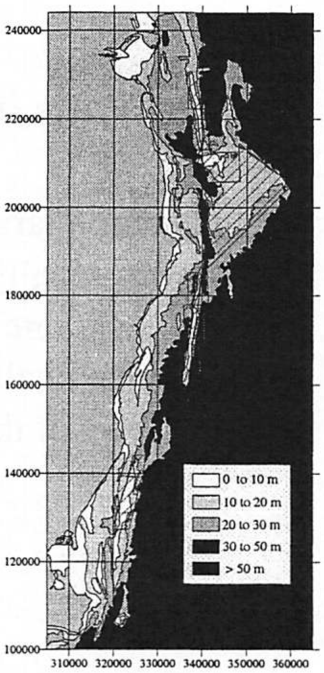
Whether a large penetration of geographically dispersed wind power or large offshore wind farms it poses a major technical challenge to the planners and operators of the Irish power system

Existing on shore wind farms and planned offhore locations



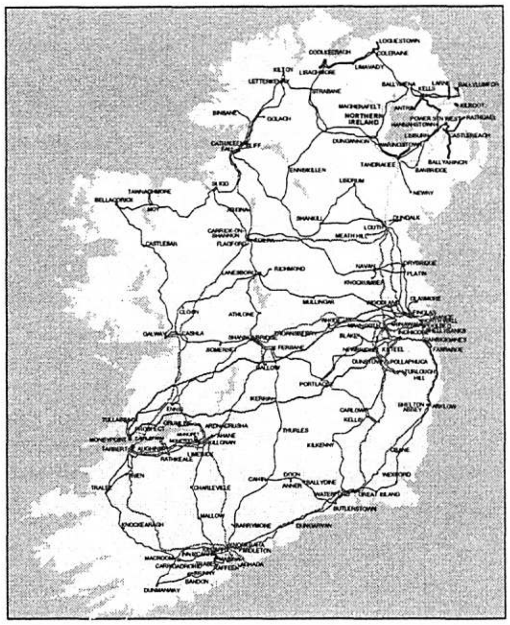
Water depth

Exploration block	Area [km²] with water depth 20m or less	Area [km²] with water depth 10m or less
Kish	28	12
Codling &India	200	12
Arklow	27	11
Blackwater	45	23
Total	300	58



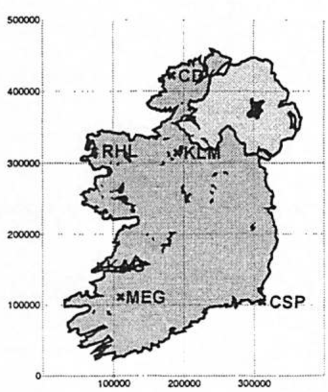
Small island power system - interconnection

- ❑North-South HVAC 300 MW
- ❑NIE-Scotland HVDC 500 MW (being commissioned)
- ❑East-West HVDC (under consideration)



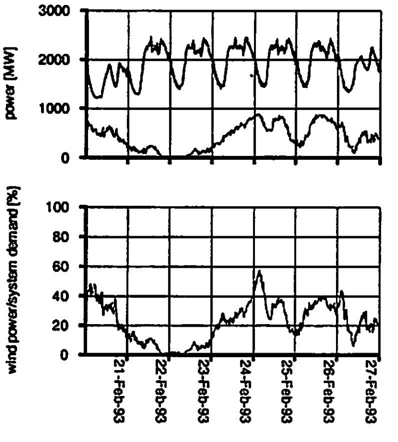
Variability study methodology

10 min mean wind speed → (WASP) → hub height wind speed → (Wind turbine power curve) → wind turbine power output → (Dispersed siting, Range of wind turbines, Losses, Scaling) → 10 min wind power time series for 20% energy penetration i.e. 1 GW wind capacity



Wind turbine	No. of turbines	Rated power [kW]	Capacity [MW]
Vestas 1650/66	20	1650	33
NEG Micon 1500/64	20	1500	30
NEG Micon 1000/54	20	1000	20
Bonus 1000/54.2	20	1000	20
Vestas 660/47	60	660	39.6
Bonus 600/44	40	600	24
Total no. of turbines	180	Total capacity	166.6

Variability



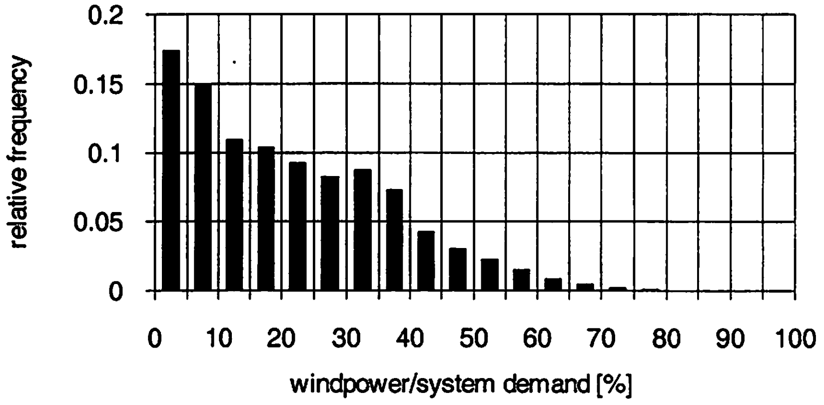
ESB has identified a 7.5% wind energy penetration limit

Based on a limit of 30% of *instantaneous* demand which could be met from wind power

30% limit derived from operator experience

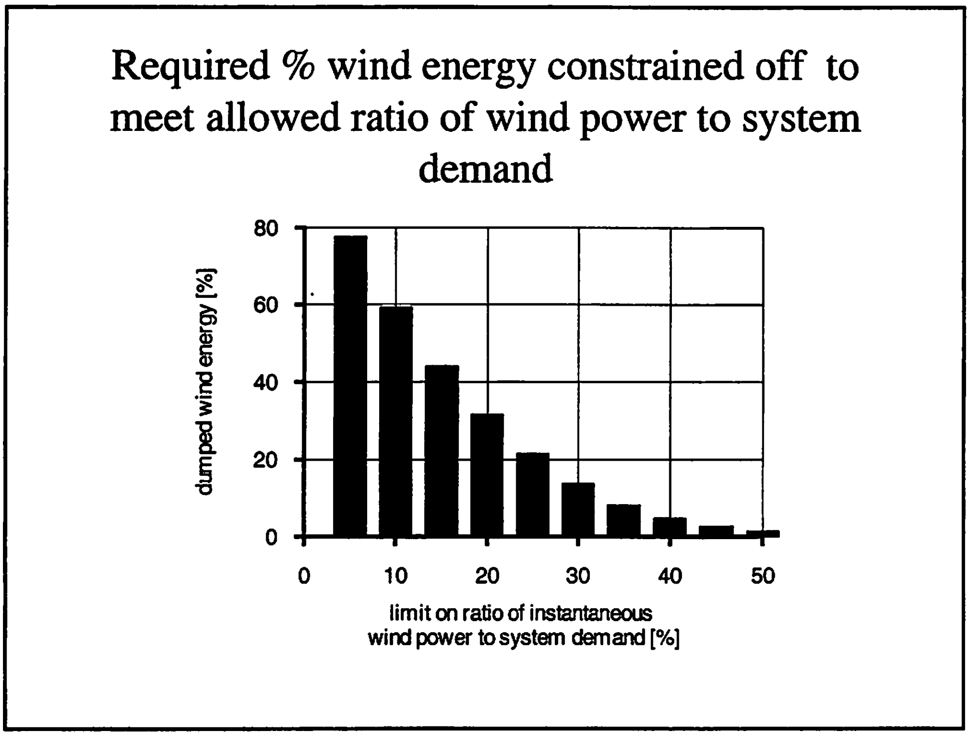
- ❑Variability and predictability of wind power
- ❑Provision of spinning reserve
- ❑Load following burden on conventional plant
- ❑Reliable and economic operation of the power system

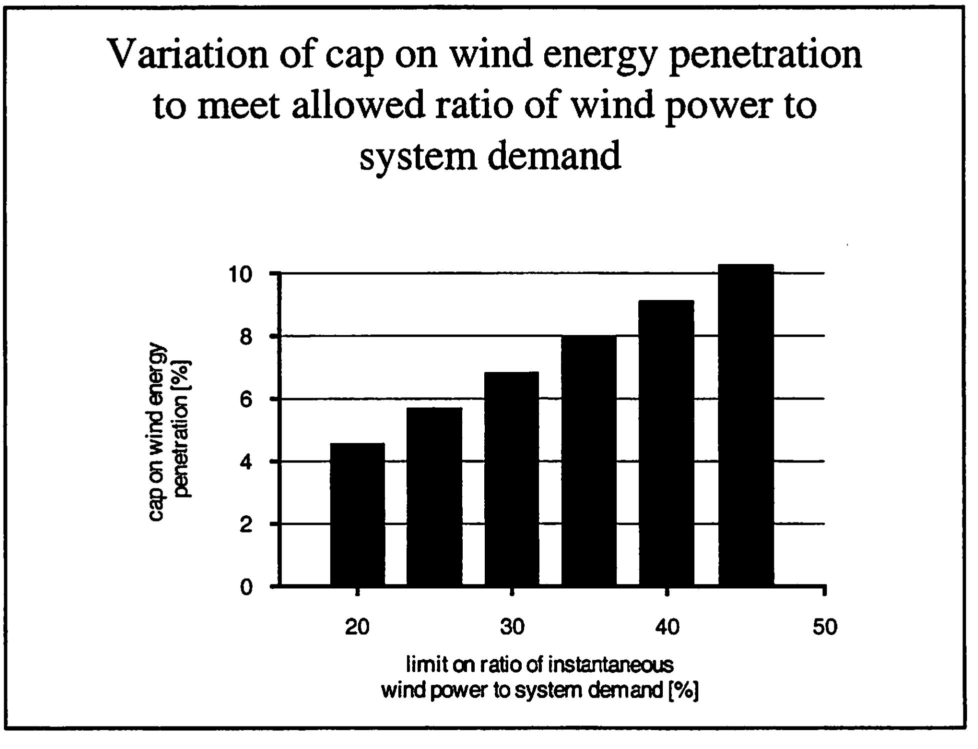
Frequency of occurrence of *instantaneous* wind power/system demand



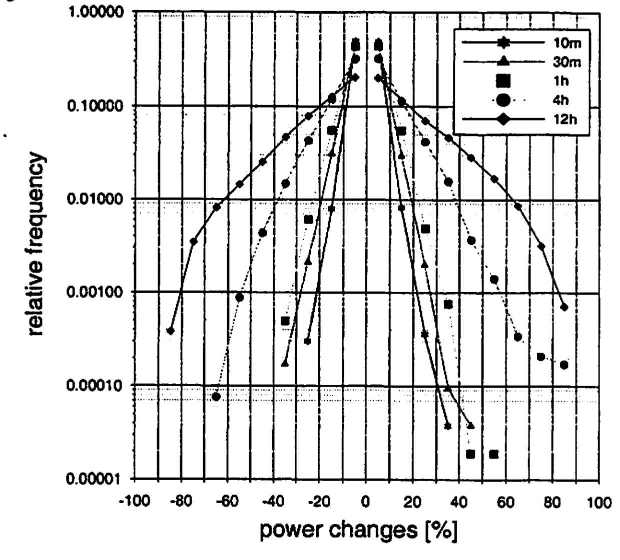
Two approaches considered

- Constrain off wind power when *instantaneous* wind power/system demand exceeds 30%
- Cap wind energy penetration so that 30% limit can never be breached

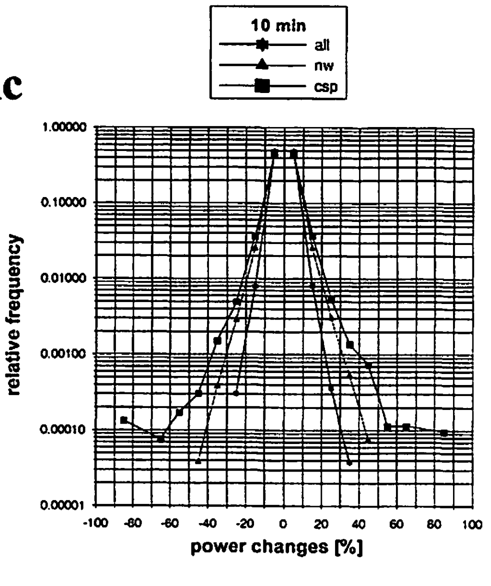

Required % wind energy constrained off to meet allowed ratio of wind power to system demand
dumped wind energy [%]
80
60
40
20
0
0
10
20
30
40
50
limit on ratio of instantaneous wind power to system demand [%]


Variation of cap on wind energy penetration to meet allowed ratio of wind power to system demand
cap on wind energy penetration [%]
10
8
6
4
2
0
20
30
40
50
limit on ratio of instantaneous wind power to system demand [%]

Power changes – effect of delay time



Power changes – effect of geographic dispersion

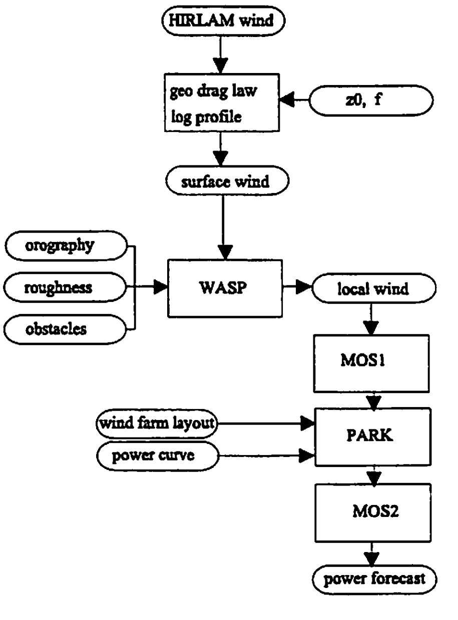


Variability conclusion

Geographic dispersion of wind power capacity reduces both the amplitude and the frequency of occurrence of wind power fluctuations.

Benefits of geographic dispersion not as great if capacity is built as large scale offshore wind farms

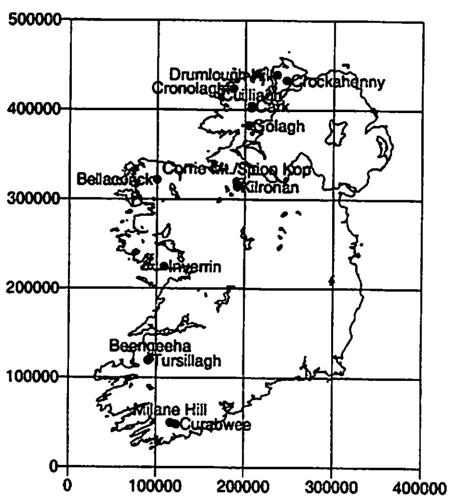
Prediktor wind power forecasting methodology



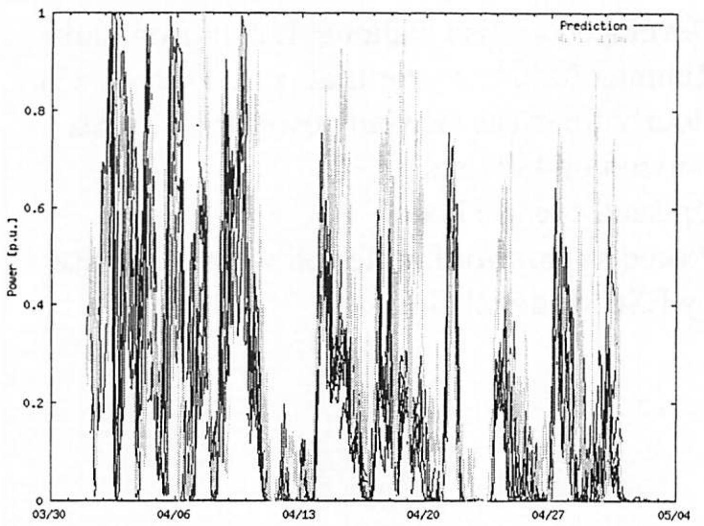
Prediktor wind power forecasting system

- ❑Developed at Risø National Lab in Denmark
- ❑Running for a one year trial period for 15 wind farms
- ❑Hourly forecasts of wind power for forecast horizon of 48 hours
- ❑Updated every 6 hours
- ❑Posted to password protected website for use by ESB National Grid

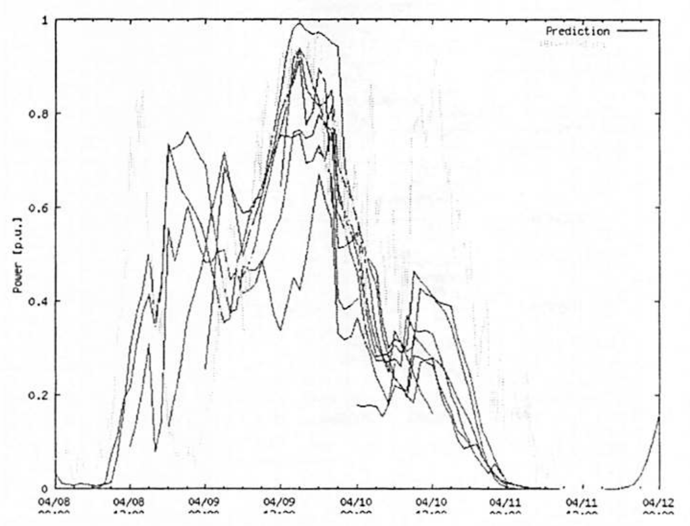
Locations of selected wind farms



Sample wind power forecasting results (1)



Sample wind power forecasting results (2)



Wind power forecasting conclusion

- Too early as of yet to assess the quality of the forecasts
- Work on tuning and calculating the MOS corrections is in progress and will hopefully build on the initial promise.
- Would be very interesting to extend study to include forecast of offshore wind measurements

Ancillary services

- Those services required to maintain a reliable and economic system operation- e.g. frequency regulation, provision of reserve, load following, dynamic voltage support, black start
- Environmental benefit of wind cancelled by additional ancillary services burden ?.

DOWEC

Jan Bozelie

Who's Dowec

N·E·G MICON®

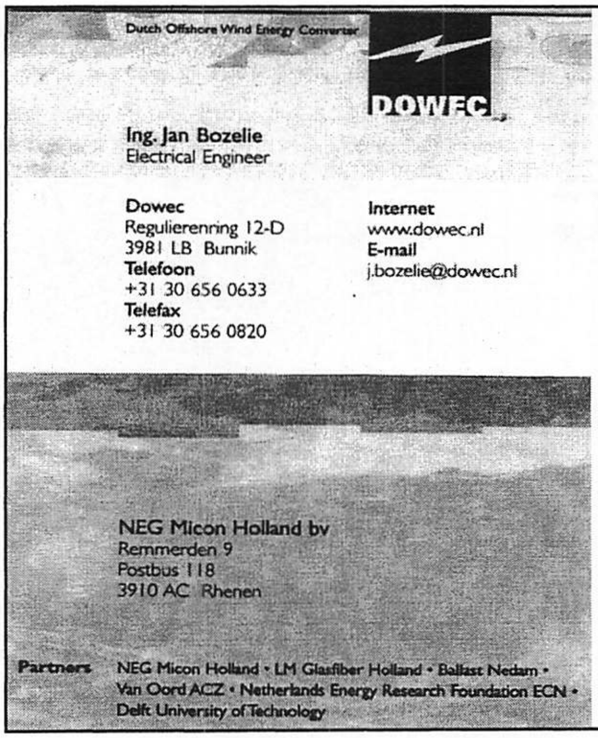
Van Oord ACZ

Ballast Nedam

LM

ECN

TU Delft



Who am I

Disclaimer

This document is not intended as a replacement of the national regulations, but as a summary of all requirements in The Netherlands, Denmark, Germany and UK.

Goal & dates

- **DOWEC = Dutch Offshore Wind Energy Converter**
- **development and testing of windturbine for use in large scale offshore wind electricity plants**
- **windturbine in 2006 in 5-6MW range dedicated for the job , and the total infrastructure (20 - 60km (from shore)**

EET funded project

No computer without wall socket

- No wind park without grid
- No wind park without grid connection
- No wind park without park grid
- No wind park without control strategy

- Optimalisation of all to get reliable and lowest kWh

Grid demands

Demands given by

- Regulations
- Utilities
- Operational aspects e.g.

From NL / UK / D / DK

- The focus in this overview is on wind farms 20-100 km from the shore and park sizes of 100 MW and more.
- Requirements during normal operation are highlighted light-grey

Power planning and control

CONDITION	REQUIREMENT	(1)	(2)	(3)	(4)
Power	Yearly average *Within ?% accuracy seems reasonable at this moment*	NL			
Active and reactive power	Monthly average *Within ?% accuracy seems reasonable at this moment*	NL			
Active and reactive 10 minute average power	Week planning with 70% assurance *Within ?% accuracy seems reasonable at this moment*	NL			
Active and reactive 10 minute average power	Daily planning with 93% assurance (36h) *Within 7 ?% accuracy seems reasonable at this moment*	NL			
Active and reactive 10 minute average power	4 hour warning system for deviations from the planned power production, for instance due to changes in weather conditions	NL			
High wind speed wind park shut down	Planning 15 min ahead (sequential switch-off over a period of 15..120 min)	NL	DK		
Low wind speed cut in	Planning 15 min ahead	NL	DK		
High wind speed cut in	Planning 15 min ahead (see notes) with dP/dt limitation	NL	DK		

Power planning and control

dP/dt	Pnom / 60sec 12MW / 60sec (~6%/60sec) 10% of nominal power / 60 sec	NL	DK	D	
Maintenance	Yearly planning on daily basis	NL			
Repair	Grid operator notification of major repairs	NL			
Rotating reserve / standstill reserve	Participation unknown	NL			
Park power set point	normal operation: 10 sec value of active power set point between 1% and 105% active power command in 2 sec 105% down to 20% (overproduction will be limited by the thermal constraints)	NL	DK DK	D	

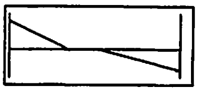
reactive power

CONDITION	REQUIREMENT	(1)	(2)	(3)	(4)
Power factor during normal operation	Between 1 and 0.8 inductive The power factor affects the voltage regulation and is subject to discussion with the utilities (Utility preference ± 0.9) Reactive power, also in no-wind periods, is valuable	NL	DK		
Reactive power setting	Reactive power command every 10 sec	NL	DK		

voltage / current related (1)

U > 106% Un	Soft switch off after 100msec			D	
110% Un > U > 90% Un	Power according to PV curve or nominal for unlimited time	NL	DK		
90% Un > U > 85% Un	Power according to PV curve or nominal for 15 min	NL			
> 80% Unom	Power according to PV curve or nominal for unlimited time			D	
<85%	Soft switch down after 3 sec			D	
85% Un > U > 70% Un	Power according to PV curve or nominal for 10 sec	NL	DK		
U < 80%	Soft switch off after 3-5sec				
70% Un > U > 60% Un	After a voltage disturbance the power has to return to normal value within 30sec Power set point control still must be active				
Voltage dips	0.7 > Unom > 0.6 for 10 sec at 90% of rated power (Utility preference 110% of rated power)	NL	DK		
	0.6 > Unom > 0.0 for 100ms (German = 150 msec)	NL	DK		
	No grid disconnection will occur			D	
	0.6 > Unom > 0.15 for <3 sec power 1.2* I_nom			D	
	If the voltage dip has a rest voltage of smaller 0,7 Un, disconnection is allowed after 300ms or 90% of the critical Isc (KKT) if 300 ms > 0.9 KKT (KKT a value depending on the running inertia) For grid connections with a voltage of 110kV or higher disconnection is allowed after 300ms or 90% of the critical Isc (KKT)	NL			
Short circuit fault	If a production unit is switched of from the grid by a short circuit condition. Then the units must be fully operational after 30min of the event unless the return will take longer than 60 min	NL			

voltage / current related (2)

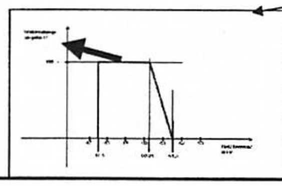
Single phase short circuit fault	0.7 > Unom > 0.4 for 300 msec at Isc conditions availability of full power 1.5 sec after fault clearance	NL	DK		
 Example of reactive power set point versus voltage	If a turbine with reactive power control capability is assumed, voltage regulation at the grid connection point is an option, similar to the voltage control of a power plant with synchronous generators. If the voltage regulation is active, but no reactive power set point is specified by the grid operator, a Q(U) characteristic similar to figure on the left can be expected.				
Voltage variation	Variation caused by the wind farm at the gridconnection point may not be more than 2% Unom DK (< 3% continuous or <2.5% 10 times per hour or <1.5% 100 times per hour) Inrush currents (due to magnetisation e.g.) may not lead to a higher deviation	NL	DK		
Asymmetry	2% for unlimited time (optionally controlled by a converter)				
Flicker	Pst < 0.3, Plt < 0.2	NL	DK		
Harmonic	THFF <1% THD < 1%	NL	DK		

voltage / current related (3)

Harmonic	THFF <1% THD < 1%	NL	DK		
Overvoltage protection	The offshore cable is extremely difficult to repair. Therefore special attention has to be taken to avoid insulation damage due to overvoltage 130% of initial voltage reduced to 120% of nominal voltage in 100msec Overvoltage and switch actions have to be analysed carefully	NL	DK		
Cut – in current	Max 1.2 * nominal grid connection capacity			D	
Disconnection	From the grid to the wind farm, a reliability of 0.9998 is expected, or average of 1.56 h/y Mostly a connection for a wind farm is not shared with others (no consumers connected to the grid through the same cable). This is also expected for the grid connection point.	NL			

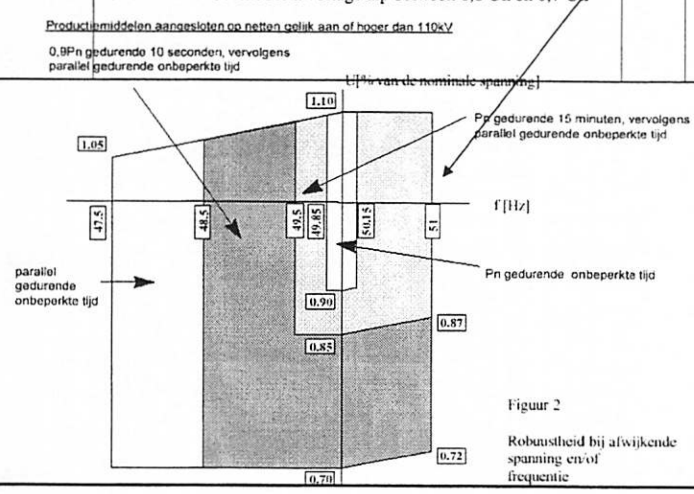
Voltage / frequency (1)

Frequency. Time and power limited	Continuous operation between 48 and 51Hz (Norm = 50 ±0.1 Hz) Limited operation range between 45 and 48Hz (>5min) Limited operation range between 51 and 53Hz (>5min) if under/above these limits, disconnection after 0.3 sec is allowed Continuous operation between 47.5 and 51.5Hz Limited operation range between <47.5Hz after 200sec) Limited operation range between >51.5Hz after 200sec) if under/above these limits, disconnection after 0.1 sec is allowed	NL	DK	D	
Frequency deviation	Contribution to the primary frequency control, limited by the control strategy and the wind conditions 1.05% Pnom at 48Hz // 100% Pnom at 50Hz >50.25Hz → reduce power Active power demand by grid operator due to frequency deviation	NL	DK	. D D	



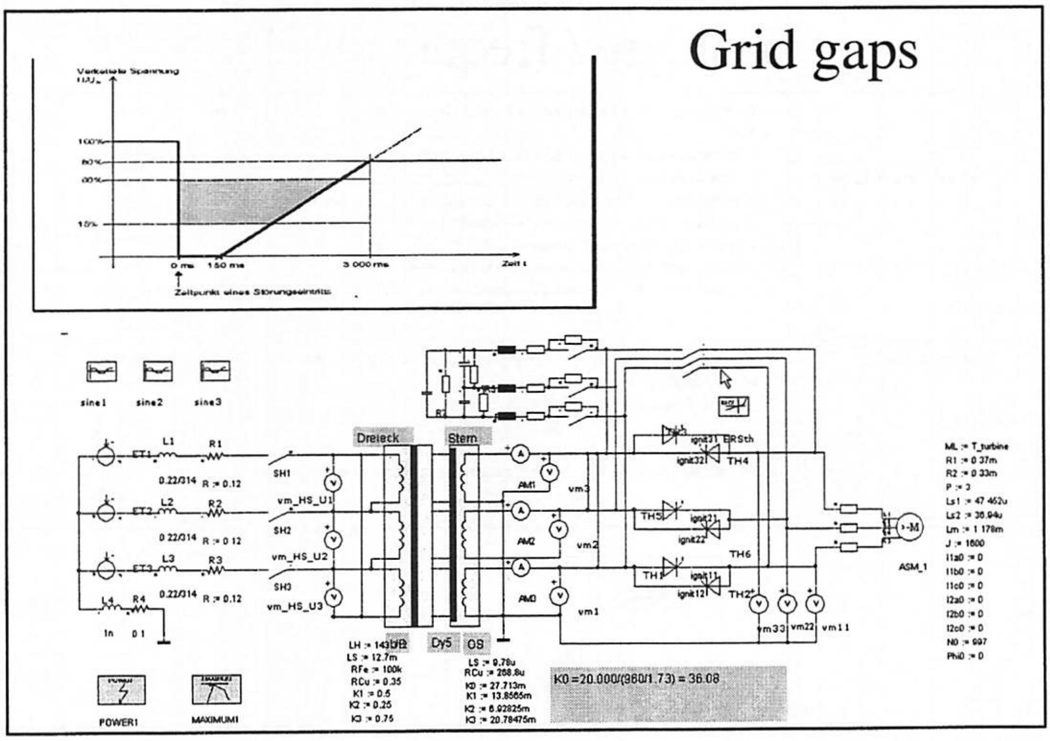
Voltage / frequency (2)

Normal and abnormal conditions	Some countries specify 0.6Un instead of 0.7Un (DK)	NL	DK		
Comments on the f-U diagram	For production units on grid lower than 110kV: disconnection is allowed after 300ms for a voltage dip between 0,8 Un en 0,7 Un	NL			



Figuur 2

Robuustheid bij afwijkende spanning en/of frequentie



Measurement by DTE or Utility (time synchronised)

Active power per phase	First power measurement at grid connection point. Accuracy better than 0.2% Second power measurement is formed by the collected park data 5 min average periods time synchronised	NL			
Reactive power per phase	First reactive power measurement at grid connection point. Accuracy better than 0.2% Second power measurement is formed by the collected park data 5 min average periods time synchronised	NL			
Active power set point	Active power command / 10 sec time synchronised	NL	DK		
Reactive power set point	Reactive power command / 10 sec time synchronised	NL	DK		

Park measurement & registration					
Voltage per phase (min/avg/max)	Accuracy better than <0.5% 5 min average periods time synchronised		DK		
Current per phase (min/avg/max)	Accuracy better than <0.5% 5 min average periods time synchronised		DK		
Frequency per phase (min/avg/max)	Accuracy better than <0.2% 5 min average periods time synchronised		DK		
Active power per phase (min/avg/max)	Accuracy better than 1% 5 min average periods time synchronised		DK		
Actual power setpoint	Reactive power command / 10 sec time synchronised				
Reactive power per phase (min/avg/max)	Accuracy better than 0.2% 5 min average periods time synchronised	NL			
Actual reactive power setting	Reactive power command / 10 sec time synchronised				

reliability shore connection					
Availability of grid connection switch boards	better than 99.78% 0.16 failures per year for a system with 4 connections repair time of 5 days		DK		
Availability of cable connection (150kVA, 60km)	4 parallel connections of 60km better than 99.7% 0.06 failures per year for a system with 4 connections repair time of 21 days most probable failure cause are anchors		DK		

reliability wind farm collection platforms

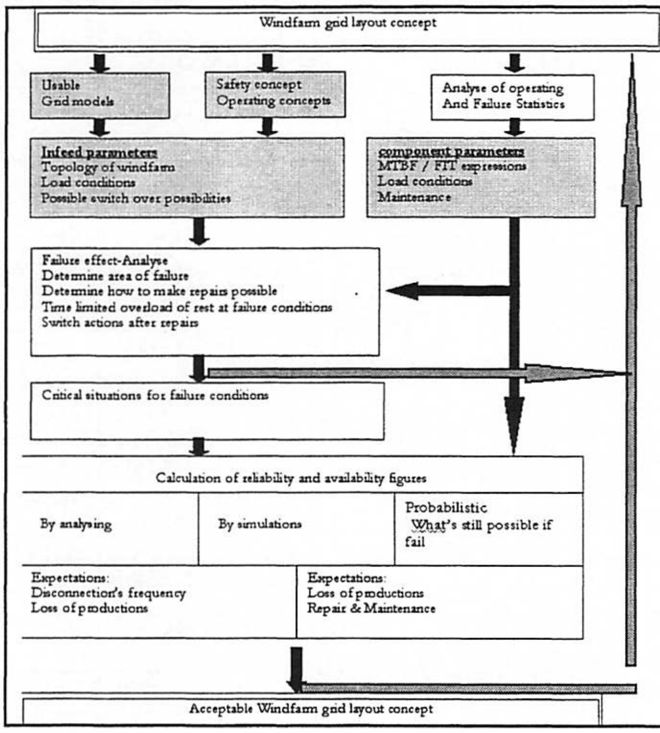
Availability of platform switch boards (150kV)	better than 99.78% 0.16 with repair time of 5 days over 4 connections		DK			
Platform transformer (150kV to 22(32) kV)	better than 99.4% 4e-6 with repair time of 60 days over 4 connections					
Availability of grid park switch boards (22 (32) kV)	better than 99.99% 1.9e-7 with repair time of 30 days over 4 connections and at lease 8 outgoing fields		DK			

For dc equivalent values has to be reached

reliability wind farm grid infrastructure

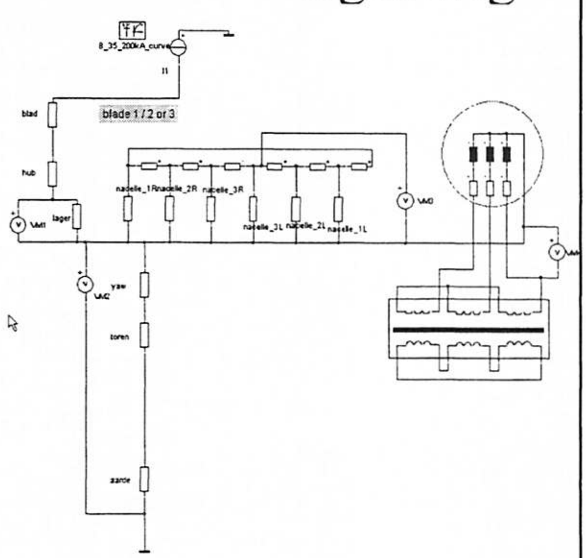
Park cable (60km)	better than 99.7% 0.06 with repair time of 21 days over 4 * 8 connections					
Availability of turbine switch boards (22 (32) kV)	better than 99.99% 1.9e-7 with repair time of 30 days over 4 connections		DK			

Total calculated grid availability 98.26 (expected)
This has to rise to 99.0 or better



Reliability research

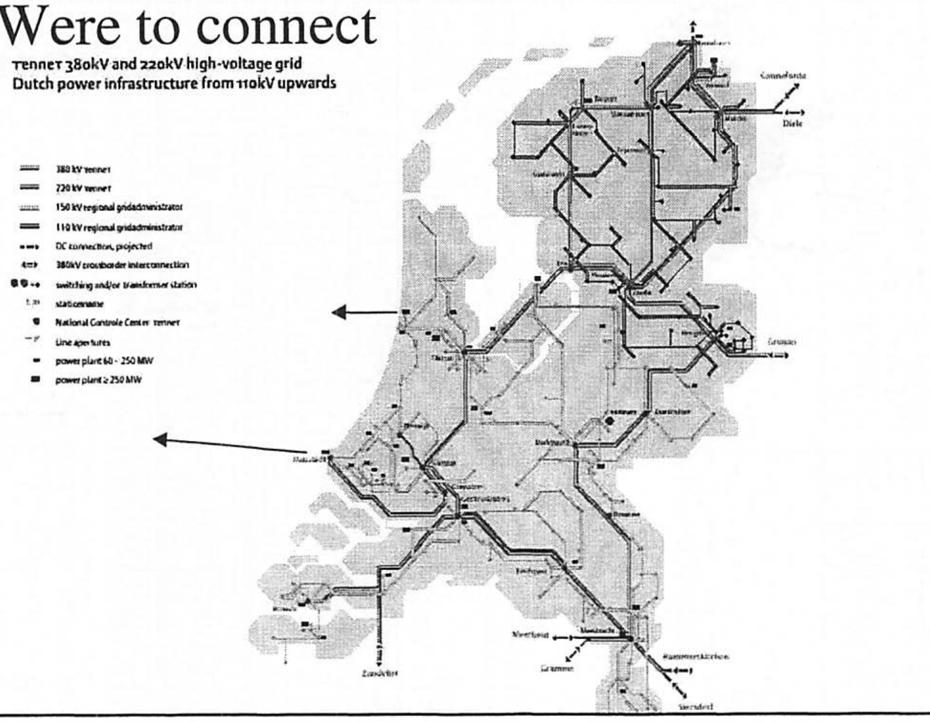
lightning



How to organize on failures		
description	Failure /100km / pc	Time to repair
Connection on shore (150kV overhead lines, e.g.)	0.06	24h
Grid connection point (switch board 4*150MVA)	0.02	24h
3 end terminations	0.01	5h
Main cables 4 * 150MVA to platform a 60km	0.3	21*24h
Platform switch 4*	0.02 *4	24h
Transformer 150MVA	0.05	21*24h
Secondary switchboards	0.02 *16	24h
Turbine cabling	0.25	21*24h
Turbine CCT	0.02 *100	24h

Were to connect

TenneT 380kV and 220kV high-voltage grid
Dutch power infrastructure from 110kV upwards



thanks

Intensive research is only possible thanks to a large number of firms willing to contribute to the research

Like

ECN , TU delft , v Oort , Ballast nedam , Shell

Tennet , Kema ,NRG

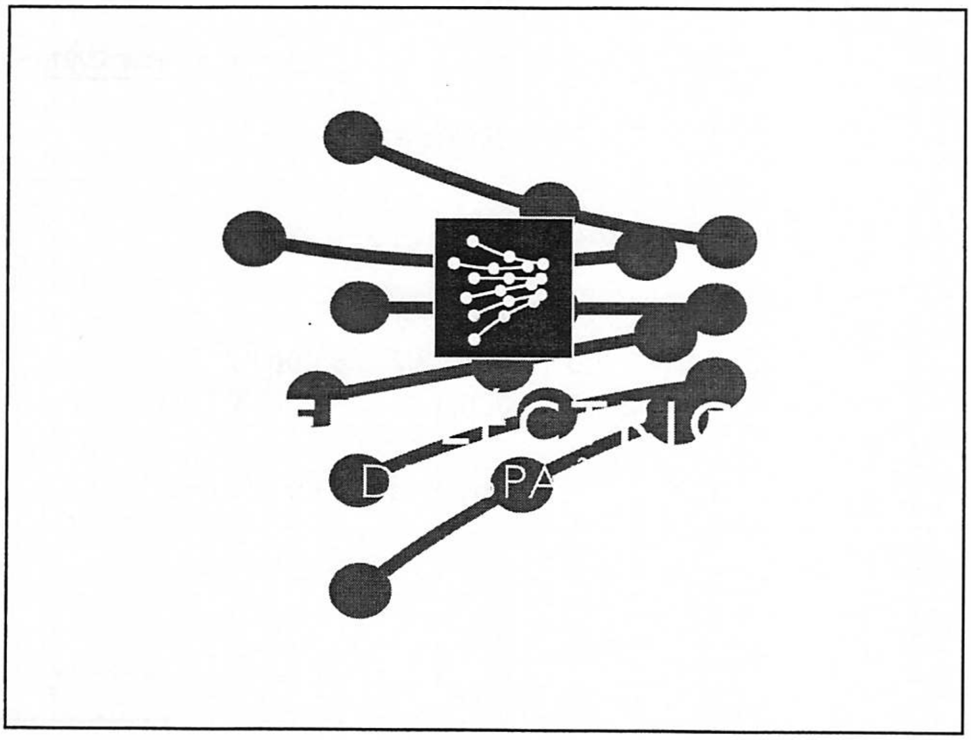
Nuon , ENW , Eneco, Delta , Elsam /Eltra , EON

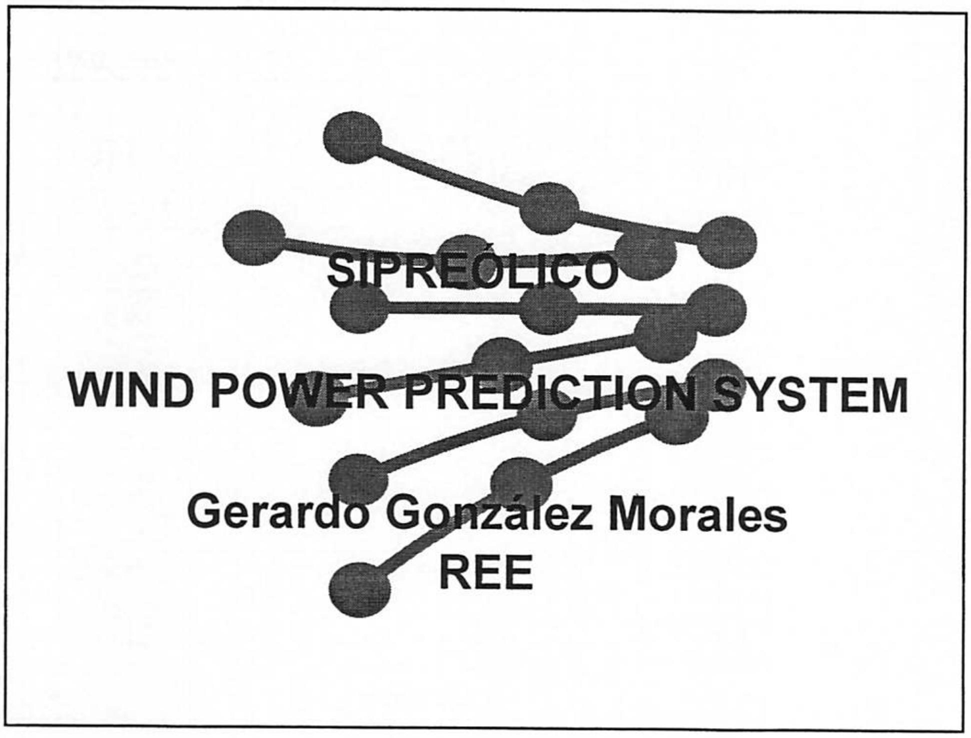
Alstohm , Siemens , ABB ,

Pirelli , NKF , TKF , Draka , F&G , Smitt trafo , SGB,...

And many more

Wind trade !an golden future!




SIPREÓLICO
WIND POWER PREDICTION SYSTEM
Gerardo González Morales
REE

IEA 5 - 6 November 2001

Wind forecasts

- High number of proyects
  - June 2001 : 2.700 MW
  - December 2005 : 6.500 MW - 8.000 MW
  - December 2010 : 9.000 MW - 15.000 MW
- Minimize the impact on the System Operation

3

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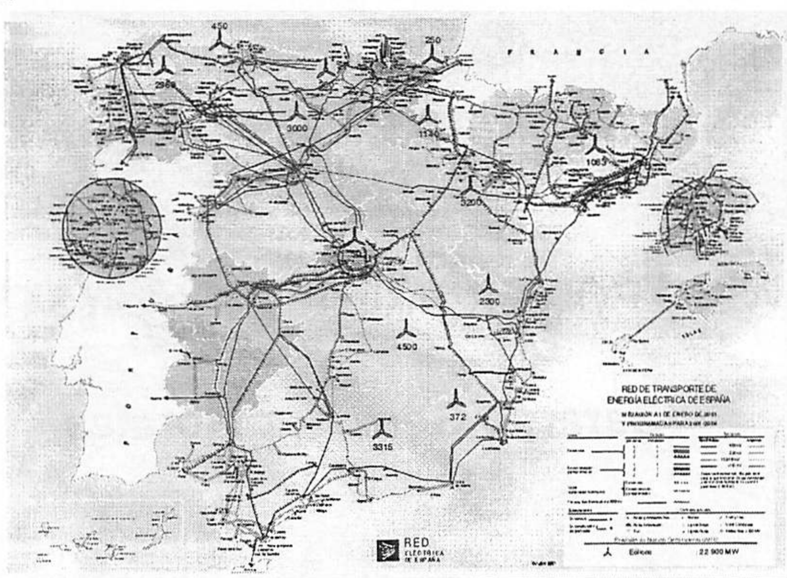

4

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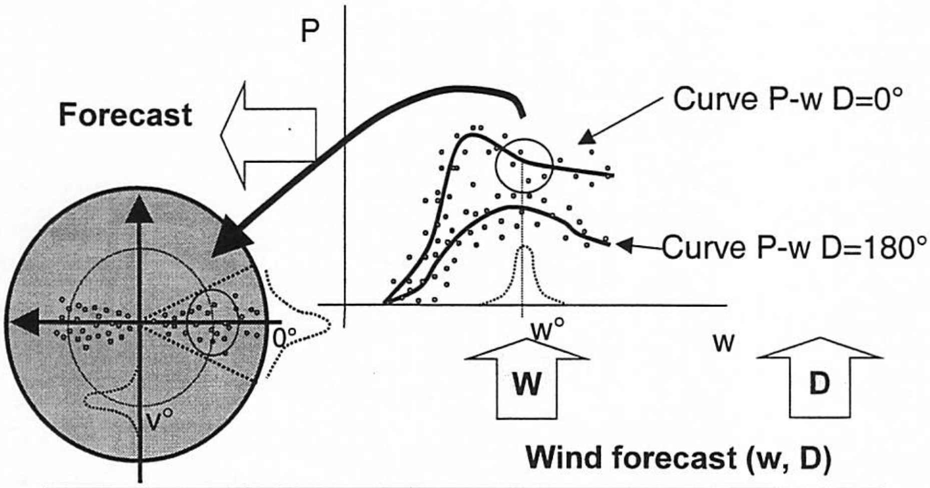
Prediction Power-Wind



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Impact on the System Operation

- **Difficult forecasts**
- **No schedule**
- **Affect demand**
- **Power oscilations**

- **System penetration:**
  - **Year 2000: 4%**
  - **Year 2010: 15-20%**

IEA 5 - 6 November 2001

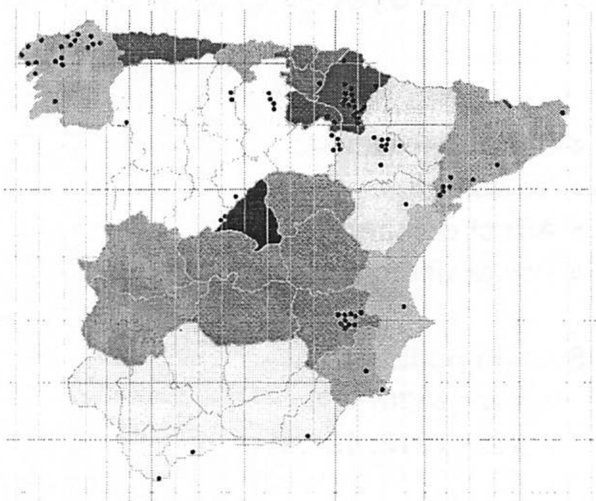
Program

- Running a prototipe
- Platform PC
- MATLAB
- National Metheorological Institute forecasts

7

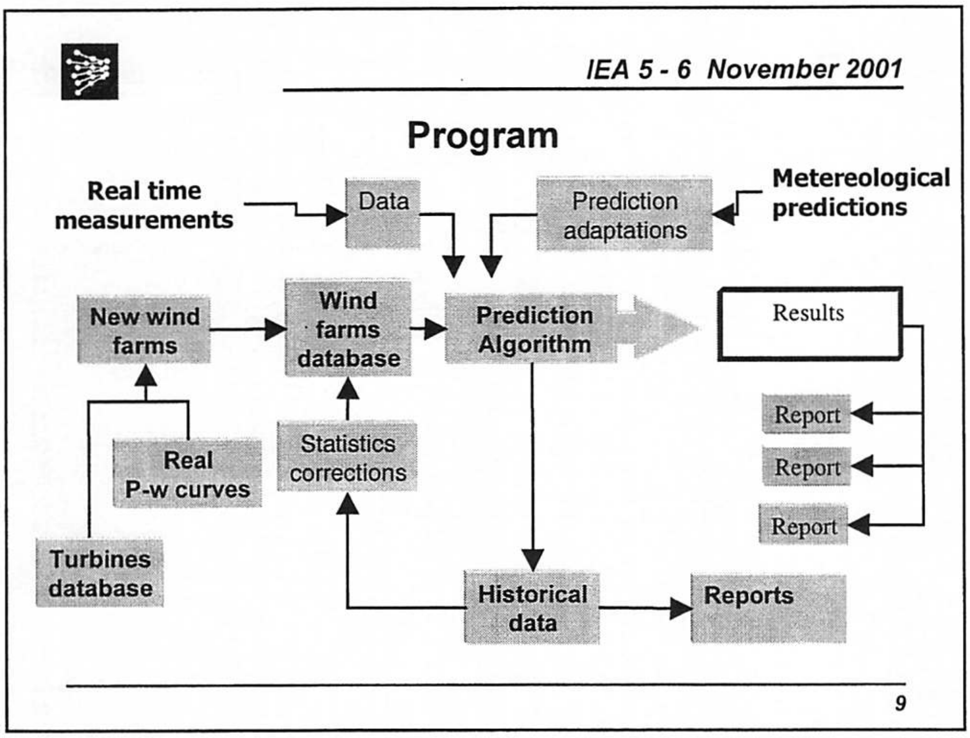
IEA 5 - 6 November 2001

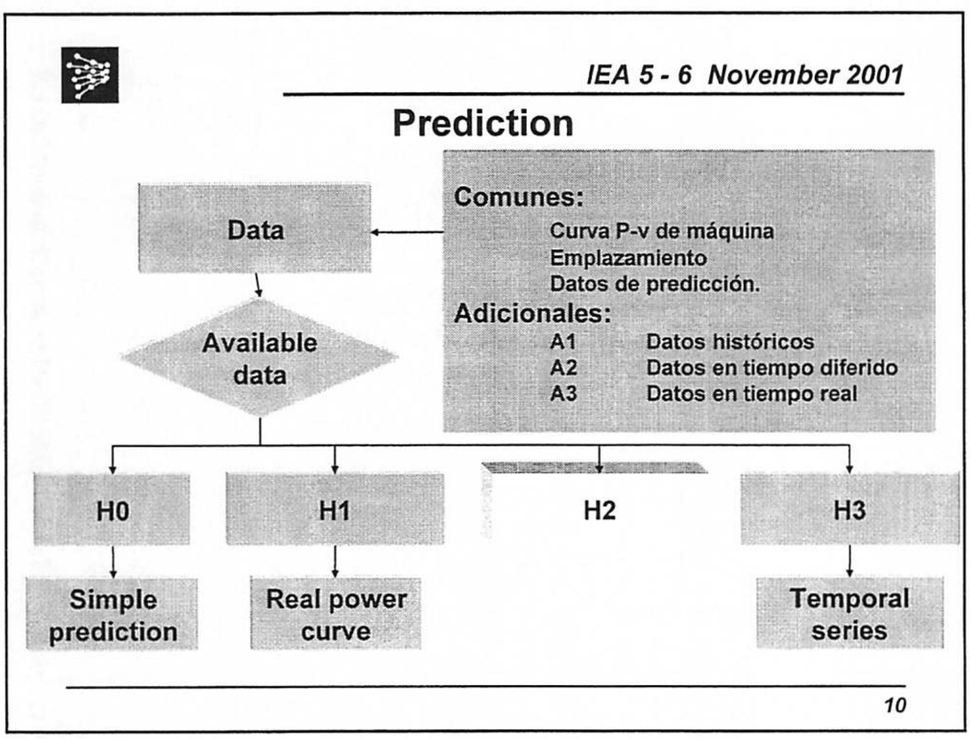
Wind farms



Andalucia	171
Aragón	342
C. La Mancha	445
C. León	297
Cataluña	102
C.Valenciana	20
Galicia	725
La Rioja	24
Murcia	13
Navarra	610
Pais Vasco	24
Total MW	2.773

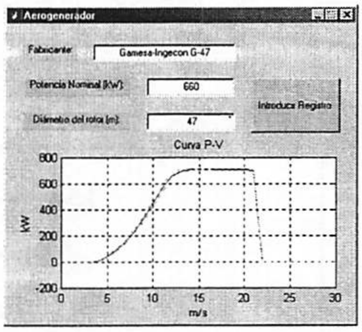
8

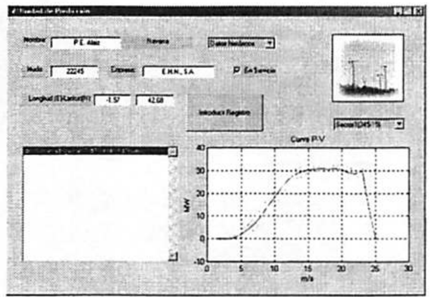

IEA 5 - 6 November 2001
Program
Real time measurements
Data
Prediction adaptations
Metereological predictions
New wind farms
Wind farms database
Prediction Algorithm
Results
Report
Report
Report
Real P-w curves
Statistics corrections
Turbines database
Historical data
Reports
9


IEA 5 - 6 November 2001
Prediction
Data
Comunes:
Curva P-v de máquina
Emplazamiento
Datos de predicción.
Adicionales:
A1 Datos históricos
A2 Datos en tiempo diferido
A3 Datos en tiempo real
Available data
H0
H1
H2
H3
Simple prediction
Real power curve
Temporal series
10

IEA 5 - 6 November 2001

Wind farms database





P-ws curve **Wind farm**

11

IEA 5 - 6 November 2001

Reports

Informes :

- Producción total peninsular.
- Producción por CC.AA.
- Producción por parques.
- Otros formatos cualesquiera son posibles


```
EOLICA;REE;
2001;10;18;05;39;v;
2001;10;19;01;00516;2001;10;18;02;00;
2001;10;19;02;00560;2001;10;18;02;00;
2001;10;19;03;00502;2001;10;18;02;00;
2001;10;19;04;00441;2001;10;18;02;00;
2001;10;19;05;00378;2001;10;18;02;00;
2001;10;19;06;00345;2001;10;18;02;00;
2001;10;19;07;00318;2001;10;18;02;00;
2001;10;19;08;00298;2001;10;18;02;00;
2001;10;19;09;00320;2001;10;18;02;00;
2001;10;19;10;00350;2001;10;18;02;00;
2001;10;19;11;00389;2001;10;18;02;00;
2001;10;19;12;00551;2001;10;18;02;00;
2001;10;19;13;00751;2001;10;18;02;00;
2001;10;19;14;00983;2001;10;18;02;00;
2001;10;19;15;00886;2001;10;18;02;00;
2001;10;19;16;00802;2001;10;18;02;00;
2001;10;19;17;00730;2001;10;18;02;00;
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2001;10;19;19;00566;2001;10;18;02;00;
2001;10;19;20;00507;2001;10;18;02;00;
2001;10;19;21;00468;2001;10;18;02;00;
2001;10;19;22;00434;2001;10;18;02;00;
2001;10;19;23;00405;2001;10;18;02;00;
2001;10;19;24;00306;2001;10;18;02;00;
2001;10;19;25;00244;2001;10;18;02;00;
*
```


12

IEA 5 - 6 November 2001

Report by regions

Producción horaria prevista en MW, por Zonas
Fecha: 21-Sep-2001

ZONAS		13:00	14:00	15:00	16:00	17:00	...	C.I.r MW
Andalucía	...	6.238	6.74	5.19	3.64	2.09	...	105.0
Aragón	...	0.843	0.178	0.134	0.09	0.05	...	226.2
C.Val	...	0	0	0	0.011	0.034	...	2.6
C.la Manc	...	0.006	0.008	0.196	1.026	2.606	...	197.3
C. y León	...	0	0	0	0	0.001	...	221.9
Cataluña	...	8.098	8.227	8.227	8.227	8.227	...	59.5
Galicia	...	1.784	1.139	2.322	4.015	6.193	...	605.3
La Rioja	...	0	0.001	0.001	0.001	0.001	...	24.4
Murcia	...	0.368	0.368	0.368	0.368	0.368	...	12.5
Navarra	...	5.433	2.695	2.261	1.907	1.127	...	479.7
P. Vasco	...	0	0	0	0	0	...	24.4

IEA 5 - 6 November 2001

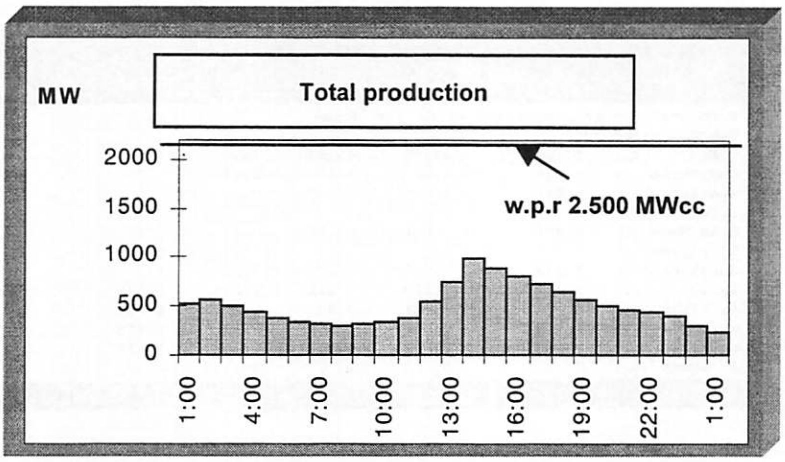
Reports by wind farms

Produccion horaria prevista en MW, por Parques
Fecha: 21-Sep-2001

PARQUE		13:00	14:00	15:00	16:00	17:00	...
KW Tarifa	...	1.25	0.833	0.417	0	0	...
PEESA	...	0.271	0.271	0.181	0.09	0	...
P.E. LOS LLANOS	...	2.28	2.28	1.778	1.275	0.256	...
P.E. Higueruela	...	0.002	0.002	0	0.167	0.538	...
P.E. BELEN II	...	0	0	0.098	0.207	0.316	...
Les Colladetes	...	3.339	3.339	3.339	3.339	3.339	...
C DE LA TEIXETA	...	4.158	4.158	4.158	4.158	4.158	...
P.E. OS CORVOS	...	0.051	0.051	0.099	0.146	0.194	...
P.E. Coriscada	...	1.223	0.848	1.223	1.597	1.972	...
P.E. Echague	...	0.78	0.531	0.277	0.024	0.018	...
P.E. Alaiz	...	0.696	0.662	0.776	1.175	1.094	...

IEA 5 - 6 November 2001

Total production



w.p.r : wind power registered

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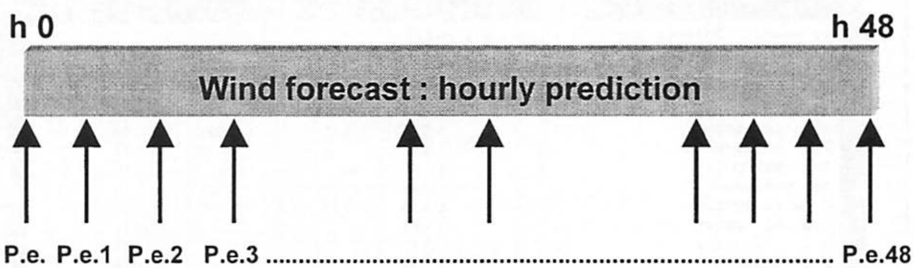
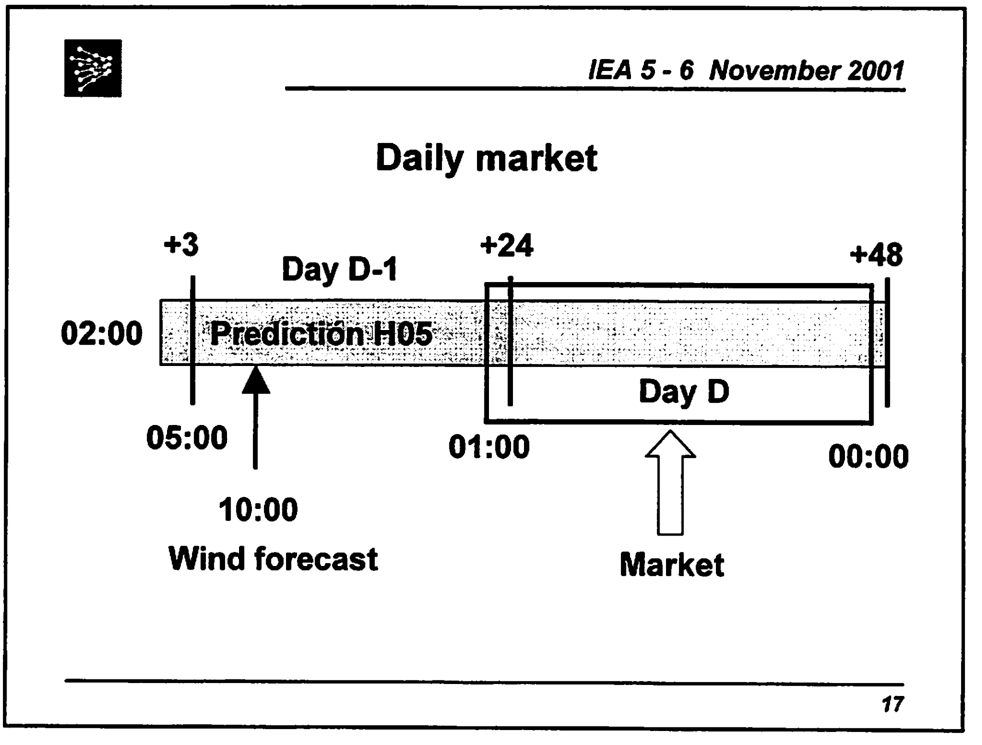
Wind predictions in the system operation



16


IEA 5 - 6 November 2001
Daily market
+3
Day D-1
+24
+48
02:00
Prediction H05
Day D
05:00
01:00
00:00
10:00
Wind forecast
Market
17

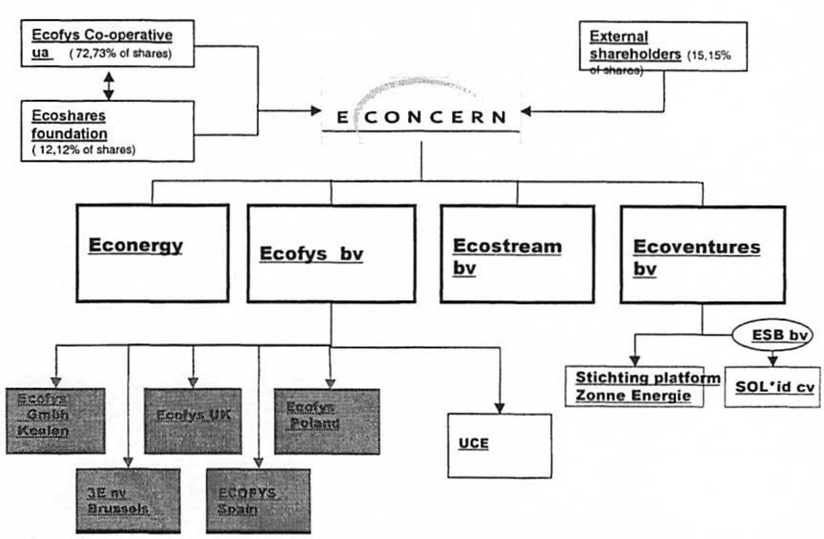
Grid integration design using prediction and control

Dr. K. Burges

ECO**FYS**, Utrecht (NL)

A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE

Ecofys



A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE

Overview

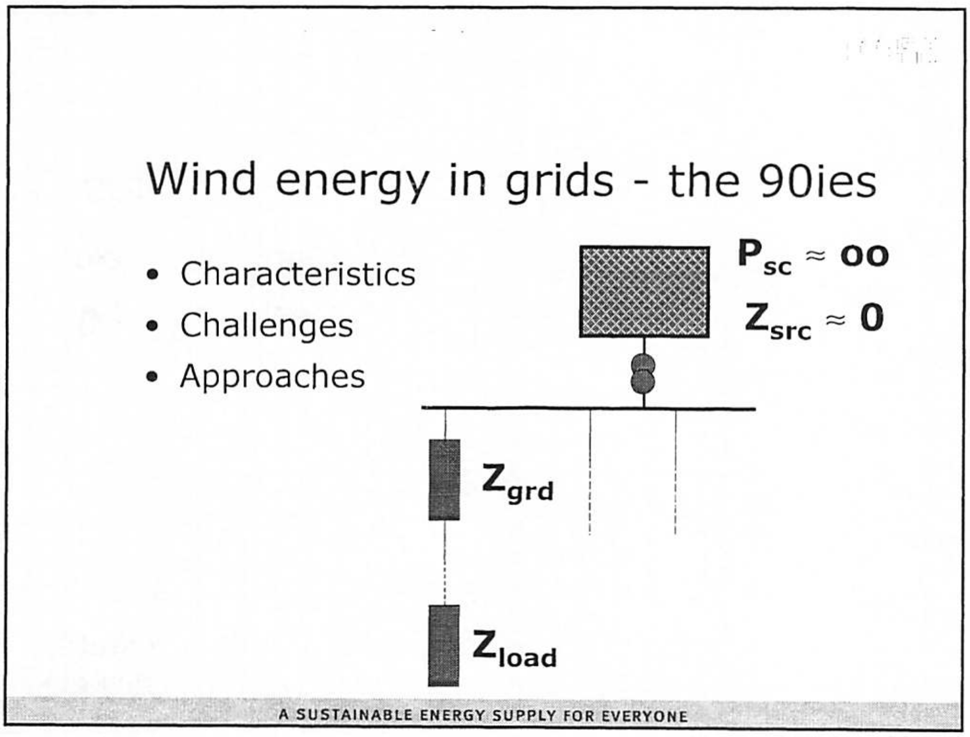
- Introduction
- Integration wind energy up to now
- Integration large wind farms
- Outlook

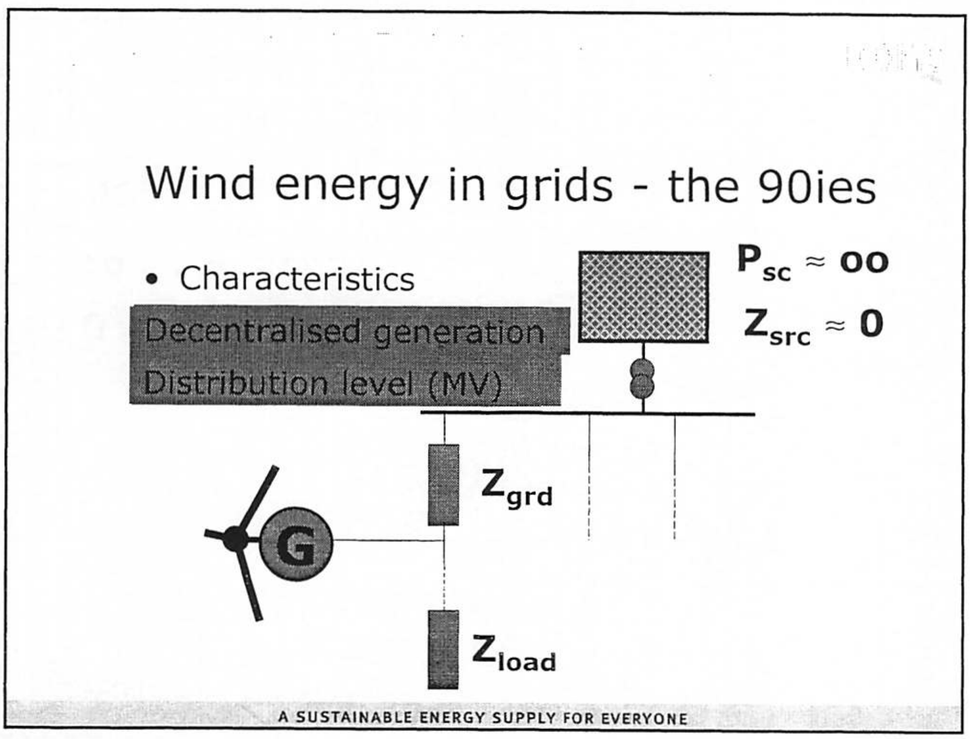
Framework conditions

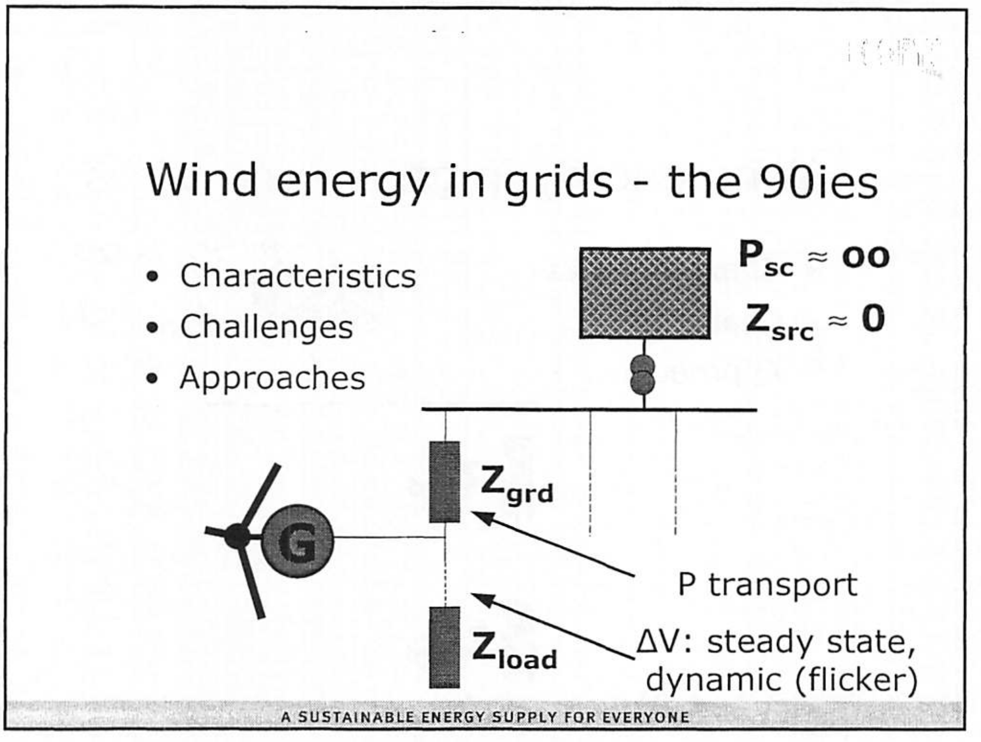
- Liberalisation
- Upcoming decentralised production

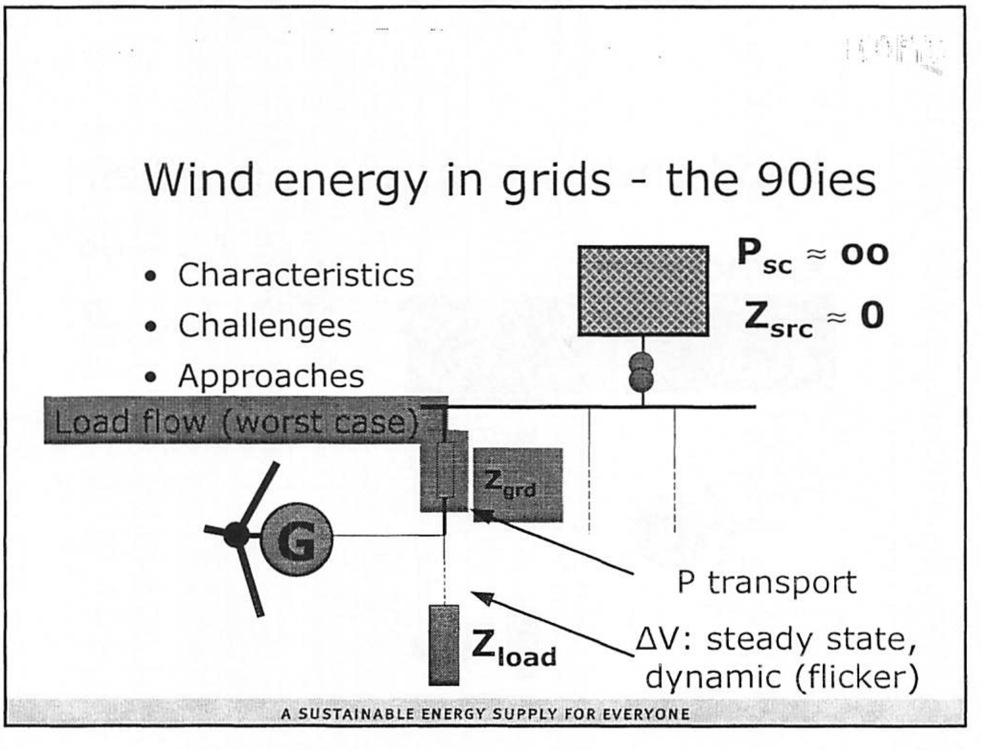
➢ From central dispatch to market optimisation

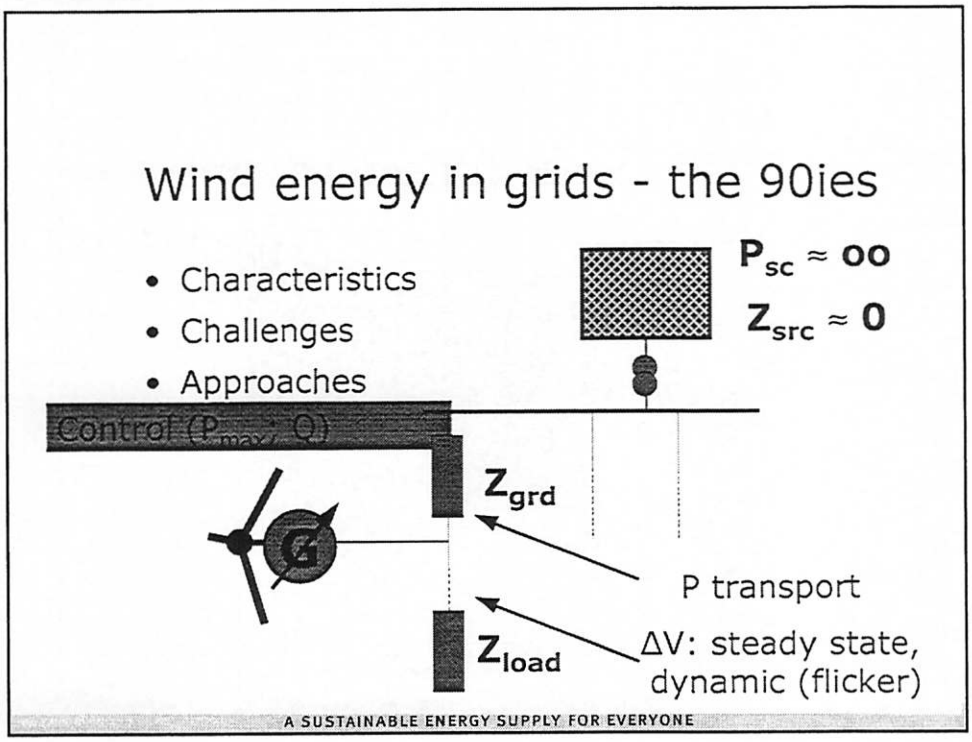
- Renewable energy??

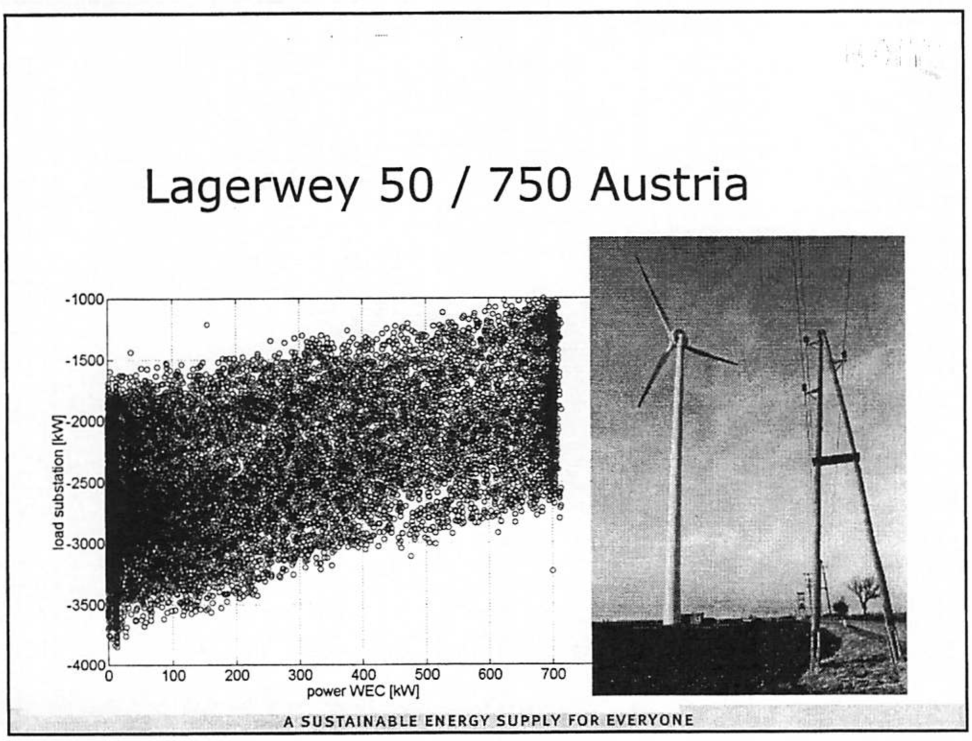

Wind energy in grids - the 90ies
• Characteristics
• Challenges
• Approaches
P_sc ≈ oo
Z_src ≈ 0
Z_grd
Z_load
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


Wind energy in grids - the 90ies
• Characteristics
Decentralised generation
Distribution level (MV)
P_sc ≈ oo
Z_src ≈ 0
G
Z_grd
Z_load
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE

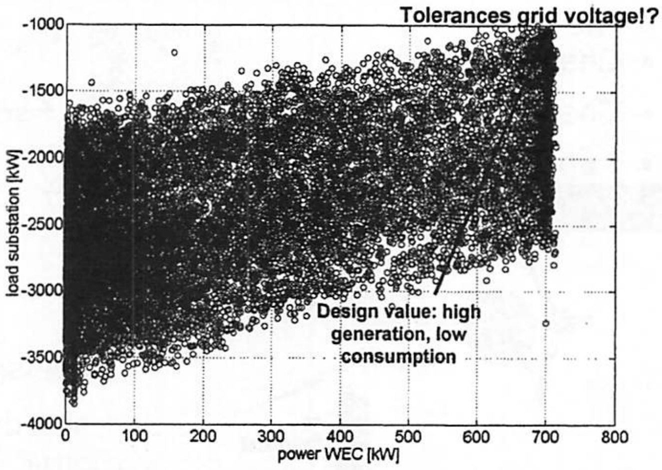

Wind energy in grids - the 90ies
• Characteristics
• Challenges
• Approaches
$P_{sc} \approx oo$
$Z_{src} \approx 0$
Z_{grd}
G
P transport
Z_{load}
ΔV: steady state, dynamic (flicker)
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


Wind energy in grids - the 90ies
• Characteristics
• Challenges
• Approaches
Load flow (worst case)
$P_{sc} \approx oo$
$Z_{src} \approx 0$
Z_{grd}
G
P transport
Z_{load}
ΔV: steady state, dynamic (flicker)
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


Wind energy in grids - the 90ies
• Characteristics
• Challenges
• Approaches
Control (P_{max}; Q)
$P_{sc} \approx oo$
$Z_{src} \approx 0$
Z_{grd}
G
P transport
Z_{load}
ΔV: steady state, dynamic (flicker)
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


Lagerwey 50 / 750 Austria
-1000
-1500
-2000
-2500
-3000
-3500
-4000
load substation [kW]
0
100
200
300
400
500
600
700
power WEC [kW]
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE

Conventional considerations



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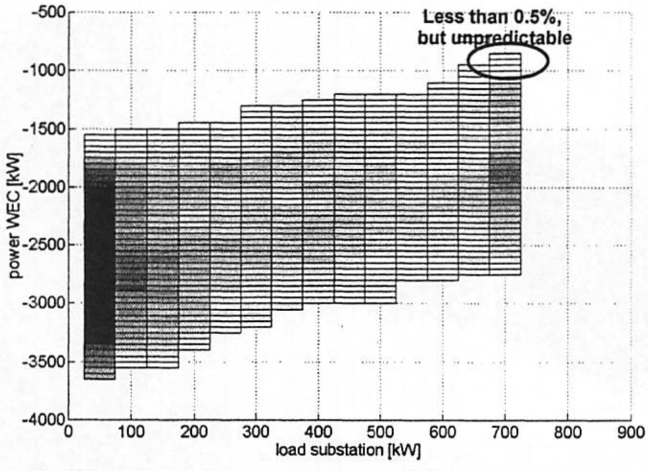
Optimal?



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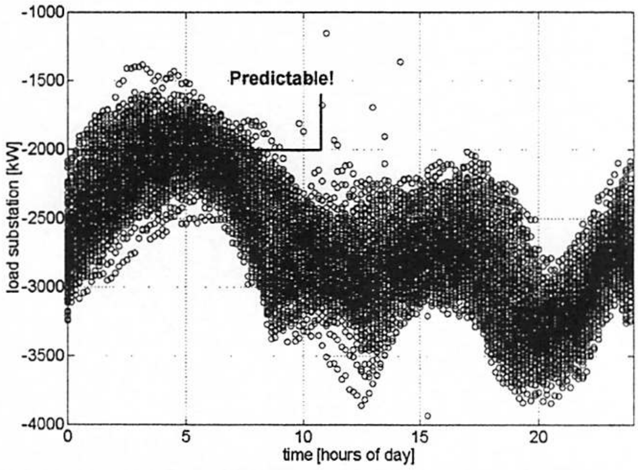
Prediction and control



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Optigrid - applied knowledge

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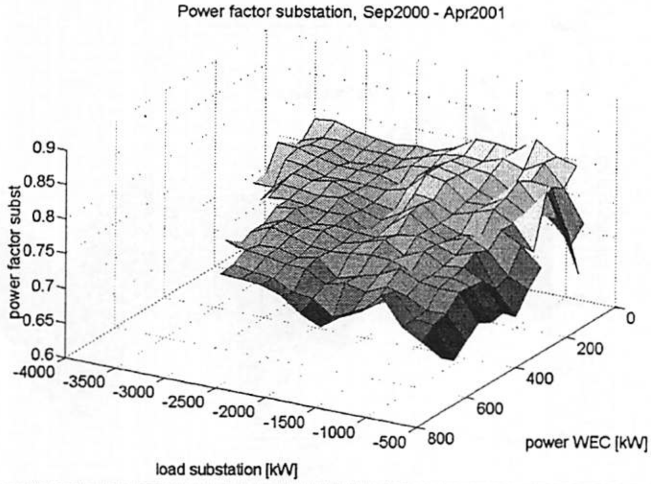
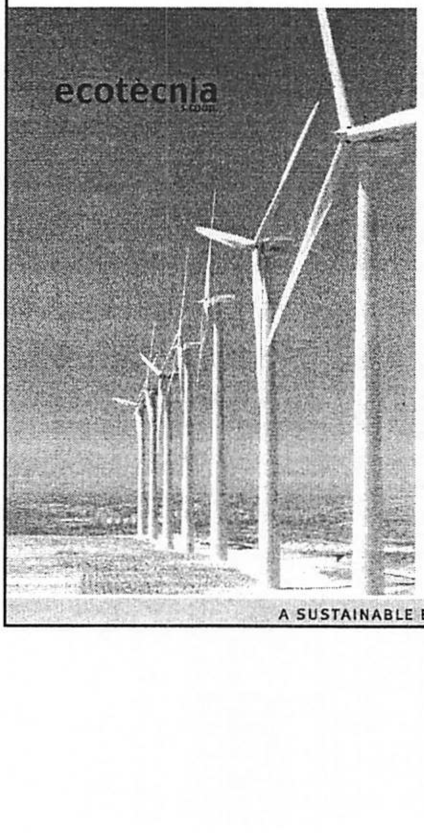
Extended opportunities



A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE



Novogrid

- Wind farm with 15 conventional and 10 variable speed
- control criteria power factor, flicker, ...?

NovoGrid

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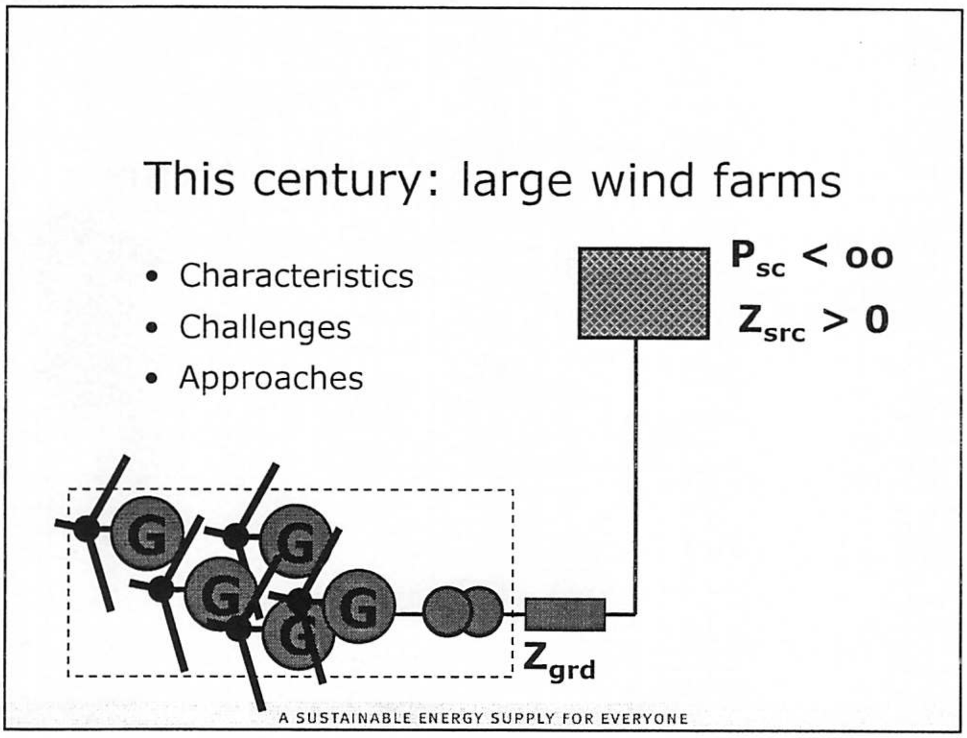
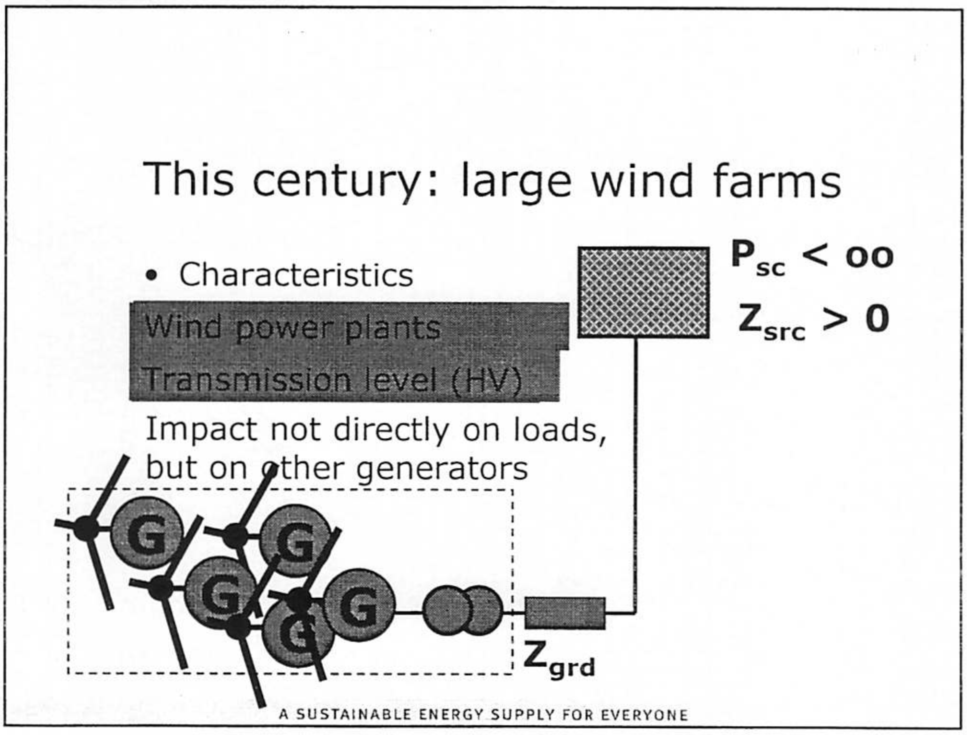
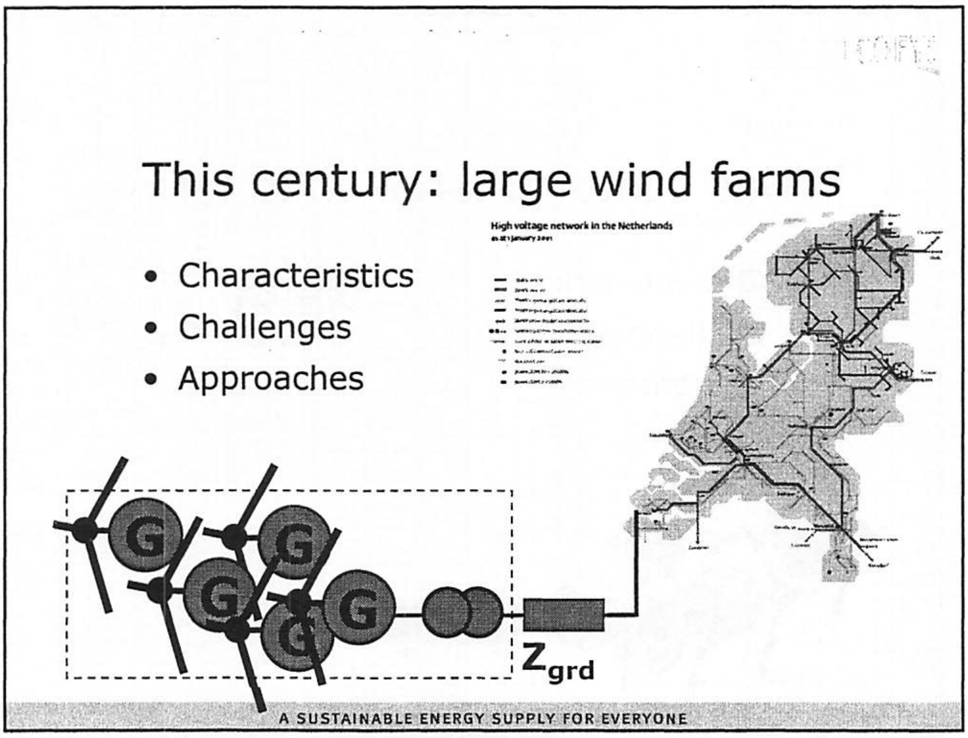
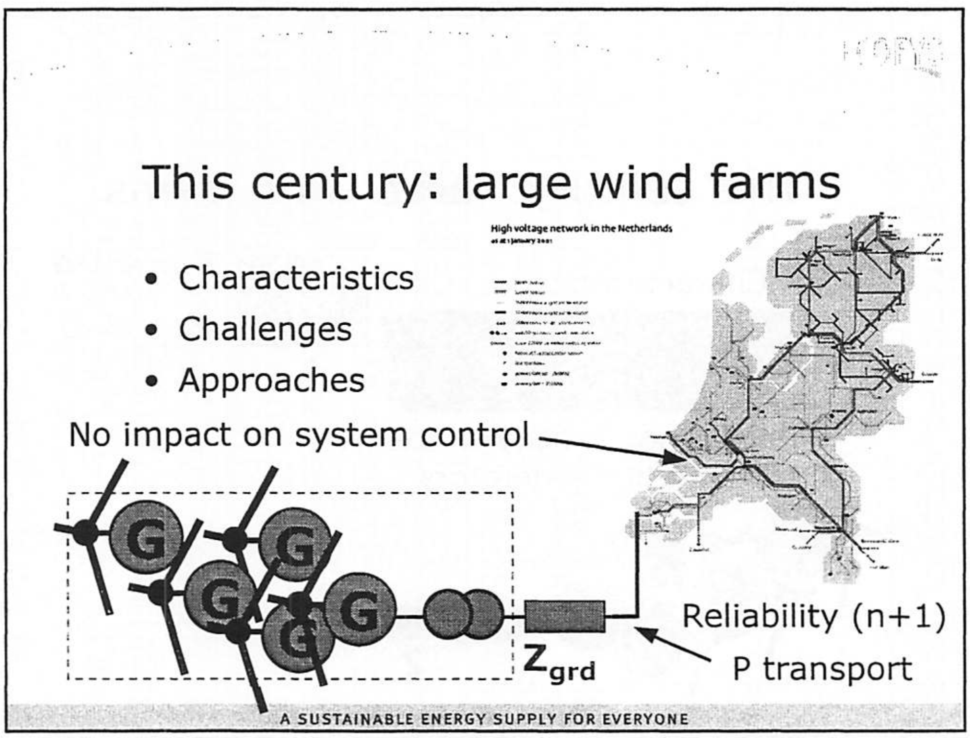
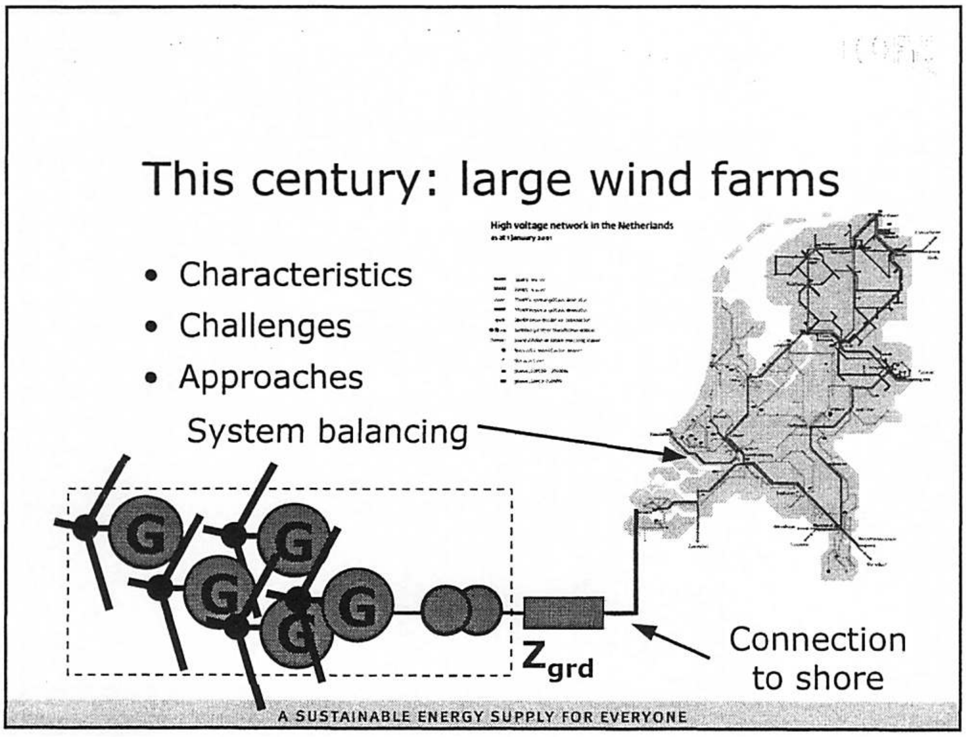
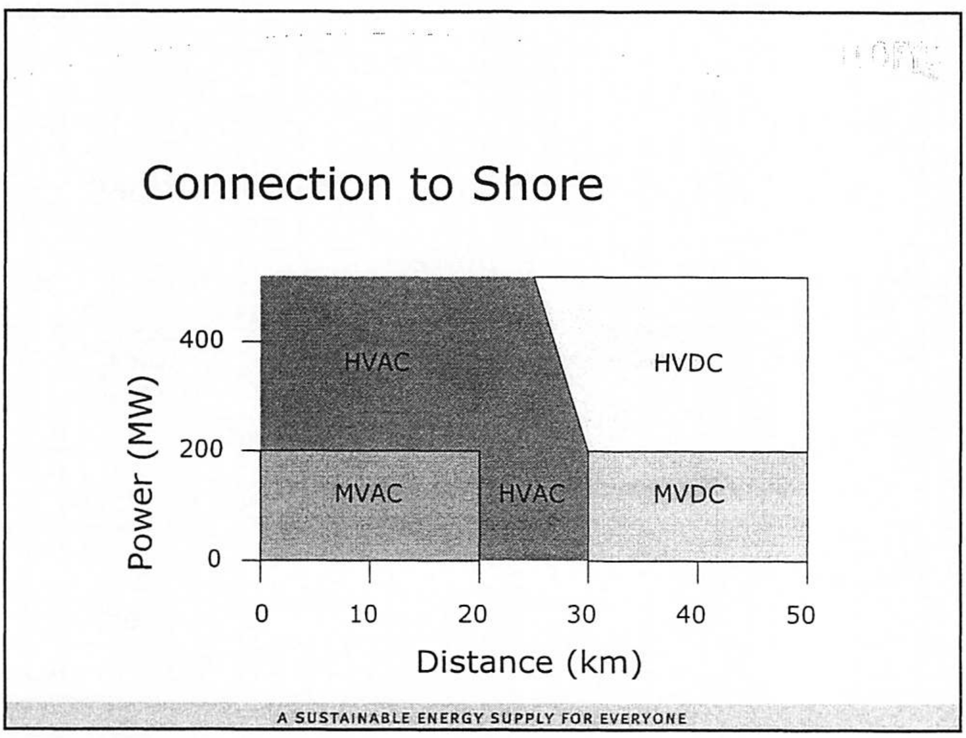

This century: large wind farms
• Characteristics
• Challenges
• Approaches
P_{sc} < oo
Z_{src} > 0
G
Z_{grd}
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


This century: large wind farms
• Characteristics
Wind power plants
Transmission level (HV)
Impact not directly on loads, but on other generators
P_{sc} < oo
Z_{src} > 0
G
Z_{grd}
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


This century: large wind farms
High voltage network in the Netherlands
• Characteristics
• Challenges
• Approaches
G
Z_grd
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


This century: large wind farms
High voltage network in the Netherlands
• Characteristics
• Challenges
• Approaches
No impact on system control
G
Z_grd
Reliability (n+1)
P transport
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


This century: large wind farms
• Characteristics
• Challenges
• Approaches
System balancing
G
Z_grd
Connection to shore
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


Connection to Shore
HVAC
HVDC
MVAC
HVAC
MVDC
Power (MW)
0
200
400
0
10
20
30
40
50
Distance (km)
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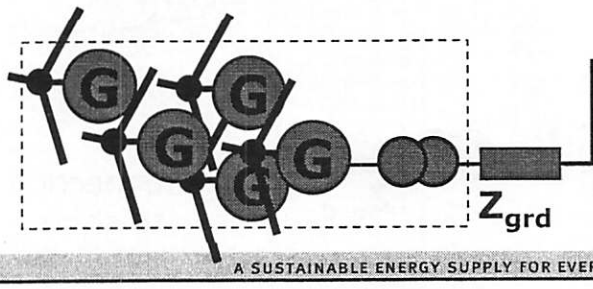
System balancing

- Negative load
- Predicted capacity (with ΔP)
- Predicted capacity with control features



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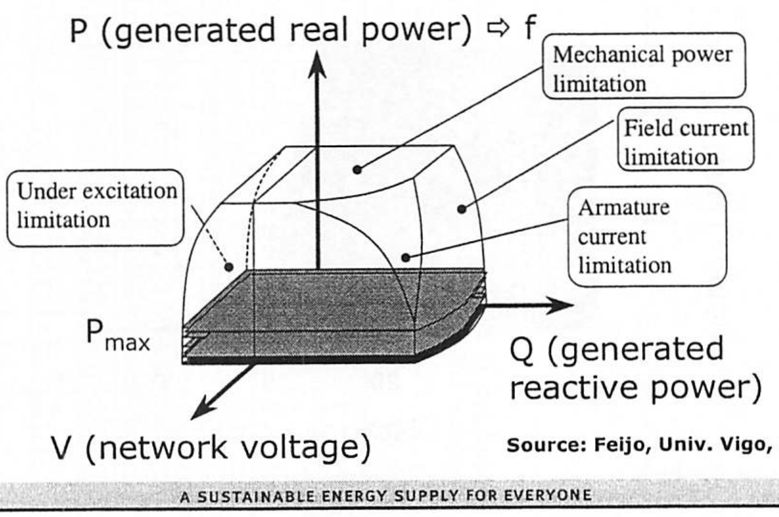
Control synchronous generators



Source: Feijo, Univ. Vigo, 2001

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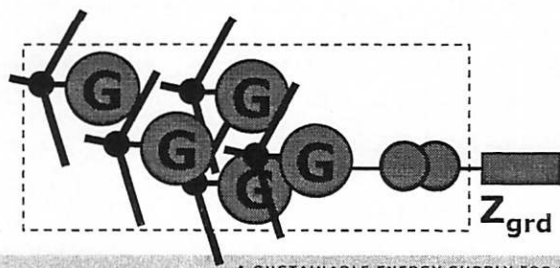
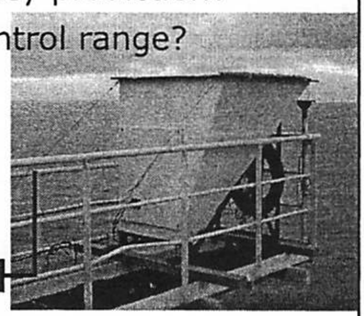
Wind farm control

- Q, V
- P_{36h} (steady state): accuracy prediction?
- P_{60s} (dynamic control): control range?





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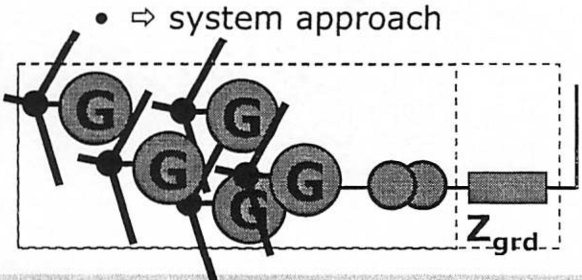
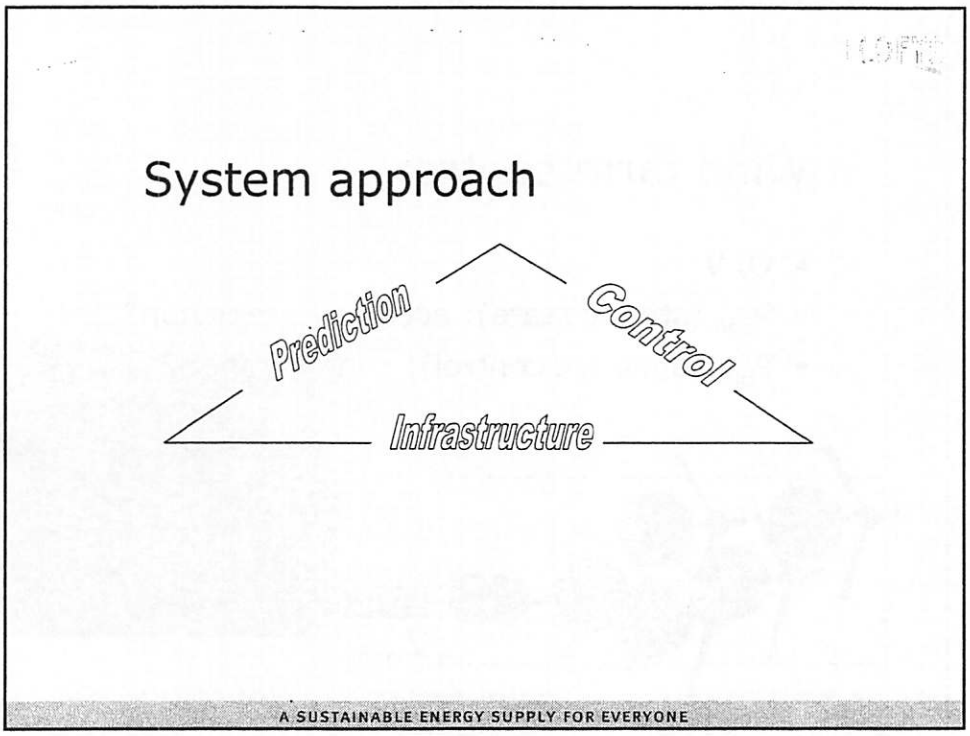
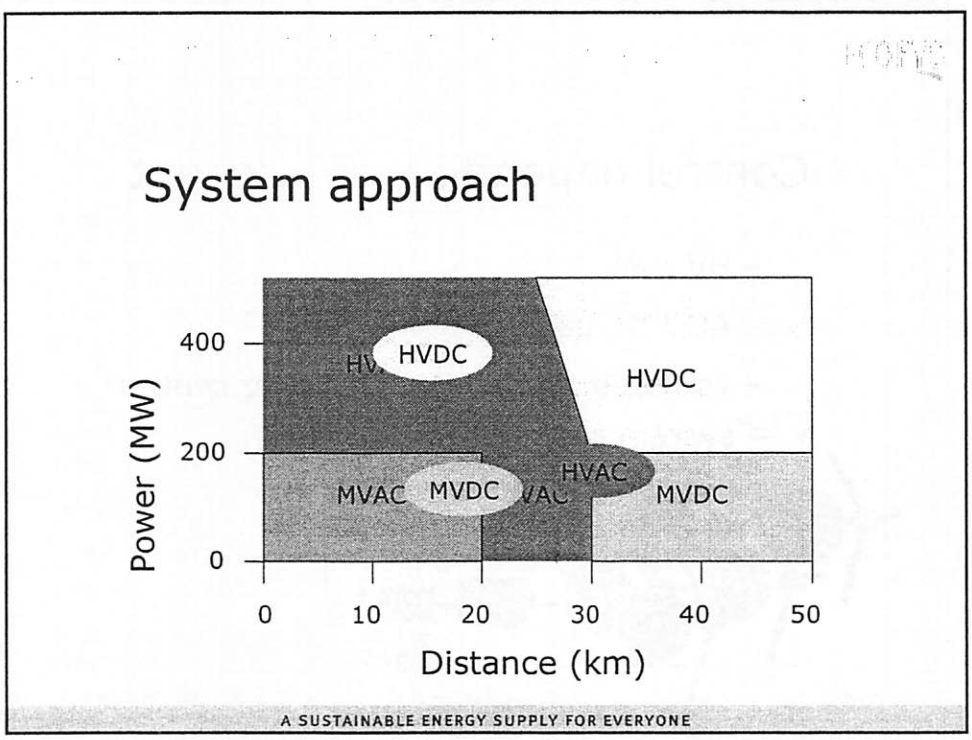
Control depending on concept

- – HV / MV
- – AC / DC cable,
- – vs WECs with electronic power control?
- ⇨ system approach



A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


System approach
Prediction
Control
Infrastructure
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE


System approach
400
200
0
Power (MW)
HVDC
HVDC
HVAC
MVAC
MVDC
MVDC
0
10
20
30
40
50
Distance (km)
A SUSTAINABLE ENERGY SUPPLY FOR EVERYONE

Future: multi-source integration

- Ecopark Waalwijk (multi-party mixed technology)
- wind: 7.5 MW; PV: 800 kW; landfill gas

Economic performance

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Dynamic Modeling, Grid Impact and Large Scale Integration of Wind Turbines

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Aspects of grid integration

- Power quality impact - Only important in weak OH-line grids with small utilities
- Protection of wind turbine and grid - robustness towards grid disturbances
- Controllability - reactive power control sufficient locally ?
  Communication between power system components
- Controllability - active power control?
  Communication between power system components
- Cost (Connection, Reduction/increase of local grid losses)
- DC-connection of large sea-based wind parks

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Dynamic Modelling of Wind Turbines

Examples of application:

- •Determine loads and stresses on the turbine
- •Derive rotor speed control systems (high E capture + low stresses)
- •Determine power quality impact
- •Determine voltage stability impact
- •Determine stresses on grid, conv, gen and drive train at fault conditions

Verification extremely important !!!

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Composition of the model:

- •Which phenomena needs to be included ?
- •Which timescale am I working with ?
- •How much time can the model use to calculate the results ?
- •Can I investigate the built-in modules, do I trust them ?
- •Critically analyze the results !

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Important parts of wind turbine models

Wind field: wind shear, turbulence (temperature profile, terrain, moisture, coherence, low-level jets, wakes ...)

Aerodynamic conversion: blade profile (2D/3D) dynamic hysteresis,

Drive train: Blade, HUB, primary shaft, gearbox, secondary shaft, generator, suspension of components

Wind turbine structure: tower, nacelle

Generator: Saturation, non-sinusoidal effect, iron losses, skin effect

Generator control system: flux, speed & position sensing, control algorithm, non-idealities of power electronic valves

Grid connection: Transformer, line capacitance, resistance and inductance

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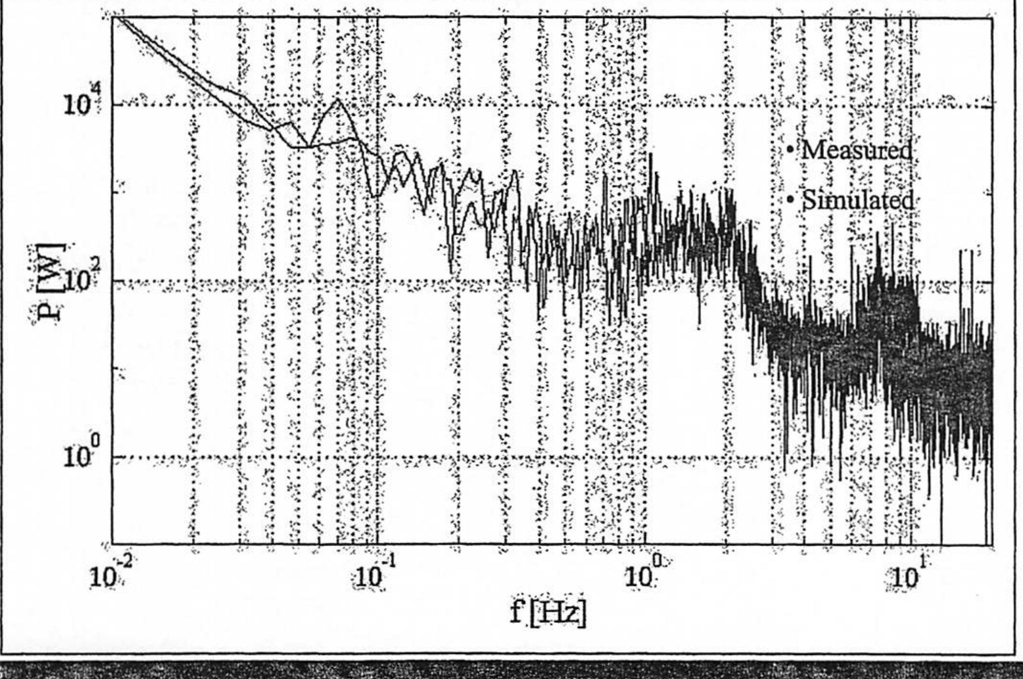
Comparison of measured and calculated power from a stall-regulated WEC



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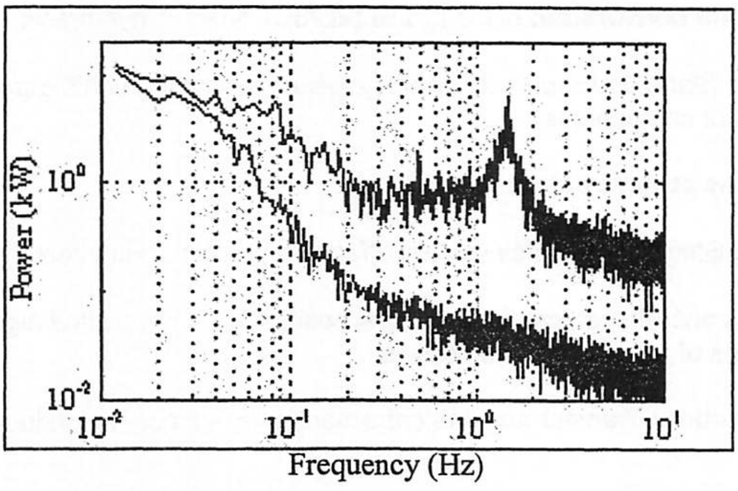
Comparison of spectrum of the output power at fixed and variable speed



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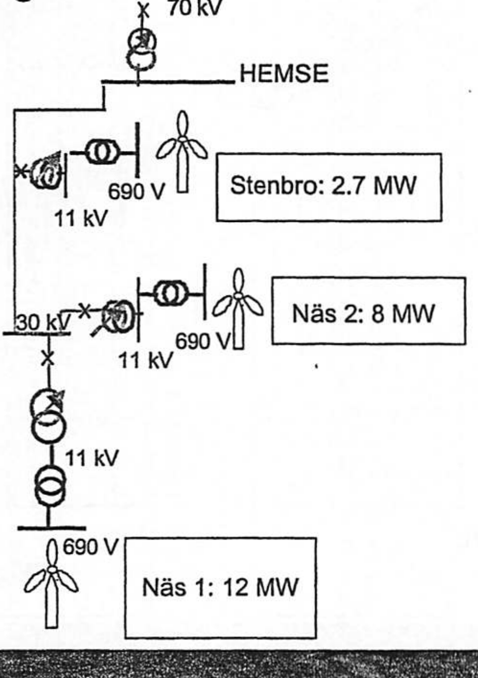
Southwestern Gotland grid summer 1999



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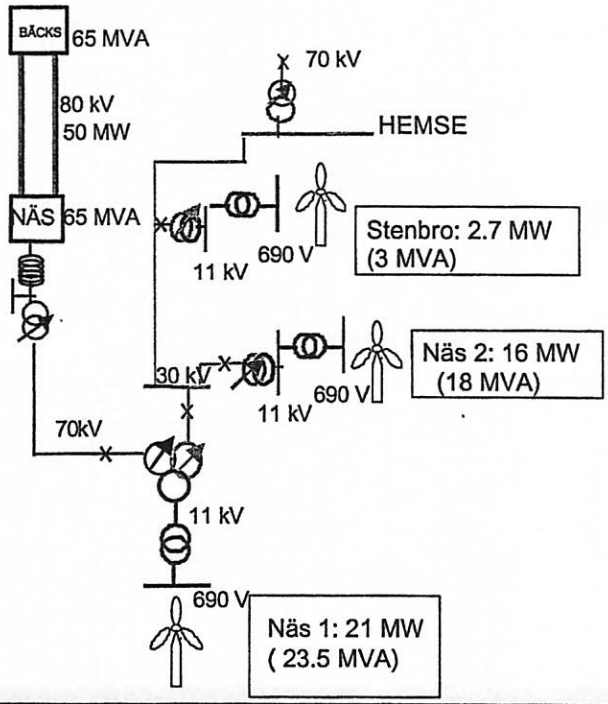
Southwestern Gotland grid summer 2000



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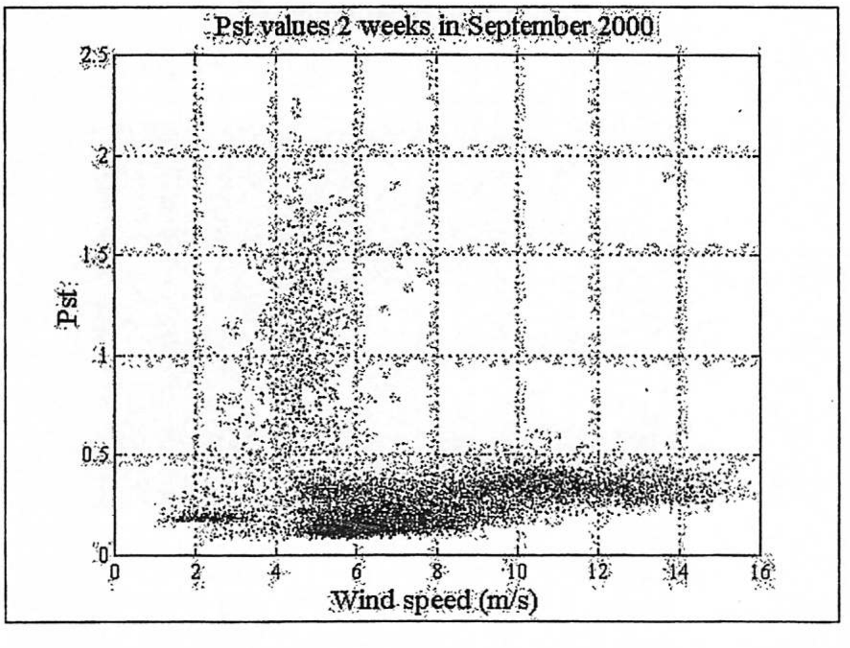

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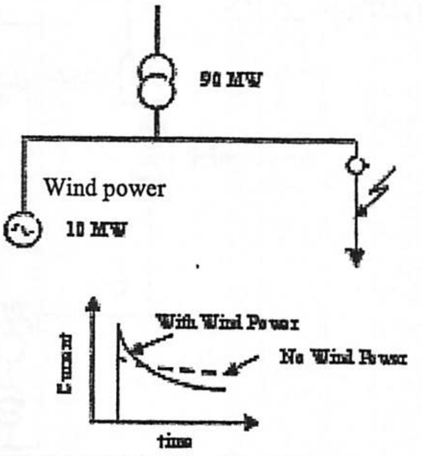
Changes in fault current due to wind power

* 30 % higher fault current

* Protective equipment not operate correctly



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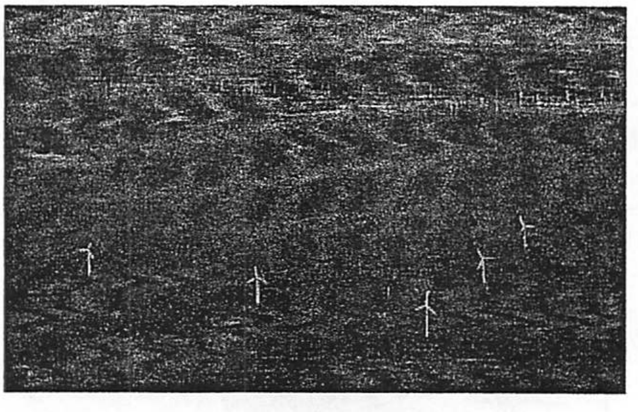
Bockstigen windpark

specially designed for a weak 10 kV grid



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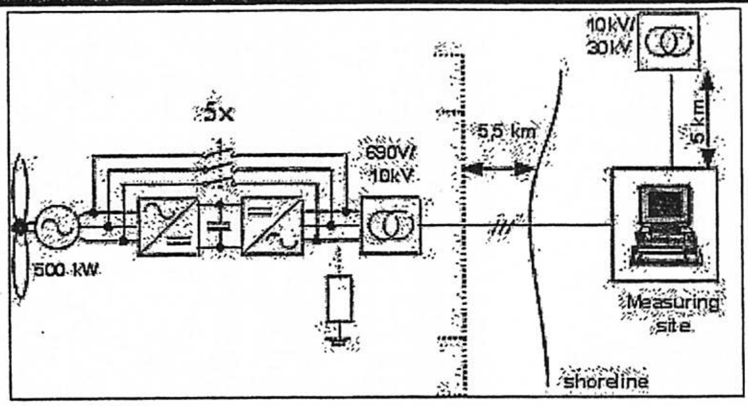
System layout



Operational mode

- Variable Speed System < 100kW
- 100kW < Fixed Speed System + Antiflicker algorithm DQ = k DP

Control objectives

- voltage level control = below 11 kV
- minimise voltage fluctuations
- minimum reactive power consumption

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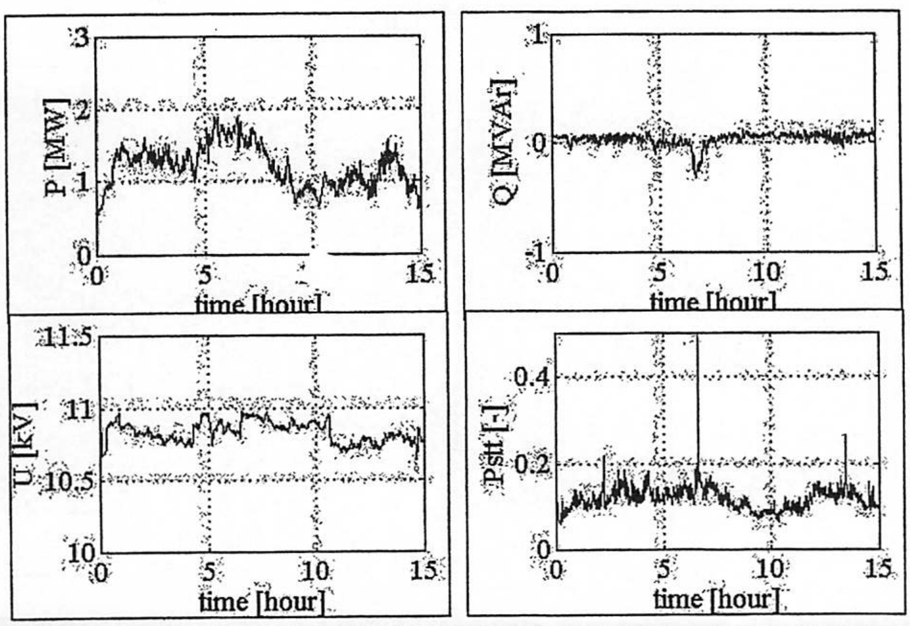
Operation at medium wind speed



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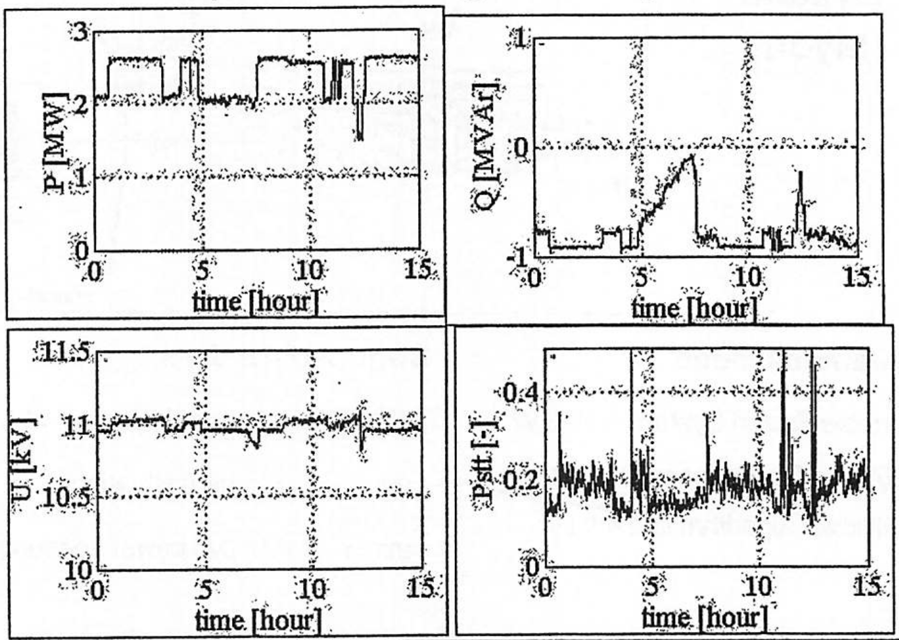
Operation at high wind speed



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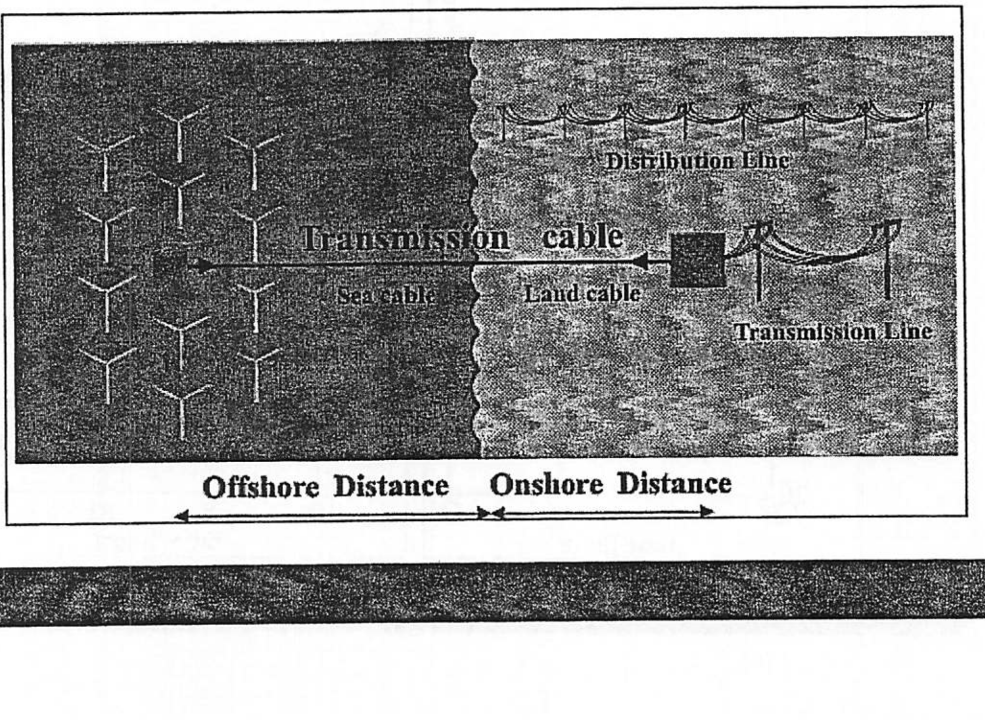
DC Grid for Wind farms 1

Distances



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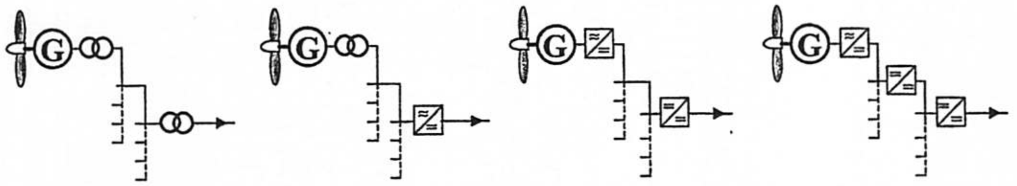
DC Grid for Wind farms 2
Configurations



Today's system *AC bus* *DC bus* *Multiple level DC*

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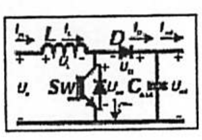
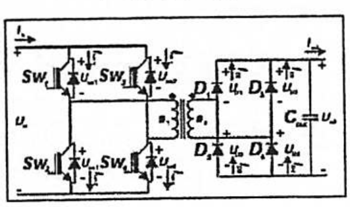
DC Grid for Windfarms 3
Topologies

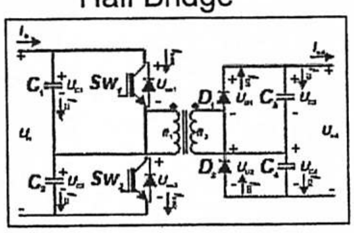
Boost



Full Bridge



Half Bridge



Voltage adjustment converter

DC/DC Transformers

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Advantages with HVDC

- **Asynchronous connection**
- **Control of power flow**
- **Improvement of power system stability**
- **No increase of short circuit currents**
- **Smaller and less costly transmission lines**
- **Lower losses for long distance transmissions**

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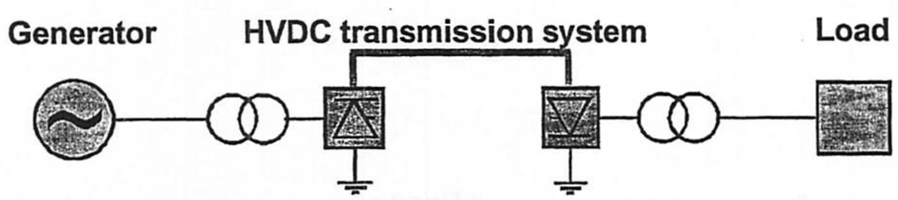
HVDC characteristics



Why use HVDC instead of AC?

- **Decrease total cost for long distance power transmission with overhead lines or cables**
- **Connect AC systems asynchronously**
- **Fast and accurate control of the power flow**

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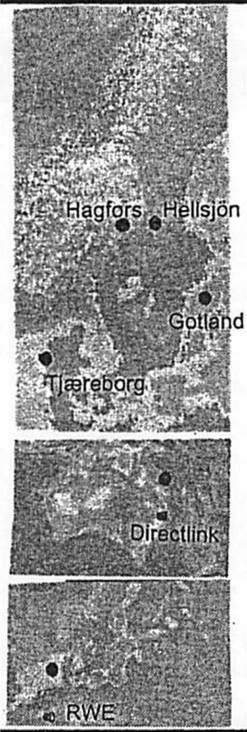

HVDC/SVC Light projects

Project	Rating	Dist.	Application	Ordered
Hellsjön	3 MW	10 km	Converting AC to DC AC network connection	April 1994
Hagfors	± 22 MVAr	-	Flicker mitigation	April 1997
Gotland	50 MW	70 km	Wind power Underground cable	Dec 1997
Tjære- borg	7 MW	4 km	Wind power Underground cable	June 1998
Directlink	180 MVA	65 km	Inter connection Underground cable	Dec 1998
RWE Energie	0-38 MVAr	-	Flicker mitigation	April 1999

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Remarks

Grid integration is becoming more important as more wind turbines are being connected

In order to determine grid influence (power quality, stability, fault conditions) good models are needed

More measurements in combination with analysis needed

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V. Akhmatov, A.H. Nielsen, *Fixed-speed active-stall wind turbines in offshore applications*, in Proceedings of Topical Expert Meeting on Large scale integration into the grid, IEA R&D Wind Annex XI, 6-7 November 2001, Hexham, Near Newcastle, Great Britain.

FIXED-SPEED ACTIVE-STALL WIND TURBINES IN OFFSHORE APPLICATIONS

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Abstract: *The first large offshore wind farm in the Eastern Danish power system will be constructed at Rødsand by the year 2003; its power capacity is 150 MW. For this large offshore application, the robust and known wind technology has been chosen – fixed-speed active-stall wind turbines equipped with induction generators. In this paper, topics dealing with maintaining and improving voltage stability are discussed and systematised in terms of this wind technology.*

Keywords: *Wind power, voltage stability, active-stall, windmill parameters, PSS/E.*

1. Introduction

In Denmark the construction of a number of large offshore wind farms is announced, as shown in Fig. 1.

The first large offshore wind farm connected to the Eastern Danish transmission power system will be commissioned by the year 2003 and have the power capacity 150 MW [1]. For the wind farm, the robust and known from existing settings wind technology is chosen – fixed-speed active-stall wind turbines equipped with induction generators with a shorted rotor circuit from the Danish manufacturer Bonus Energy A/S.

The amount of grid-connected wind power on-land and small, but many, combined heat-power units has increased drastically during last few years where the power capacity of the windmills on-land will be around 400 MW and the similar power capacity of the combined heat-power units is expected. These counts have to be seen with respect to the power system size of around 4000 MW [1] where the minimum and maximum loads over a year are 750 MW and 3000 MW, respectively. The power production from the large thermal power plants and, then, their control ability with respect to voltage and frequency will be reduced.

Further, the wind power is constructed intensively in south, but the consumption is in north of the Eastern Danish power system why the power transport through long distances will be in the power system.

This situation makes it necessary to find solutions with respect to maintaining dynamic stability of the power system with large amount of wind power and its reliable operation.

These solutions shall be based on the Specifications for Connecting Wind Farms to the Transmission Network [2] formulated by the Danish power system operators with respect to operation of the large offshore wind farms and the entire power system in case of failure events in the entire system. In accordance with the Specifications [2], the voltage stability at a short circuit fault in the entire power system shall be maintained without any sub-sequential disconnection of the large offshore wind farms. Establishing of dynamic reactive compensation of the large offshore wind farms will be, therefore, necessary.

Fig. 1. Incorporation of wind power in Eastern Danish power system, the counts are collected in table below:

Mark	Wind Farm	Year	Capacity
1.	Middleground	2001	40 MW
2.	Rødsand	2003	150 MW
3.	Omø Stålgrunde	2005	150 MW
4.	Gedser Rev	2008	150 MW
	On-land settings	2001-2008	400 MW

The amount of the dynamic reactive compensation depends on several factors with respect to the wind turbine parameters and their control ability. This subject is explained in this paper.

2. Fixed-speed wind turbines

The fixed-speed active-stall wind turbines are treated as complex electromechanical systems and the model used in dynamic stability investigations is given by [3, 4]

a. the induction generator model with stator transients,

V. Akhmatov, A.H. Nielsen, *Fixed-speed active-stall wind turbines in offshore applications*, in Proceedings of Topical Expert Meeting on Large scale integration into the grid, IEA R&D Wind Annex XI, 6-7 November 2001, Hexham, Near Newcastle, Great Britain.

b. the model of the drive-train system,
c. the model of the rotating wind turbine,
d. the active-stall control system by the generator speed with the blade servo.

The model of the wind turbine equipped with the conventional induction generator been defined in [3] is reproduced in Fig. 2 and the model of the active-stall control system is set up in accordance with [5] and includes the PD and PI controllers, as shown in Fig. 3. The active-stall control system is with respect to the sampled value of the generator speed and other delay mechanisms in the control system are implicit included in the model. The blade servo is simulated as the first order system. The model is implemented in the dynamic tool PSS/E.

3. Wind farm model

The fixed-speed active-stall wind turbines will be installed offshore about 20 km from the coast, south to the Danish island of Lolland. The induction generators of the wind turbines are no-load compensated and through the 0.7/30 kV transformers connected to the wind farm internal network (30 kV). Through the tertial 30/30/132 kV transformer and the 136 kV sea/ underground cable, the wind farm, will be ac-connected to the transmission power system (132 kV) of the Eastern Denmark with establishing of dynamic reactive compensation in the connection point, as shown in Fig. 4.

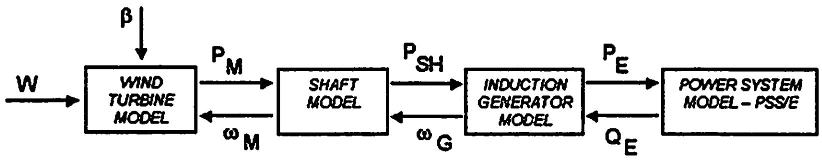


Fig. 2. The model of fixed-speed wind turbines equipped with induction generators, in accordance with [3]: W is the incoming wind, β is the blade angle, ω_M is the rotational speed of the wind turbine, P_M is the mechanical power defined by $P_M = ½\rho{\cdot}W^3{\cdot}A{\cdot}C_P(\lambda,\beta)$ with the power efficiency C_P and the tip-speed ratio λ, ρ is the air density, A is the swept area, P_{SH} is the shaft power, ω_G is the generator rotor speed, P_E is the electric power supplied to the grid, and Q_E is the reactive power absorbed by the induction generator (no-load compensated).

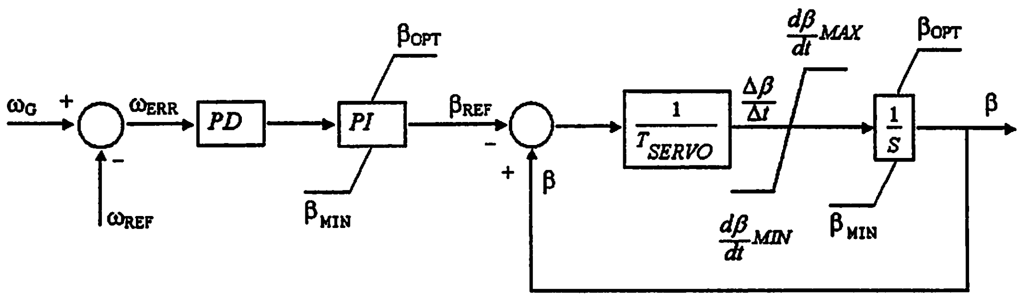


Fig. 3. Active-stall control system by the speed and the blade servo model: ω_{REF} is the reference speed, β_{REF} is the reference angle, β_{OPT} is the optimal at the given wind blade angle, $d\beta/dt$ is the pitch rate, T_{SERVO} is the servo constant.

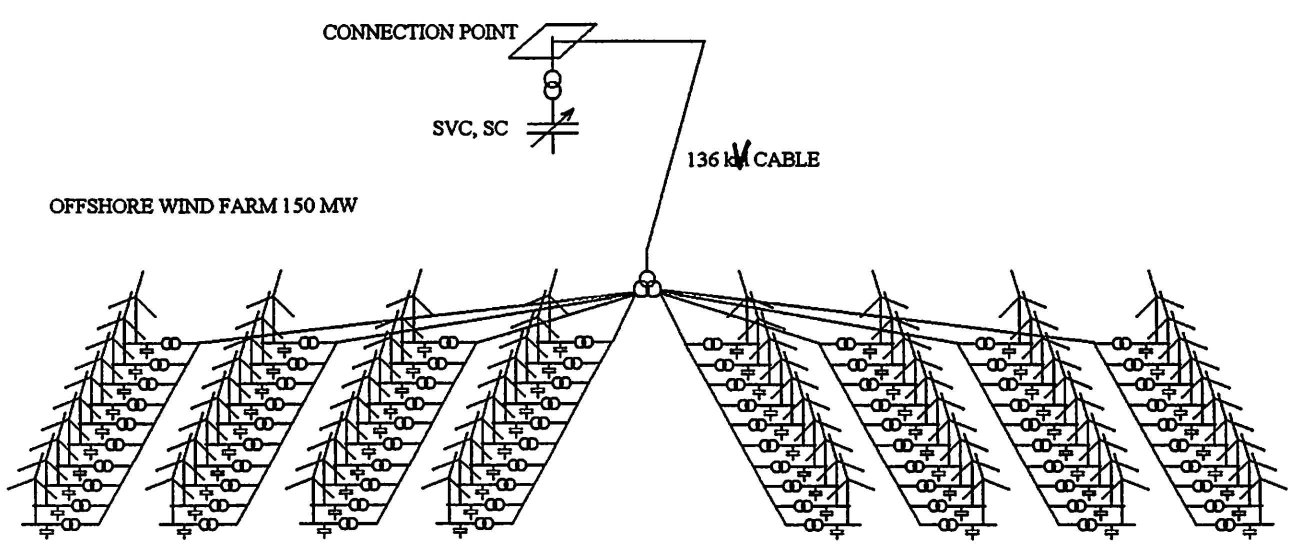


Fig. 4. Construction of the large offshore wind farm of 80 wind turbines.

V. Akhmatov, A.H. Nielsen, *Fixed-speed active-stall wind turbines in offshore applications*, in Proceedings of Topical Expert Meeting on Large scale integration into the grid, IEA R&D Wind Annex XI, 6-7 November 2001, Hexham, Near Newcastle, Great Britain.

An SVC unit, a synchronous condensor (SC) or a combined solution consisting of a unit with continuous reactive power control and a number of discrete thyristor-switched elements will be chosen as dynamic reactive compensation. In [4] it is found that SVC and SC have similar control abilities with respect to maintaining voltage stability at a short circuit fault in the entire power grid.

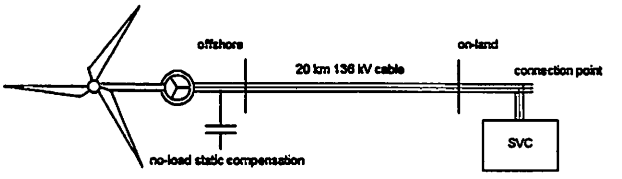
The dynamic reactive compensation unit will be constructed in the connection point on-land, what means somewhere 20 km away from the wind farm. This implies that the capacity of the compensation unit can be extremely large, if the wind turbines have no control ability with respect to maintaining voltage stability or their construction is not optimised.

4. Improving voltage stability

First at all, the wind turbines (the wind technology and its realisation) to be chosen for large-scale applications shall fulfil *the specifications for the grid-connection defined by the local system operator.* In case of Denmark, this is the Specifications [2]. The technical solution to be chosen shall be robust, known from previous practical operation and relatively cheap. When using the wind technology with conventional induction generators with a short-circuited rotor for large applications, the reactive power demands of the generators at and after a short-circuit fault shall be covered by the compensation units. This is necessary for re-establishing the voltage profile in the power system after the fault.

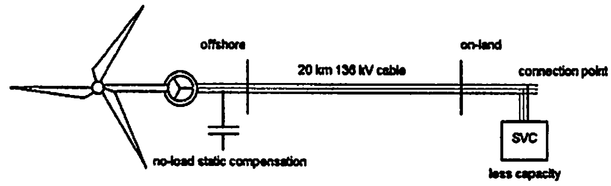
The capacity of the dynamic reactive compensation unit that is necessary for maintaining voltage stability depends on the wind turbine parameters and on the control ability of the wind turbines. Reducing the dynamic reactive compensation demands or replacing the continuous control of large capacity by a less number of the discrete thyristor-switched compensating elements will normally lead to reducing the total cost of the project.

4.1. Stall-controlled wind turbines



As the simplest, quick solution, "passive" stall-controlled wind turbines equipped with induction generators can be chosen for large-scale applications. When the wind turbine construction is not optimised with respect to improving voltage stability and the dynamic reactive compensation unit is grid-connected electrically seen far from the wind turbine generators, the capacity of the compensating unit will be large. It may have sense to investigate if the compensation unit can be made as a combination of continuous-controlled and discrete thyristor-switched elements for reduction of the project cost.

4.2. Wind turbine parameters

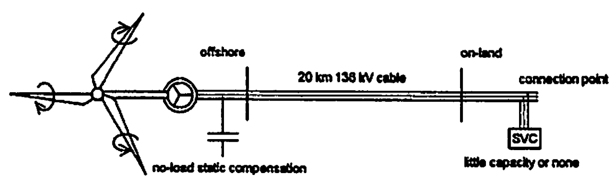


The capacity of the dynamic compensation unit that is necessary for maintaining voltage stability at and after a short circuit fault in the power grid depends on the wind turbine parameters. In other words, the wind turbine parameters can be optimised for improving voltage stability. As demonstrated in [6], this can be achieved by:

a. Increasing the rotor resistance,
b. Reducing the stator reactance, the magnetising reactance, the rotor reactance and the stator resistance, and
c. Enforcing the mechanical construction in means of increasing the mill inertia, the generator inertia and the stiffness of the shaft system.

These arrangements will lead to significant reduction of the dynamic reactive compensation demands.

4.3. Blade angle control



The capacity of the dynamic compensation unit that is necessary for re-establishing the voltage after a short circuit fault in the power grid depends on the control ability of the wind turbines as well. Blade angle control, in this case active-stall control, used for temporary reduction of the mechanical power of the wind turbines at a short circuit fault is found to be a very power tool for improving voltage stability. This relation is firstly discovered, described and explained by *Vladislav Akhmatov* in [7, 8]. This control ability, when used at disturbances in the power system, will significantly reduce demands of dynamic reactive compensation. The compensation unit can be so small that this can be arranged as a couple of discrete thyristor-switched elements. If the power system is strong enough, the dynamic reactive compensation can be even avoided so that the control ability of active-stall is enough for the voltage re-establishing. In practical solution, a little compensation unit will be used as a back-up for the control ability of the wind turbines.

The temporary reduction of the mechanical power at a short circuit fault using active-stall control can be achieved by:

V. Akhmatov, A.H. Nielsen, *Fixed-speed active-stall wind turbines in offshore applications*, in Proceedings of Topical Expert Meeting on Large scale integration into the grid, IEA R&D Wind Annex XI, 6-7 November 2001, Hexham, Near Newcastle, Great Britain.

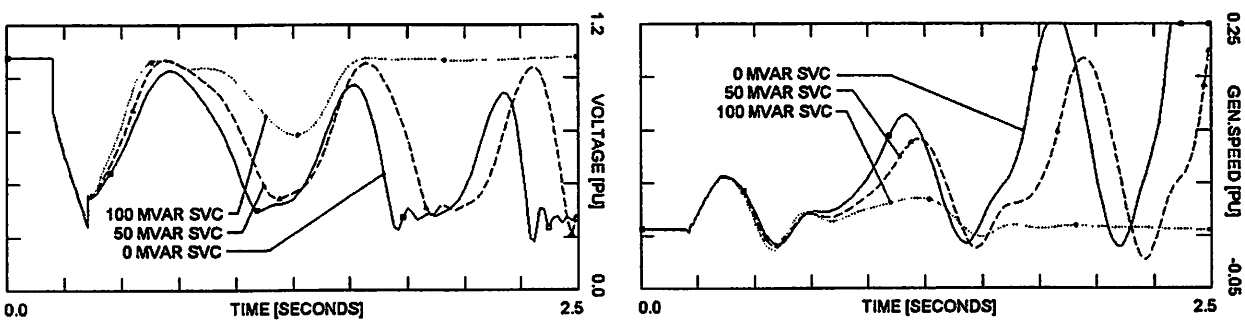
a. Continuously control of the blade angle position by the generator rotor speed as shown in Fig. 3, or
b. Ordering by the external signal, as described in the Specifications [2]. In accordance with the Specifications [2], the offshore wind farm shall be able to reduce its power production from an arbitrary level to less than 20% of its power capacity during less than 2 s by an external signal.

Simulated curves illustrating the control ability of active-stall for the voltage stability at a short circuit fault are given in Fig. 5. The both routines for the temporary power reduction by use of the active-stall control are investigated. The pitch rates are kept in the range of $-3°/s < d\beta/dt < 3°/s$, as in case of normal operation of the active-stall wind turbines. Faster pitch rates are used for safety stop of the wind turbines.

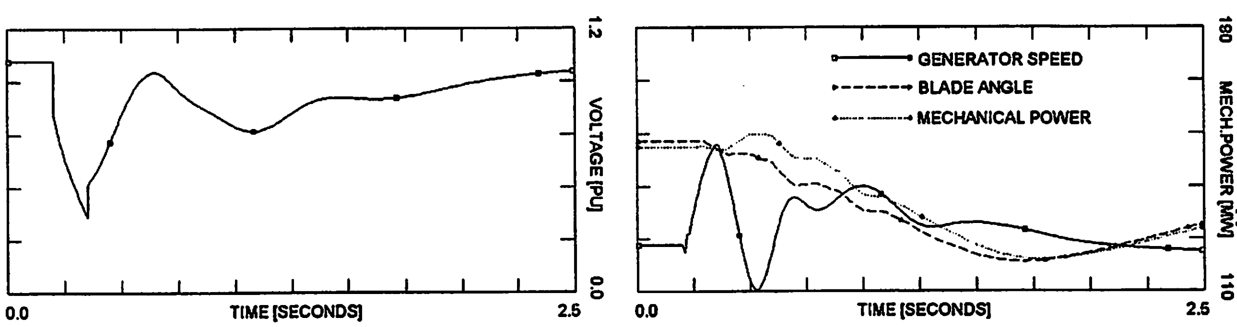
As seen, the blade angle control applied for the wind farm stabilisation will reduce 100 MVAr of dynamic reactive compensation.

5. Practical applications

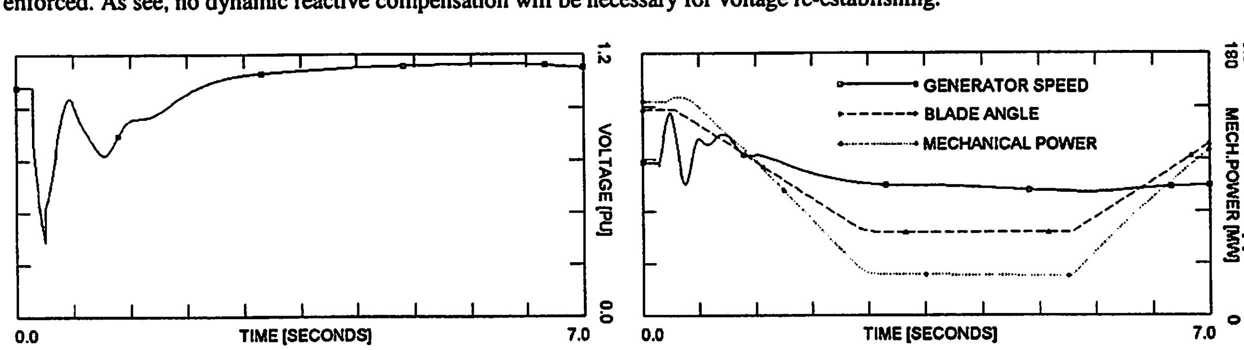
The wind turbine models and the ideas with respect to improving voltage stability in terms of the conventional wind technology, described in this paper, have been used in practical dynamic stability investigations according to incorporation of the large offshore wind farm at Rødsand, Eastern Denmark, by the year 2003.



a. Voltage and generator rotor speed of the offshore wind farm in case of "passive" stall wind turbines with the data typical for on-land applications. As see, 100 MVAr of dynamic reactive compensation will be necessary.



b. Voltage, generator rotor speed, blade angle and mechanical power of the offshore wind farm in case of active-stall wind turbines where the blade angle position is controlled by the (sampled) generator rotor speed. Mechanical construction of the wind turbines is enforced. As see, no dynamic reactive compensation will be necessary for voltage re-establishing.



c. Voltage, generator rotor speed, blade angle and mechanical power of the offshore wind farm in case of use of active-stall for the power reduction by the external signal (ordering 300 ms after the fault occurrence). Mechanical construction of the wind turbines is enforced. As see, no dynamic reactive compensation will be necessary for voltage re-establishing.

Fig. 5. Demonstration of control ability of active-stall for maintaining voltage stability at and after a short circuit fault.

The control ability of active-stall will be used for the voltage re-establishing in the power system after a short circuit fault and the capacity of the dynamic reactive compensation is significantly reduced. For the offshore wind farm to be constructed at Rødsand, the solution with ordering by the external signal is chosen in accordance with the Specifications [2].

Formulation of the Specifications [7] contributes to creation of a better competition between the wind technologies and activates the windmill manufacturers to improving control abilities of the wind turbines to be used in large-scale applications and design of a new generation of grid-friendly wind turbines.

6. Conclusions

The fixed-speed active-stall wind turbines equipped with induction generators represent robust and relatively cheap technical solution for large offshore applications. The wind technology has been in application in on-land settings in Denmark for many years why this concept will be attractive for large offshore applications as well.

The new is that the blade angle control will be used as the tool for improving voltage stability at a short circuit fault in the power system. This control ability has been firstly described by *Vladislav Akhmatov* in [7, 8].

This technical solution is chosen for the Danish offshore wind farm to be constructed at Rødsand by the year 2003.

7. Acknowledges and credits

This work is granted by the Danish Academy of Technical Sciences and NESA A/S, Copenhagen, Denmark, grant EF-823.

NESA Transmission Planning, NESA A/S, has the know-how about incorporation of wind power in power systems, and is working with modelling wind turbines of different concepts, dynamic reactive compensation and large network models using the dynamic simulation tool PSS/E.

Technical University of Denmark is an educational institution, and Dept. of Electric Power Engineering is offering a number of educational courses within the MSc program with specialisation in wind technology.

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9. Biographies

Vladislav Akhmatov received his MSc degree from Technical University of Denmark (1999). He is currently employed at NESA Transmission Planning, NESA A/S, Copenhagen, Denmark, and working on the Industrial PhD on dynamic stability of power systems with large amount of wind power.

Arne Hejde Nielsen is associate professor at Technical University of Denmark. After his master degree in 1978 he was employed as research assistant at the University. In the early eightieths he was at ASEA Central Research and Development Department in Sweden working with motor control and general measurement technologies. Since then he is back at the University where he has worked with as different subjects as electrical materials, microprocessor control and now electric power systems.

Large Scale Integration of Wind Turbines Into Grid - Modelling Requirements for Utilities

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Wind Power Penetration on NG System

- NG believes that the government target of 10% renewables by 2010 can be accommodated by the transmission system
- NG is actively addressing the system issues arising from wind power generation
- NG will facilitate the connection of wind farms

NG Guidance Document for Renewable Energy Projects

- A new document that will be published shortly
- Aimed at actual or potential developers of renewable sources with particular reference to offshore wind projects
- It will provide guidance on:
  - connection process
  - cost

Modelling Requirement

- Utilities need to have standard models of wind generators that are accurate enough for system studies (loadflow, short circuit and transient/voltage/dynamic stability)
- Impact of large scale wind power generation on system security and integrity can be established with more confidence via modelling
- Manufacturer/developer co-operation to develop models

Modelling Requirement

- **Models to be developed and verified for:**
  - Directly connected asynchronous generator
  - Asynchronous/ synchronous generator with series convertor connection
  - Doubly fed asynchronous generator
  - 'Aggregated' model for wind farms

What Are We Doing?

- **Discuss modelling issues with UK parties**
- **Establish links with working groups**
- **Establish benchmark models with industry for utility use**

Advantages

- **Standard models will:**
  - Establish transparent data requirement
  - Enable a quicker analysis method
  - Facilitate manufacturer, developer and utility discussions
  - Enable TSO / DNO interaction to be studied efficiently

Large Scale Integration of Wind Turbines Into Grid - Modelling Requirements for Utilities

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Simulation of Electrical Power Systems with a High Wind Energy Penetration

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Ever more wind turbines are connected to electrical power systems, in order to reduce the adverse environmental impact of conventional electrical power generation. To use regions with a good wind climate efficiently and to concentrate the visual impact of modern wind turbines at certain locations, a tendency to erect new turbines in wind parks can be observed. These wind parks are connected to high voltage transmission grids and thus directly influence the dynamic behaviour of an electrical power system.
Using widely available power system dynamics simulation software packages for the simulation of electrical power systems with a high wind energy penetration is not a straightforward task. There are no standard models for wind turbines included, like is the case for synchronous generators, loads and other common components of electrical power systems. In this paper, simulation of the dynamics of power systems with a high wind power penetration is discussed. An overview over the progress that has been made is given and issues still to be resolved are pointed out.

1. Introduction

As a result of increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are made to generate electricity from renewable sources. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and the in principle infinite availability of the prime mover that is converted into electricity. One way of generating electricity from renewable sources is to use wind turbines that convert the energy contained in flowing air into electricity. Up to this moment, the amount of wind power integrated into large scale electrical power systems only covers a small part of the total power system load. The rest of the power system load is for the largest part covered by conventional thermal, nuclear and hydro power plants.
Wind turbines do hardly ever take part in voltage and frequency control and if a disturbance occurs, the wind turbines are disconnected and reconnected when normal operation has been resumed. Thus, notwithstanding the presence of wind turbines, frequency and voltage are maintained by controlling the large power plants as would have been the case without any wind turbines present. This is possible, as long as wind power penetration is still low. However, a tendency to increase the amount of electricity generated from wind can be observed. Therefore, the penetration of wind turbines in electrical power systems will increase and they may begin to influence overall power system behaviour. It will then no longer be possible to operate a power system by only controlling the large scale conventional power plants. Therefore, it is important to study the behaviour of wind turbines in an electrical power system and their interaction with other generation equipment and with loads.
Further, a tendency to concentrate the turbines in wind parks can be observed in order to use regions with a good wind climate efficiently and to concentrate the visual impact of modern wind turbines, that can easily reach heights of more than a 100 m, at certain locations. These wind parks are connected to the high voltage transmission grid and thus directly influence the dynamic behaviour of an electrical power system, which increases the need for adequate models.
In this paper, an overview over the issue of simulation of electrical power systems with a high wind energy penetration is given. First, the three most common actual wind turbine concepts are described and the grid interaction of each of these concepts is commented upon. Then, various ways to the simulate large scale power systems are described. Different wind turbine modelling approaches are introduced, simulation results are given and the investigation of power systems with a high wind energy penetration is discussed. To conclude, topics for further research are pointed out.

2. Grid interaction of wind turbines

2.1 Actual wind turbine concepts

The three most important currently applied wind turbine concepts are:

1. A constant speed wind turbine, which consists of a directly grid coupled squirrel cage induction generator. The wind turbine rotor is coupled to the generator through a gearbox. The power extracted from the wind is limited using the stall effect. This means that the rotor is designed in such a way that its efficiency decreases in high wind speeds, thus preventing the mechanical power extracted from the wind to become too large. In most cases, no active control systems are used to this end.
2. A variable speed wind turbine with doubly fed (wound rotor) induction generator. The rotor winding is fed using a back-to-back voltage source converter. Like in the first concept, the wind turbine rotor is coupled to the generator through a gearbox. In high wind speeds, the power extracted from the wind can be limited by pitching the rotor blades.
3. A variable speed wind turbine with a direct drive synchronous generator. The synchronous

generator can have a wound rotor or be excited using permanent magnets. It is grid coupled through a back- to-back voltage source converter or a diode rectifier and voltage source converter. The synchronous generator is a low speed multi pole generator, therefore no gearbox is needed. Like in the second concept, the power extracted from the wind is limited by pitching the rotor blades in high wind speeds.

For a more elaborate description of these wind turbine concepts and their advantages and disadvantages, [1] should be consulted. The concepts are depicted in figure 1.

The different wind turbine types have their specific advantages and disadvantages. A constant speed wind turbine is relatively simple and robust. It has, however, a number of disadvantages, namely:

- Lack of control possibilities of both active and reactive power.
- Large mechanical loads, because power fluctuations are translated into torque pulsations. This can lead to gear box failure.

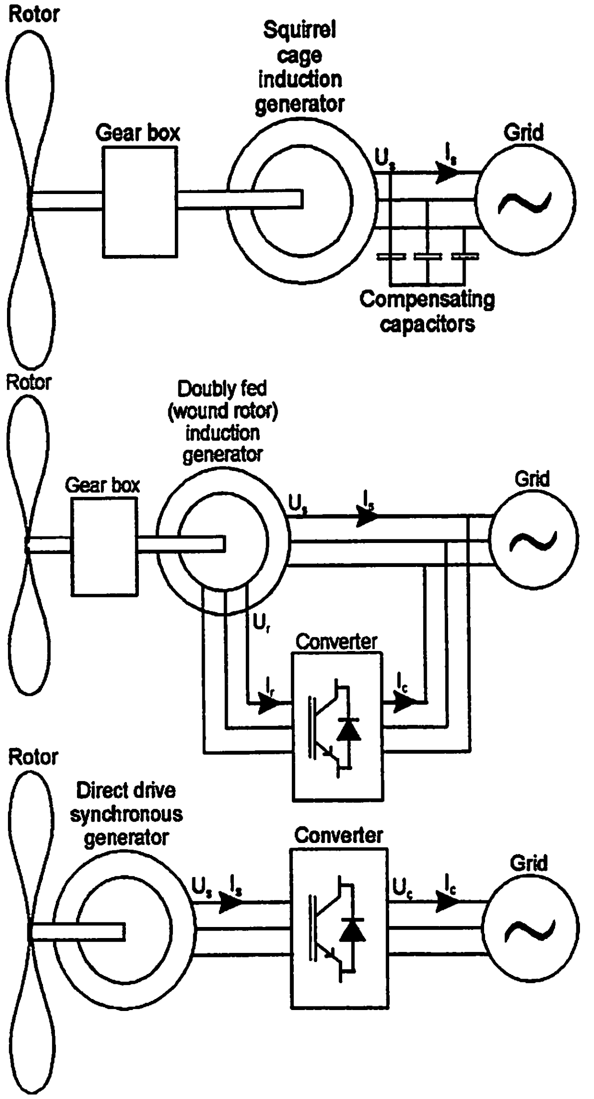

Figure 1. Actual wind turbine concepts. From above: constant speed, variable speed with doubly fed (wound rotor) induction generator, variable speed with direct drive synchronous generator.

- Large fluctuations in output power, because no energy buffer in the form of a rotating mass with varying rotational speed is present.

Wind turbine manufacturers are increasingly moving to variable speed concepts. This observation can be explained by considering the following:

- Power electronics, indispensable for variable speed operation of wind turbines, is rapidly becoming cheaper and more reliable.
- Variable speed wind turbines offer a higher energy yield in comparison to constant speed turbines, because the optimal rotor speed for each wind speed can be achieved. This outweighs the losses of the power electronic converter [2].
- Wind turbines are becoming increasingly large. The reduction of mechanical loads, which can be achieved by variable speed operation, hence becomes more important.
- Variable speed wind turbines offer extensive controllability of both active and reactive power (of course within the limitations imposed by the actual wind speed and the ratings of the generator and the power electronic converter), which is an advantage particularly in remote locations and off shore [3].
- Variable speed wind turbines can easier comply with the requirements of grid companies, especially with those applied to large wind parks [4].
- Variable speed wind turbines show less fluctuations in output power, because the large rotor inertia smooths variations in wind speed, thus reducing flicker problems.

When comparing the two variable speed wind turbine concepts, the advantage of the concept with the doubly fed induction generator is that a power electronic converter that has a rating of only about one third of the nominal power of the wind turbine can be used. The size of the converter can be reduced even further by practising star-delta switching in the rotor winding. However, still a gearbox is necessary, which may decrease the reliability and increases the cost. In the direct drive wind turbine, no gearbox is needed, but this advantage must be paid for by the disadvantage of a larger power electronic converter and a more complicated, heavier and thus more expensive generator.

2.2 Grid interaction of wind turbine concepts

The grid interaction of the wind turbine concepts was already touched upon in the last paragraph in the enumeration of their specific advantages and disadvantages. The following is important to consider when connecting wind turbines and wind parks to the grid:

- Harmonics
- Flicker
- Contribution to fault currents
- Steady state node voltages
- Thermal limits of lines and cables
- Protection scheme

The last four issues do not only apply to the connection of wind turbines but are important when connecting any type of new generation equipment. Apart from these, the overall issue of transient and small signal stability of the power system under study needs to be investigated. This issue will be commented upon in paragraph 5.

With respect to the above enumeration, first it can be said that harmonics should not be a problem when a constant speed wind turbine is used. In this concept, no power electronic converter, which forms the main source of harmonics, is present. Harmonics can theoretically be a problem in case of the two variable speed concepts. However, due to the high switching frequency of modern power electronic converters and the application of advanced switching patterns to the semiconductors, it is normally not a problem to comply with the limits that are imposed on harmonics injection in the connection requirements.

For flicker, the opposite applies. In a constant speed wind turbine, variations in wind speed that cause variations in mechanical power applied to the generator shaft, can not be smoothed out by using the rotor inertia as an energy buffer. The rotor speed variations are only in the per cent range, and are therefore too small to have a significant smoothing effect. As a result, fluctuations in mechanical power are directly reflected in electrical power and may cause flicker problems, especially in weak grids where changes in generated power results in larger voltage fluctuations than in strong grids.

In case of isolated wind turbines, the flicker is most severe at the connection point and is relatively easy to compute if an adequate model of the wind turbine is available. However, when increasing numbers of wind turbines are connected to the system or the wind turbines are connected in parks, the flicker from the various sources is added in the network and the flicker problems may be more severe at some distant point then at the connection point of the flicker sources due to this summation. In that case, more complicated flicker calculations are necessary [5].

Contributions to fault current are only an issue in case of constant wind turbines as well. Constant speed wind turbines are based on a direct grid coupled squirrel cage induction generator. If a fault occurs, the generators supply a fault current, that should not exceed the rating of the switchgear that must isolate the faulted component. If this would be the case, the faulted part of the system will not be disconnected and the fault will persist.

Variable speed wind turbines are equipped with a power electronic converter, which measures the grid voltage in order to be able to control the converter current. When a fault occurs, the converter notices this quickly. The power electronic converters are equipped with self commutating semiconductor switches and can thus block the current rapidly if they recognize a fault.

In case of the doubly fed induction generator, the blocking of the converter current results in the removal of the generator excitation. Therefore, the generator does not contribute to the fault current anymore. In case of the synchronous direct drive generator, the blocking off of the converter current results in the disconnection of the wind turbine from the grid, so that any contribution to the fault current is removed. Due to the high switching frequency of the power electronic converter, this process takes only tens of milliseconds. Therefore, in case of a fault, both variable speed wind turbine types are disconnected before the normal switchgear acts, which takes at least a 100 ms, and the turbines do not contribute to the fault current that must be interrupted by the switchgear.

Note that this can be either an advantage or a disadvantage, depending on the local situation. If fault currents are approaching the rating of the installed switchgear, it would be an advantage to have wind turbines that do not contribute to the fault current. However, when the fault currents are low due to a large distance to the nearest power plant, it becomes difficult for the protection to distinguish between normal and faulted situations. In that case, it would be more advantageous to have wind turbines contributing to the fault current.

With respect to the steady state node voltages, there is also a difference between constant and variable speed wind turbines. Constant speed wind turbines are not able to control their terminal voltage. There is an intrinsic relation between the active and the reactive power, that is determined by the generator parameters. Although the reactive power consumption of the squirrel cage induction generator can be compensated for by using a capacitor, this does not enable terminal voltage control. This would only be possible by adding a controllable source of reactive power such as a STATCOM or SVC. This solution is not occurring frequently.

In variable speed wind turbines, however, not only the generator torque or active power can be controlled by the converter, but also the reactive power [3]. In the doubly fed (wound rotor) induction generator, the generator torque, and thus the active power, is directly dependent on the q-component of the rotor current and the reactive power is directly dependent on the d-component of the rotor current when using a dq-reference frame. In the direct drive synchronous generator, the active and reactive power fed into the grid can be controlled by the grid side of the power electronic converter through which the direct drive synchronous generator is coupled to the grid. Thus, with respect to grid voltage/reactive power control, there is an important difference between the constant speed concept and the two variable speed wind turbine concepts.

It must, however, be said that although the variable speed wind turbine concepts theoretically offer possibilities for voltage control, these are hardly used nowadays. This is caused by the requirements of grid companies that force wind turbines to operate at unity power factor and by the desire to use a power electronic converter with a rating as low as possible in order to decrease cost. To be able to control reactive power and terminal voltage, the rating of the power electronic converter needs to be slightly higher than in case only unity power factor operation is considered. The rating of the converter present in the current wind turbines is not always high enough to contribute to grid voltage control. This applies particularly to the variable speed wind turbine concept with the doubly fed induction generator. The last two last points of the above enumeration, thermal limits of lines and cables and protection schemes, very much differ between specific cases and do not depend very much on the wind turbine concept being installed. It is difficult to make any general statements on this issue and on general differences between the effects of constant and variable speed wind turbines in this respect.

3. Simulation of electrical power systems

3.1 Subtransient and dynamics simulation

The dynamic behaviour of electrical power systems can be simulated in various time domains. Simulations in the time domain in which even the shortest time constants are represented are called subtransient simulations. Subtransient simulation software, such as ATP, EMTP or the MATLAB Power Systems Blockset is used for performing simulations on this time scale. The typical time step of this kind of simulations is below 1 ms and when detailed models of power electronics are present, it can even be as low as 1 μs. The typical problems investigated using subtransient simulations are fault currents, overvoltages and the behaviour of power electronic converters under various circumstances.

Power system dynamics simulation software is used to investigate the transient behaviour and the small signal stability of power systems, which will be commented upon in the next section. An example of a power system dynamics simulation package is PSS/E. Power system dynamics simulation software can be used when the phenomena of interest have a frequency of about 1 to 10 Hz. The typical phenomenon that is studied using power system dynamics simulation software is that of transient stability, i.e. the response of generator speeds to severe disturbances such as faults and generator tripping. The time step in transient stability is 1 ms to 10 ms.

The main difference between dynamics simulation software and subtransient simulation software is that in the first only the fundamental harmonic component of voltages and currents is taken into account. This approach enables the representation of the network by a constant impedance or admittance matrix, like in load flow calculations and it reduces the number of differential equations, because no differential equations are associated with the network and fewer with generating equipment. By these simplifications, the small time constants are removed from the power system model. This enables the use of a larger simulation time step, which leads to a substantial reduction in the computation time [6].

Some advanced software packages, such as Digsilent and Simpow, offer both transient and subtransient simulation capabilities and are able to switch between equipment representations appropriate for the subtransient and transient domain, depending on the event to be simulated.

3.2 Small signal stability simulations

In small signal stability simulations, a linearized representation of the power system is developed and its eigenvalues are calculated. This gives a full overview over the response of the power system to small disturbances of the actual operating state. The damping of all dynamic modes and the state variables involved can be identified, as well as the frequency of any oscillatory modes that may exist. However, due to the non linearity of the equations describing an electrical power system, the eigenvalues are only valid for one operating point and the calculation must be repeated for other operating points. For a more elaborate description of the calculation and meaning of the eigenvalues of a power system, [6] should be consulted.

Note the principal difference between transient and small signal stability simulations. In transient simulations, only one event at a time can be simulated, but the non linearity of the system is taken into account and the behaviour of the system can be studied over a longer time frame. On the opposite, in small signal stability simulations, non linearities are neglected and only one instant can be investigated instead of a time interval. However, all possible disturbances can be analysed at once, instead of only one event at a time as is the case in dynamics simulations.

4. Wind turbine modelling

4.1 Modelling wind turbines in the load flow analysis

The modelling of wind turbines in the load flow analysis is not very complicated. For variable speed wind turbines, it is most easy. When the wind turbines are operated at unity power factor, the reactive power of the wind turbines must be set to zero in the load flow set up. When a terminal voltage controller is present, the reactive power limits of the turbine and the reference value of the terminal voltage must be specified. Thus, variable speed wind turbines hardly differ from conventional synchronous generators in load flow set ups.

For constant speed wind turbines, it is slightly more complicated. In a normal load flow calculation, the active and reactive power of the generators are assumed to be independent of their terminal voltage and are assumed to stay at the values that are specified in the load flow set up [7]. However, in case of squirrel cage induction generators, this assumption is not true. A squirrel cage induction generator has an intrinsic relation between reactive power, active power and terminal voltage. This relation is determined by the generator parameters.

This problem can be solved in two ways. It is most simple to keep the active and reactive power of the terminal voltage constant when solving the load flow. When the load flow equations are solved, the active power consumption of the squirrel cage induction generator at the resulting terminal voltage and active power generation is calculated. By adding the reactive power generation as specified in the load flow set up and the reactive power consumption of the generator at the given operating point, and dividing the resulting value by the terminal voltage, the size of a compensating capacitor can be calculated which is assumed to be connected at the generator terminals and to generate both the reactive power consumed by the generator and supplied to the grid. This solution to the problem of representing squirrel cage induction generators in load flow set ups seems to be applied in most widely available software packages.

The second possibility is to modify the load flow calculations to take into account the relationship between active power, reactive power and terminal voltage of a squirrel cage induction generator [8]. This introduces a second iteration process, in which the operating point of the squirrel cage induction generator is determined. Therefore, this approach complicates the calculations. No commercial software in which this solution is applied could be identified.

4.2 Modelling wind turbines in subtransient simulations

A subtransient model of a constant speed wind turbine would consist of some model of the mechanical part, from which for a certain wind speed the generator mechanical power or torque results. This value must then be applied to a subtransient model of a squirrel cage induction generator. Such an induction generator model has at least five states, namely stator and rotor fluxes in the d- and q-axis and mechanical rotor speed. The smallest time constant in this model is in the range of 10 ms, depending on generator size. If a constant time step is used for the simulations, it should be a number of times smaller than this time constant, depending on the integration algorithm used in the calculations and therefore be equal to about 1 ms.

The first part of subtransient models of variable speed wind turbines again consists of a conversion from wind speed to mechanical generator power or torque. Depending on the wind turbine type being modeled, the result is applied to a subtransient model of a doubly fed induction generator, which has at least five states, or a subtransient model of a synchronous machine which has at least five states and if the damper windings are taken into account seven or eight.

Further, detailed models of the power electronic converters are needed, including the semiconductor switches. Both the current control loops of the power electronic converters and the higher level controllers controlling generator torque and real and reactive power injected in the grid must be modeled. The switching frequency of power electronic converters used in wind turbines varies from above 10 kHz for small wind turbines to about 1 kHz for larger ones. The smallest time step should be a number of times smaller than the switching frequency, resulting in time steps in the range of 0.1 ms to 1 μs, depending on the size of the wind turbine studied and the control of the power electronic converter. Subtransient models of the two most important variable speed wind turbines are presented in [9,10].

4.3 Modelling wind turbines in dynamics simulations

The third kind of wind turbine models, in addition to load flow models and subtransient models, are transient or dynamic models. Starting from a subtransient model, a transient model can be developed in the following way [11]:

- In the constant speed wind turbine model, the $d\psi/dt$ terms in the stator voltage equations must be neglected.
- In the model of the variable speed wind turbines, the $d\psi/dt$ terms in both the rotor and the stator voltage equations are neglected.
- The power electronic converters are no longer modelled as controlled voltage sources, but as controlled current sources. This is possible due to the neglect of the $d\psi/dt$ terms in both the network and the voltage equations. Therefore, instantaneous current changes do not lead to high overvoltages as would have been the case with the $d\psi/dt$ terms included.

In case of the constant speed wind turbine, a quite straightforward model results, which consists of some model of the mechanical part connected to a model of a squirrel cage induction generator that is normally available in power system dynamics simulation packages.

For the two variable speed wind turbines, the above assumptions enable a last substantial simplification. As a result of these assumptions, an algebraic equation between generator torque and rotor current in the wind turbine with doubly fed induction generator and between generator torque and stator current in the wind turbine with direct drive synchronous generator results. When an algebraic relation between generator rotor or stator current and generator torque exists, a generator torque set point can be reached instantaneously by injecting the appropriate rotor or stator currents. However, when torque set points can be reached instantaneously, it is not necessary to drag along the equations describing the generator. Instead, the generator can be modeled as a torque source, which immediately generates an amount of torque equal to the set point generated by the controller.

An important advantage of this approach is that it opens the way to model both kinds of variable speed wind turbines with one model, a general variable speed wind turbine model. The differences in behaviour of the two generator types used are compensated by the power electronic converters and the controllers and the result is a great similarity with respect to grid interaction for both kinds of variable speed wind turbines, which is the main point of interest in power system dynamics simulations [11].

An important reference for the modeling of constant speed wind turbines in power system dynamics simulations is [12], in which an approach to simulate a subtransient model in a transient software package is described. In this reference, it is also argued that in constant speed wind turbines, the turbine shaft must be modeled, because it has an important effect in case of large voltage disturbances and should not be neglected.

4.4 Modelling wind turbines in small signal stability simulations

As discussed above, in small signal stability investigations, only one operating point of the system is investigated at one moment in time. This enables substantial simplifications in the modelling of wind turbines in small signal stability simulations.

Because only one instant is simulated, it is not necessary to model a wind speed sequence, as is the case in dynamics simulations. In the small signal stability analysis, time does not change and because wind speed can not change instantaneously, it does not change either. The wind turbine stays at its operating point as defined in the load flow set up during the small signal stability analysis and small perturbations of the state variable around this operating point are investigated.

Constant speed wind turbines can be modelled using a conventional squirrel cage induction generator model which is normally available in power system dynamics simulations software. For modelling variable speed wind turbines, a source with constant active power and an amount of reactive power that depends on whether the wind turbine is equipped with a terminal voltage controller or not can be used.

No models of a pitch angle controller, rotor speed controller, etc. are necessary. This is due to the fact that the amount of active power generated by a variable speed wind turbine is not dependent on grid frequency or terminal voltage as is the case in conventional directly coupled generators. Small changes in grid quantities are compensated for by the power electronic converter within 10 ms or 20 ms and as a result generated active power can be assumed not to be effected by grid quantities in small signal stability simulations. In case the wind turbine is equipped with an interface that takes part in grid frequency control, this can be easily represented in the small signal stability analysis.

As can be concluded from the above, the modelling of wind turbines in small signal stability simulations is less complicated than in subtransient and transient simulations. This can be explained by realizing that the major difference between wind turbines and conventional generation equipment are caused by the time-varying prime mover of wind turbines, which is not reflected in small signal stability simulations, because these cover only one instant.

5. Simulation of power systems with wind turbines

5.1 Simulation results of single wind turbines

In this paragraph, some simulation results of models of single wind turbines for the transient/dynamic domain will be given. The models used here are described in detail in [13,14].

The constant speed wind turbine model consists of a rotor model that is based on an algebraic relation describing the power curve and a conventional squirrel cage induction generator model as described in [6].The changes in rotor speed, that are only in the per cent range, are neglected in the equation representing the rotor and as a result, the mechanical power extracted from the wind is determined only by the actual wind speed. Aerodynamic phenomena are neglected when modelling the rotor in this way.

The variable speed wind turbine models consist of the following components:

- A rotor model consisting of a $c_p(\lambda,\theta)$ curve depicted in figure 2. Again, aerodynamic phenomena are neglected by using this representation.
- A generator model in which the simplifications described in paragraph 4.3 have been carried out.
- A terminal voltage controller.
- A rotor speed controller which optimizes the energy yield, whose control characteristic depicted in figure 3 for an example wind turbine with a nominal power of 2 MW.
- A pitch angle controller.

In figure 4, the simulation results are depicted for a measured wind speed sequence and an example wind turbine with 2 MW nominal power. The model can be used to represent other wind turbines with as well.

Starting from above, the wind speed, the rotor speed, the pitch angle, the output power delivered to the grid and the terminal voltage are displayed. In all figures, the solid line corresponds to the constant speed wind turbine, the dotted line to the variable speed wind turbine with doubly fed induction generator and the dashed line to the variable speed wind turbine with direct drive synchronous generator. Because the constant speed wind turbines is stall regulated, in the third graph no pitch angle is displayed for this concept.

It can be concluded that the fluctuations in output power are much lower for the two variable speed wind turbines, than for the constant speed wind turbine. As already discussed above, this can be explained by noticing that in a variable speed wind turbine the rotating mass functions as an energy buffer, which is not

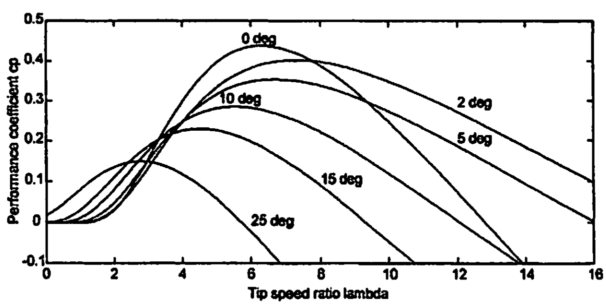

Figure 2. Performance coefficient c_p as a function of the tip speed ratio λ and the pitch angle θ [deg]

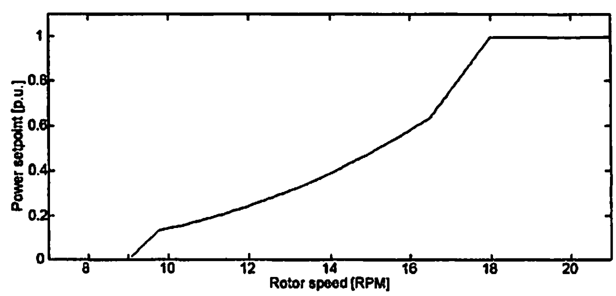

Figure 3. Rotor speed versus power control characteristic.

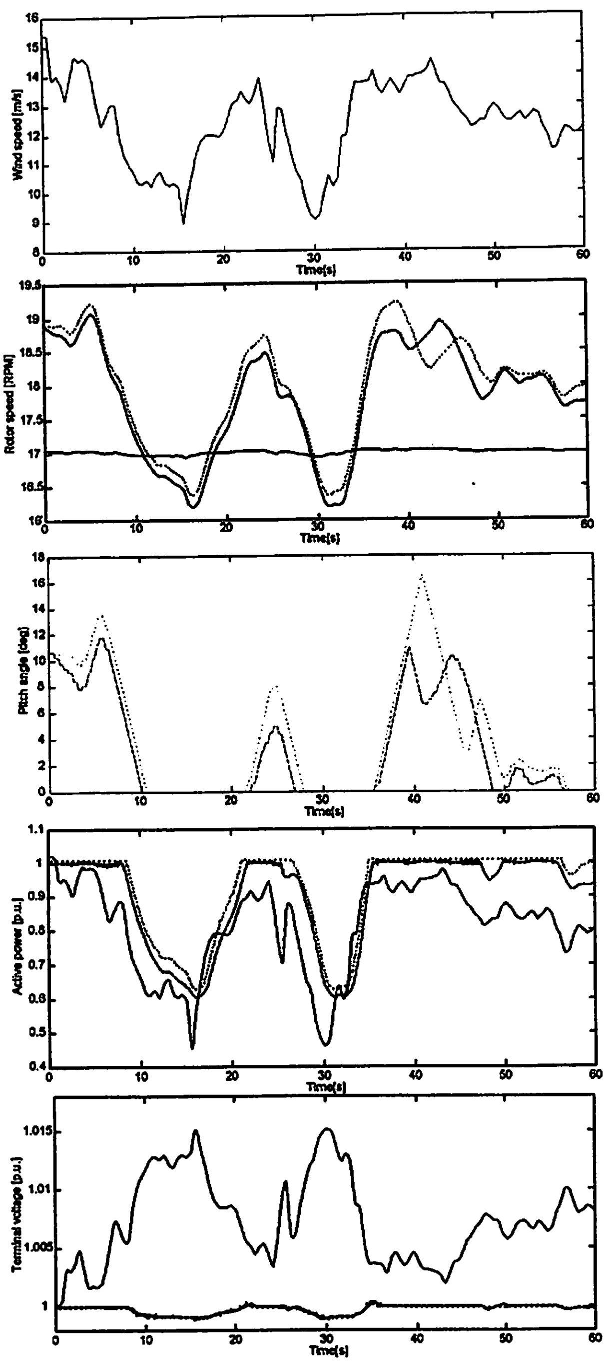

Figure 4. Simulation results. Starting from above: wind speed, rotor speed, pitch angle, output power and terminal voltage. The constant wind speed turbine and the variable speed wind turbines with doubly fed induction generator and direct drive synchronous generator are represented by solid, dotted and dashed lines respectively.

possible in a constant speed wind turbine, because the rotor speed hardly varies. The functioning of the rotor as an energy buffer is especially illustrated during the last 20 seconds of the simulation. The speed of the rotor of the variable speed wind turbines varies with the varying wind speed, but the output power hardly changes. On the contrary, in the constant speed wind turbine the rotor speed is approximately constant, but the output power follows the wind speed variations making the output power less smooth.

Furthermore, it can be observed that the terminal voltage in case of the variable speed wind turbines deviates far less from the desired value of 1 p.u. than in case of the constant speed wind turbine. This can be explained by noticing that the variable speed wind turbines simulated here are equipped with grid voltage control. This can particularly be advantageous when the wind turbine is connected to a weak grid or used off shore. Differences between the two simulated variable speed wind turbine concepts are small, which can be explained by noticing that the controllers and the moment of inertia are similar.

5.2 Transient stability simulations

Using the models presented in the last paragraph, it is possible to investigate the transient behaviour of electrical power systems with a wind energy penetration that is so high that the wind turbines start to impact the behaviour of the overall power system and can not be represented as a load reduction anymore. It has, by the way, to be stressed that the wind penetration level at which this is indeed the case, is not clear yet and is a topic for further research.

To simulate the transient behaviour of the power system during normal operation, it is enough to set up a load flow scenario, initialize the dynamics simulation and let it run for a certain time, using a measured wind speed signal or wind speed generator to represent the prime mover of the wind turbine. Note that, without wind turbines, this approach would not make sense, because the power system would stay at its initial operating point during the simulation. However, due to wind speed changes, branch flows, node voltages and generator speeds change and this kind of simulation yields useful information on the behaviour of the system under study.

The models described in the last paragraph can also be used to simulate the power system's response to severe disturbances, such as faults and generator trips. However, the protection scheme should be incorporated in the simulations as well, in order to correctly simulate the response of the turbines to voltage and frequency changes that may result from the applied disturbance.

The models can of course not be used for the investigation of subtransient phenomena, such as voltage transients, fault currents, and harmonics, because subtransient characteristics of the generators and converters have not been incorporated in the model. However, this applies to power system dynamics simulation software itself as well, and is therefore not considered a problem.

Preliminary results of transient stability simulations of power systems with a high wind energy penetration show the following:

- Due to stochastic nature of short term (about 2-0.1 s) wind speed variations and the distance between the turbines in a wind park, the aggregated short term power output variations of large numbers of wind turbines are small and are no problem for the conventional generation to cope with, which is in agreement with empirical findings [15].

- The effect of constant speed wind turbines on power system transient stability is mixed and depends very much on the electrical distance of the wind turbines to the conventional synchronous generators. This observation applies to squirrel cage induction machines in general [16].
- The effect of variable speed wind turbines are difficult to characterize in general as well. First, when the current operating strategies with respect to voltage drops are kept, faults will lead to the loss of large amounts of variable speed wind turbine generation because of their extreme sensitivity to voltage drops. This could lead to problems, that perhaps can be solved by changing the protection settings. Second, with respect to the effects of variable speed wind turbines on the post-fault transient stability, no clear trends have been observed in the studies carried out so far. However, the comment that the transient stability could be improved by equipping variable speed wind turbines with grid voltage and frequency control seems justified, based on preliminary results.

As yet, it is too early to make more specific statements and research into this topic is still continuing.

5.3 Small signal stability simulations

No small signal stability investigations of power systems with a high wind energy penetration have been carried out up to this moment. These are planned for the near future. Because the grid interaction of both constant speed and variable speed wind turbines substantially differs from that of conventional directly grid coupled synchronous machines, it is expected that increasing amounts of wind energy will impact the small signal stability of electrical power systems. A start has been made with the development of models of variable speed wind turbines for use in small signal stability studies.

6. Future research topics

In order to acquire more insight in the impact of high wind energy penetrations on the dynamics and small signal stability of power systems, further research must be devoted to the following topics:

- The wind turbine models used for the simulations in paragraph 5 are not verified yet. There is a need for experimentally verified models, particularly of variable speed wind turbines. However, it has not been possible to acquire the necessary measurements up to now.
- Measurements must be taken in wind parks in order to acquire more knowledge of the short term power output variations that must be compensated by conventional generation in order to keep the system balanced. Although preliminary results are encouraging, more profound investigations are necessary.
- The effect of high wind power penetration on the transient and small signal stability of power systems must be investigated further.

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Simulation of Electrical Power Systems with a High Wind Energy Penetration

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TU Delft EPS

Presentation structure

- Actual wind turbine concepts
- Aspects of grid interaction
- Electrical power systems simulation
- Wind turbine modeling
- Simulation results
- Future plans

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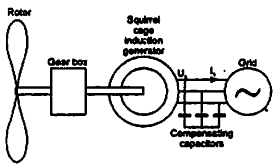
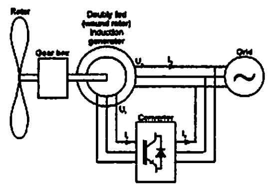
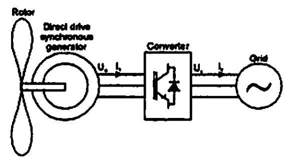
Actual wind turbine concepts



Danish concept: Constant speed, (active) stall controlled



Doubly fed induction generator: Variable speed, pitch controlled



Direct drive synchronous generator: Variable speed, pitch controlled

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Aspects of grid interaction

Aspect	Constant speed	Variable speed
Harmonics	Hardly a problem, because no power electronics are present, the main source of harmonics	Can be a problem, normally not a bottle-neck due to high switching frequency and sophisticated switching patterns
Flicker	Can be a problem due to power fluctuations, especially in weak grids	Normally not a problem due to smoothing effect of rotating mass
Fault currents	Can be a problem: directly grid coupled generator	Should be no problem because converter is faster than protection
Steady state voltages/ Reactive power	Can be a problem because reactive power/voltage control is impossible without additional measures	Can be a problem at unity power factor operation, however voltage control capability

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Power System Simulation

- Steady state load flow calculations
  (steady state voltages and line flows)
- Subtransient simulation: 10 Hz to >10 kHz, typical time step 1 ms to 1 us
  (fault currents, harmonics, voltage transients)
- Transient/Dynamic simulation: 1 to 10 Hz, typical time step 10 ms
  (small-signal and dynamic stability)

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Wind Turbine Modeling (1)

Subtransient model

Generator modeling:
• Both stator and rotor time constants are taken into account

Converter modeling (if applicable):
• Power electronic switches and both high and low-level controllers are modeled

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Wind Turbine Modeling (2)

Can be used for:
- Controller tuning
- Fault current calculation
- Harmonics calculation
- Transient overvoltage studies

Can NOT be used for:
- Transient/dynamic simulations because of the presence of higher harmonics, the small time step and the large number of parameters required

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Wind Turbine Modeling (3)

Transient/dynamic model

Generator modeling:
- In the Danish concept, only rotor time constants are taken into account
- In the other concepts, the generator is represented by algebraic equations

Converter modeling (if applicable):
- Fundamental harmonic current/voltage source

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Wind Turbine Modeling (4)

Can be used for:
- Transient/dynamic simulations
- High level controller tuning

Can NOT be used for:
- Low level controller tuning
- Short circuit current calculations
- Harmonics calculations

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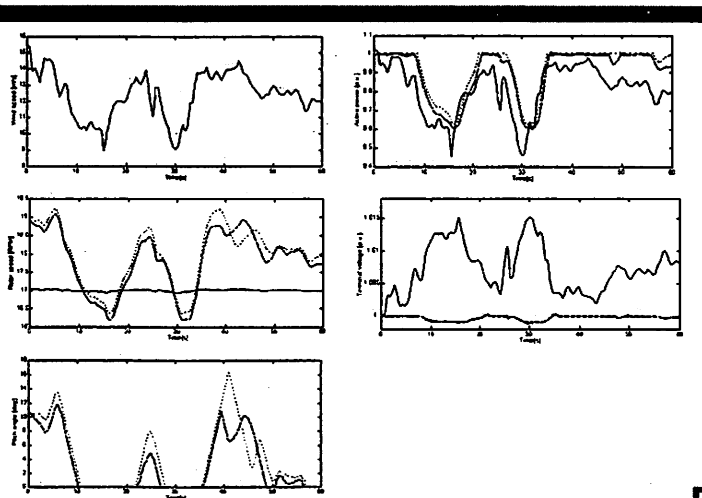
Simulation results



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Future plans

- Wind turbine model verification, but difficulties in obtaining measurements
- High frequency measurements (10-100 Hz) in wind parks to obtain more insight in output power fluctuations
- Use wind turbine models to investigate impact on transient and small signal stability of test systems (IEEE, Cigré)

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STEADY STATE ELECTRICAL DESIGN, POWER PERFORMANCE AND ECONOMIC MODELING OF OFFSHORE WIND FARMS

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Abstract A load flow model has been developed for the evaluation of thirteen different electrical architectures for large offshore wind farms. In a case study, these architectures have been evaluated for two wind farm sizes (100 and 500 MW) and two distances to shore (20 and 60 km). The case study has shown that systems C1 (string layout) and C2 (star layout), have the lowest contribution of the electrical system to the price per kWh (Partial Levelized Production Cost PLPC). C1 and C2 system prices are 19.7 and 24.9 MEuro (100 MW, 20 km), 36.9 and 42.1 MEuro (100 MW, 60 km), 91.7 and 109.5 MEuro (500 MW, 20 km) and 132.9, 150.7 MEuro (500 MW, 60 km).
Keywords: offshore wind energy, electrical models, economic models, power performance.

1 Introduction

The project 'Electrical and Control Aspects of Offshore Wind Farms' has two main objectives, which will be achieved in consecutive project phases. In Phase 1 a steady state model is made of the electrical system of an offshore wind farm and the cable to the high voltage grid. The model is used in the electrical design, power performance evaluation and economic comparison of 13 electrical systems based on AC and AC-DC concepts. Phase 1 has now been completed.

The project started with an inventory of architectures to collect the electric power from individual wind turbines in an offshore wind farm and transmit this power to an on-shore high-voltage grid node. The inventory included constant speed, individual variable speed, cluster variable speed and park variable speed options using AC as well as mixed AC-DC-AC modes. Steady state electrical models have been developed for all electrical components in the architectures to calculate load flow and electrical losses. Based on these models, the *EEFARM* computer program (*E*lectrical and *E*conomical wind *FAR*m *M*odel) has been made, which includes a database of electrical and economic parameters of the components. The *EEFARM* program has been used in a case study to compare 13 electrical architectures. The voltage, current, active and reactive power have been calculated in all system nodes. Based on the aerodynamic performance of the chosen wind turbine, the electrical losses have been calculated over the entire wind speed range. From budget prices obtained from manufacturers, the investment costs of the electrical systems and the contribution to the costs per kWh have been determined.

In the second phase of the project the electrical interaction in an offshore wind farm and the control of the most promising concepts will be investigated. For this purpose, a dynamic model of an offshore wind farm will be developed, with emphasis on the modeling of the electrical system. In a case study the control of a farm will be designed. Park control is expected to be an important aspect of large multi megawatt offshore wind farms in order to optimize park behaviour, to minimise negative effects on the high voltage grid and to assist in frequency and reactive power management of the grid.
This paper presents the results of the first phase.

2 Electrical concepts for offshore wind farms

The electrical system concerns the electrical power components between the generator shaft and the grid connection and the way these components are interconnected and operated. Its function is to convert mechanical power into electric power, to collect electric power from individual turbines, to transmit it to the shore and to convert it to the appropriate voltage and frequency. The system consists amongst other of generators, cables, transformers and power electronic converters. Systems are mainly characterised by the type of voltage (AC or DC) and the frequency (fixed or variable).

2.1 Constant speed and type of clustering

Several methods to collect the power can be distinguished. In figure 1 two constant speed configurations are shown, one with string clustering and one with star clustering. The busbars on the right hand platforms will be referred to as the park nodal point and the busbar on the left platform in configuration C2 as the cluster nodal point. The power and voltage rating of the MV cable is comparable in both cluster options. The power rating of the LV cable in the star cluster is substantially lower than the power rating of the MV cable.
The necessity of transformers near the turbines depends on the voltage rating of the cable and the voltage rating of the generators. With star clustering a turbine transformer can possibly be left out, as indicated in system C2, if the generator voltage is sufficiently high (about 5 kV). With string clustering the transformer can only be left out if the generator voltage is at least several tens of kV because of the limited current rating of cables. These generators are presently not available, so for the moment a turbine transformer will be needed, as indicated system C1. This means that the number of transformers with star clustering can possibly be lower then with string clustering. On the other hand, the number of platforms with star clustering is higher then with string clustering, as each cluster needs its own

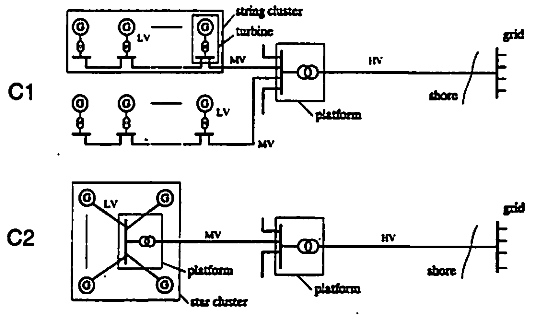

Figure 1: *Constant speed systems*

nodal platform for switch gear and a transformer. As the figure shows, the type of clustering does not directly affect the architecture of the rest of the park, however the type of clustering is important for the voltage rating of converters in the cluster. The costs of converters is more or less linear with the apparent power of the converter, however it also rises progressively with the voltage rating because of the spacious equipment needed for insulation. This means that low power high voltage converters are relatively expensive.

2.2 Individual variable speed

Two options for individual variable speed are shown in figure 2 and 3. The systems of figure 2 consist of traditional variable speed turbines with back-to-back low voltage (about 1 kV) converters. In system IV2 voltage converters will be required in the range of 2-10 kV when the converters are directly connected to the cable.

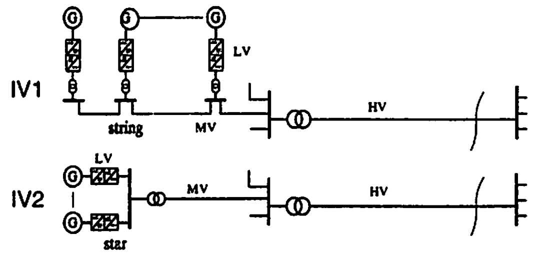

Figure 2: *Individual variable speed systems with back-to-back converters*

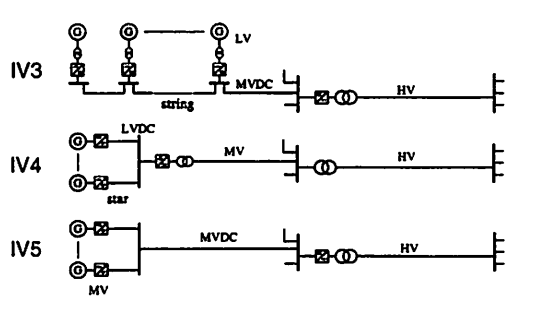

Figure 3: *Individual variable speed systems with multi-terminal DC*

In figure 3 the back to back converter is split in separate AC/DC converters and DC/AC converters. The voltage rating of the DC-system is in the medium voltage range (10-50 kV). These medium voltage DC systems, also referred to as HVDC-Light or HVDC-Plus, are being developed by ABB and Siemens and are based on voltage source converters. DC-systems with multiple DC-inputs (multi-terminal HVDC-Light/Plus) are not available yet and will require additional development. In configuration IV4 the DC/AC converter is placed near the cluster node whilst in configuration IV5 the DC/AC converter is placed down stream the collection point of all clusters, which results in the elimination of a cluster transformer. On the other hand the power rating of the DC/AC converter and the DC-cable will be much higher and so is the required voltage level. Because of the high voltage level of the turbine sided converters and because of the limited power rating these converters will have relatively high costs per kVA.

2.3 Cluster-coupled variable speed

When all turbines in a cluster have a common AC/DC converter, the cluster coupled variable speed concept arises. In such a system the speed and electrical frequency vary more or less proportional with the average wind speed in the cluster. The fatigue loads on turbine components are possibly higher then in an individual variable speed system. In figure 4 two systems are shown with the DC/AC converter placed on shore. Instead of placing the DC/AC converter on shore, the converter can also be placed on the park nodal platform. In that case probably a lower DC voltage can be applied at the expense of an extra step up transformer at the park nodal platform. Moreover the cluster nodal transformer can be eliminated in system CV2, if the DC voltage can be lowered sufficiently.

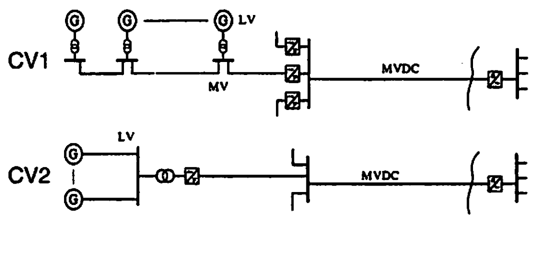

Figure 4: *Cluster-coupled variable-speed systems with DC-Light*

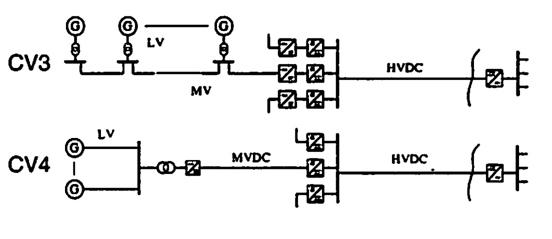

Figure 5: *Cluster-coupled variable-speed DC-systems with step-up chopper or DC-transformer*

By inserting a step-up chopper or an electronic DC-transformer in the DC-link, as shown in figure 5, a relatively low DC voltage near the turbines can be combined with a higher DC-voltage for the transmission cable. The DC-transformer is a power electronic subsystem with an intermediate high-frequency link inside. For this option, a high power DC-DC converter is needed, that has to be developed. A system with step-up chopper might be costly as the apparent power is approximately equal to the product of step-up ratio and real power when the step ratio is high. Note that a step-up chopper can also be used in the systems of figure 3 and figure 6.

2.4 Park-coupled variable speed

Figure 6 shows some systems for park coupled variable speed. All generators have the same electrical frequency. The electrical frequency can either be constant or can be controlled more or less proportional to the average wind speed in the park. Again, the fatigue loading will be higher then with individual variable speed.

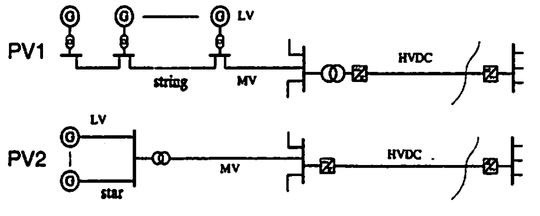

Figure 6: *Park-coupled variable-speed system with DC*

3 Aerodynamic performance

To calculate the electrical losses of a wind farm, the power production of the individual turbines has to be known. For the estimation of the farm power performance the *FYNDFARM* program, developed at ECN, was used. *FYNDFARM* is a graphical user interface driven computer program, which calculates the aerodynamic wake conditions inside a wind farm. *FYNDFARM* estimates the mechanical loads, the produced noise and the power production of individual turbines. Two wake models can be chosen: the *WAKEFARM* model, developed by ECN or the *GL* model by Risø. For the present calculations the *WAKEFARM* model is used and the results are compared to the *GL* model. Only power performance values are determined, mechanical loads and noise are outside the scope of this study. The reference conditions for the study are:

- park sizes: 100 MW and 500 MW;
- turbine size: 5 MW;
- distance to shore: 20 and 60 km;
- distances between turbines: 8D.
- two layouts (string and star);
- turbine type: ERAO5000Var.

3.1 Power performance of single turbine and farm

Prior to the evaluation of the different park designs, the energy produced by a stand alone turbine was calculated. Table 1 summarizes the aerodynamic performance calculations. The results show a fairly high capacity factor. This is caused by the size of the rotor with respect to the rated power of the turbine and the excellent wind regime at a height of 100 m at sea. The deviations in energy production are highest for the string configurations with the highest number of turbines. Although this shows that the differences in power performance betwixt individual turbines can be significant, the differences between turbines in the park will not be taken into account in the calculation of the load flow. The primary objective of the load flow calculations is to estimate the total electrical losses of the park and these will hardly be influenced by differences between individual turbines.

Table 1: FYNDFARM *results ERAO500Var turbines*

Config	E_{av} (MWh/y)	CF_{min} (%)	CF_{max} (%)	E_{tot} (MWh/y)
Single 5 MW turbine:				
-	23413	53.45	53.45	23413
20 × 5 MW turbines at 8D:				
string	22647	51.02	52.58	452946
star	22538	50.40	52.22	450762
100 × 5 MW turbines at 8D:				
string	22416	50.67	52.57	2241578
star	22435	50.10	52.22	2243534

4 *EEFARM* computer program

The *EEFARM* computer program is developed to calculate the voltages, currents and electrical losses in offshore wind farms as well as the costs of the main electrical components. This is combined with the aerodynamic performance of the farm to calculate the PLPC (Partial Levelised Production Cost): the contribution of the electrical infrastructure to the cost of 1 kWh averaged over the lifetime of the wind farm. For all configurations identified in section 2, component parameters and prices were obtained from manufacturers for 2 park sizes: 100 and 500 MW.

The *EEFARM* program contains:

- single phase models for the steady state calculation of the electrical components in an offshore wind farm (transformers, rectifiers, inverters, cables etc.);
- preprogrammed system configurations (especially string and cluster layouts);
- a database with component and configuration data.

For each component the output voltage and current phasors are calculated for the given input voltage and current phasors. Superposition is applied to simplify the calculation of the node voltages and currents. No iteration is performed, since small deviations in voltages and currents are irrelevant. For an estimation of the loading of the farm and the losses this approximation will be sufficient. The voltages, currents and losses are calculated over the complete operational envelope of the farm, viz. for all wind speeds in the P(V) table of the wind turbine. In this way, the electrical losses can easily be evaluated for a given turbine type and wind regime and combined with the aerodynamic performance for that turbine type and wind regime.

The program takes care of the correct connection of the components by defining park configurations. In each configuration the components are fixed. When the program is started, the parameters for these components are read from the database.

MATLAB was used to program the models and perform the calculations. All 13 configuration can be calculated in a single run for all power levels producing a single number of merit for each configuration: the contribution of the electrical system to the kWh price. Furthermore, the voltage and current distribution in the farm is shown. The MATLAB output is redirected to the LaTeXdocument preparation system for evaluation and reporting. Tables are produced containing the voltage and current phasors at all nodes in the farm at rated wind speed. Other tables list the components chosen in a configuration. Figures are produced to compare the costs and losses of the different configurations.

5 Case studies

The economic analysis of the electrical architectures of section 2 is based on:

- the average aerodynamic performance;
- the load flow and electrical losses;
- the costs of the electrical systems.

The cost calculation excludes the turbines (also the turbine generators) and turbine installation costs. All major electrical equipment between turbine generator and shore is included. Small auxiliary electrical equipment, e.g. switches and safety equipment, is not taken into account.
The economic parameters are:

- operation and maintenance cost as percentage of the investment: 5%;
- nominal interest rate: 7%;
- rate of inflation: 2%;
- economic life time of the wind farm: 12 years;
- an availability of 90%.

The intermediate voltage level for the 100 MW as well as the 500 MW farm is 33 kV. The rectifiers and inverters in systems with an MVDC connection are of the PWM type (HVDC-Light/Plus). The maximum currents of the components in all configurations were checked for the rated power level. The capacitive currents in the cables are not compensated by additional inductors.
Figure 7 gives an overview of the results for the 100 MW farm at 20 km distance. The differences in aerodynamic performance between the string and star layouts at 8D are small. Under the economic assumptions mentioned above, the contribution of the electrical system to Levelised Production Cost varies between 0.8 for system C1 and 5.2 EuroCent for system CV3.
Figure 8 gives an overview of the results for the 100 MW farm at 60 km distance. The contribution of the electrical system to the price of one kWh is now in the range of 1.4 (C1) to 5.5 EuroCent (CV3).

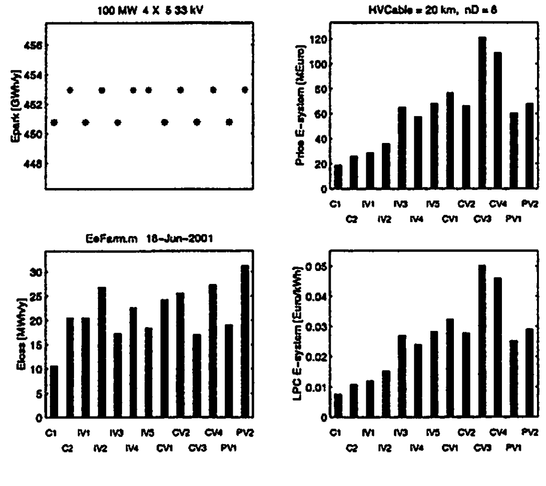

Figure 7: *Production, E-system price, E-losses and PLPC of 100 MW systems at 20 km*

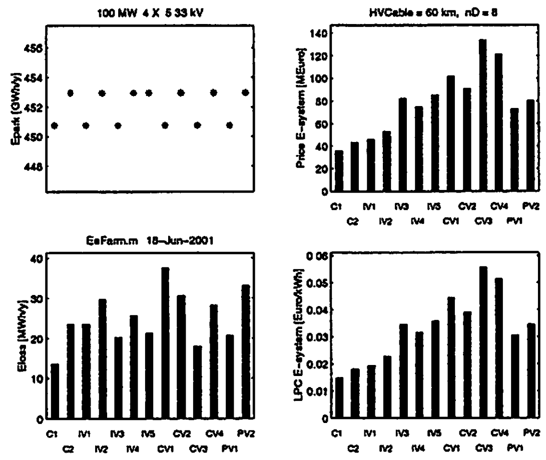

Figure 8: *Production, E-system price, E-losses and PLPC of 100 MW systems at 60 km*

Figure 9 gives an overview of the results for the 500 MW farm at 20 km distance. The contribution of the electrical system to the price of one kWh ranges from 0.6 EuroCent for system C1 to 4.2 EuroCent for CV3.
In figure 10 the results for the 500 MW - 60 km options are summarized. Again the conclusion is not much different from the 100 MW case, although the differences between some systems have reduced. The contribution of the electrical system to the price of one kWh is lower as in the 100 MW - 60 km case, as could be expected, and the range is 1.0 EuroCent (C1) to 4.5 EuroCent (CV3).

6 Conclusions

The *EEFARM* computer program, developed in this project, is a flexible and fast tool for the investigation of electrical configurations for offshore wind farms. It is capable of performing scoping calculations for electrical architectures which can not be calculated easily over the complete range of operating conditions with other tools. A single run gives the load flow (voltages, currents, active and re-

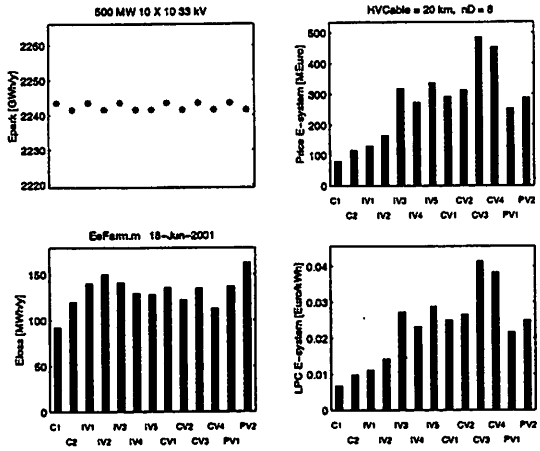

Figure 9: *Production, E-system price, E-losses and PLPC of 500 MW systems at 20 km*

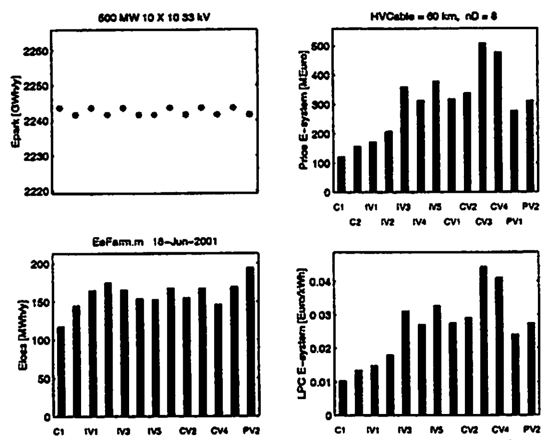

Figure 10: *Production, E-system price, E-losses and PLPC of 500 MW systems at 60 km*

active powers) in all system nodes and the electrical losses for all wind speed bins. *EEFARM* also estimates the contribution of the electrical system to the kWh price, based on budget prices received from manufacturers.

The *EEFARM* program has been validated by PSS/E calculations for two configurations: an all-AC wind farm and a farm with a DC link to shore. The differences in power between *EEFARM* and PSS/E were less than 1%.

The program has been used to evaluate 13 electrical architectures (see figures 1 to 6). In a case study, two wind farm sizes (100 and 500 MW) at two distances to shore (20 and 60 km) have been investigated. The study has shown that systems C1 (constant speed, string layout) and C2 (constant speed, star layout) have the lowest contribution of the electrical system to the price per kWh.

Figure 11 compares the system and component costs of three system concepts: constant speed system (C1), individual variable speed (IV1) and individual variable speed with HVDC-Light/Plus (IV3). For a 100 MW wind farm at 20 km the converters for individual variable speed increase the price by about a factor 1.5. The HVDC connection further increases the price by about a factor 2 compared to the

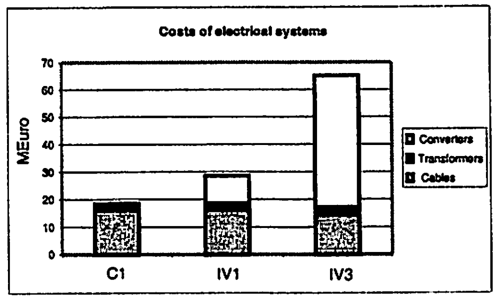

Figure 11: *Electrical component costs for a 100 MW constant speed system (C1), an individual variable speed (IV1) and a individual variable speed with HVDC Light (IV3) at 20 km offshore*

variable speed solution.

Table 2 shows the effect of the system size and the distance to shore on the electrical losses and the investment costs. Since the HV cable to shore is the major item in the costs of the 100 MW C1 configuration, the increase in distance has a strong effect on the price. For the 500 MW system the contribution of the cable to the total price of the electrical system is less significant.

Table 2: *Losses and investment costs of electrical system C1, IV1 and PV1 (excl. generators)*

	Size [MW]	Dist [km]	E loss $[\frac{MWh}{y}]$	E loss [%]	Costs [MEuro]	Rel Cost $[\frac{MEuro}{MW}]$
C1	100	20	10539	2.3	19.73	0.20
	100	60	13620	3.0	36.93	0.37
	500	20	91906	4.1	91.75	0.18
	500	60	117555	5.2	132.95	0.27
IV1	100	20	20513	4.5	29.73	0.30
	100	60	23470	5.1	46.93	0.47
	500	20	139885	6.2	141.75	0.28
	500	60	164345	7.3	182.95	0.37
PV1	100	20	19002	4.1	61.41	0.61
	100	60	20642	4.5	73.97	0.74
	500	20	136777	6.1	263.71	0.53
	500	60	168851	7.5	288.83	0.58

It is clear that, from an economic point of view, the 'all AC' systems C1 and C2 are to be preferred. At moderate distances to shore, these systems combine low costs and low losses. However, the evaluation did not consider differences in aerodynamic power performance caused by different turbine designs, i.e. constant versus variable speed. Only aerodynamic performance differences caused by the wind park layout (string and star layout) have been taken into account and these differences were small. In an evaluation for a specific wind farm project, the turbine design has to be taken into account as well. At moderate cost increase, due to the converter system (see also table 2), this may tip the balance towards individual variable speed systems IV1 and IV2.

Studies in other countries already indicated that, for reasons of grid stability and increasing distance to shore, standard AC solutions may not always be feasible. In those cases, the park variable speed configuration PV1 appears

to be the best alternative. For the investigated distances and park sizes, this currently increases the investment costs by more than a factor 2 compared to the C1 configuration (see table 2).
In Phase 2 of the project dynamic models will be developed to investigate the electrical interaction in an offshore wind farm and to design the park control. Park control is expected to be an important aspect of large multi megawatt offshore wind farms by minimising negative effects on the high voltage grid and assisting in frequency and reactive power control. The results from the present study serve to identify the most promising electrical architectures.

Acknowledgements

This project has been executed on a partial grant of the Ministry of Economic Affairs of the Netherlands in the Novem programme on Renewable Energy TWIN-2 1998 and TWIN-2 1999 (project number 224.750-9859).

Offshore Windfarm Electrical Design, Power Performance and Economics

Jan Pierik (ECN)
Michiel Damen, Paul Bauer and Sjoerd de Haan (TUD)

1. Introduction
2. System concepts
3. Eefarm computer program
4. Aerodynamic performance
5. Case study
6. Conclusions
7. Eefarm demo

ECN

Introduction

Objective: **develop a model for steady state electrical design of different E-systems for Offshore Wind Farms including a cost and power performance calculation**

Focus:

- compare AC to a number of AC-DC options
- obtain component parameters and budget prices
- aerodynamic performance, load flow and losses calculation

Method:

- Eefarm model (Matlab) for load flow and economics
- Fyndfarm model (Fortran) for wind farm aerodynamic
- Case study

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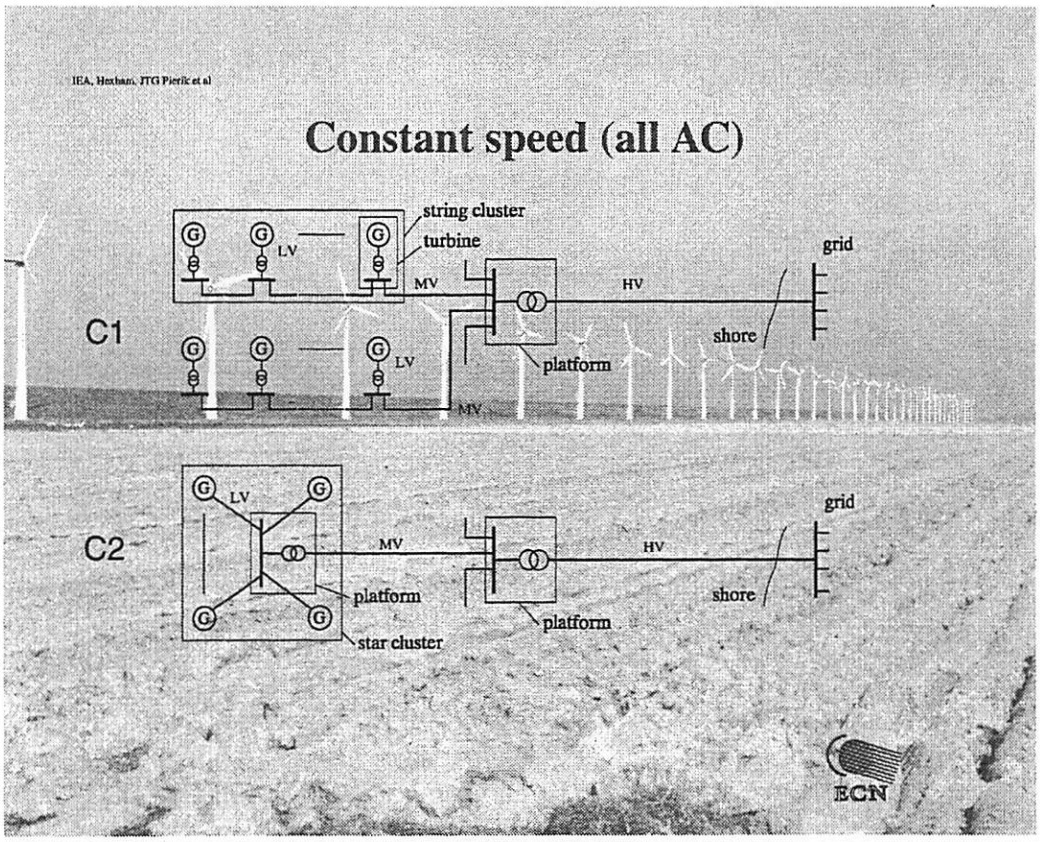
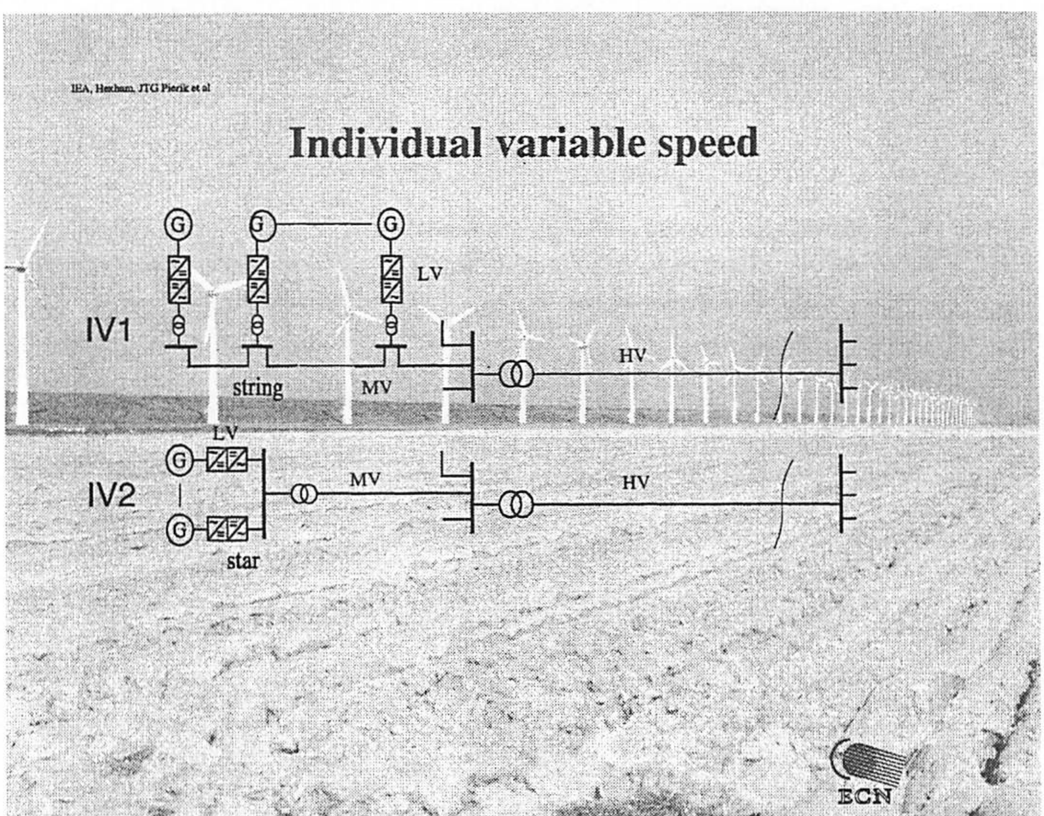
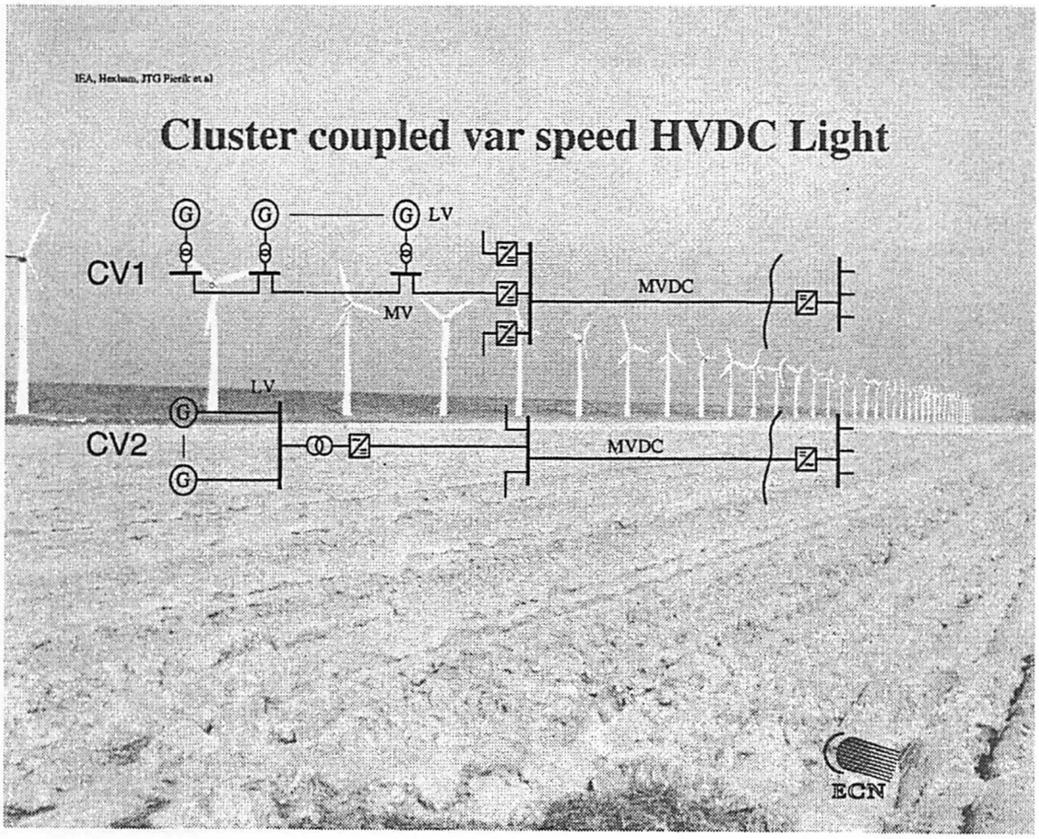
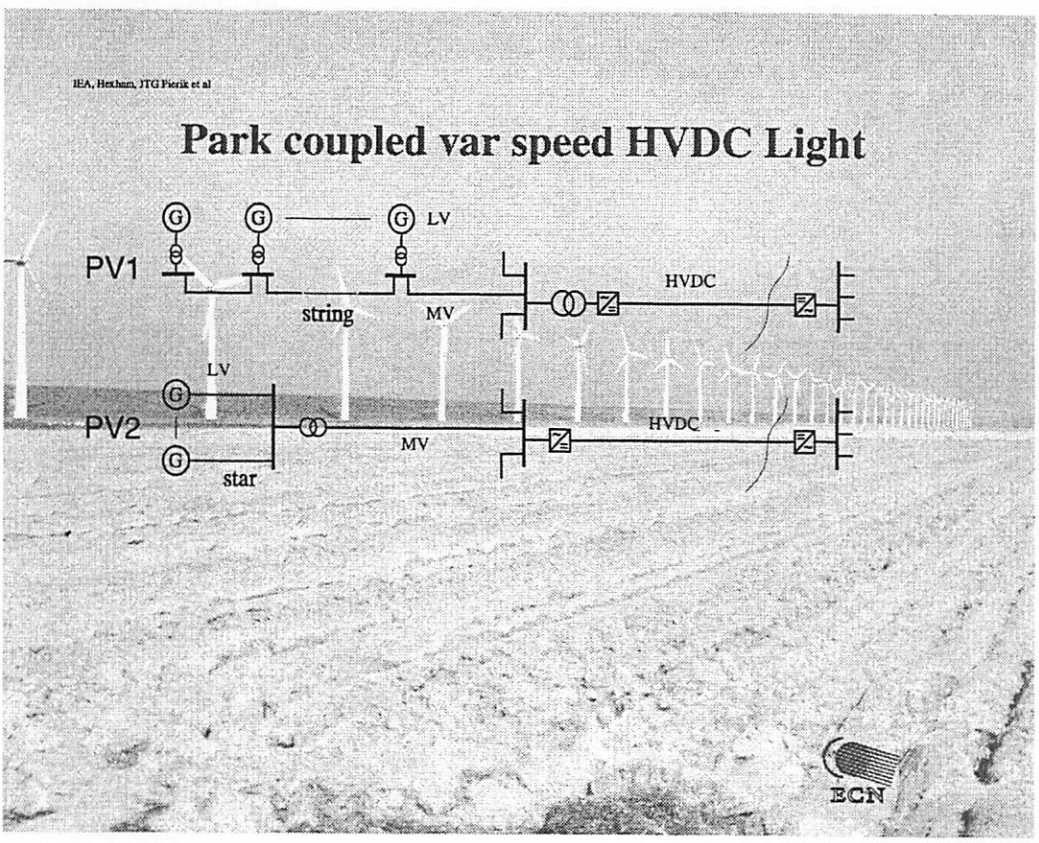

IEA, Hexham, JTG Pierik et al
Constant speed (all AC)
string cluster
turbine
LV
MV
HV
grid
C1
shore
platform
C2
platform
star cluster
ECN


IEA, Hexham, JTG Pierik et al
Individual variable speed
LV
IV1
string
MV
HV
IV2
star
ECN


IEA, Hexham, JTG Pierik et al
Cluster coupled var speed HVDC Light
CV1
LV
MV
MVDC
CV2
LV
MVDC
ECN


IEA, Hexham, JTG Pierik et al
Park coupled var speed HVDC Light
PV1
LV
string
MV
HVDC
PV2
LV
MV
HVDC
star
ECN

IEA, Hexham, JTG Pierik et al

Eefarm computer program

- calculates voltage and current phasors in all nodes for wind speed bins in P(V) curve
- calculates electrical losses per component
- single phase component models
  - transformer
  - AC and DC cable
  - thyristor rectifier and invertor
  - IGBT rectifier and invertor
  - opchopper
- pre-programmed system configurations
- data base with component parameters and prices

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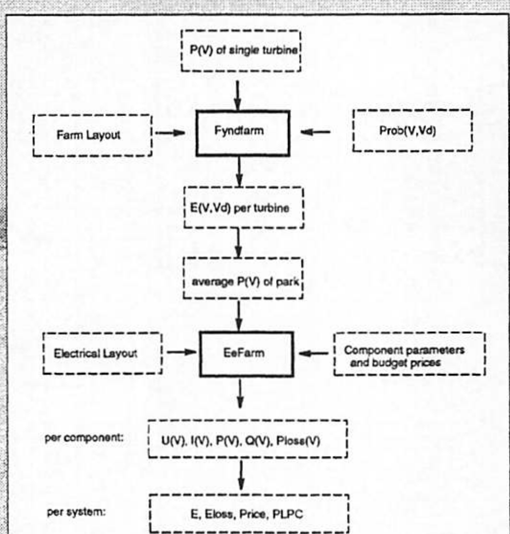
IEA, Hexham, JTG Pierik et al

Eefarm calculation



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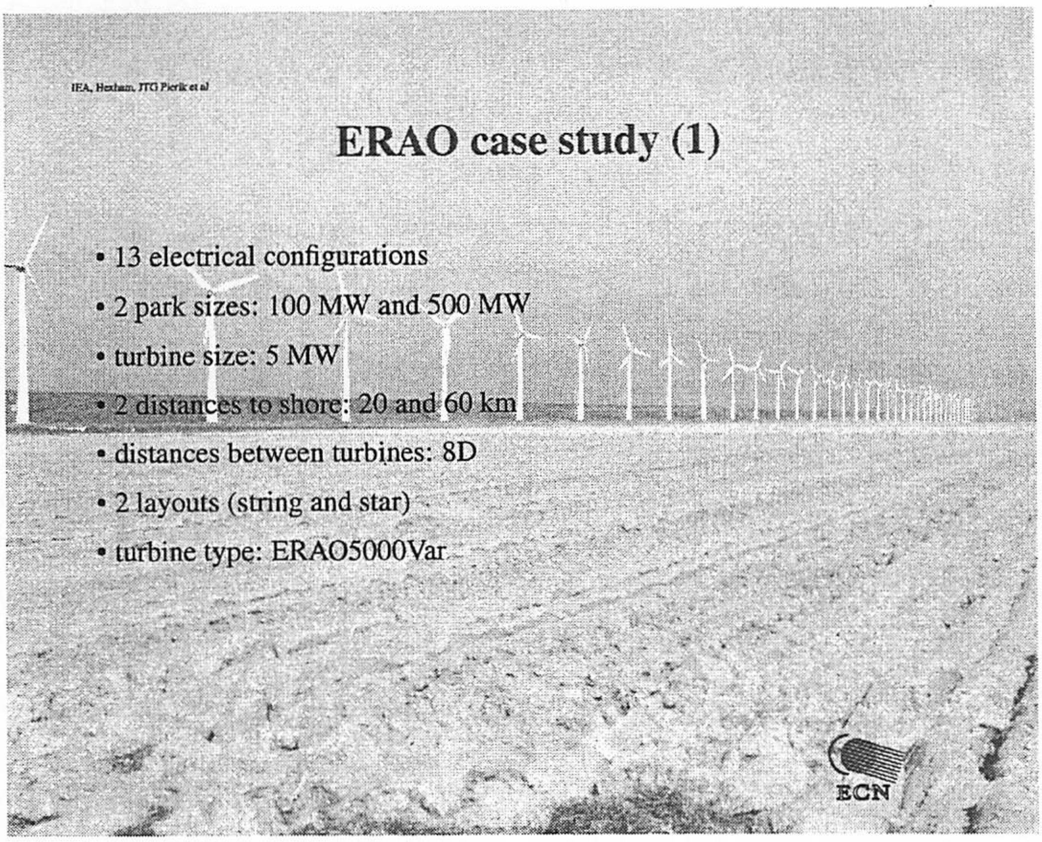
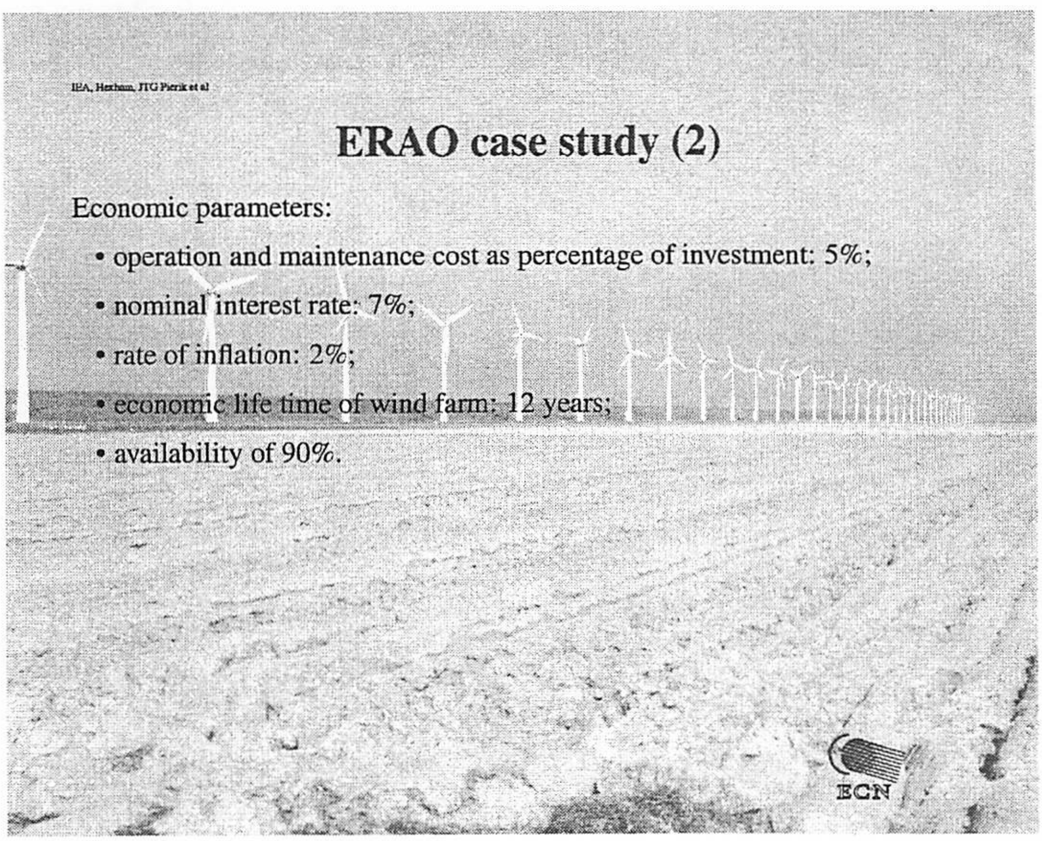
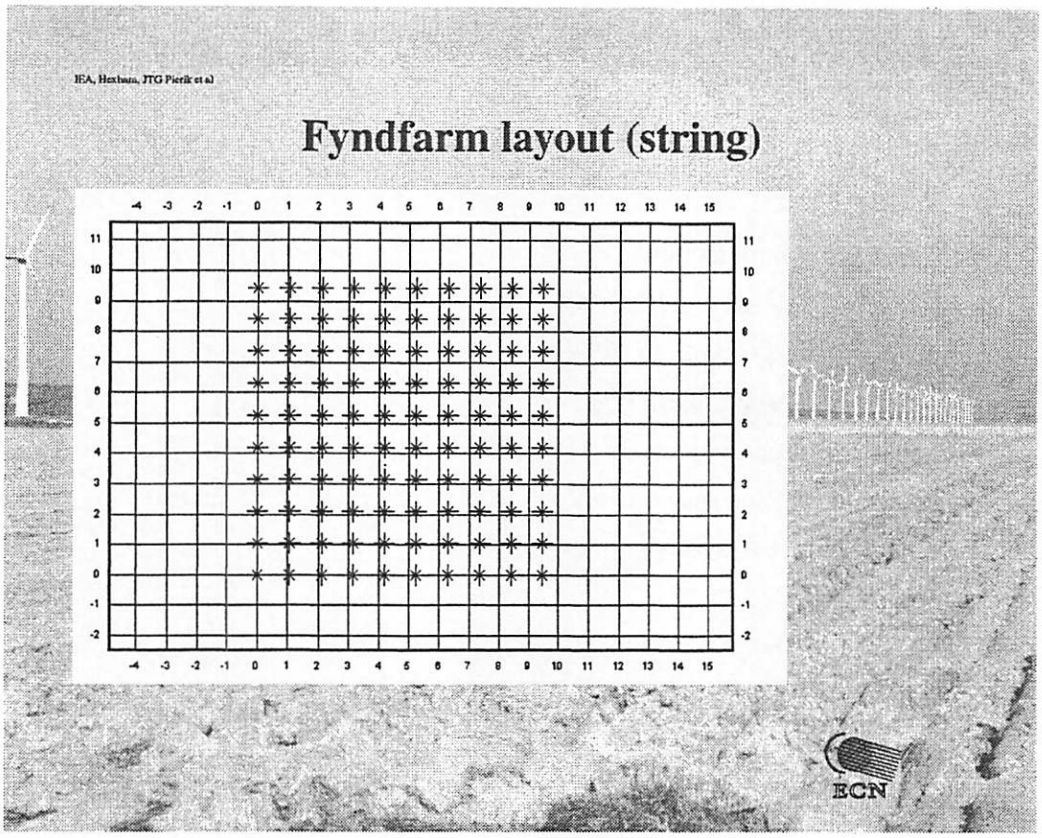
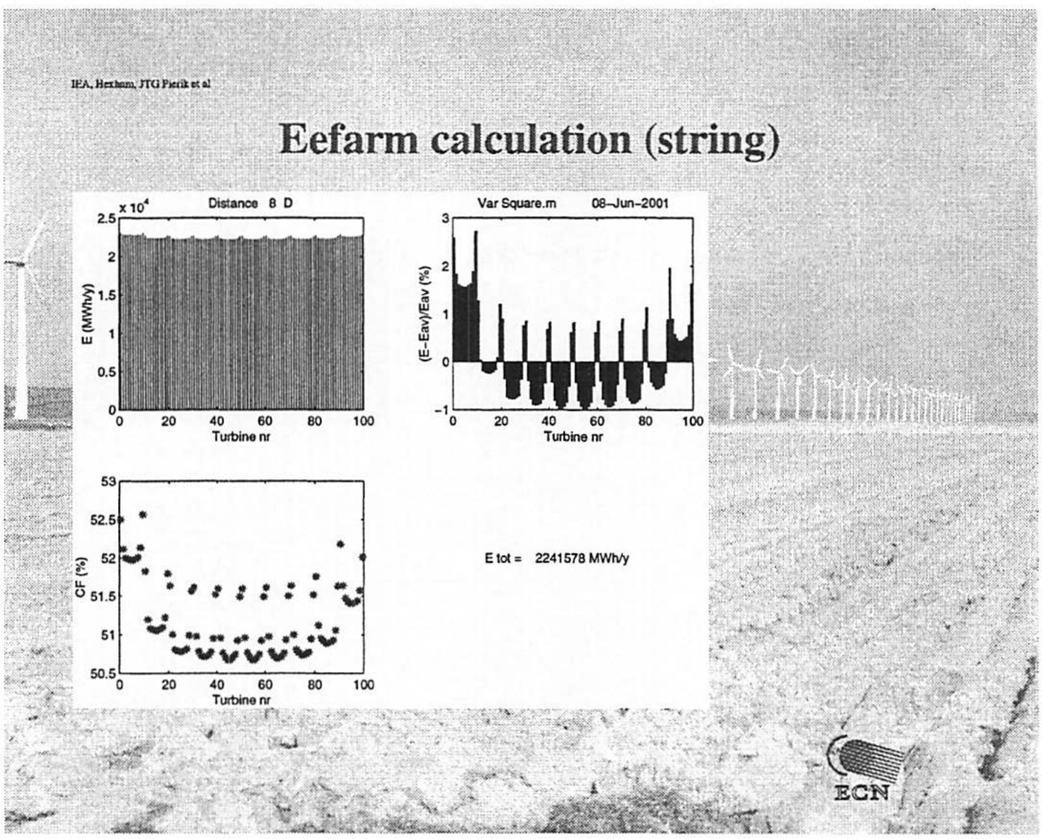
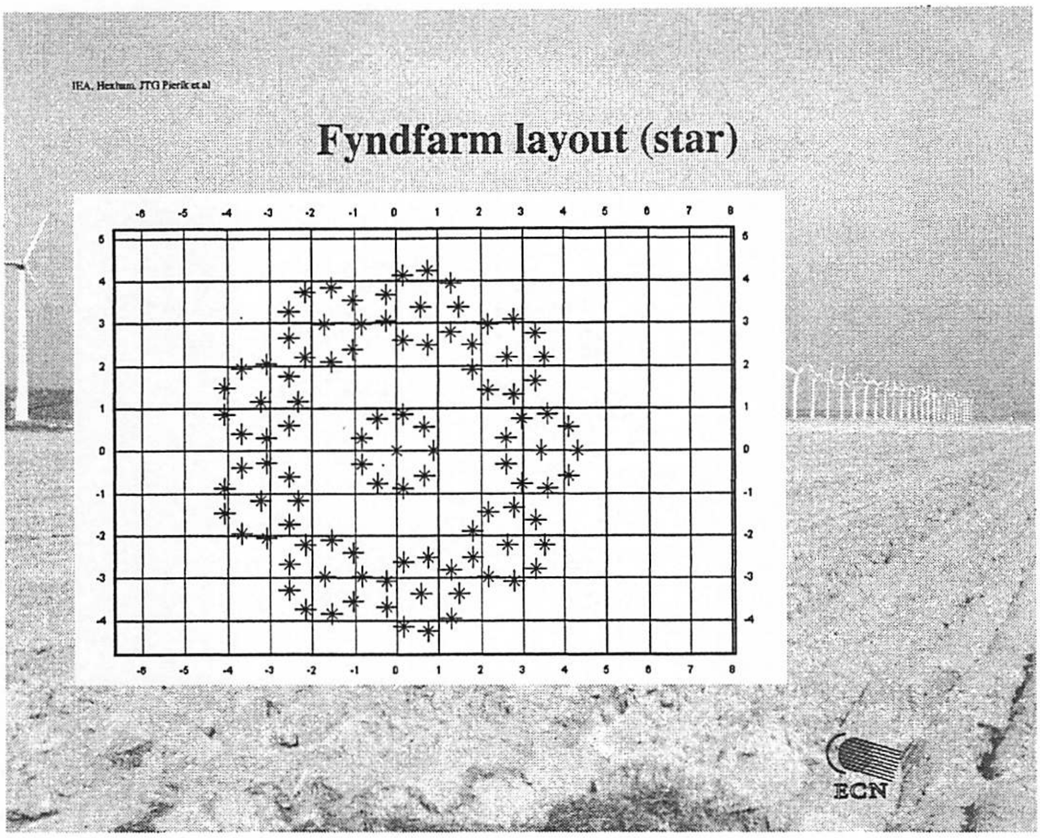
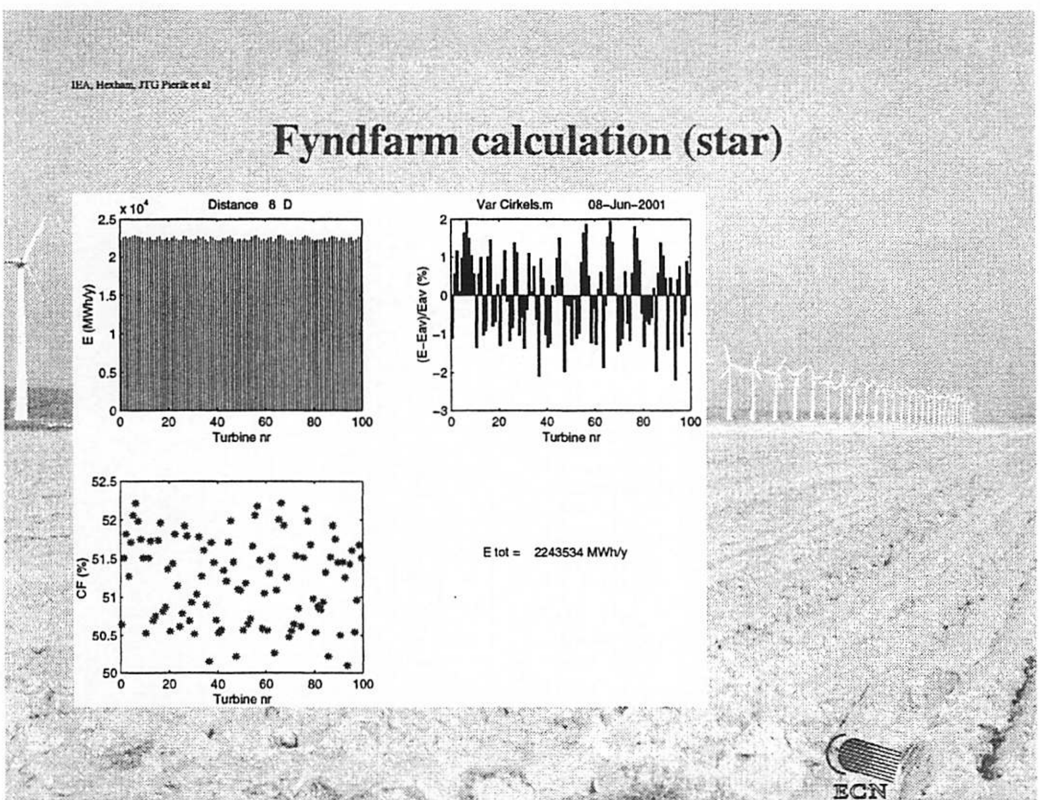

IEA, Hexham, JTG Pierik et al
ERAO case study (1)
• 13 electrical configurations
• 2 park sizes: 100 MW and 500 MW
• turbine size: 5 MW
• 2 distances to shore: 20 and 60 km
• distances between turbines: 8D
• 2 layouts (string and star)
• turbine type: ERAO5000Var
ECN


IEA, Hexham, JTG Pierik et al
ERAO case study (2)
Economic parameters:
• operation and maintenance cost as percentage of investment: 5%;
• nominal interest rate: 7%;
• rate of inflation: 2%;
• economic life time of wind farm: 12 years;
• availability of 90%.
ECN


IEA, Hexham, JTG Pierik et al
Fyndfarm layout (string)
ECN


IEA, Hexham, JTG Pierik et al
Eefarm calculation (string)
Distance 8 D
Var Square.m 08-Jun-2001
E (MWh/y)
(E-Eav)/Eav (%)
CF (%)
Turbine nr
E tot = 2241578 MWh/y
ECN


IEA, Hexham, JTG Pierik et al
Fyndfarm layout (star)
ECN


IEA, Hexham, JTG Pierik et al
Fyndfarm calculation (star)
Distance 8 D
E (MWh/y)
Turbine nr
Var Cirkels.m 08-Jun-2001
(E-Eav)/Eav (%)
Turbine nr
CF (%)
Turbine nr
E tot = 2243534 MWh/y
ECN

IEA, Hexham, JTG Pierik et al

Fyndfarm results

Config	E_{av} (MWh/y)	CF_{min} (%)	CF_{max} (%)	E_{tot} (MWh/y)
Single 5 MW turbine:				
-	23413	53.45	53.45	23413
20 × 5 MW turbines at 8D:				
string	22647	51.02	52.58	452946
star	22538	50.40	52.22	450762
100 × 5 MW turbines at 8D:				
string	22416	50.67	52.57	2241578
star	22435	50.10	52.22	2243534

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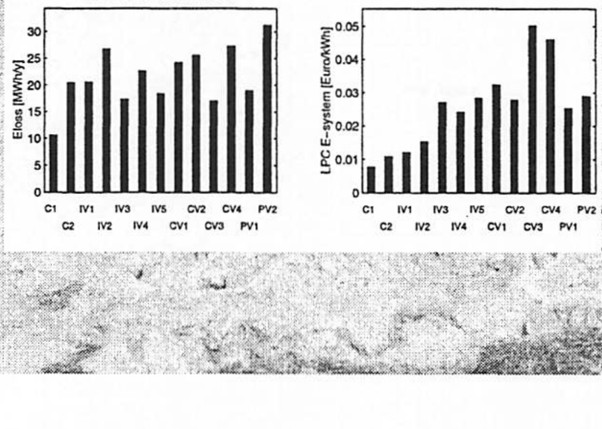
IEA, Hexham, JTG Pierik et al

Eefarm results 100 MW, 20 km



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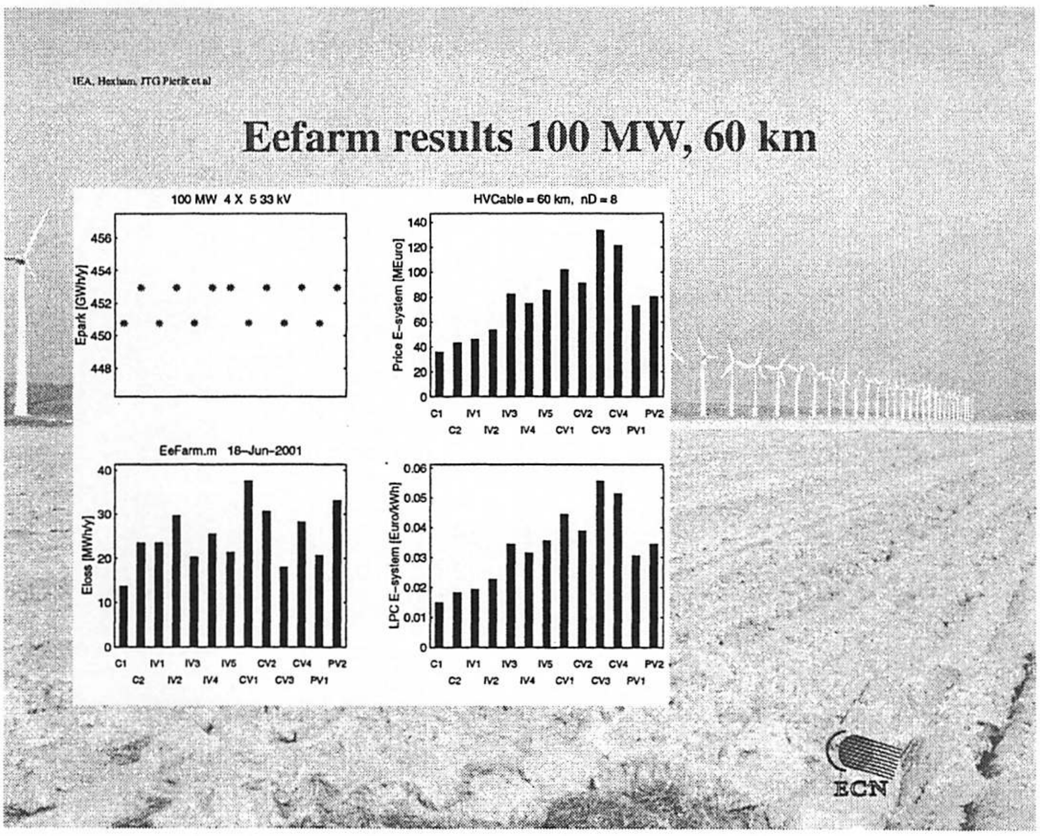
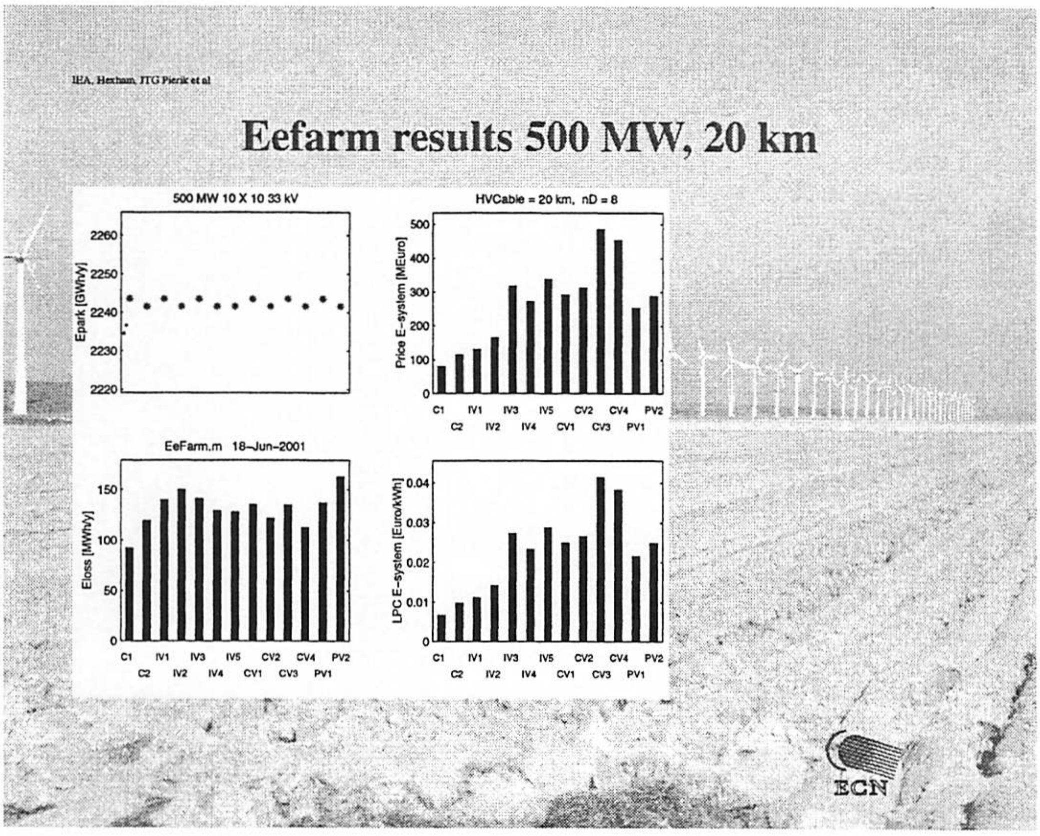
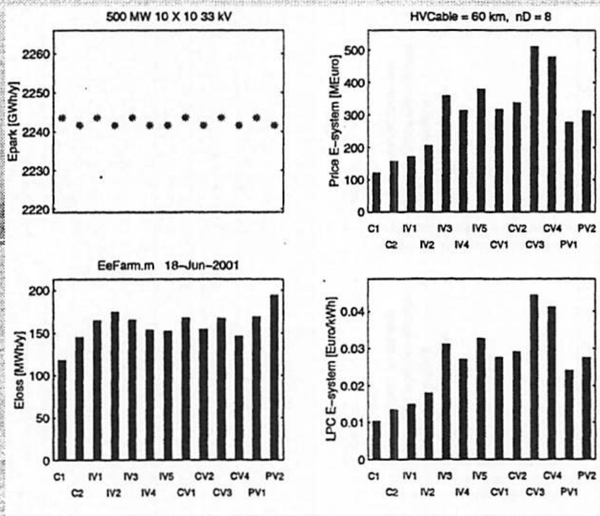

IEA, Hexham, JTG Pierik et al
Eefarm results 100 MW, 60 km
100 MW 4 X 5 33 kV
Epark [GWh/y]
HVCable = 60 km, nD = 8
Price E-system [MEuro]
EeFarm.m 18-Jun-2001
Eloss [MWh/y]
LPC E-system [Euro/kWh]
C1 IV1 IV3 IV5 CV2 CV4 PV2
C2 IV2 IV4 CV1 CV3 PV1
ECN


IEA, Hexham, JTG Pierik et al
Eefarm results 500 MW, 20 km
500 MW 10 X 10 33 kV
Epark [GWh/y]
HVCable = 20 km, nD = 8
Price E-system [MEuro]
EeFarm.m 18-Jun-2001
Eloss [MWh/y]
LPC E-system [Euro/kWh]
C1 IV1 IV3 IV5 CV2 CV4 PV2
C2 IV2 IV4 CV1 CV3 PV1
ECN

IEA, Hexham, JTG Pierik et al

Eefarm results 500 MW, 60 km



ECN

IEA, Hexham, JTG Pierik et al

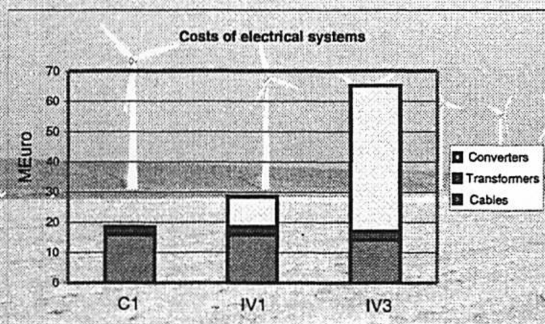
Eefarm costs and losses

	Size [MW]	Dist [km]	E loss $[\frac{MWh}{y}]$	E loss [%]	Costs [MEuro]	Rel Cost $[\frac{MEuro}{MW}]$
C1	100	20	10539	2.3	19.73	0.20
	100	60	13620	3.0	36.93	0.37
	500	20	91906	4.1	91.75	0.18
	500	60	117555	5.2	132.95	0.27
IV1	100	20	20513	4.5	29.73	0.30
	100	60	23470	5.1	46.93	0.47
	500	20	139885	6.2	141.75	0.28
	500	60	164345	7.3	182.95	0.37
PV1	100	20	19002	4.1	61.41	0.61
	100	60	20642	4.5	73.97	0.74
	500	20	136777	6.1	263.71	0.53
	500	60	168851	7.5	288.83	0.58

ECN

IEA, Hexham, JTG Pierik et al

Eefarm economic results



ECN

IEA, Hexham, JTG Pierik et al

Conclusions

- AC systems C1/C2 lowest investment and LPC (for assumed interest rate and life time)
- AC systems C1 lowest electrical losses
- aerodynamic performance differences caused by different turbine design not considered
- control and stability issues may favour DC solution PV1 best alternative
- electrical interaction to be investigated in ERAO Phase 2

ECN

SIMULATION OF DYNAMIC IMPACT OF WIND FARM ON POWER SYSTEM

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ABSTRACT: This paper describes a model of a wind farm including the nearest grid. The model is implemented in a commercial software tool for power system simulation. It comprises the substation, where the wind farm is connected, the power collection system in the wind farm, electric, mechanic and aerodynamic models for the wind turbines, and finally a wind model. The model is built to enable assessment of power quality, control strategies and behaviour in the event of grid faults. In this paper, the model is presented, and the ability of the model to predict flicker emission is demonstrated.
Keywords: Grid, Integration, Electrical Systems, Power Quality

1 INTRODUCTION

The purpose of the work is to develop a tool to study and improve the dynamic interaction between large wind farms and the power system to which they are connected.

The background is the fast development of wind energy, which is concentrated in areas with good wind resources. Wind energy is becoming a significant supply in the power systems in these areas, and therefore wind energy is becoming an important role in the operation of these power systems.

As a first step towards models for interaction between wind farms and power systems, the present work provides a simulation model for the 12 MW wind farm installed in Hagesholm in Denmark consisting of six NM 2000/72 wind turbines from NEG-Micon, with active stall control.

The simulation model of the wind farm is developed in the dedicated power system analyses tool DIgSILENT combines models for electromagnetic transient simulations of instantaneous values with models for electromechanical simulations of RMS values. This makes the models useful for (transient) grid fault studies as well as for studies of (longer-term) power quality issues.

The wind farm model consists of a grid model, six almost identical wind turbine models and a model for the wind speed.

The Hagesholm wind farm is connected to the 50/10 kV substation in Grevinge, which is situated 5 km away from the wind farm. The grid model includes the electric components in the wind farm power collection system and the substation, and uses equivalents for the remaining grid.

The individual wind turbine model includes an electric part, a mechanical part and an aerodynamic part. The electric model includes induction generator, softstarter, capacitor banks for reactive power compensation and the step-up transformer. The mechanical model describes the dynamics of the drive train, whereas the aerodynamic model is a standard C_p based model, extended with dynamic stall effects.

The wind speed model accounts for the coherence of the wind speeds at different wind turbines as well as the effects of the wind variations in the rotor plane [1] (i.e. 3p due to rotationally sampled turbulence [2], [3] and tower shadow).

Validation of the models for fault free operation are presented in the paper. The validations are based on power quality measurements on one of the wind turbines.

The simulation model is the first of its kind, which includes all the above aspects in a single model. This makes the model unique to predict the influence of wind farms on the power quality.

2 GRID MODEL

The grid model is shown in Figure 1. The grid is built on standard component models from the DIgSILENT library.

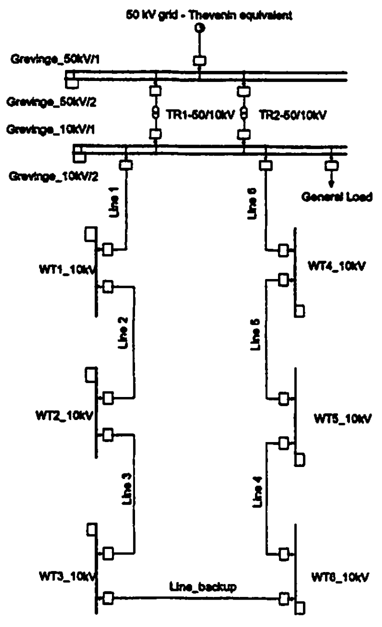

Figure 1: Grid model for the connection of Hagesholm wind farm.

Each of the six wind turbines are connected to its own 10 kV bus WTn_10kV. The figure shows how the wind farm is connected to the substation in two groups. A backup line is also installed between the ends of the two lines.

The substation is modelled with double busbars and transformers with automatic tap changers. The 50 kV grid is simply modelled by a Thevenin equivalent. This is a fair approximation for power quality studies, because the wind farm has relatively little influence on the power quality of the 50 kV grid, which is strong compared to the installed wind power capacity.

A number of load feeders are also connected to the substation in Grevinge. As a tentative solution, these loads are modelled by a single, general load directly connected to the 10 kV busbar of the substation.

3 WIND TURBINE MODEL

A dynamic wind turbine model is connected to each of the wind turbine terminals WTn_10kV in Figure 1. Each of the wind turbines are modelled individually, providing a realistic model for the dynamics of the wind farm, where the wind turbines can operate with different wind speed and mechanical fluctuations, coupled through the grid.

The model of an individual wind turbine is shown in Figure 2. It includes an electric part, a mechanical part and an aerodynamic part. The electric part provides the interface to the grid as the currents I_{WTT} and voltages U_{WTT} on the wind turbine terminals, while the aerodynamic part is feeded by an equivalent wind speed u_{eq} described in section 4. The wind model uses the turbine rotor position θ_{WTR} from the mechanical part of the wind turbine model.

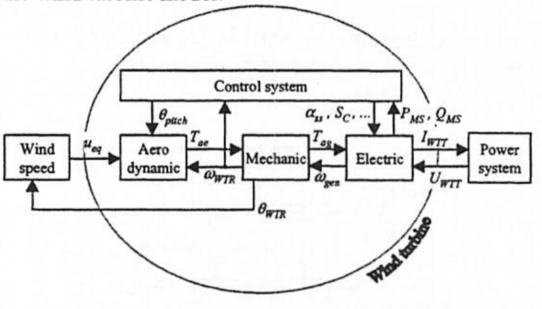

Figure 2: Wind turbine model with interface to power system (grid) model and wind speed model.

The wind turbine model is controlled by the control system block. Inputs to the control system block are the active and the reactive power P_{MS} and Q_{MS} measured at the main switch, and the turbine rotor speed ω_{WTR}. The outputs from the control block are the pitch angle θ_{pitch} for the aerodynamic model, and a number of control signals for the electric model, including soft starter firing angle α_{ss} and capacitor switch signals S_C.

3.1 Electric model

The electric part of the wind turbine model is shown in Figure 3. It includes induction generator, softstarter, capacitor banks for reactive power compensation and the step-up transformer. The transformer is placed in the hub. Also the 10 kV cable through the tower is included in the model.

P_{MS} and Q_{MS} in Figure 2 are taken from the low voltage side of the step-up transformer, corresponding to where the actual control system measures voltage and current on the main switch.

The capacitor bank consists of 10 steps, which are controlled independently. The control system model sends signals to the contacts, to close or open the individual capacitors, based on the measured Q_{MS}.

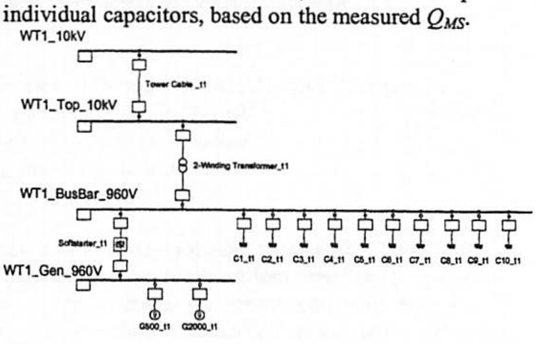

Figure 3: Model of the electric part of the wind turbine.

The softstarter is controlled by the firing angle. The control system model calculates this firing angle like the control system of the real wind turbine. This is implemented in DIgSILENT, based on the dynamic simulation language.

Two different generators are connected to the 960 kV busbar in Figure 3. This corresponds to the two sets of windings in the real generator with 4 and 6 poles.

3.2 Mechanical model

The mechanical model of the wind turbine is shown in Figure 4. It is essentially a two mass model connected by a flexible shaft characterised by a stiffness k_{ms} and a damping c_{ms}. Moreover, an ideal gear with the exchange ratio $1{:}f$ is included.

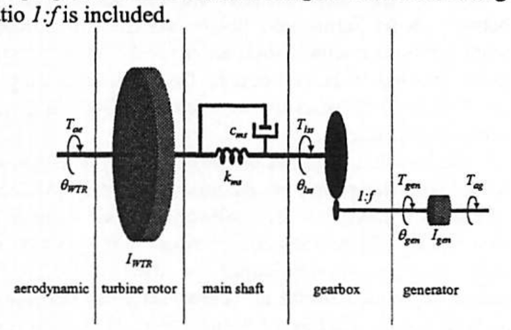

Figure 4: Model of the mechanical part of the wind turbine.

The masses used in this model correspond to a large turbine rotor inertia I_{WTR} representing the blades and hub, and a small inertia I_{gen} representing the induction generator. The generator inertia is actually included in the generator model, specified as an inertia time constant.

The stiffness and damping components are modelled on the low speed shaft, but flexibility in the gear and on the high speed shaft can also be included here, if they are corrected for the gear ratio.

3.3 Aerodynamic model

The aerodynamic model is based on tables with the aerodynamic efficiency $C_p(\lambda, \theta_{pitch})$, i.e. C_p depends on the tip speed ratio λ and the blade pitch angle θ_{pitch}.

At first, only one C_p table was applied, corresponding to the steady state aero loads in the power curve. However, this simplification showed to underestimate the power fluctuations in the stall region. Therefore, a model for dynamic stall was included.

The applied model for dynamic stall is based on Øye's dynamic stall model [4], simulating dynamic stall as time lag of separation. Øye implements the time lag directly on the lift coefficients in the individual blade sectors, but this is not possible in our case, because we base the aerodynamic calculations on C_p.

We have therefore implemented a similar time lag on C_p instead, and shown that this is a good approximation. The implementation requires another two C_p tables, one for separated flow and one for attached flow.

4 WIND MODEL

The wind model includes the (park scale) coherence of the wind speeds at different wind turbines as well as the effects of the wind variations in the rotor plane [5]. The park scale coherence is included, because it ensures realistic fluctuations in the sum of the power from each wind turbine, which is important for the maximum power output from the wind farm, while the variations in the rotor plane are included because they provide the 3p effect, which causes most of the flicker emission during continuous operation.

The structure of the wind model is shown in Figure 5. It provides an equivalent wind speed for each of the wind turbines, i.e. a single time series for each wind turbine, which is used as input to the aerodynamic model of that wind turbine.

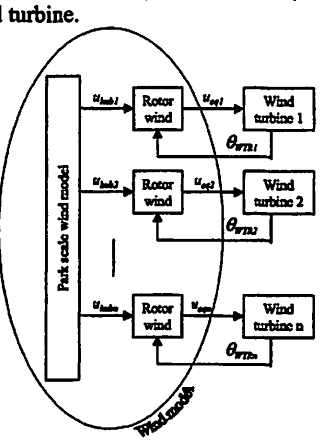

Figure 5: Structure of wind model.

It is seen in Figure 5 that the wind model is divided into one model for the park scale coherence and a rotor wind model for each wind turbine. The park scale model simulates time series at each wind turbine hub, and each wind turbine uses one of these wind speeds as input. The rotor wind model adds the effect of integration along the blades and rotational sampling, which causes the 3p effect.

4.1 Park scale coherence model

The park scale coherence model is a stochastic model, which simulates wind speeds with the same stochastic characteristics as measured wind speeds in fixed points. These characteristics are power spectral densities (PSDs) which describe the frequency content of the fluctuations, and the coherence functions which describe the coherence between wind speeds in different points (i.e. at the wind turbines) in the frequency domain.

To simulate wind speeds at each wind turbines, a dedicated program PARKSIMU has been developed, which uses a similar procedure as Veers [6] used to simulate wind speeds in wind turbine rotors. , but using coherence values from a study of separations greater than the measurement height [7].

The PARKSIMU model includes a delay in the correlated part of the wind speeds, corresponding to the travel time in the wind direction between the points.

Figure 6 shows one minute mean values of measurements of the wind speeds on two sea masts SMW and SMS in Vindeby offshore wind farm, with 807 m separation between the masts. The flow is almost longitudinal from SMW to SMS.

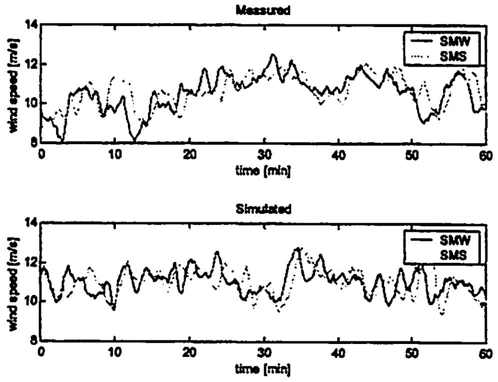

Figure 6: Simulation of wind speeds compared to measurements on two sea masts in Vindeby offshore wind farm.

One minute mean values of PARKSIMU simulations with the same mean wind speed and wind direction are also shown in the figure. Both measurements and PARKSIMU indicate a delay of SMS with a little more than one minute relative to SMW.

4.2 Rotor wind model

The rotor wind model adds the effect of integration along the blades and rotational sampling of a wind field. A stochastic model for the turbulence contribution and a deterministic model for the tower shadow are combined to determine the wind field in the rotor. The azimuth position of the turbine rotor provides the frequency and phase of the 3p fluctuation.

The advantage of the applied 3p model is that it includes the significant 3p effect without having to interpolate along all the blades in a three dimensional wind field like in Veers. Although this approach is effective, the model is directly applicable for variable speed wind turbines.

5 VERIFICATION

Some verification results, demonstrating the ability of the model to predict the power quality of the wind turbines, are shown in [8]. In this paper, we will focus on the power fluctuations, and the influence of these fluctuations on flicker emission from the wind turbine during continuous operation.

Figure 7 shows the power spectral densities (PSDs) of measured and simulated power during continuous operation. It is seen from the measured PSD, that the dominating fluctuations are the low frequencies (below about 0.1 Hz) and the area around the 3p frequency 0.9 Hz.

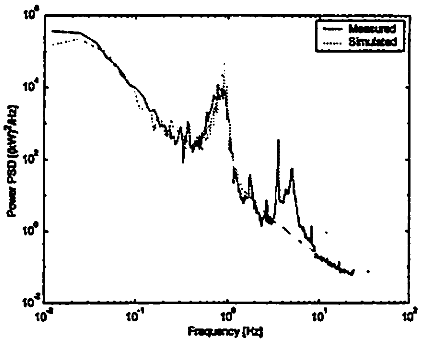

Figure 7: PSD of measured and simulated power from wind turbine 1.

Comparing the simulated PSD to the measured, it is also observed that these frequencies are predicted quite well by the simulations. The torsional vibration mode of the main shaft with an eigenfrequency around 0.7 Hz can also be observed in both measurements and simulations.

Also the 6p (1.8 Hz), 9p (2.7 Hz) and especially the 12 p frequency (3.6 Hz) are visible in the measurements. These frequencies can easily be included in the model, but it will increase simulation time.

Besides, there is a significant frequency around 5 Hz. A study of measured mechanical loads indicate that this frequency is due to some vibration mode of the rotor together with the tower, which is more complicated to include in the model.

The influence of the different frequencies of the fluctuations on the flicker emission from the wind turbine during continuous operation are illustrated in Figure 8.

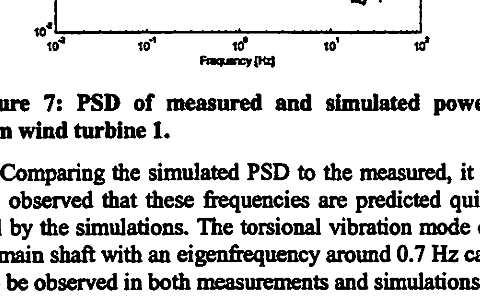

Figure 8: Flicker contributions from low pass filtered active and reactive power fluctuations.

The figure shows the flicker emission from the wind turbine, if only fluctuations below the cut-off frequency f_cut were present. The results are obtained by filtering the active and reactive power from the wind turbine with a 8th order Butterworth low pass filter, and then calculate the flicker emission from the filtered power with a power based flicker calculation [9].

It is seen from the comparison in Figure 8 that the 3p frequency provides the main contribution to flicker, and that this contribution is overestimated with approximately 20 % by the simulations. There can be many reasons for this overestimation. It will require comparisons of many more time series to reveal if this is a systematic deviation.

6 CONCLUSIONS

The conclusion is, that a model for the interaction between a wind farm and the surrounding grid has been developed. The model includes the main effects that contribute to the standard characteristics [10] of the power quality of the wind farm: maximum power, reactive power consumption, flicker emission and voltage drops during switchings. The ability of the model to simulate flicker during continuous operation has been validated.

ACKNOWLEDGEMENTS

The Danish Energy Agency is acknowledged for the funding of this work in contract 1363/00-0003. Besides, a special thanks is given to North-West Sealand Energy Supply Company, NVE, who has participated in the project discussion based on own funding and assisted at the power quality measurements. Also thanks to the Danish transmission system operators Eltra and Elkraft System, who have also provided useful experience as members of an advisory committee for the project. Finally thanks to SEAS Wind Energy Centre for funding to maintain Vindeby data.

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Simulation of dynamic impact of wind farm on power system

Poul Sørensen, Anca D. Hansen,
Lorand Janosi, John Bech,
Frede Blaabjerg, Birgitte Bak-Jensen, Zhe Chen

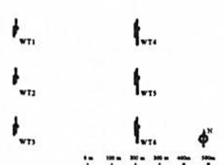
Project description

- Sponsor
  - Danish Energy Agency
- Participants
  - Risø National Laboratory / Aalborg University
  - DanControl Engineering a/s
  - (North-westSealand Energy Supply Company, NVE)
- Advisory committee
  - Eltra (TSO DK-west)
  - Elkraft System (TSO DK-east)
- Purpose
  - Provide wind turbine industry with a tool to assess and improve interaction of wind farms with power systems
  - Provide wind turbine industry with a tool to demonstrate the behaviour of their wind farms
  - Provide a tool for international consultancy

Simulation of dynamic impact of wind farm on power system

Project methodology

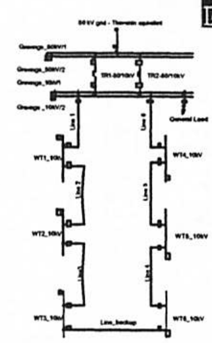
- Use dedicated power system simulation software- DigSILENT Power Factory
- Library with standard grid components and block structure with access to dynamic simulation language for movers (wind turbines)
- Build models for Hagesholm wind farm
  - grid model
  - wind turbine model
  - wind model
- Verify models
- Demonstrate application of models for tentative assessment of power quality



Simulation of dynamic impact of wind farm on power system

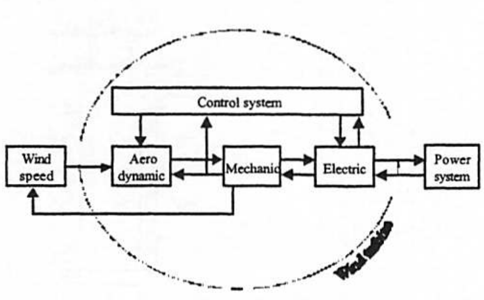
Grid model

- Two lines to Grevinge substation
- Backup line
- Substation
  - double busbar
  - transformers with automatic tap changers
- Lumped load
- 50 kV grid by Thevenin equivalent (S_k/S_w 75)



Simulation of dynamic impact of wind farm on power system

Wind turbine model



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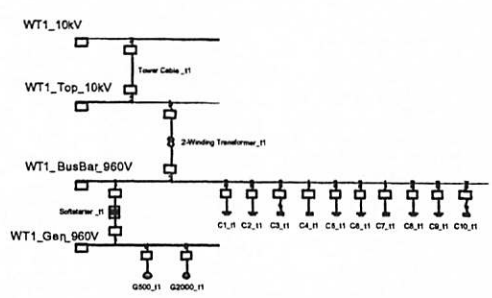
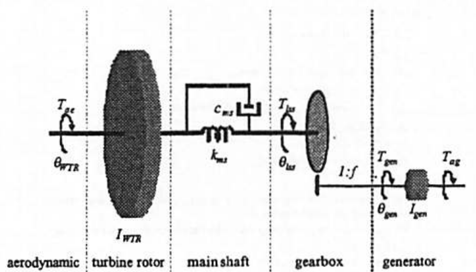
Wind turbine electric model



Simulation of dynamic impact of wind farm on power system

Simulation of dynamic impact of wind farm on power system

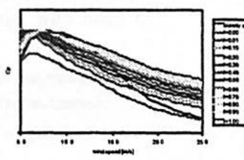
Wind turbine mechanical model



Simulation of dynamic impact of wind farm on power system

Wind turbine aerodynamic model

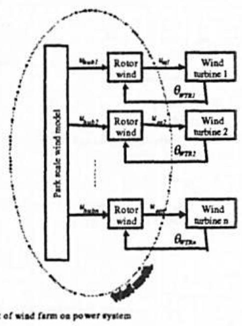
- C_p based model (one wind speed per wind turbine)
- $C_p(\lambda, \theta_{pitch})$ table
- Steady state insufficient for power fluctuations in stall region
- Dynamic stall simulated as time lag of separation (Øye)
- Interpolation in C_p
- Three C_p tables



Simulation of dynamic impact of wind farm on power system

Wind model

- Park scale model to account for coherence of wind speeds at wind turbines, to predict maximum (and standard deviation) power of a wind farm
- Rotor wind model to include 3p effects, which are main source of flickers during continuous operation



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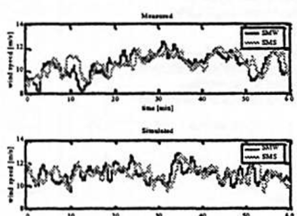
Longitudinal flow simulation (Vindeby)



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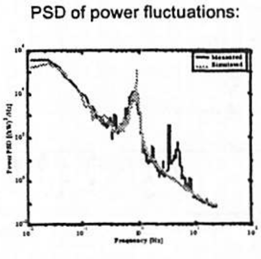
Influence of power fluctuations on flicker

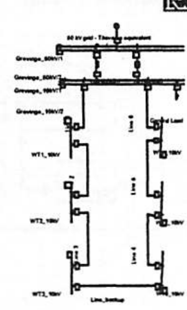
PSD of power fluctuations:



Simulation of dynamic impact of wind farm on power system

Conclusions

- A model for wind farm interaction with grid has been implemented in a power system simulation software
- The model includes the main characteristics to predict power quality
- The simulation results have been compared with measurements, showing fair agreement
- The model needs further validation for transient behaviour.



Simulation of dynamic impact of wind farm on power system

Simulation of dynamic impact of wind farm on power system

Summary of IEA Topical Expert Meeting on Large scale integration into the grid

6-7 November 2001, Hexham, England

Ola Carlson and Sven-Erik Thor

Background

Wind power penetration is increasing in many grid systems world-wide. In some areas in Europe, e.g. Northern Germany or Denmark, wind power supplies already more than 10 % of the yearly average demand. Hence, during times with high wind speeds and low loads (at night), the wind power penetration can be well above 50 % in some network areas.

As wind power penetration increases also in other areas of the world, e.g. Spain, Texas or California, the influence of large wind power penetration becomes more and more of a common international interest. The Danish and German experiences thereby provide valuable information; however, it has to be discussed how these experiences can be transferred to other network configurations.

In addition, a new challenge is the integration of large wind farms into the grid. At present, the largest wind farms have a power output of from 50 MW to about 150 MW. In the U.S. and Europe, wind farms with a power output of well over 150 MW are currently planned. In Europe, for example, large offshore wind farms with a total installed capacity of up to 1000 MW are investigated, and in the US, particularly on the West Coast and along the Great Plains, projects of more than 500 MW will soon be installed.

Participants

The meeting gathered 22 participants, representing grid owners, manufacturers and researchers. Grid representatives came from the UK, Scotland, Ireland, Italy and Spain. Researchers came from Denmark, the Netherlands, Finland, Sweden, Norway, Spain, Ireland and the UK.

Presentations

Hannele Holttinen from VTT in Finland presented a study regarding power balance and regulation in the Nordic Countries (Denmark, Norway, Sweden and Finland) at different wind power penetrations. Some of the conclusions were:

- 4-5 % wind electricity will not be noted
- 10-15 % gives a change in the production planning of the operation of the grid, resulting in increased export/import and a negligible cost increase
- More than 15 % gives extra costs for regulation

She also showed that 10% wind does not give any contribution to the power variations on an hourly basis; this implies that there is no need for extra power capacity in the grid.

Jan Pierik from ECN in the Netherlands reported from an offshore study in which different grid layouts for a 500MW wind farm were studied. The calculations were made for a 5 MW wind turbine with a capacity factor of 50%. Among the studied layouts were ones including directly coupled induction machines with an AC-grid, generators connected via converters, a

DC-grid in the wind farm and DC-connection on shore. The conclusion was that a simple electrical system with an AC-connection on shore was the cheapest alternative for distances up to 60km off shore.

Jan Bozelie presented a thorough investigation of grid manuals and regulations from the NL, the UK, DK and DE. Great variations on the demands were shown in the different countries. Participants proposed that the compilation should be extended with figures from other countries.

Most of the participants thought that the utilities should have the possibility of setting requirements or the performance in different situations, for example, in control of active and reactive power at normal operation and at fault situations. Performance at faults should be declared in a clear way. This leads to what all participants considered to be most important, namely, to be able to develop and have access to reliable electrical models for simulation of grid interaction. This is crucial for the safe transmission of electricity in the grid. A working group of grid owners from the UK, Ireland and Scotland has been set up. The aim is to develop reliable models of wind power plants incorporating:

- Induction generators directly connected to the grid
- Induction- and synchronous generators connected to the grid via converters
- Double-fed induction generators

There is also a need for advanced and simple models of single wind turbines. The simpler models are important for connecting a large number (thousands) of wind turbines and calculations with a rather slow time variation, up to 10 Hz. The more advanced models are used when there is a need for calculations with a short time constant, less then 100 ms. Of course, the computer calculation time is much longer for the advanced model.

Arne Hejde Nielsen from DTU in Denmark discussed the importance of incorporating the power control of the wind turbine when analyzing three-phase short-cuts in the grid. It was shown that wind turbines equipped with active stall in a wind farm of 150MW can help and support the grid at a short circuit situation and will continue to produce when the fault is repaired. On the other hand, if a wind turbine is equipped with passive stall control, a strong oscillation will occur. These simulations were performed with PSS/E.

Conclusions

The conclusion from the meeting was that it is essential to have good simulation tools and reliable models of the wind turbines when performing grid simulations. There was a great interest for further co-operation within this field. At the meeting it was decided to prepare a proposal for a new Annex covering these issues. The proposal should cover the following points:

- Model exchange/evaluation/comparison
- A common database with model parameters and measurements
- Best practice guidelines, such as, grid connection codes specific for wind turbines

It was pointed out that it is essential that manufacturers of wind turbines participate in the work. This will secure that the different ways of operating wind turbines will be covered.

In order to be able to formulate the proposal, an AdHoc group was set up with the following persons: John Tande (Norway), Jan Pierik (the Netherlands), Karsten Burges (the Netherlands) and Ola Carlson (Sweden). The intention is to present the proposal at the next ExCo meeting on April 16-17, 2002. The indicative time schedule for the work:

Nov 2001	Send templates for starting an Annex to Tande	Thor	
Nov01-Jan02	Prepare and circulate proposal and get comments	All	
March 2002	Send proposal to ExCo secretary for circulation to members	Tande	

During this process it is essential that the organizations that are interested in participating in the Annex, keep their national representative informed about the content of the proposal. This will facilitate discussion and decisions in this matter at the ExCo meeting.

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IEA R&D Topical Expert Meeting on Large Scale Integration
Newcastle 6-7 November 2001
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