INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

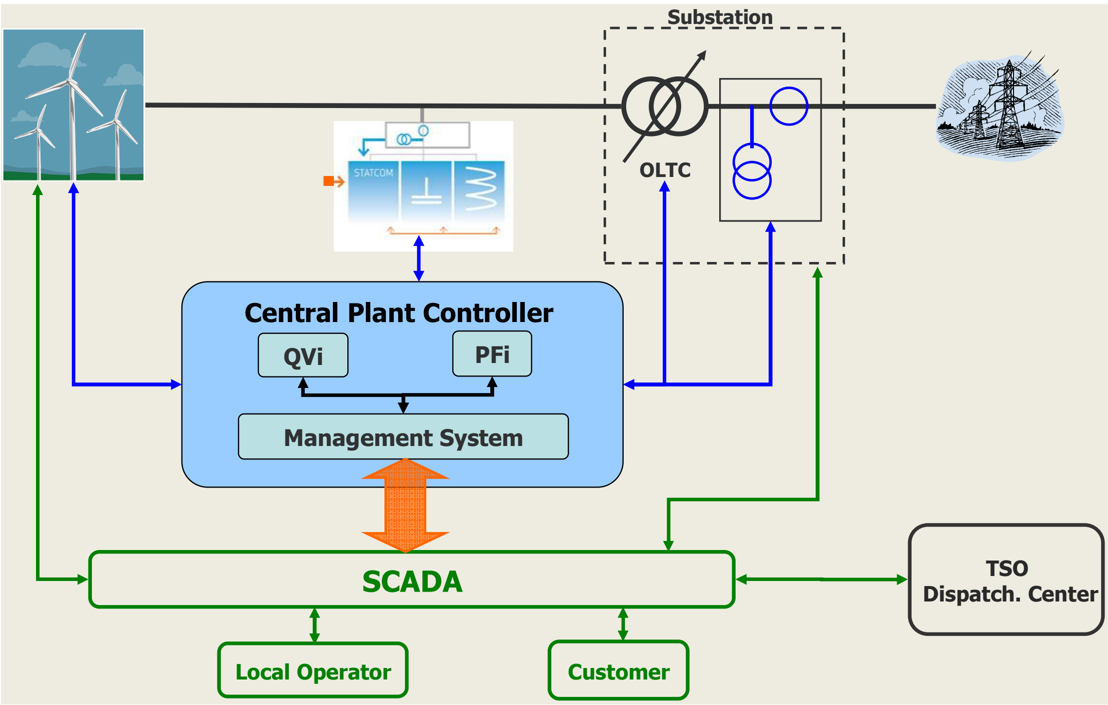
IEA R&D Wind Task 11 - Topical Expert Meeting

"Wind Farm Control Methods"

VATTENFALL

Solna – SWEDEN

November 27/28 2012



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For more information about IEA Wind see www.ieawind.org

International Energy Agency

Implement Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems: IEA Wind

The IEA international collaboration on energy technology and RD&D is organized under the legal structure of Implementing Agreements, in which Governments, or their delegated agents, participate as Contracting Parties and undertake Tasks identified in specific Annexes.

The IEA's Wind Implementing Agreement began in 1977, and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 24 contracting parties from 20 countries, the European Commission, and the European Wind Energy Association (EWEA) participate in IEA Wind. Australia, Austria, Canada, Denmark, the European Commission, EWEA, Finland, Germany, Greece, Ireland, Italy (two contracting parties), Japan, the Republic of Korea, Mexico, the Netherlands, Norway (two contracting parties), Portugal, Spain, Sweden, Switzerland, and the United States are now members.

The development and maturing of wind energy technology over the past 30 years has been facilitated through vigorous national programs of research, development, demonstration, and financial incentives. In this process, IEA Wind has played a role by providing a flexible framework for cost-effective joint research projects and information exchange.

The mission of the IEA Wind Agreement continues to be to encourage and support the technological development and global deployment of wind energy technology. To do this, the contracting parties exchange information on their continuing and planned activities and participate in IEA Wind Tasks regarding cooperative research, development, and demonstration of wind systems.

Task 11 of the IEA Wind Agreement, Base Technology Information Exchange, has the objective to promote and disseminate knowledge through cooperative activities and information exchange on R&D topics of common interest to the Task members. These cooperative activities have been part of the Wind Implementing Agreement since 1978.

Task 11 is an important instrument of IEA Wind. It can react flexibly on new technical and scientific developments and information needs. It brings the latest knowledge to wind energy players in the member countries and collects information and recommendations for the work of the IEA Wind Agreement. Task 11 is also an important catalyst for starting new tasks within IEA Wind.

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

The objective of this Task is to promote disseminating knowledge through cooperative activities and information exchange on R&D topics of common interest. Four meetings on different topics are arranged every year, gathering active researchers and experts. These cooperative activities have been part of the Agreement since 1978.

Two Subtasks

The task includes two subtasks.

The objective of the first subtask is to develop recommended practices (RP) for wind turbine testing and evaluation for each topic needing recommended practices. In June 2011 was edited the RP on "Consumer Label for Small Wind Turbines". A new RP about "Performance and Load Conditions of Wind Turbines in Cold Climates" is expected to be edited this year.

The objective of the second subtask is to conduct topical expert meetings in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates topics in research areas of current interest, which requires an exchange of information. So far, Topical Expert Meetings are arranged four times a year.

Documentation

Since these activities were initiated in 1978, more than 68 volumes of proceedings have been published. In the series of Recommended Practices 11 documents were published and five of these have revised editions.

All documents produced under Task 11 and published by the Operating Agent are available to citizens of member countries participating in this Task.

Operating Agent

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COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
COUNTRY	**INSTITUTION**
Denmark	Danish Technical University (DTU) - Risø National Laboratory
Republic of China	Chinese Wind Energy Association (CWEA)
Finland	Technical Research Centre of Finland - VTT Energy
Germany	Bundesministerium für Unwelt , Naturschutz und Reaktorsicherheit -BMU
Ireland	Sustainable Energy Ireland - SEI
Italy	Ricerca sul sistema energetico, (RSE S.p.A.)
Japan	National Institute of Advanced Industrial Science and Technology AIST
Republic of Korea	POHANG University of Science and Technology - POSTECH
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	SenterNovem
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Spain	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas CIEMAT
Sweden	Energimyndigheten
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	The National Renewable Energy Centre (NAREC)
United States	The U.S Department of Energy -DOE

CONTENTS

PRESENTATIONS

1. INTRODUCTORY NOTE

Historically, the automatic control of wind power installations has been implemented in the individual wind turbines. The development of large wind farms (WF) has initiated the development of advanced, automatic wind farm controllers that supervised the control of wind turbines from a higher level.

Large WFs must be considered as a controllable generating unit, in a similar way as conventional power units. This requires a supervisory controller as an interface between the grid operational system and the wind turbine units of the farm. There are different control strategies to maximize power production of wind farms, as well as to minimize loads on the wind turbines.

The main aim of the developed wind farm controllers has been to meet grid integration challenges. On the other hand, the development of wind power from smaller distributed installations to large wind farms has introduced new aspects of the influence of the wind power on the power systems.

Wind turbines in a wind farm are influenced by wakes in many ways. Consequently optimization of wind farm behavior is accomplished by employment of the wind field models that describes the dynamic development of wakes inside a wind farm. Combination of the wind field model and models of wind turbines yields an overall dynamic wind farm model suitable for optimization.

The main problem of WF connected to weak grids is the quasi-static voltage level. The amount of power production that can be absorbed by the grid at the point of connection is limited. In a grid without wind turbines connected, the main concern by the utility is the minimum voltage level at the far end of the feeder when the consumer load is at its maximum. So the normal voltage profile is that the highest voltage is at the bus bar at the substation and it drops to reach the minimum at the far end.

When wind turbines are connected to the same feeder as consumers, the voltage profile of the feeder will be different from the case without WF. Due to the production at the WF the voltage level can be higher and could exceed the maximum allowed when the consumer load is low and the power output from the WF is high. This is what might limit the capacity of the feeder.
Another possible challenge with WF in weak grids is the voltage fluctuations as a result of the power fluctuations produced by the turbulence in the wind and from starts and stops of the wind turbines. The weaker the grid is, the larger voltage fluctuations are and are more prone to cause flicker.

One option to increase the absorbed capacity of a weak grid is to develop a power control concept for wind turbines which will even out the power fluctuations and make it possible to increase the wind energy penetration.

The target of this TEM was to update information of the state of the art of wind farm control strategies and to simulate the development of wind farm controllers, which mainly aim at improving the power system integration, but keeps the influence on structural loads and energy production in mind.

Substantial research has been undertaken in the field of wind farm control methods. However it is also apparent that there is a diversity of control strategies to increase the efficiency of energy production, to reduce loads on the wind turbines, to increase the absorbed capacity of a grid, and to minimize the negative impact of the WF in weak grids.

Topics selected for the meeting were:

- Wind Farm Modeling including wakes
- Models for WF located in complex terrains
- Wind Farm controllers
- Control Strategies for WF
- Experimental Data of WF connected to the Weak Grids
- Dynamic Studies of WF connected to Weak Grids
- Energy Buffer Systems
- Load and energy optimization

2. AGENDA

Tuesday 27th November

9:00 **Registration**. Collection of presentations

9:30 **Introduction by Host**
Sven Erik Thor, Vattenfall

09:50 **Recognition of Participants**

10:00 **Introduction by Task 11 Operating Agent.**
Felix Avia, Operating Agent Task 11 IEAWind R&D

●10:30 Coffee Break

1st Session Individual Presentations:

11:00 Control Strategies and Regulation Possibilities for Wind Farms with Multi Terminal Topology
Mads Rajczyk Skjelmose, Vattenfall, Denmark

11:30 A Maximum Power Point Tracking Approach for Wind Farm Control
P.M.O. Gebraad, Delft University of Technology, The Netherlands

12:00 Variable Operating Points for Wind Turbines
Henk-Jon Kooijman & Stefan Kern, GE Power, Germany

12:30 Model-based Control of Wind Turbines: Look-Ahead Approach
Alexander Stotsky, Chalmers University of Technology, Sweden

●13:00 Lunch

2nd Session Individual Presentations:

14:00 **Control Strategies for WF**
Di Xiao, Goldwind Science & Technology Co., Ltd China

14:30 **Wind farm deficits and park efficiency**
Kurt S. Hansen, DTU - Department of Wind Energy, Denmark

15:00 Gamesa identification of R&D necessities in Control of Wind Farms

Marta Barreras & Carlos Pizarro, GAMESA, Spain

15:30 LIDAR measurements for wind farm control

D. Schlipf, Universität Stuttgart – SWE, Germany

16:00 End of the Tuesday meetings

19:00 Informal dinner in the city centre

Wednesday 28th November

3rd Session Individual Presentations

09:00 Reactive Power Control for Wind Parks Connected to Weak Grids

Melanie Hau, Fraunhofer IWES Kassel, Germany

09:30 Wind Farm Modelling and Control in China and at NCEPU

Liu Yongqian, North China Electric Power University, Republic of China

10:00 Presentation 11

Jens Geisler & HG Gehl, Repower Systems SE, Germany

●10:30 Coffe Break

11:00 Discussion

●12:30 Lunch

13:30 Discussion (Cont)

14:30 Summary of Meeting

15:00 End of the meeting

3. LIST OF PARTICIPANTS

The meeting was attended by 18 participants from 6 countries (China, Denmark, Germany, The Netherlands, Spain, and Sweden). Table 1 lists the participants and their affiliations.

Last Name	Name	Job Center	Country	E-mail
Liu	**Yongqian**	North China Electric Power University	China	yongqianliu@gmail.com
Di	**Xiao**	Goldwind Science & Technology Co., Ltd	China	xiaodi@goldwind.cn
Wang	**Bin**	Goldwind Science & Technology Co., Ltd.	China	wangbin1@goldwind.cn
Mads Rajczyk Skjelmose	**Mads**	Vattenfall	Denmark	madsrajczyk.skjelmose@vattenfall.com
Hansen	**Kurt S.**	DTU - Department of Wind Energy	Denmark	kuhan@dtu.dk
Kooijman	**Henk-Jon**	GE Power	Germany	henkjan.kooijman@ge.com
Kern	**Stefan**	GE Global Research	Germany	kerns@ge.com
Gehl	**HG**	Repower Systems	Germany	harald.gehl@repower.de
Geisler	**Jens**	Repower Systems SE - Systems and Control Engineer R&D	Germany	jens.geisler@repower.de
Hau	**Melanie**	Fraunhofer IWES Kassel	Germany	melanie.hau@iwes.fraunhofer.d
Pizarro	**Carlos**	GAMESA	Spain	cpizarro@gamesacorp.com
Barreras	**Marta**	GAMESA	Spain	mbarreras@gamesacorp.com
Avia	**Felix**	CENER - OA Task 11	Spain	favia@cener.com
Thor	**Sven-Erik**	Vattenfall Research and Development	Sweden	Sven-Erik.Thor@vattenfall.com
Stotsky	**Alexander**	Chalmers University of Technology	Sweden	alexander.stotsky@chalmers.se
Erol	**David**	Vattenfall Research and Development	Sweden	david.erol@vattenfall.com
Gebraad	**P.M.O**	Delft Center for Systems and Control - Delft University of Technology - PhD student	The Netherlands	p.m.o.gebraad@tudelft.nl

Table 1 Participants in IEA Wind TEM on WIND FARM CONTROL METHODS

Eleven presentations were given:

1. **Control Strategies and Regulation Possibilities for Wind Farms with Multi Terminal Topology.** *Mads Rajczyk Skjelmose, Vattenfall, Denmark*

2. **A Maximum Power Point Tracking Approach for Wind Farm Control.** *P.M.O. Gebraad, Delft University of Technology, The Netherlands*

3. **Variable Operating Points for Wind Turbines.** *Henk-Jon Kooijman & Stefan Kern, GE Power, Germany*

4. **Model-based Control of Wind Turbines: Look-Ahead Approach.** *Alexander Stotsky, Chalmers University of Technology,Sweden*

5. **Control Strategies for WF.** *Di Xiao, Goldwind Science & Technology Co. Ltd, China*

6. **Wind farm deficits and park efficiency.** *Kurt S. Hansen, DTU - Department of Wind Energy, Denmark*

7. **Gamesa identification of R&D necessities in Control of Wind Farms.** *Marta Barreras & Carlos Pizarro, GAMESA, Spain*

8. **LIDAR measurements for wind farm control.** *D. Schlipf, Universität Stuttgart – SWE, Germany*

9. **Reactive Power Control for Wind Parks Connected to Weak Grids.** *Melanie Hau, Fraunhofer IWES Kassel, Germany*

10. **Wind Farm Modeling and Control in China and at NCEPU.** *Liu Yongqian, North China Electric Power University, Republic of China*

11. **A Toolbox for Offshore Wind Farm Cluster Design.** *Jens Geisler & HG Gehl, Repower Systems SE, Germany*

4. SUMMARY

Following the 11 presentations, the floor was opened and a general discussion took place among the participants.

Topics selected for the discussion were:

- Open problems in wind farm control
- How can active power be controlled w/o synchronous generator power-frequency relation ship?
- Valid wake models for large wind turbines
- What is the most important knowledge gap?

Open problems in wind farm control

Several challenges were identified during the two days presentations associated to the wind farm control. In particular the following:

- Data transfer and standard communication. Better and faster systems are required to help the optimization of the wind farm control.
- Wake models. Also better and faster tools are need it to model the wakes of the wind farms, that will contribute to improve the wind farm control
- Wind farms with special conditions, like the located in complex terrain or connected to weak grids, need important attention, requiring extensive research to better understand the required strategies for control.
- Use of Lidar systems for validate wake models is an important challenge that need more development.
- Another important challenge is to make the optimization of wind farm control with the target of reaching maximum net present value (NPV) instead maximum AEP. Intelligent farm control aimed at maximizing NPV will replace turbine power curve as main performance characteristic.
- Required coordination between wind farm operators, manufacturers, grid operators and meteorologist it is strongly required. The question is how should meteorologist, turbine OEM, and grid operator work together on this?

- Broad knowledge about turbulent intensity in wind farms in stable and unstable wind conditions will help the design of the wind farm control procedures. More knowledge about the deficit of AEP related to stable/not stable atmosphere it is need it.
- The use of flow wind deviation yawing the WT to reduce the wake impact, should be deeper studied.

<u>How can active power be controlled w/o synchronous generator power-frequency relation ship?</u>

The necessity of synchronous generators connected to the grid was discussed. It was stated that as large is the wind power penetration most important will be the problem. In Ireland (isolated grid with high penetration) there is already a study to identify the percentage of synchronous generator required to guarantee the stability of the grid.

The converter needs the synchronous generator as reference.

Also was discussed the possibility of use storage systems to improve the stability of the grid

It was reported that in China part of the Electrical Systems may in periods be unavailable due to maintenance problems, faults of the grid and other reasons, like during commissioning activities. Grid Code Requirements in PCC cover:

- Curtailment of Active Power
- Frequency Response
- Voltage Control

Advantages of Multi Terminal Wind Farm Control with Automatic Power Flow Calculations:

- Full Grid Compliance in all configurations
- Simplified Operation
- Minimization of losses → $

<u>Valid wake models for large wind turbines</u>

Existing tools to model the flow inside wind farms has to be improved. The best CFD models have the main constrain of the long time required to run it. On the other hand there is a clear necessity of measured data to validate the models. Luckily there are several initiatives in order to improve and validate the already existing models, as for instance the ongoing Task 31 of the IEA Wind "WakeBench" with the purpose of bechmarking of flow and park models against validation data from wind farm measurements. Accuracy versus computational time it is also an important point on this issue.

When it comes to design and validate Wind Farm Control strategies oriented to manage the performance of a Wind Farm as a whole but taking into account site-dependent variables, the required dynamics to be evaluated make the WTG model and hence the WF model more complex.

More accurate, validated wind farm wake models with turbine location effective design loading are desired. SOWFA is an OpenFOAM CFD solver coupled with FAST developed by NREL NWTC. OpenFOAM 3D CFD solver calculates 3D flow around turbine blades (actuator line) and FAST model 5MW turbine dynamics.

What is the most important knowledge gap?

Despite having a lot of development in this subject in recent years, still there is an important requirement in order to improve the existing knowledge. Along the meeting presentations several points were identified that require more research.

Before implementing an active wind farm control it is required to identify the potential benefit (AEP and fatigue life consumption); Turbine cumulative fatigue damage and encountered extreme load levels should be more integrated in turbine controller.

When it comes to design and validate Wind Farm Control strategies oriented to manage the performance of a Wind Farm as a whole, but taking into account site-dependent variables, the required dynamics to be evaluated make the WTG model and hence the WF model more complex.

Lidar is a valuable tool to

- Measure the near wake from the nacelle
- Measure the flow and wakes in a wind farm
- Improve the control of individual turbines

For wind farm control Lidar it can help to

- Validate wake models
- Monitor the improvement of control strategies
- Give online information for a wind farm controller

The Lidar systems should be installed in wind turbines and wind farm to supply information of the real wind conditions. Special development should be performed with the main target of cost reduction of these equipments. LIDAR measurements can be used to validate/improve wake models and integrated in Model Predictive Control of wind farms.

Forecasting (short and medium time) should be also improved with better accuracy, and should be integrated in the control strategy.

There is a clear necessity of having holistic tool s taking into consideration grid integration, optimization of energy production and reduction of loads in wind turbines that will allow defining the strategy of the wind farm control.

More real data are required to better control wind farms. More sensors and more should be installed in WF. Already existing SCADA data are not sufficient to optimize the WF control, and also the time to have these data should be reduced. Discussion: Is it enough a WF control architecture based in SCADA?

Therefore WF control strategies that use the information gathered from each WTG to return individual action commands for each turbine or group of turbines are of high interest in terms of developing a fast calculation module to predict with some anticipation the propagation of wind characteristics throughout the site.

Use of additional specific sensors, which would not be economically feasible at WTG level, but would be at WF level (e.g. with some sensors distributed along the perimeter of the Wind Farm). Identifying faulty operation caused by malfunctioning sensors. The use of the signal of adjacent WTGs could avoid triggering alarms or WTG stops, increasing the global availability of the WF.

PRESENTATIONS

Control Strategies for Wind Farms with Multi Terminal Topology

TEM #71 Wind Farm Control Methods
Stockholm

2012.11.27

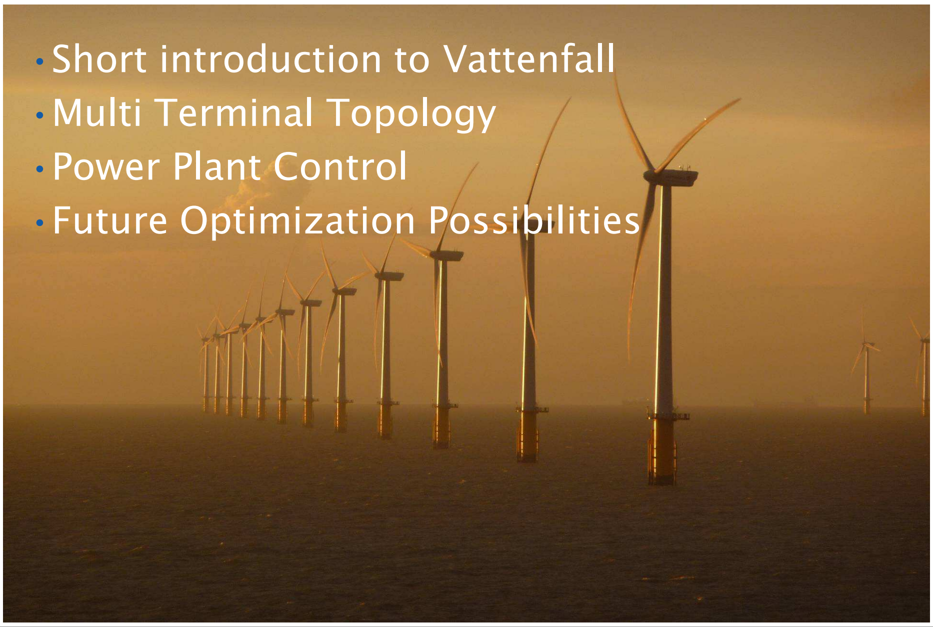
Confidentiality class: None (C1)

A few words about myself

Name: Mads Rajczyk Skjelmose
Job title: Electrical Engineer
Vattenfall BD Sustainable Energy Projects,
BU Offshore Wind Projects, Technology
Office: Fredericia, Denmark

- B.Sc.EE from Engineering College in Aarhus, DK 2003
  - Joined Vattenfall in September 2012
  - 5 years experience with Wind Power SCADA and Regulation
  - 9 years experience in total with SCADA and Automation
- Power Plant Control of Wind Farms
- Grid Code Compliance of Wind Farms
- SCADA systems for Wind Farms

Agenda



Vattenfall at a glance

- Europe’s fifth largest generator of electricity and the largest producer of heat
- Operations in Sweden, Finland, Denmark, Germany, Poland, the Netherlands, Belgium and the UK
- 37,000 employees
- Vattenfall AB is wholly owned by the Swedish state
- Wind Power in DK: Offices in Esbjerg and Fredericia

Operates about 900 wind turbines / 1.6GW

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Confidentiality class: None (C1)

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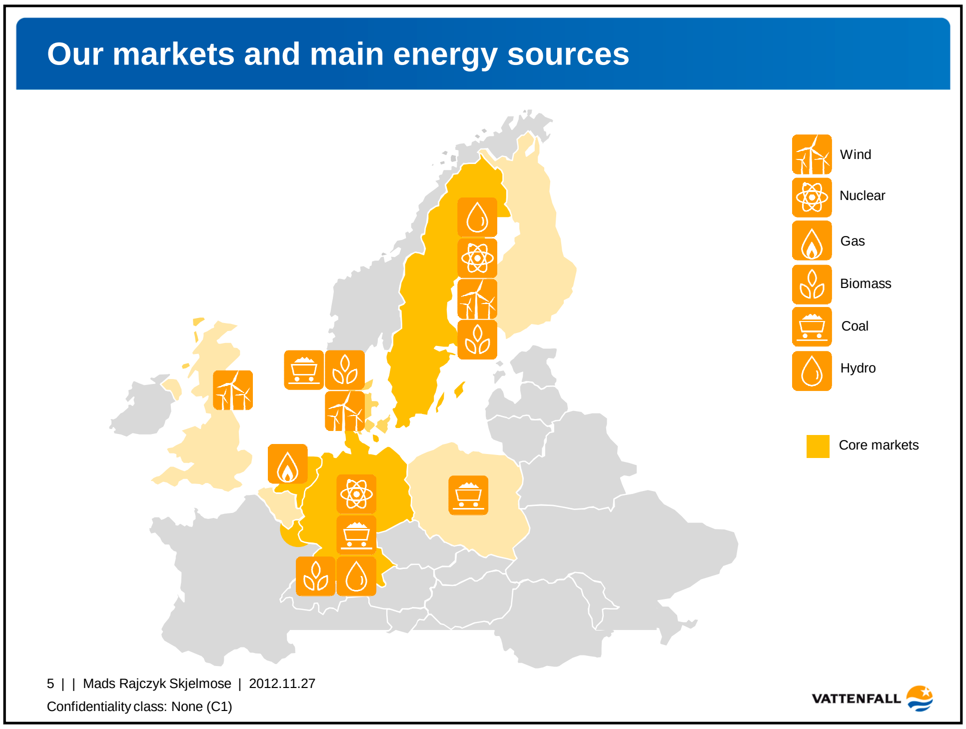
Our markets and main energy sources
Wind
Nuclear
Gas
Biomass
Coal
Hydro
Core markets
5 | | Mads Rajczyk Skjelmose | 2012.11.27
Confidentiality class: None (C1)
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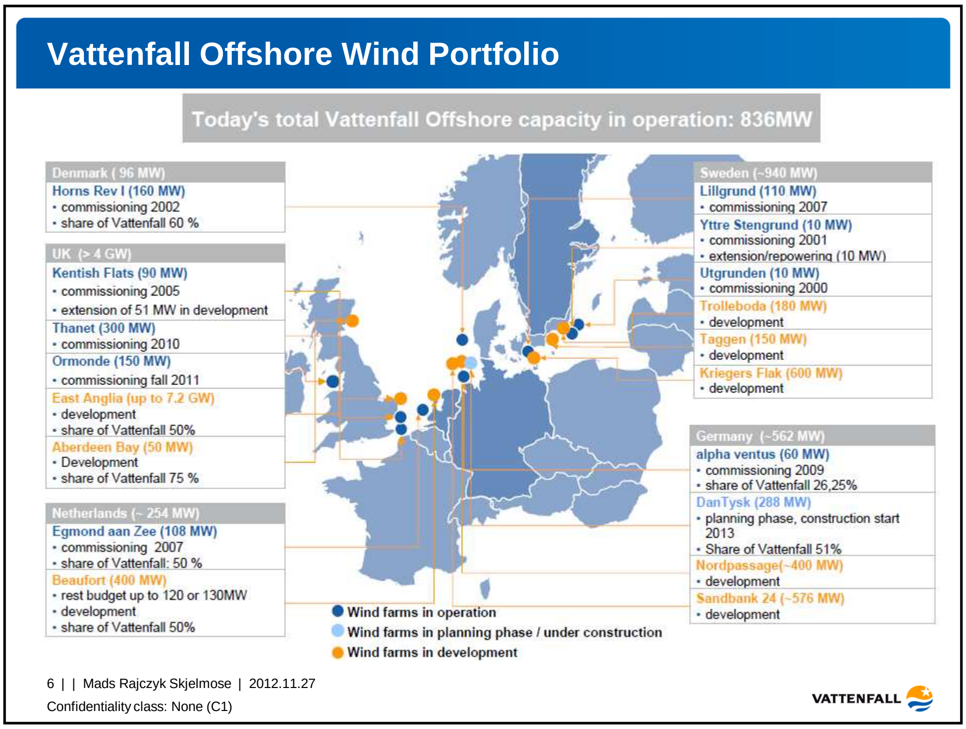
Vattenfall Offshore Wind Portfolio
Today's total Vattenfall Offshore capacity in operation: 836MW
Denmark (96 MW)
Horns Rev I (160 MW)
• commissioning 2002
• share of Vattenfall 60 %
UK (> 4 GW)
Kentish Flats (90 MW)
• commissioning 2005
• extension of 51 MW in development
Thanet (300 MW)
• commissioning 2010
Ormonde (150 MW)
• commissioning fall 2011
East Anglia (up to 7.2 GW)
• development
• share of Vattenfall 50%
Aberdeen Bay (50 MW)
• Development
• share of Vattenfall 75 %
Netherlands (~ 254 MW)
Egmond aan Zee (108 MW)
• commissioning 2007
• share of Vattenfall: 50 %
Beaufort (400 MW)
• rest budget up to 120 or 130MW
• development
• share of Vattenfall 50%
Sweden (~940 MW)
Lillgrund (110 MW)
• commissioning 2007
Yttre Stengrund (10 MW)
• commissioning 2001
• extension/repowering (10 MW)
Utgrunden (10 MW)
• commissioning 2000
Trolleboda (180 MW)
• development
Taggen (150 MW)
• development
Kriegers Flak (600 MW)
• development
Germany (~562 MW)
alpha ventus (60 MW)
• commissioning 2009
• share of Vattenfall 26,25%
DanTysk (288 MW)
• planning phase, construction start 2013
• Share of Vattenfall 51%
Nordpassage(~400 MW)
• development
Sandbank 24 (~576 MW)
• development
Wind farms in operation
Wind farms in planning phase / under construction
Wind farms in development
6 | | Mads Rajczyk Skjelmose | 2012.11.27
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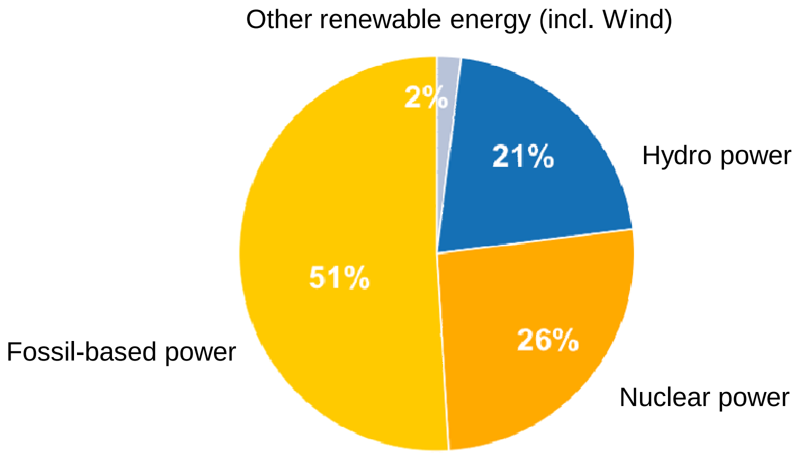
Vattenfall Energy Production



7 | | Mads Rajczyk Skjelmose | 2012.11.27
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Wind Farms

Multi Terminal Topology

Goal: To get the most out of the Asset

8 | | Mads Rajczyk Skjelmose | 2012.11.27
Confidentiality class: None (C1)
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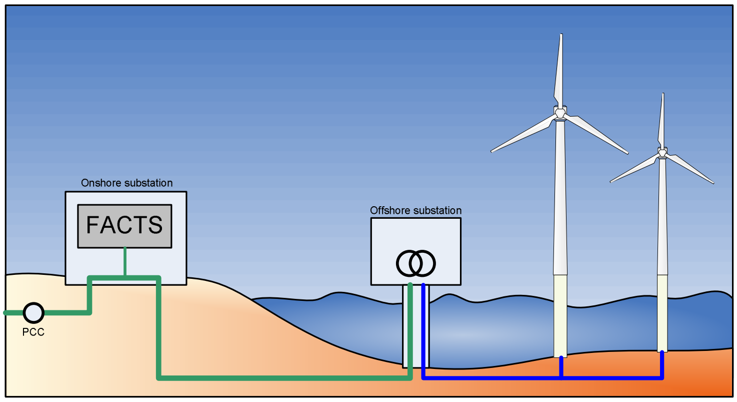
Typical Offshore Wind Farm



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Confidentiality class: None (C1)

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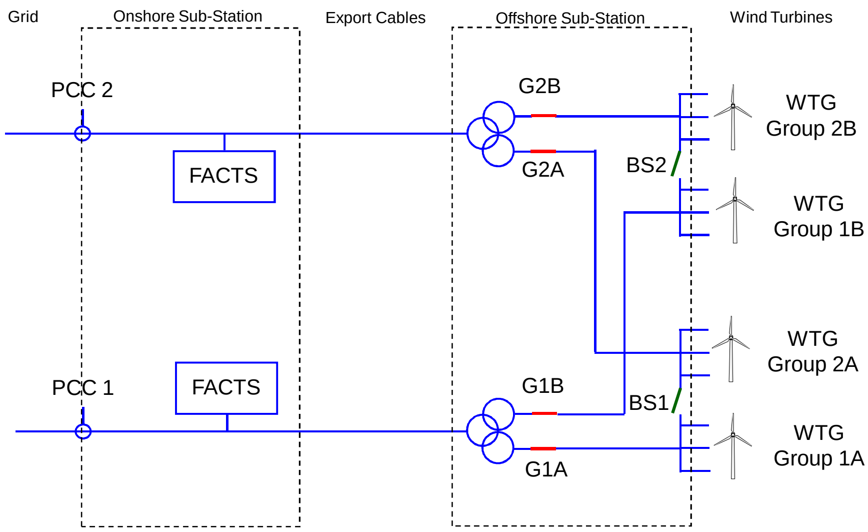
Simplified SLD of Wind Farm



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Confidentiality class: None (C1)

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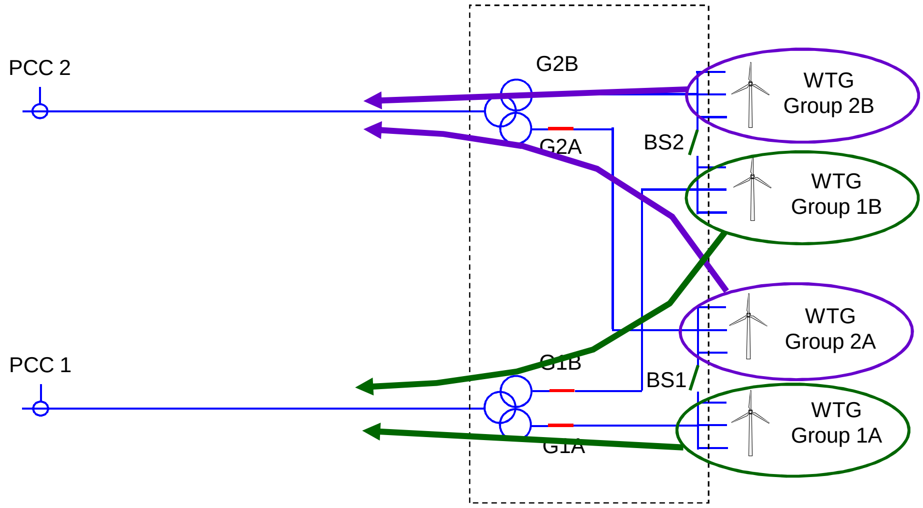
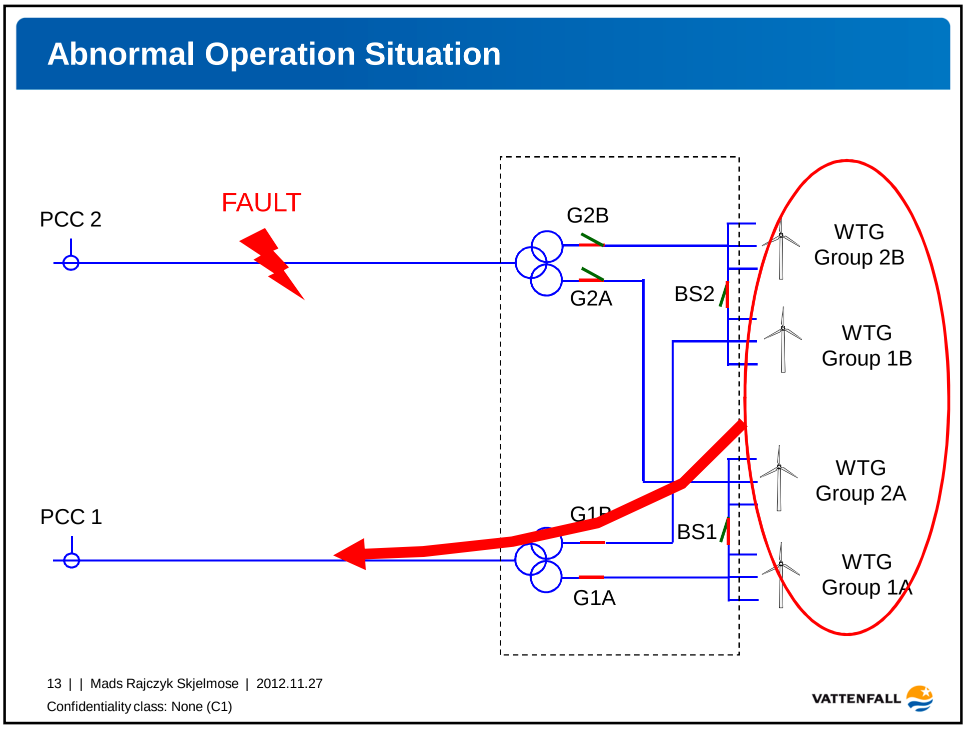
Normal Operation



Maintenance and Faults

Part of the Electrical Systems may in periods be unavailable due to:

- Maintenance.
- Faults
- Other reasons (e.g. During commissioning)


Abnormal Operation Situation
FAULT
PCC 2
PCC 1
G2B
G2A
BS2
G1B
BS1
G1A
WTG Group 2B
WTG Group 1B
WTG Group 2A
WTG Group 1A
13 | | Mads Rajczyk Skjelmose | 2012.11.27
Confidentiality class: None (C1)
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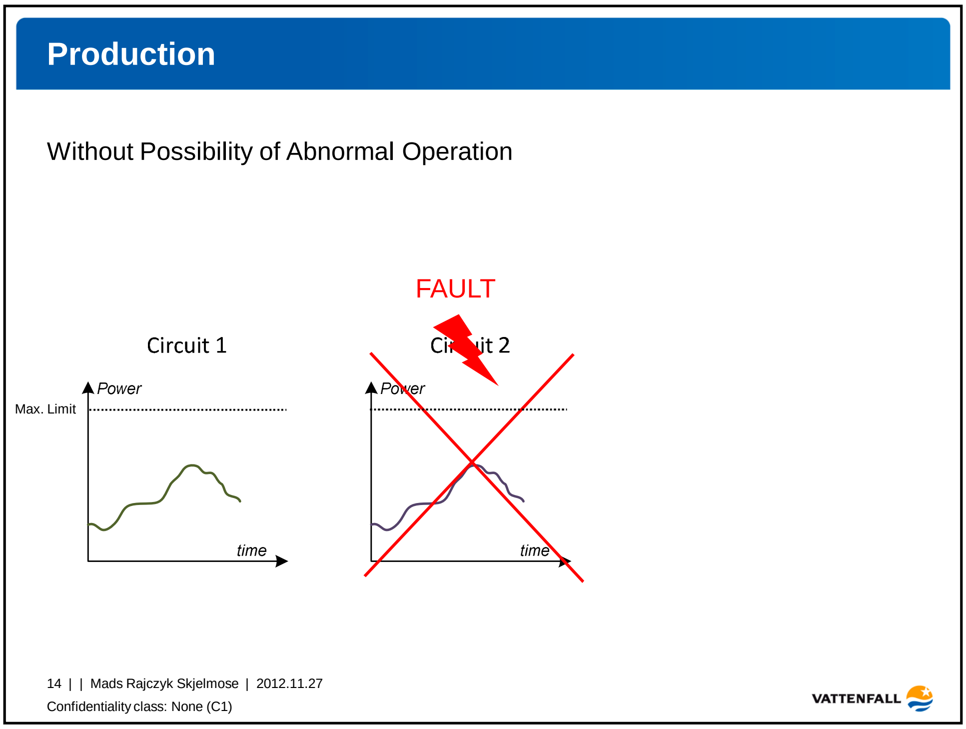
Production
Without Possibility of Abnormal Operation
FAULT
Circuit 1
Circuit 2
Power
Max. Limit
time
Power
time
14 | | Mads Rajczyk Skjelmose | 2012.11.27
Confidentiality class: None (C1)
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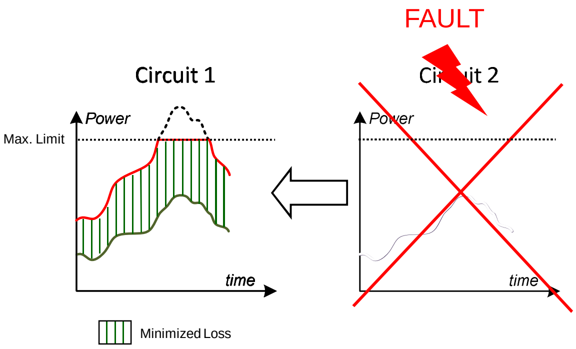
Production

With Abnormal Operation Possible



15 | | Mads Rajczyk Skjelmose | 2012.11.27
Confidentiality class: None (C1)

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Wind Farms

Power Plant Control

16 | | Mads Rajczyk Skjelmose | 2012.11.27
Confidentiality class: None (C1)

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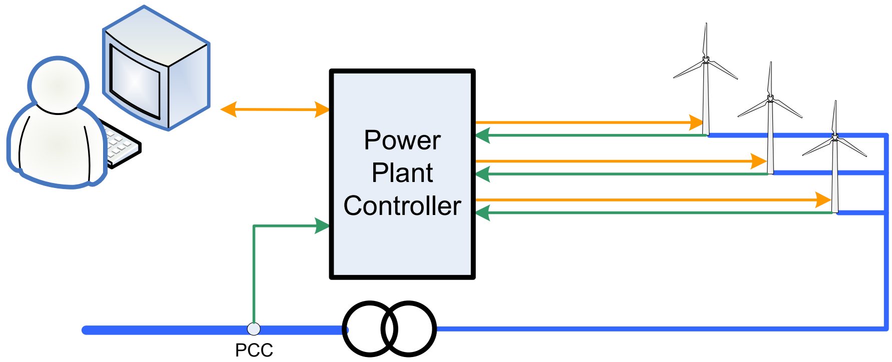
Wind Farm Control - Principle



Examples of Grid Code Requirements in PCC:
- Curtailment of Active Power
- Frequency Response
- Voltage Control

17 | | Mads Rajczyk Skjelmose | 2012.11.27
Confidentiality class: None (C1)
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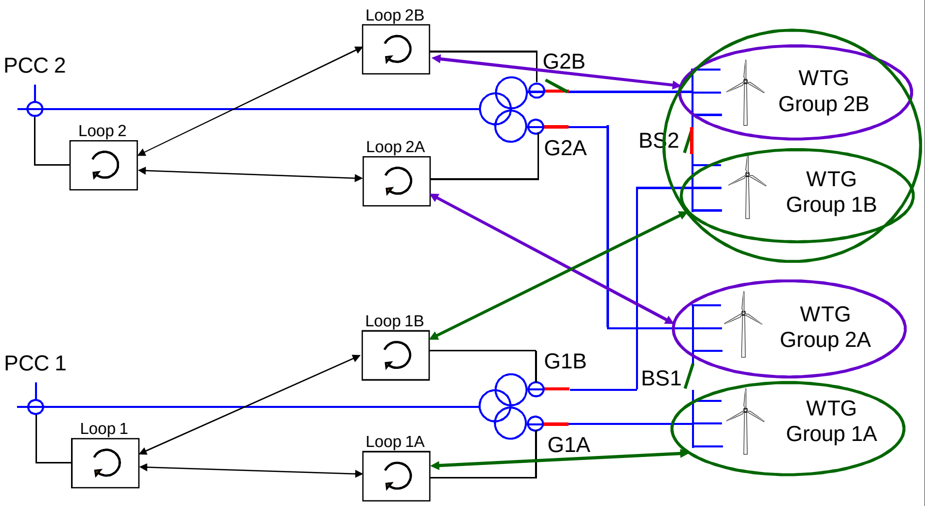
Example of a Multi Terminal Controller Design



18 | | Mads Rajczyk Skjelmose | 2012.11.27
Confidentiality class: None (C1)
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Summary

Advantages of Multi Terminal Wind Farm Control with Automatic Power Flow Calculations:

- Full Grid Compliance in all configurations
- Simplified Operation
- Minimization of losses → $

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Confidentiality class: None (C1)

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Future Possibilities

Additional optimization topics:

- Optimization on string level in Ring-connected strings?
- Optimization utilizing Connection between Wind Farms?
- Optimization based on DTS (Distributed Temperature Sensing) of the cables.

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A Maximum Power Point Tracking Approach for Wind Farm Control

Pieter Gebraad, Jan-Willem van Wingerden
29-11-2012

This work is supported by:
• Far Large Offshore Wind (FLOW) project no. 201101 "Offshore wind power plant control for minimal loading",
• NWO Veni Grant no. 11930 "Reconfigurable floating wind farm".

Collaborative research with:

Overview

- Introduction
- MPPT approach for wind farm control
    - Explanation of algorithm
    - Simulation model
    - Simulation study
    - Conclusions
- Experiments on SOWFA, a 3D CFD wind farm model

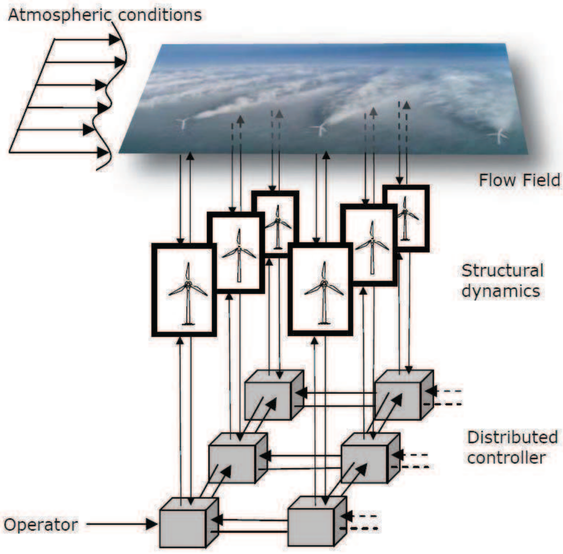
Wind farm control
Introduction

Source: Horns Rev (Christian Steiness)

Wind farm control
Introduction

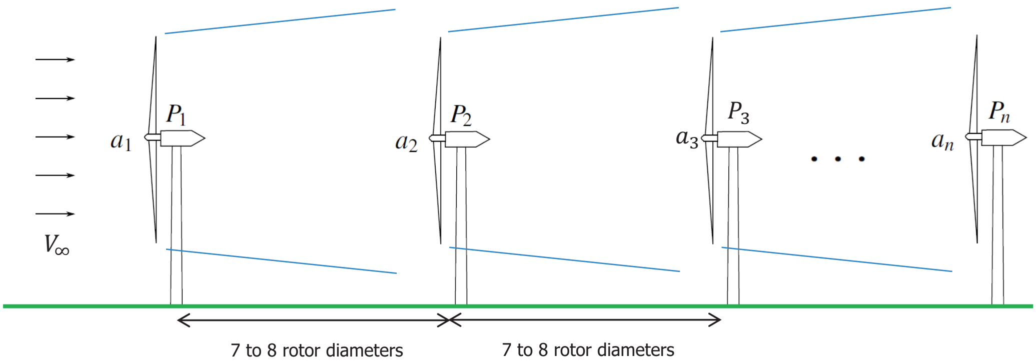
- Wind farm control
  Maximize power and limit loads, using pitch, torque, (yaw) control.
- Current
  Decentralized power and load control of each individual turbine.
- Challenge
  Distributed control taking into account
  - *wake interaction,*
  - *time-varying* dynamic behaviour.

  Main focus on power maximization.



Wind farm control

Introduction



- Consider a row of n turbines:
  - Power productions P_i
  - Control parameters a_i = axial induction factor (generalized)
- Goal: $\max_{a_i} \sum_{i=1}^{n} P_i(V_\infty, a_1, a_2, \cdots, a_i)$
- Model-free approach: function $P_i(V_\infty, a_1, a_2, \cdots, a_i)$ not known

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Wind farm control

A Maximum Power-Point Tracking Approach

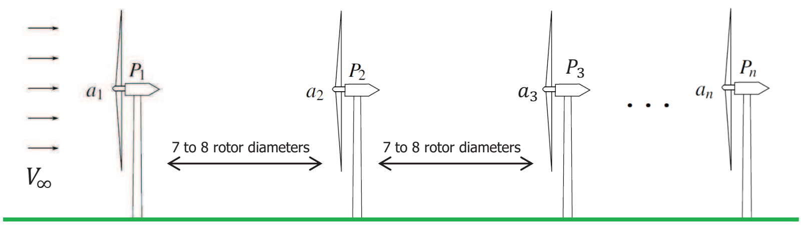
- Goal: $\max_{a_i} \sum_{i=1}^{n} P_i$
- Maximum Power Point Tracking with Gradient-Descent (MPPT-GD) :

$$a_i(k+1) = a_i(k) + K \sum_{j=i}^{n} \frac{\partial P_j}{\partial a_i}(k)$$

- Gradients approximated using 1st order backwards differencing:

$$\frac{\partial P_j}{\partial a_i}(k) \approx \frac{P_j(k) - P_j(k-1)}{a_i(k) - a_i(k-1)}$$

- Advantage: Data-based, no model needed.
- Problem: To calculate all gradients, wait until wake has travelled through complete wind farm ($T_{s,farm}$).



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Wind farm control

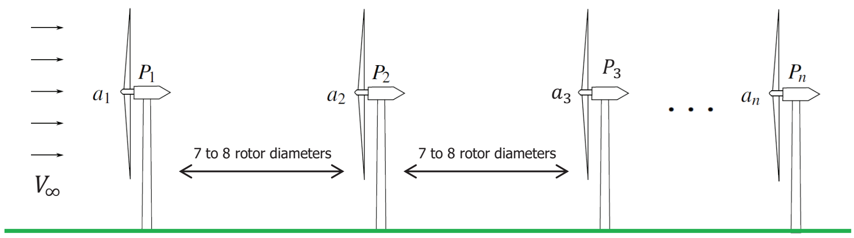
A Maximum Power-Point Tracking Approach

- Speed-up: consider power of nearest downstream neighbour $d(i)$ only:

$$a_i(k+1) = a_i(k) + K\left(\frac{\partial P_i}{\partial a_i}(k) + \frac{\partial P_{d(i)}}{\partial a_i}(k)\right)$$

in case of row of turbines: $d(i) = i + 1$.

- Motivation: because of wake recovery, effect on nearest neighbour is biggest



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Wind farm control

A Maximum Power-Point Tracking Approach

- Speed-up: consider power response of nearest downstream neighbour $d(i)$ only:

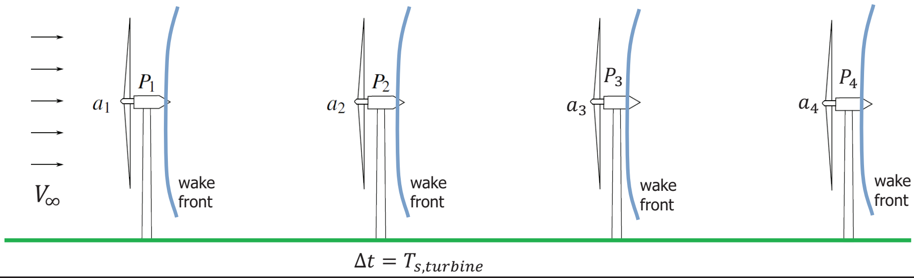
$$a_i(k+1) = a_i(k) + K\left(\frac{\partial P_i}{\partial a_i}(k) + \frac{\partial P_{d(i)}}{\partial a_i}(k)\right)$$

in case of row of turbines: $d(i) = i + 1$.

- Update gradients:

$$\frac{\partial P_i}{\partial a_i}(k) \leftarrow \frac{P_i(k) - P_i(k-1)}{a_i(k) - a_i(k-1)} \; at \; \Delta t = T_{s,turbine}$$

$$\frac{\partial P_{d(i)}}{\partial a_i}(k) \leftarrow \frac{P_{d(i)}(k) - P_{d(i)}(k-1)}{a_i(k) - a_i(k-1)} \; at \; \Delta t = T_{s,wake}$$



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Wind farm control

A Maximum Power-Point Tracking Approach

- Speed-up: consider power response of nearest downstream neighbour $d(i)$ only:

$$a_i(k+1) = a_i(k) + K\left(\frac{\partial P_i}{\partial a_i}(k) + \frac{\partial P_{d(i)}}{\partial a_i}(k)\right)$$

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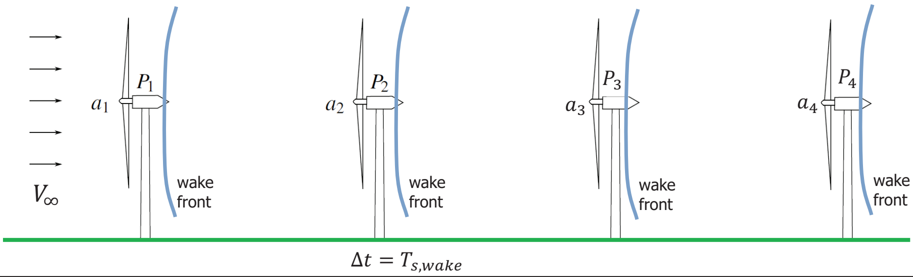
- Update gradients: $\frac{\partial P_i}{\partial a_i}(k) \leftarrow \frac{P_i(k) - P_i(k-1)}{a_i(k) - a_i(k-1)}$ $at\ \Delta t = T_{s,turbine}$

$$\frac{\partial P_{d(i)}}{\partial a_i}(k) \leftarrow \frac{P_{d(i)}(k) - P_{d(i)}(k-1)}{a_i(k) - a_i(k-1)}\ at\ \Delta t = T_{s,wake}$$

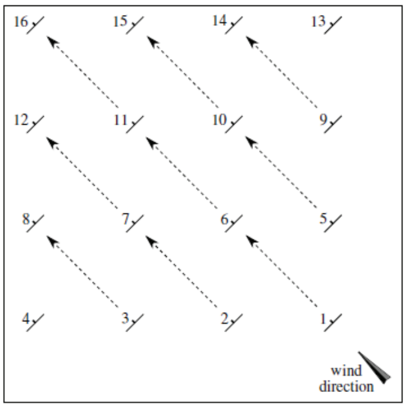


Wind farm control

A Maximum Power-Point Tracking Approach

- Generalization: MPPT for row of turbines → MPPT for wind farm:

Find neighbour $d(i)$ based on wind plant configuration and estimate of wind direction:



turbine index i	1	2	3	5	6	7	9	10	11
turbine $d(i)$	6	7	8	10	11	12	14	15	16

Wind farm control

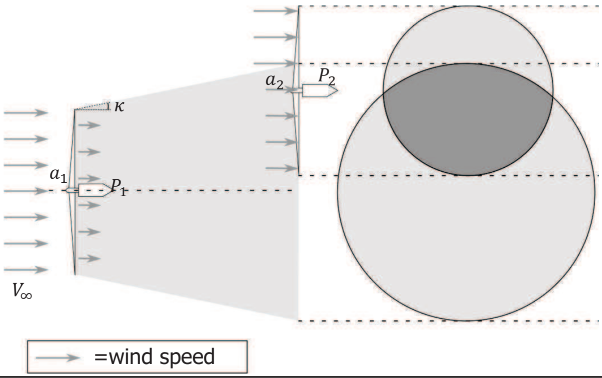
A Maximum Power-Point Tracking Approach

Simulation model:

- Park / Jensen wake model (static):
  - Estimates wind speeds and powers given a_i, V_∞
  - Parameter κ tuned to fit offshore wind farm data (Horns Rev)
- Added wake travelling dynamics:
  - Estimate delays $T_{s,wake}, T_{s,farm}$ from wind speeds
  - Change in a_i has delayed effect on downwind turbines

\- Less detailed than SOWFA

\+ Fast simulation



Wind farm control

A Maximum Power-Point Tracking Approach

Simulation study:

- Princess Amalia Wind Park (60 2MW turbines)
- Comparison with Game Theoretic approach:
  - Take random steps on a_i
  - Keep new settings a_i if they increase *total power*

\+ Finds global optimum $\max_{a_i} \sum_{i=1}^{n} P_i$

\- Evaluating change in total power is slow

See: J. Marden, S. Ruben, L. Pao. (University of Colorado)

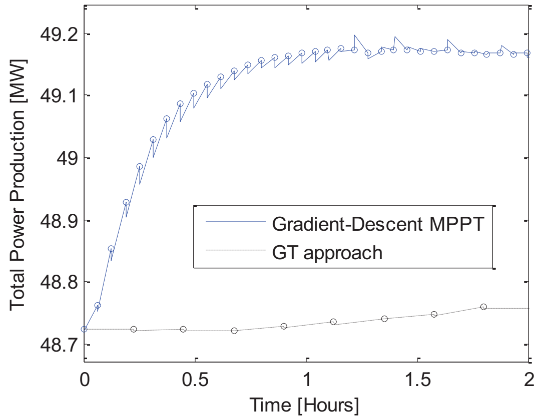
- "Surveying Game Theoretic Approaches for Wind Farm Optimization", Proc. of the AIAA Aerospace Sciences Meeting, 2012
- "A Model-Free Approach to Wind Control Using Game Theoretic Methods", submitted for journal publication, 2012

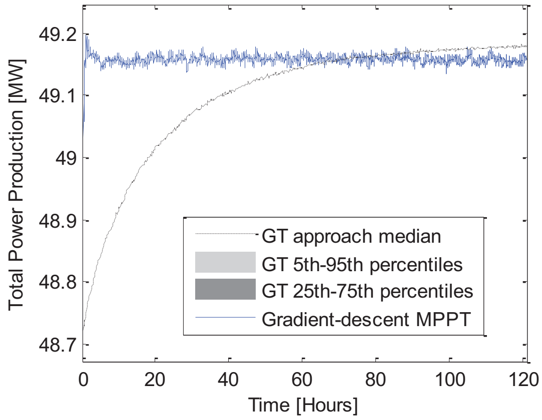
Princess Amalia Wind Park

Wind plant control

A Maximum Power-Point Tracking Approach

Simulation study:
constant wind speed $V_\infty = 8m/s$, wind direction = 25°, $K = 0.01$





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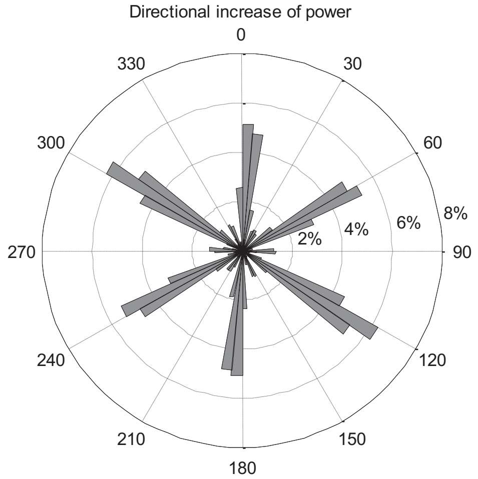
Wind farm control

A Maximum Power-Point Tracking Approach

Results: Princess Amalia Wind Park (60 2MW turbines)

Princess Amalia Wind Park



→ Total annual increase of power ≈ 1.4%

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Wind farm control

A Maximum Power-Point Tracking Approach

Conclusions:

- MPPT-GD: optimization of power through gradient-descent
  + Model-free, adaptive to changing wind conditions
- Speed-up: take into account effect on neighbouring turbines only

→ Result: Faster convergence than existing game-theoretic method

Future work:

→ Further evaluation using a model with more detailed wake dynamics (3D CFD with SOWFA)

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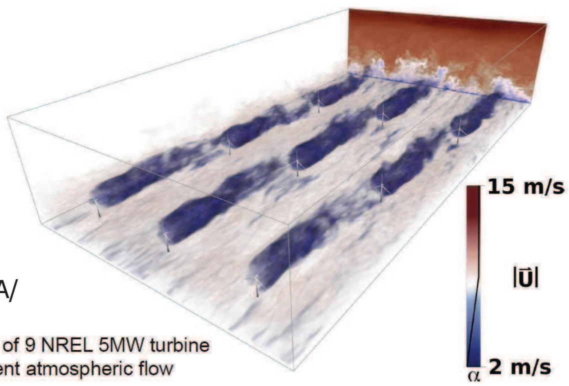
Wind plant control

Experiments on SOWFA, a 3D CFD wind farm model

- SOWFA is an OpenFOAM CFD solver coupled with FAST developed by NREL NWTC (Matt Churchfield, Sang Lee and others).
  - OpenFOAM 3D CFD solver
    - Calculates 3D flow around turbine blades (actuator line)
  - FAST model 5MW turbine dynamics
    - Loads analysis
    - Controller implementation in C

      New: Supervisory controller

See:
http://wind.nrel.gov/designcodes/simulators/SOWFA/



An array of 9 NREL 5MW turbine in turbulent atmospheric flow

Source: Sang Lee, Matt Churchfield, NREL

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Wind plant control

Experiments on SOWFA, a 3D CFD wind farm model

- Supervisory/distributed controller implementation in SOWFA

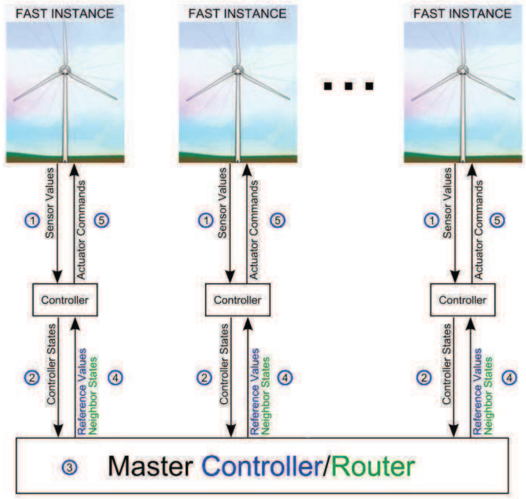
  Paul Fleming, Sang Lee, John Michalakes (NREL NWTC), Pieter Gebraad (TU Delft)

- Generic framework to test wind farm control

  program your own super controller and individual turbine controller in C

- SOWFA is meant to be ran on a cluster

  e.g. Red Rocks/Red Mesa

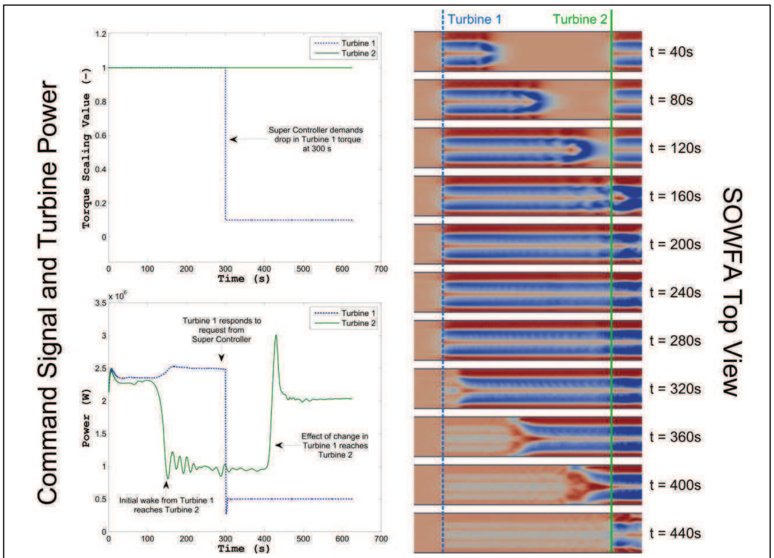


Wind plant control

Experiments on SOWFA, a 3D CFD wind farm model

Proof of principle using SOWFA simulation of a 2 turbine setup:

- Step on control setting (torque)
- First P_i responds: decrease
- Then wake travels
- Then $P_{d(i)}$ responds: increase



Simulator for Offshore Wind Farm Applications (SOWFA): http://wind.nrel.gov/designcodes/simulators/SOWFA/.
Matt Churchfield, Sang Lee, Paul Fleming
National Renewable Energy Laboratory

Questions?

Variable Operating Points for Wind Turbines

Suggestions for more wind farm-oriented design & operation

Wind Farm Optimization, IEA R&D WIND ANNEX XI TEM #71

Henk-Jan Kooijman and dr. Stefan Kern

November 2012

imagination at work

Fantanele-Cogealac, Romania: 240 GE 2.5 MW wind turbines, 600 MW farm power.
Installation was completed in November 2012

imagination at work

Paradigm shift

Towards a more wind power plant-centred perspective

- The role of the OEM for farm lay-out optimization is key because it knows the turbine design limits and load response (aero-elastic model).

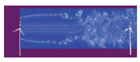
Turbine-centered view

Designed as *stand alone unit*

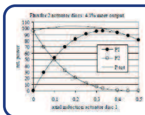
Operated as single units in a wind farm

Accurate wind farm flow models

Holistic farm-level view



Better site lay out with diverse turbine options in a farm



Co-operative, 'distributed' farm control for max AEP

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3
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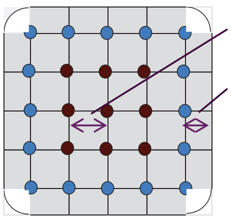
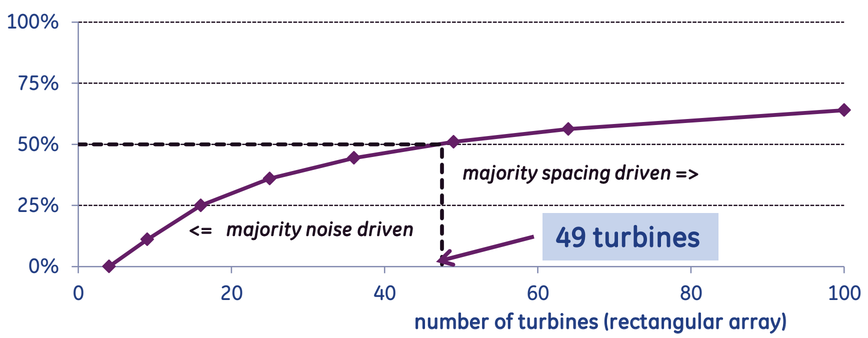
Turbine acoustics and wakes

Proposition
For large wind farms there are more turbine positions affected by wake spacing constraints than by noise set back requirements.



Wake spacing

Noise set back



Assumption:
Artificial rectangular lay-out.
Comparing # turbines along the perimeter of the farm with # turbines on 'other positions'

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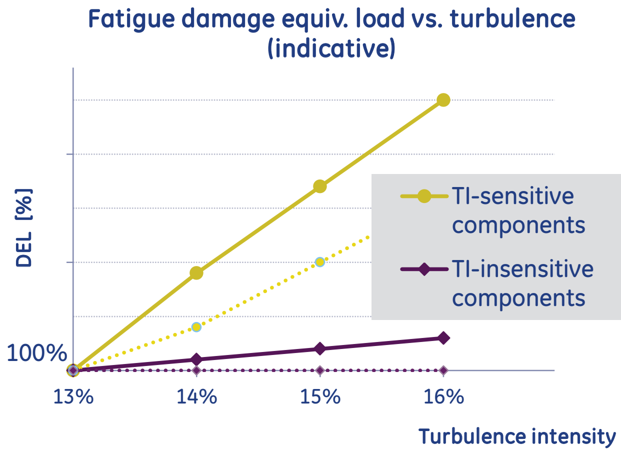
Turbine loads in a wind farm

Proposition
The fatigue loading per turbine location depends more on effective turbulence intensity (TI) (+1% to +4%) than on mean wind speed (~ -1 m/s)*.

- Torque and blade edgewise bending are quite insensitive to TI
- Weibull shape importantly effects actual change in DELs
- Differences in TI per turbine location are crucial for ultimate design loads.



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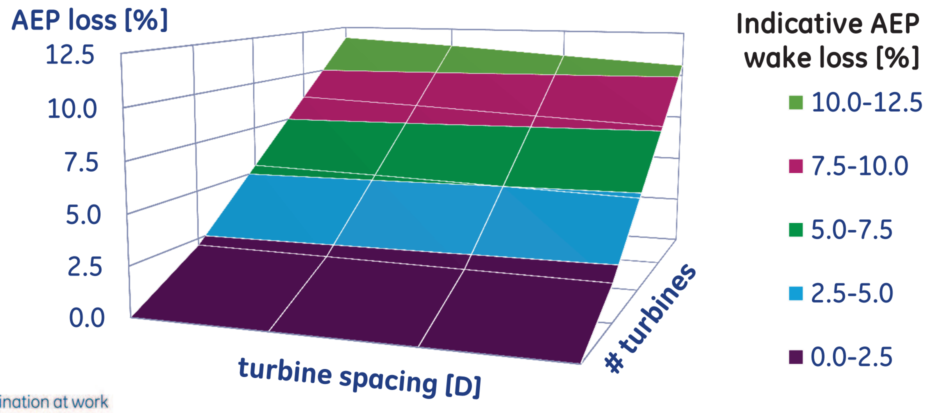
Wake induced AEP losses

Proposition:
Wake induced AEP loss can be decreased by x% to y% through better design lay out models.

Where x% and y% are for flat and complex terrains respectively.

What is your expert estimate for x and y?



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6
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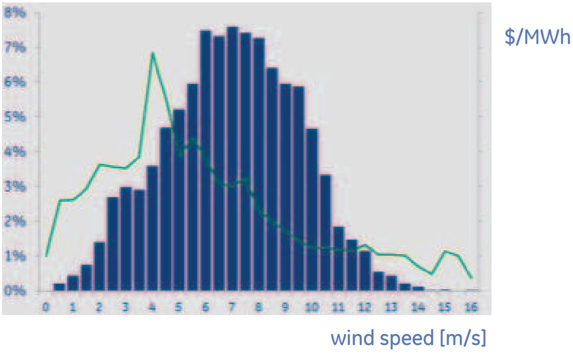
Grid congestion

Proposition:
'Smart' wind farm operation is paramount for a larger penetration of wind power.

- Power demand side requires better load management by grid operator.
- Forecast models will play a bigger role
- Variable electricity pricing models should be more linked with wind farm operating schemes.



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Controlling power

Proposition:
Turbine power management for balancing grid load can improve farm NPV.

- 'Generating wind energy is burning remaining fatigue margin'.
- The probability of exceeding extreme design load only moves when turbine is operating, except for idling load cases.
- Wind turbines are designed for 20 years-equivalent operating time.

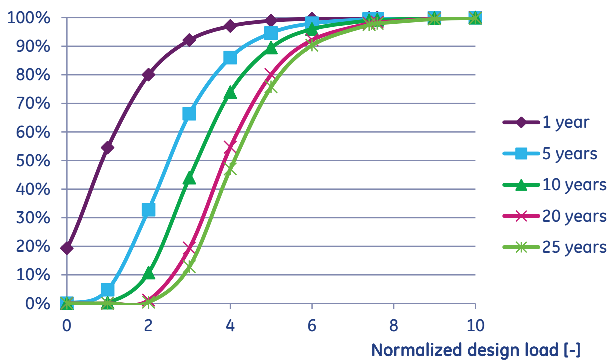

Illustration: Shift in Gumbel cumulative probability distribution for different operating life.

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Focus areas for IEA Wind Annex XI ?

Turbine cumulative fatigue damage and encountered extreme load levels should be more integrated in turbine controller.

- What is a suitable sensor set-up and diagnostics algorithm?

More accurate, validated wind farm wake models with turbine location effective design loading are desired.

- Is collaboration between institutes and industry essential?

Intelligent farm control aimed at maximizing NPV will replace turbine power curve as main performance characteristic.

- How should meteorologist, turbine OEM, and grid operator work together on this?

imagination at work

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Thank you

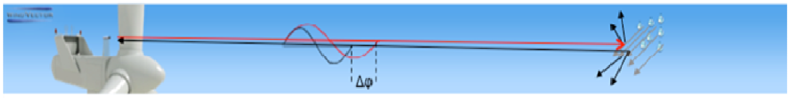
Acknowledgement (arbitrary order):

- Ravi Penmatsa
- Roger Drobietz
- Justin Sabrsula
- Jaco Nies
- Philippe Giguere
- Chris Schmitt
- Christoph Hessel
- Jeff Bergman
- Mike Barnas
- Barry Vree
- .... and others

imagination at work

Model Based Control of Wind Turbines: Look-Ahead Approach

Vattenfall, November 27, 2012, 12:30



Alexander Stotsky and Bo Egardt

Signals & Systems, Chalmers University

Abstract:

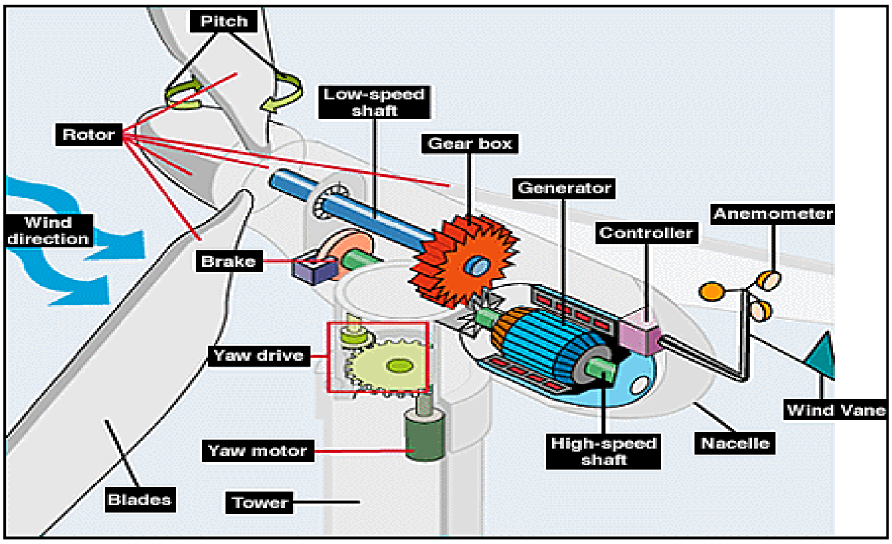
A new turbine control concept with run-ahead model in the loop based on upwind velocity measurements is developed. The concept creates an easy-to-upgrade control architecture which can easily be integrated into existing industrial turbine speed controller.

SWPTC SWEDISH WIND POWER TECHNOLOGY CENTRE

OUTLINE

- Wind Turbine Modeling
- Control Problem Statement
- Bounding of Blade Loads
- Run-Ahead Model in the Loop
- Spline Interpolation Method
- Turbine Speed Composite Controller
- Improved Blade Pitch Controller
- Simulation Results
- Conclusions

Wind Turbine Modeling and Control



Wind Turbine Control Oriented Model

Model Includes:

1) Aerodynamics (Aero-loads)
2) Driveline Model
3) Pitch Actuation Model
4) Wind Model → Wind Measurement Data from Hönö Turbine
5) New Control Strategy with RA Model

Aerodynamic model:

$$P_{wind} = \frac{1}{2}\rho A V^3$$

$$C_p(\lambda, \beta) = \frac{P_r}{P_{wind}}, \quad \lambda = \frac{\omega_r R}{V}, \quad T_a = \frac{P_r}{\omega_r}$$

Driveline model of a flexible rotor shaft:

$$J_r \dot{\omega}_r = \underbrace{\frac{P_r}{\omega_r}}_{=T_a} - \underbrace{K_s \alpha - K_d \dot{\alpha}}_{Torque\ shared\ by\ shafts}$$

$$J_g \dot{\omega}_g = \frac{K_s}{N}\alpha + \frac{K_d}{N}\dot{\alpha} - T_g$$

$$\dot{\alpha} = \omega_r - \frac{1}{N}\omega_g$$

This model can be reduced to one mass model

Drivetrain Model Reduction

$$J_r \dot{\omega}_r = \underbrace{\frac{P_r}{\omega_r}}_{=T_a} - \underbrace{K_s \alpha - K_d \dot{\alpha}}_{Torque\ shared\ by\ shafts}$$

$$J_g \dot{\omega}_g = \frac{K_s}{N}\alpha + \frac{K_d}{N}\dot{\alpha} - T_g$$

$$\dot{\alpha} = \omega_r - \frac{1}{N}\omega_g$$

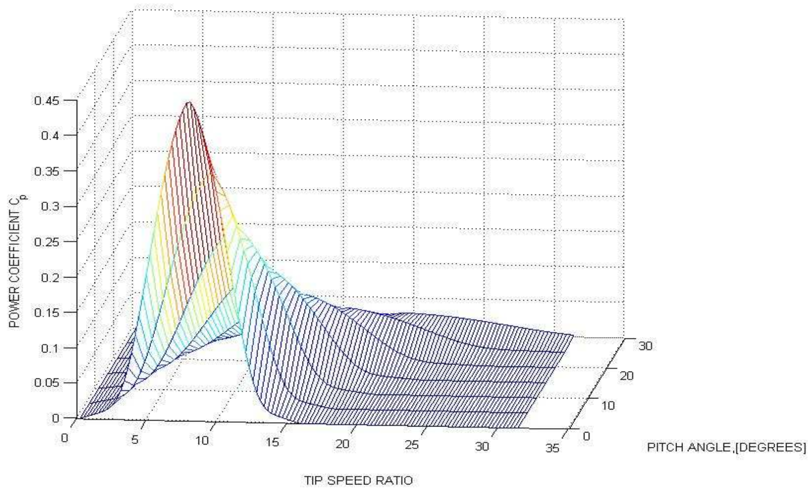
Combining: $J_r \dot{\omega}_r + N J_g \dot{\omega}_g = \frac{P_r}{\omega_r} - N T_g$

Reduced Model:

$$\omega_g = N \omega_r$$

$$J \dot{\omega}_r = \underbrace{\frac{P_r}{N \omega_r}}_{=\frac{T_a}{N}} - T_g, \quad J = \frac{J_r + N^2 J_g}{N}$$

POWER COEFFICIENT

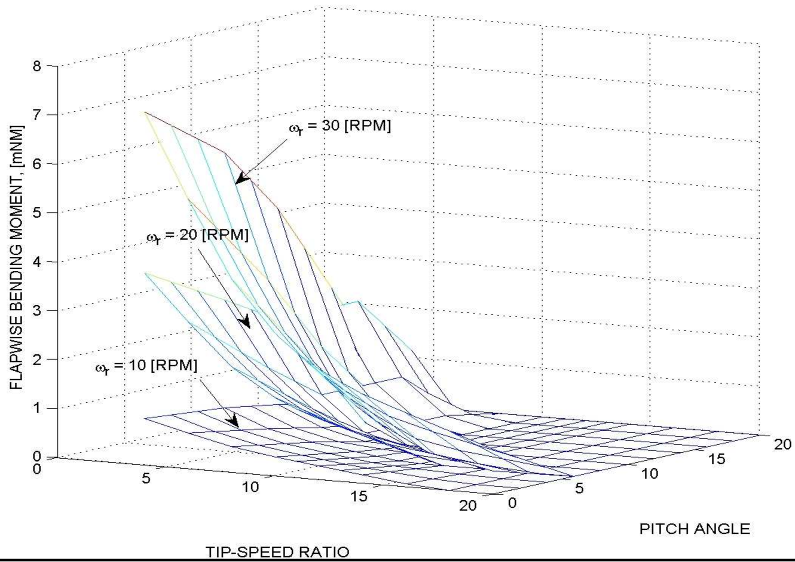


Pitch actuator model:

$$\dot{\beta} = -\frac{1}{\tau}\beta + \frac{1}{\tau}\beta_d(t - t_d)$$

$$|\beta| \leq C_\beta, \quad |\dot{\beta}| \leq C_{\dot{\beta}}$$

FLAPWISE BLADE BENDING MOMENT



Upwind Speed Measurements on Hönö Turbine

Problem Statement

$$P_r \rightarrow P_{rmax}$$

$$M_f(V, \omega_r, \beta) \leq C_f$$

$$M_e(V, \omega_r, \beta) \leq C_e$$

OUTLINE

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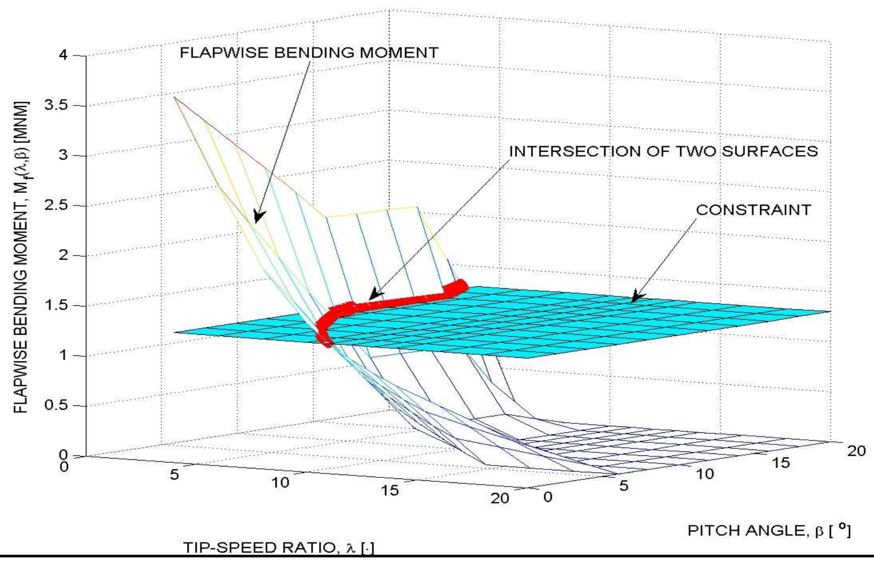
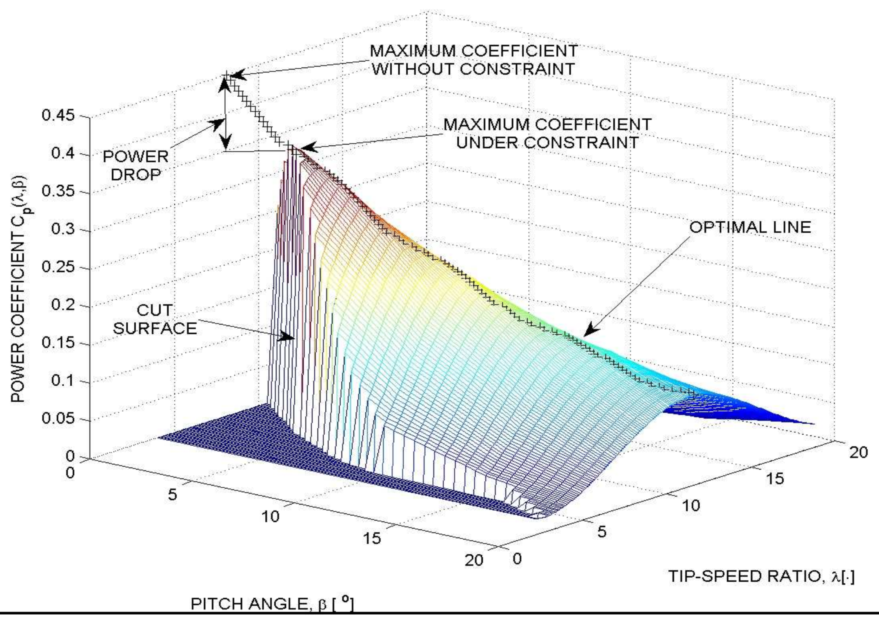
Bounding of Blade Loads



Bounding of Blade Loads



Problem Statement

$$
\begin{aligned}
\lim_{t\to\infty} \omega_r(t) - \omega_{rd} &= 0 \\
\lim_{t\to\infty} \beta(t) - \beta_d &= 0
\end{aligned}
$$

OUTLINE

- Wind Turbine Modeling
- Control Problem Statement
- Bounding of Blade Loads
- Run-Ahead Model in the Loop ←
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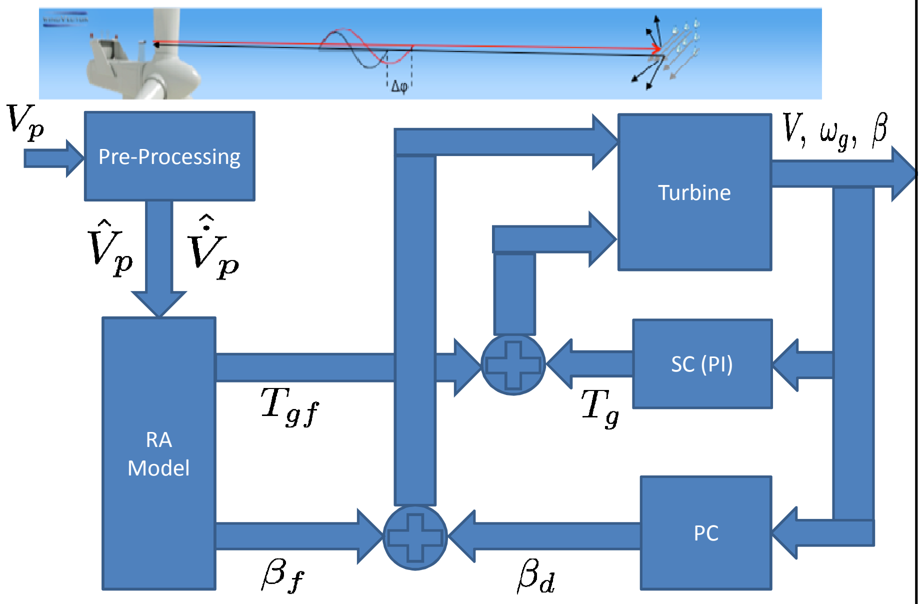
Run-Ahead Model in the Loop



Spline Interpolation Method and Preprocessing of Wind Speed

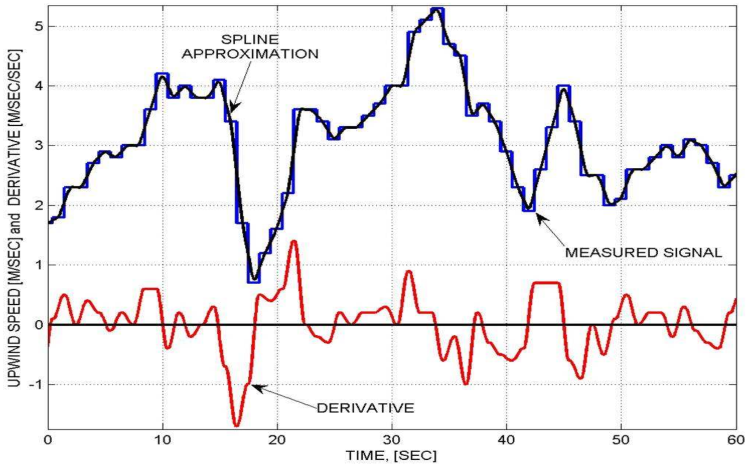
Upwind speed signal:

$$\hat{V}_p = c_0 + c_1 t + \ldots + c_n t^n$$

Performance index:

$$S_k = \sum_{j=k-(w-1)}^{j=k} (V_{pj} - (c_0 + c_1 t_j + \ldots + c_n t_j^n))^2$$

Spline Interpolation Method and Preprocessing of Wind Speed



OUTLINE

- Wind Turbine Modeling
- Control Problem Statement
- Bounding of Blade Loads
- Run-Ahead Model in the Loop
- Spline Interpolation Method
- Turbine Speed Composite Controller
- Improved Blade Pitch Controller
- Simulation Results
- Conclusions

Run Ahead Model + Controller

$$\hat{J}\dot{\omega}_{rm} = \frac{P_{rm}}{N\omega_{rm}} - T_{gm}$$

$$P_{rm} = \frac{A\rho V_p^3 C_p(\lambda_m, \beta_m)}{2}$$

$$\lambda_m = \frac{\omega_{rm} R}{V_p}, \quad \omega_{rmd} = \frac{\lambda_* V_p}{R}, \quad \dot{\omega}_{rmd} = \frac{\lambda_* \dot{V}_p}{R}$$

$$T_{gm} = \underbrace{\frac{P_{rm}}{N\omega_{rmd}}}_{feedforward\ part} + \underbrace{\gamma\,(\omega_{rm} - \omega_{rmd})}_{feedback\ part} - \underbrace{\hat{J}\dot{\omega}_{rmd}}_{predictive\ part}$$

$$\hat{J}\,(\dot{\omega}_{rm} - \dot{\omega}_{rmd}) = -\left[\frac{P_{rm}}{N\omega_{rm}\,\omega_{rmd}} + \gamma\right](\omega_{rm} - \omega_{rmd})$$

Two Speeds → One Controller

Wind Speed at a Turbine Site

$$V(t) = V_p(t) + \Delta V(t)$$

$$\omega_{rd} = \frac{\lambda_* V}{R} = \underbrace{\frac{\lambda_* V_p}{R}}_{=\omega_{rmd}} + \underbrace{\frac{\lambda_* \Delta V}{R}}_{=const}$$

$$\dot{\omega}_{rd} = \dot{\omega}_{rmd} = \frac{\lambda_* \dot{V}_p}{R}$$

Composite Controller

$$T_{gm} = \underbrace{\frac{P_{rm}}{N\omega_{rmd}}}_{feedforward\ part} + \gamma \underbrace{(\omega_{rm} - \omega_{rmd})}_{feedback\ part} - \underbrace{\hat{J}\dot{\omega}_{rmd}}_{predictive\ part}$$

$$T_g = \underbrace{\underbrace{T_{gm}}_{feedforward\ part} \underbrace{+ \gamma_r (\omega_r - \omega_{rd}) + \gamma_{r1} \int (\omega_r - \omega_{rd})}_{feedback\ part}}_{composite\ controller}$$

Closed-Loop Dynamics

$$J\dot{\omega}_r = \frac{P_r}{N\omega_r} \underbrace{- \frac{P_{rm}}{N\omega_{rmd}} - \gamma \underbrace{(\omega_{rm} - \omega_{rmd})}_{\to 0} + \hat{J}\underbrace{\dot{\omega}_{rmd}}_{=\dot{\omega}_{rd}}}_{=-T_{gm}\ (imported\ feedforward\ part)}$$

$$\underbrace{-\gamma_r (\omega_r - \omega_{rd}) - \gamma_{r1} \int (\omega_r - \omega_{rd})}_{feedback\ part}$$

Turbine Torque: $\frac{P_r}{N\omega_r} - \frac{P_r}{N\omega_{rd}} + \frac{P_r}{N\omega_{rd}} - \frac{P_{rm}}{N\omega_{rmd}}$

Closed-Loop Dynamics

$$J\dot{\omega}_r = \frac{P_r}{N\omega_r} - \frac{P_r}{N\omega_{rd}} + J\dot{\omega}_{rd} - \gamma_r \ (\omega_r - \omega_{rd})$$

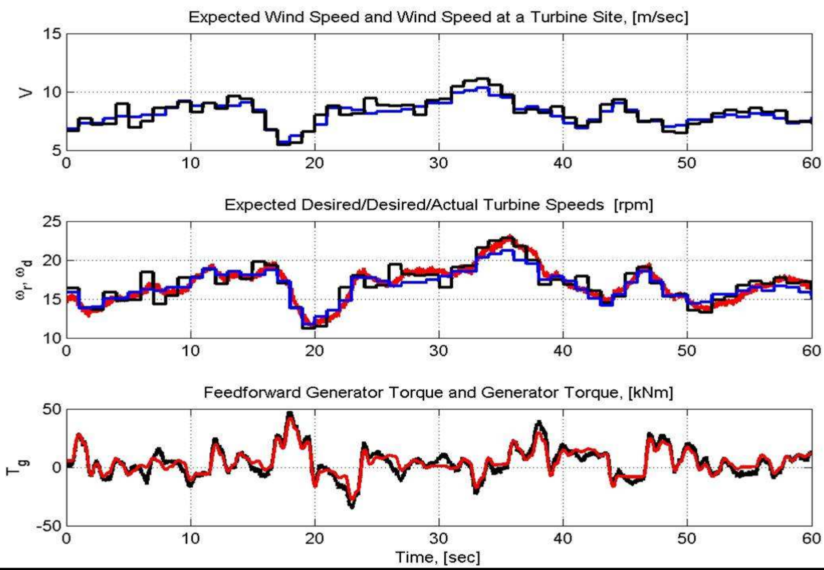
$$- \quad \gamma_{r1} \int (\omega_r - \omega_{rd}) + c$$

Finally:

$$\dot{\tilde{\omega}}_{r1} = \tilde{\omega}_r$$

$$J\dot{\tilde{\omega}}_r = -[\frac{P_r}{N\omega_r \ \omega_{rd}} + \gamma_r]\tilde{\omega}_r - \gamma_{r1}\tilde{\omega}_{r1} + c$$

Simulation Results



OUTLINE

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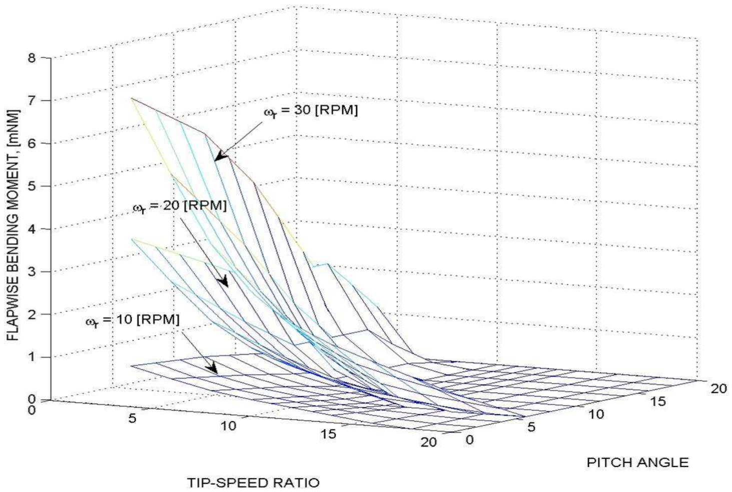
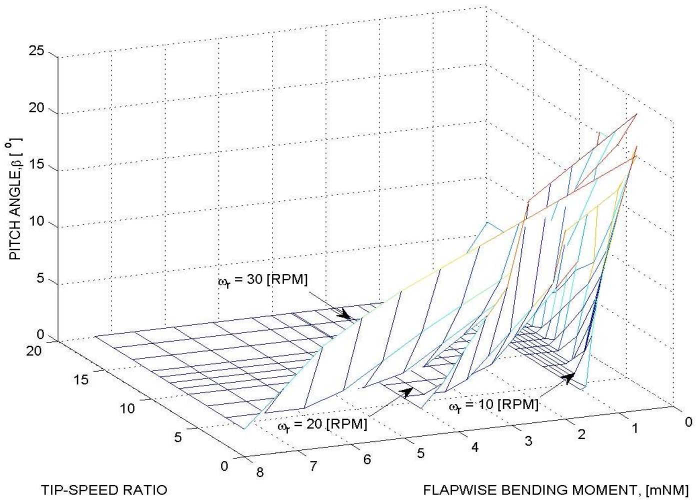
- Simulation Results
- Conclusions

Improved Blade Pitch Control



Improved Blade Pitch Control



Pitch Actuator Model:

$$\dot{\beta} = -\frac{1}{\tau}\beta + \frac{1}{\tau}\beta_d(t)$$

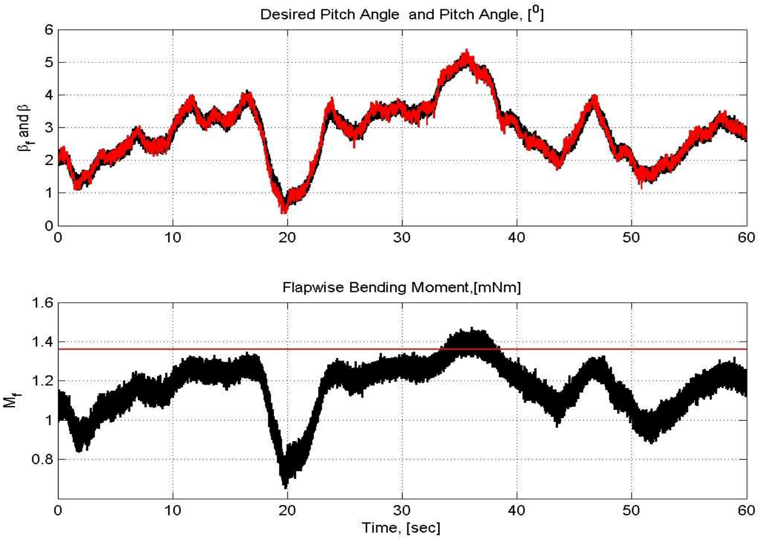
Pitch Controller: $\beta_d = \beta_f + \tau\dot{\beta}_f$

Closed Loop: $\dot{\beta} - \dot{\beta}_f = -\frac{1}{\tau}(\beta - \beta_f)$

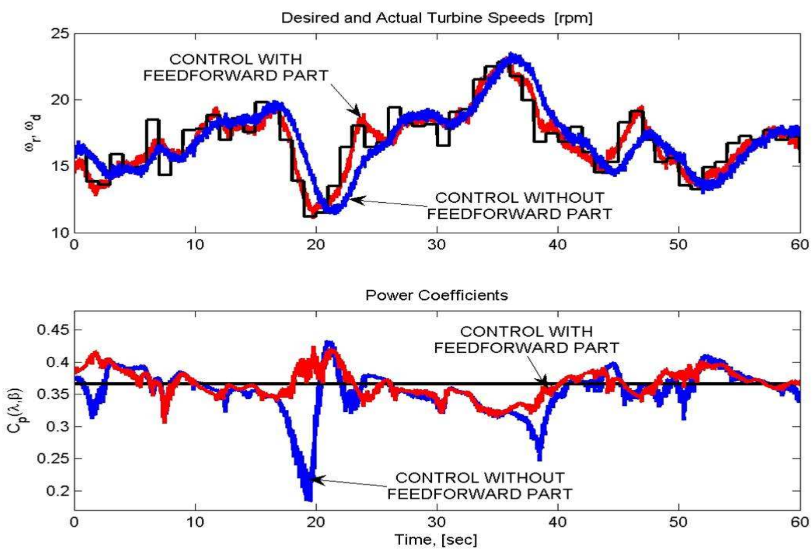
Prediction Interpretation:

$$\beta_d(t) = \beta_f(t) + \tau\Big[\underbrace{\frac{\beta_f(t+\tau) - \beta_f(t)}{\tau}}_{\approx\, \dot{\beta}_f(t)}\Big] \approx \beta_f(t+\tau)$$

Simulation Results



Comparisions



Conclusions

- A new concept of look-ahead modeling which results in the feedforward part of the turbine controller is introduced
- Concept resulted in easy-to-upgrade control architecture where the run-ahead model based feedforward part driven by the upwind speed measurements can easily be integrated into an existing industrial feedback PI or PID turbine speed controller, driven by the wind speed measurements on the turbine site
- Blade load regulation with improved performance can also be easily integrated into the proposed control architecture

SWPTC
SWEDISH WIND POWER TECHNOLOGY CENTRE

Contents

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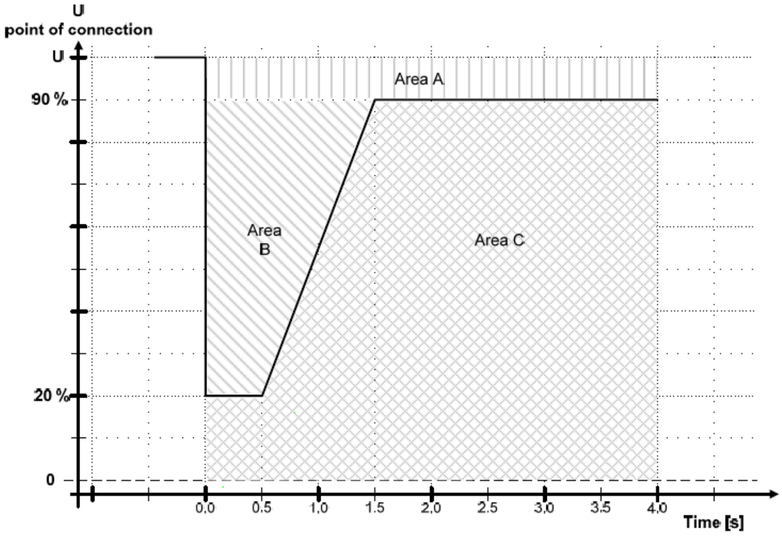
Grid Codes Overview

GOLDWIND

DK requirement for LVRT



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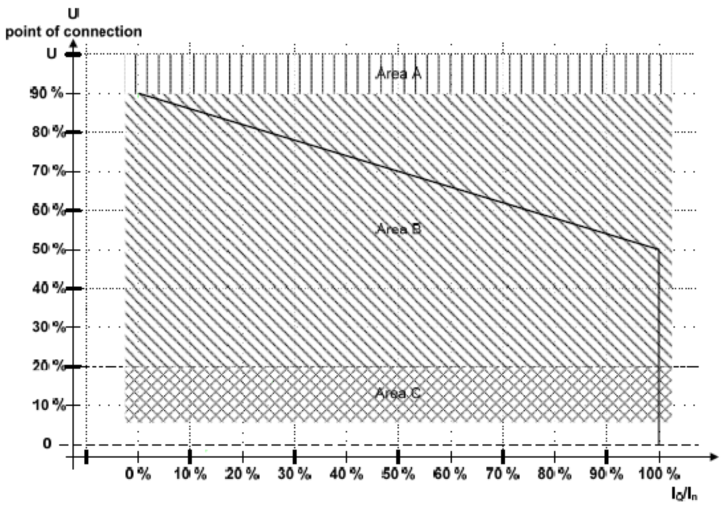
Grid Codes Overview

GOLDWIND

DK requirement for reactive power support



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Grid Codes Overview

GOLDWIND

German Requirement for LVRT

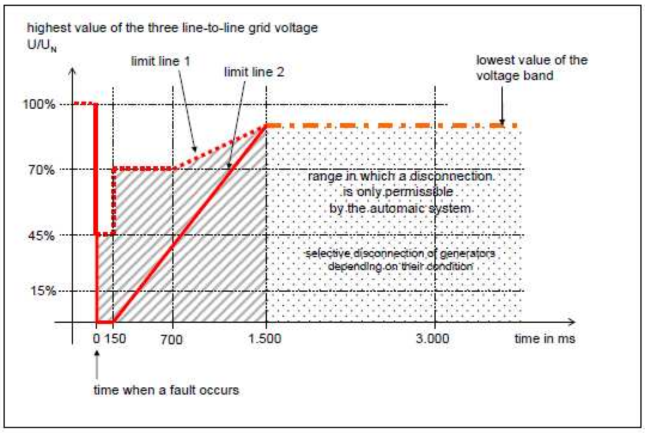

Figure 6 Limit curves for the voltage pattern at the grid connection for Type 2 generating plants in the event of a fault in the grid

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Grid Codes Overview

GOLDWIND

German requirement for reactive power support

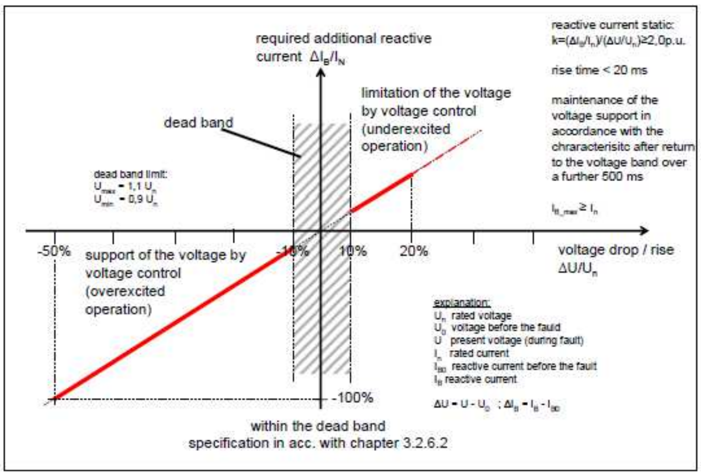

Figure 7 The principle of voltage support in the event of grid faults

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Grid Codes Overview

GOLDWIND

Power Factor Requirements for WF

US, DK, Germany, etc.   Requirement: -0.95 ~ +0.95

Australian requirement: -0.90 ~ +0.90

Ireland requirement: -0.85 ~ +0.85

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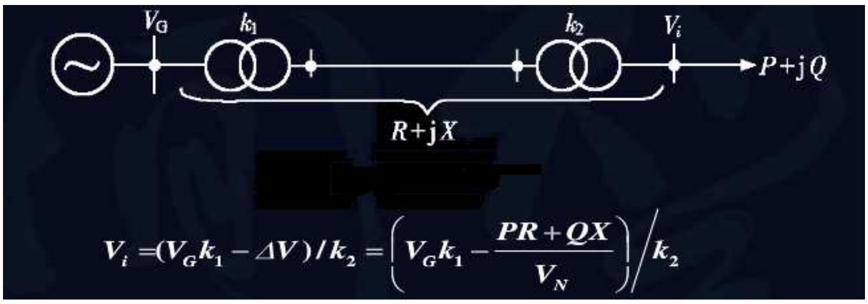
Reactive Power Vs. Voltage

GOLDWIND



Set-up transformer, 2%
Transmission Line, 6%
Main transformer, 10%

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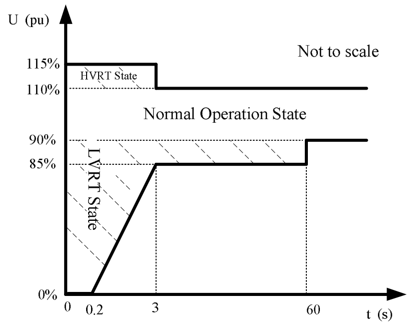
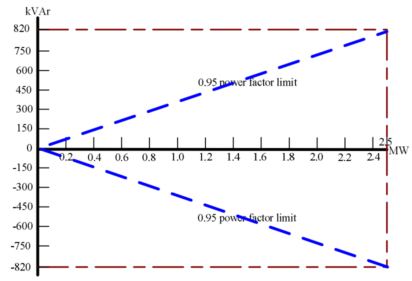
Reactive Power Vs. Voltage

The importance of the reactive power/current injection is the reactive power rised the wind turbine terminal voltage – enlarged the LVRT range.



wind turbine LVRT capability



Reactive power capability at steady-state

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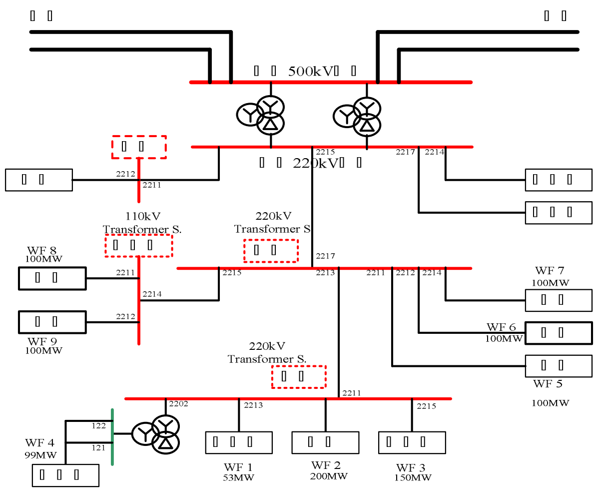
WF Disconnecting at ZhangBei, China



2011.4.17 Wind Farm disconnected

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WF Disconnecting at ZhangBei, China

GOLDWIND

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WF Disconnecting at ZhangBei, China

GOLDWIND

Background:

1. #8 wind turbine phase B short circuit with 35kV transmission line phase C (phase B – phase C short circuit)
2. 35kV transmission line voltage dip to 0.4~0.6pu
3. Wind turbines disconnected (low voltage) and SVC switch on
4. Overmuch reactive power rise up 220kV voltage to 262kV (wind farm 5~9 disconnected because of the High voltage)
5. Wind turbines disconnecting ⟶ Reactive power unbalance ⟶ overmuch compensation ⟶ Voltage rise ⟶ More wind turbines disconnecting ⟶ Active power unbalance (evil circle)

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Reactive Power Control Status quo

GOLDWIND

A. SVC response time too slow
B. Reactive power adjust depend on the SVC not on wind turbine
C. Wind turbine Reactive power capability usage not reasonable because of the even distribution of reactive power at each wind turbine.

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Reactive Power Control Status quo

GOLDWIND

SVC (TCR+MSC): 1. Q= U^2/Z the compensation capability decrease with the square voltage.

2. Expensive , Eg. 50MW wind farm with 10MVar SVC cost 2 million RMB and consumer power at least 870,000kW each year

3. High harmonics

STATCOM/SVG: Smart , but more expensive (30%)

How about **Smarter reactive power compensation**

\+

Lower cost ?

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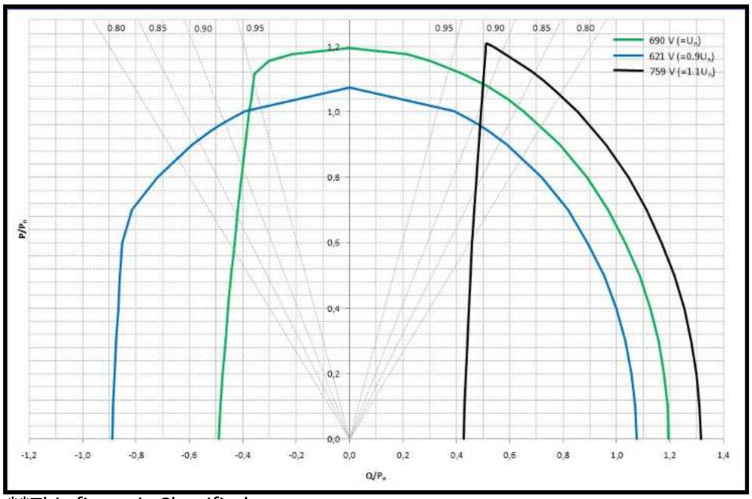
A ‘New’ Control Idea

GOLDWIND

1.5MW Wind Turbine Reactive Power Capability



**This figure is Classified

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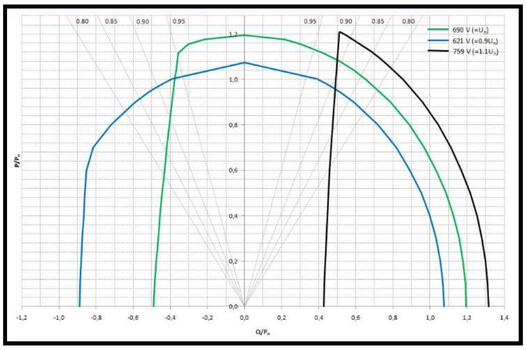
A ‘New’ Control Idea

GOLDWIND

1.5MW Wind Turbine Reactive Power Capability



Power Factor	Compensation
A. -0.95 ~ +0.95	30% Prate
B. -0.90 ~ +0.90	42% Prate
C. -0.85 ~ +0.85	50% Prate

Even at pf=0.85, the I = 1.1In, still at the safety range

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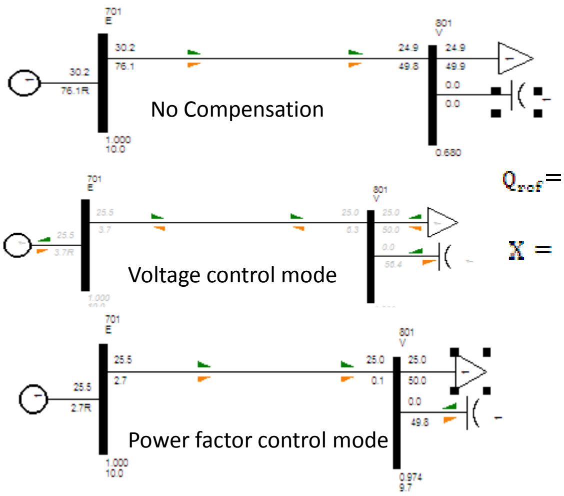
A 'New' Control Idea

GOLDWIND

Control Modes



$$Q_{ref} = U_{ref} * \left(\frac{U_{ref} - U_{now}}{X} - \frac{Q_{now}}{U_{now}}\right)$$

$$X = \frac{U2 - U1}{\frac{Q2}{U2} - \frac{Q1}{U1}}$$

A 'New' Control Idea

GOLDWIND

Temperature/Voltage Vs Reactive power capability table

T / U	25		...	...	...	...	...	...	50
0.9Un									
0.95Un									
Un									
1.05Un									
1.1Un									

System impedance for each wind turbine to get a factor X

Reactive power distribution idea: Equal percentage

**The data was omitted because of the classified and the Patent is granted for this strategy.

A ‘New’ Control Idea

GOLDWIND

Wind Turbine
Reactive Power

SVC

Purpose: Local Balance and Local consume

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The End

GOLDWIND

THANK YOU

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DTU

Wind turbine deficit and park efficiency

Kurt S. Hansen
DTU Wind Energy

kuhan@dtu.dk

Operator of
Database of wind characteristics
www.winddata.com

DTU Wind Energy
Department of Wind Energy

DTU

Outline

1. Introduction to DTU WE;
2. Recent analysis on wind farm deficit;
3. Motivation;
4. Examples based on Horns Rev and Lillgrund offshore wind farms;
5. Park power polar;
6. Park efficiency;
7. Perspectives;
8. Acknowledgement & references.

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Department of Wind Energy, DTU

DTU

- ~150 staff members, working with research and education;
- ~ 60 PhD students;
- 50-90 Master students;

8 sections:

Fluid mechanics (Composite mechanics)

Meteorology

Aeroelastic design

Wind turbines

Wind energy systems

Test and measurements

Composite and material mechanics

Materials Science and Characterisation

Wind Turbine Test sites at
1) Høvsøre & 2)Østerild

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Research at DTU Wind Energy

DTU

WIND ENERGY SYSTEMS

Wind resources and siting

Wind power integration and control

Offshore wind energy

WIND TURBINE TECHNOLOGY

Aero-elastic design

Structural design and reliability

Remote sensing and measurement technology

WIND ENERGY BASICS

Aero and hydrodynamcis

Boundary layer meteorology and turbulence

Light, strong materials

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Analysis of wind farms - history

- EU-Upwind, WP8 Flow;
  Purpose: Validation flow models covering large wind farms;
- EU-Topfarm , WP4 Flow analysis in wakes & wind farms;
  Purpose: Topology optimization of wind farm layout;
- IEA-Annex 31: WakeBench;
  Purpose:bechmarking of flow and park models against validation data from wind farm measurements;
- EERA-DTOC:bechmarking of flow models;
  Purpose: qualification of flow models for a ”Design Tool for Offshore Wind Farm Cluster”.

Motivation

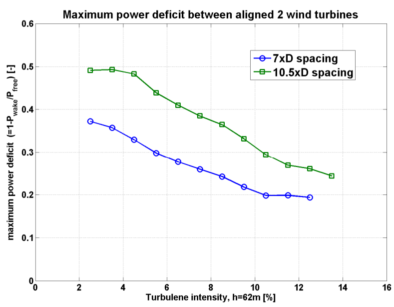
Grouping two or more wind turbines results in a loss of energy production when the turbines operate [partly] in the wake of each other.

Wake deficit highly depends on:

•Spacing;

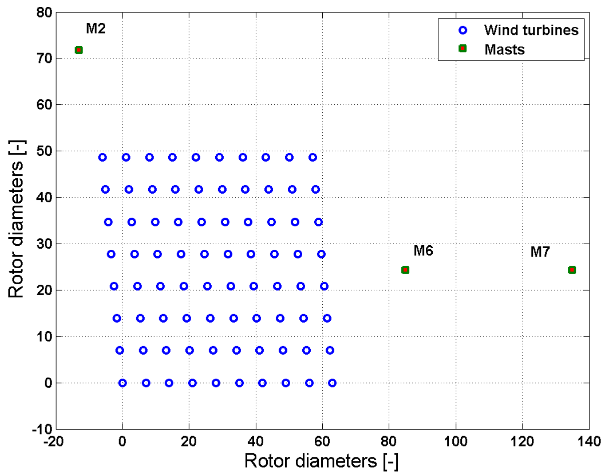
•Wind speed;

•Turbulence;



Example:
Horns Rev offshore wind farm: 80 x 2 MW, D=80m

DTU



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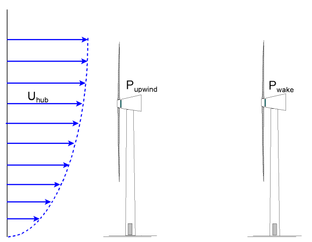
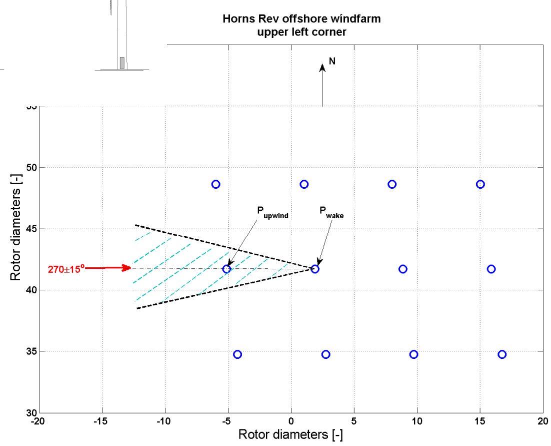


Basic flow case:
2 wind turbines
with 7D spacing



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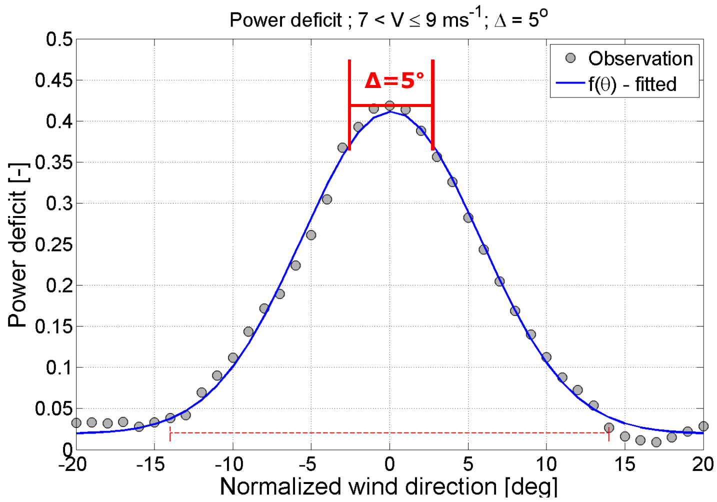
Maximum power deficit, 7D spacing



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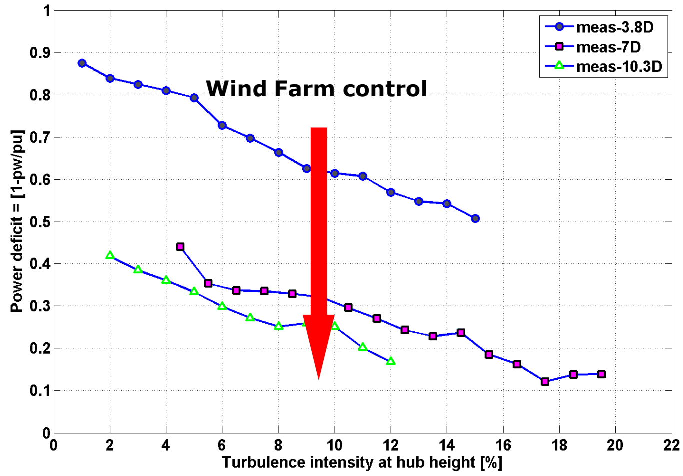
Maximum power deficit between 2 wind turbines for 3.8D, 7D & 10.3D spacing; Δ=5°



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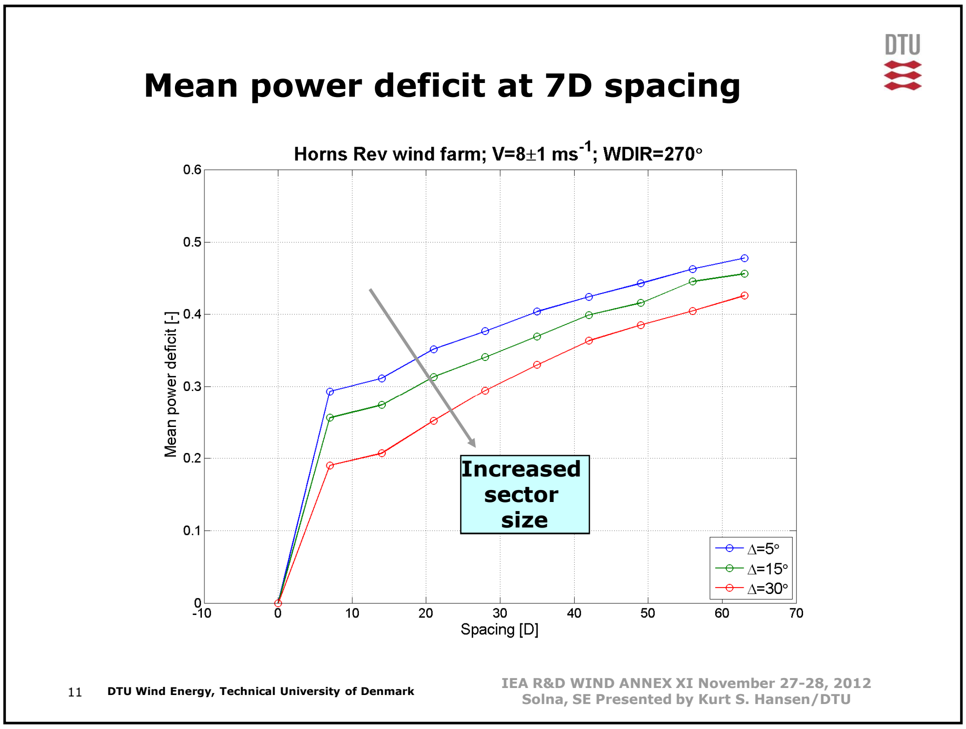
Mean power deficit at 7D spacing
Horns Rev wind farm; V=8±1 ms-1; WDIR=270°
Mean power deficit [-]
Spacing [D]
Increased sector size
Δ=5°
Δ=15°
Δ=30°
11
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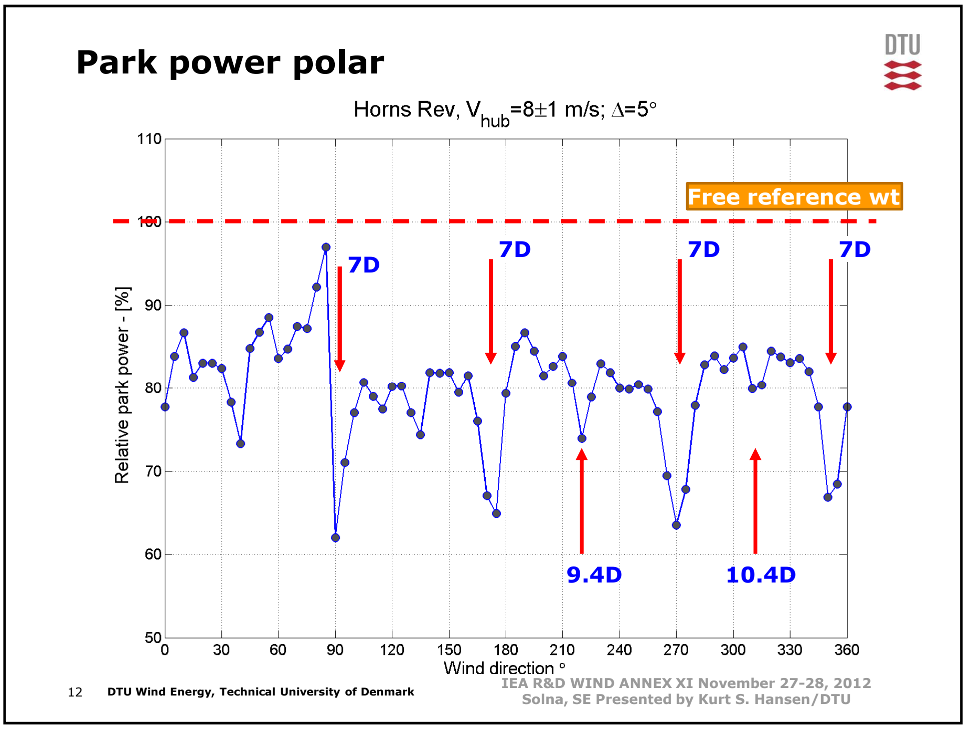
Park power polar
Horns Rev, Vhub=8±1 m/s; Δ=5°
Free reference wt
7D
7D
7D
7D
9.4D
10.4D
Relative park power - [%]
Wind direction °
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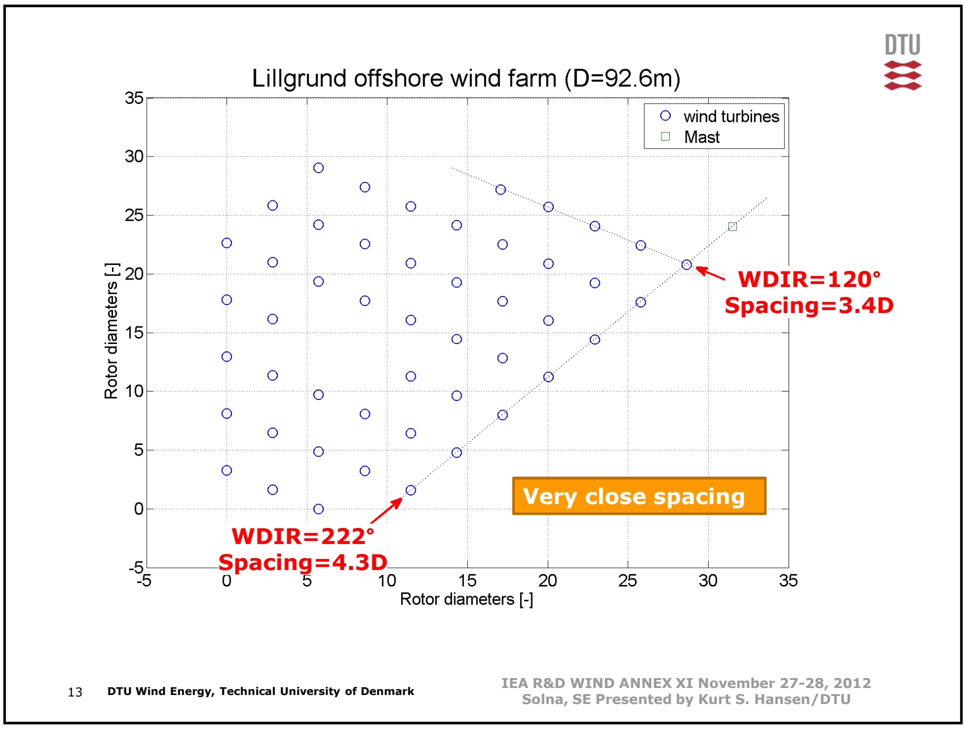
DTU
Lillgrund offshore wind farm (D=92.6m)
wind turbines
Mast
Rotor diameters [-]
Rotor diameters [-]
WDIR=120°
Spacing=3.4D
Very close spacing
WDIR=222°
Spacing=4.3D
13
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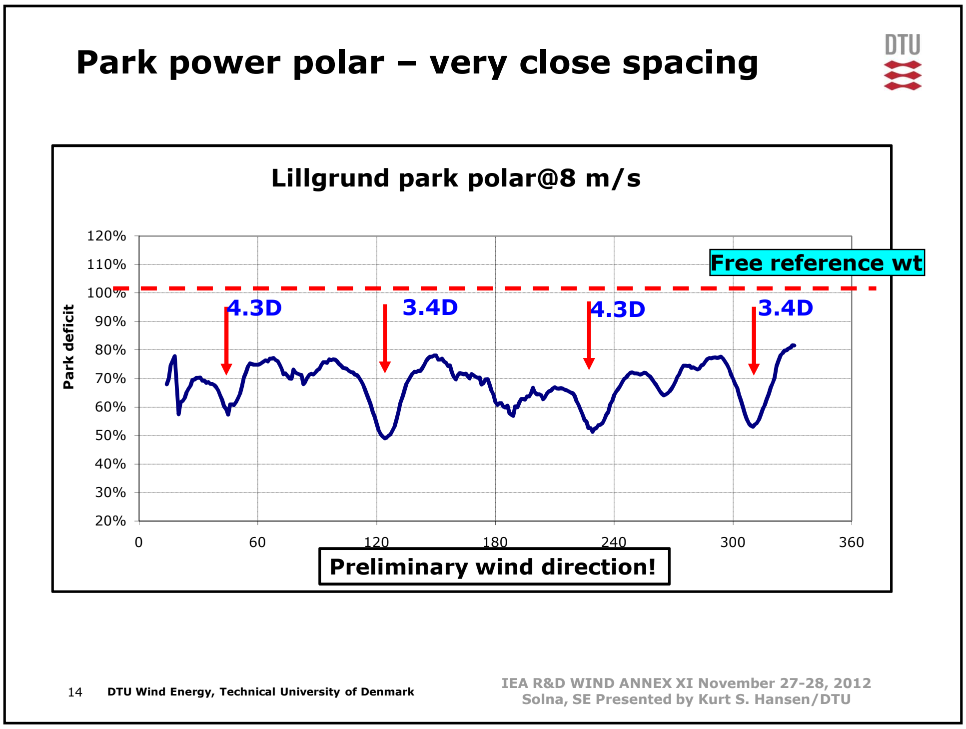
Park power polar – very close spacing
DTU
Lillgrund park polar@8 m/s
Park deficit
Free reference wt
4.3D
3.4D
4.3D
3.4D
Preliminary wind direction!
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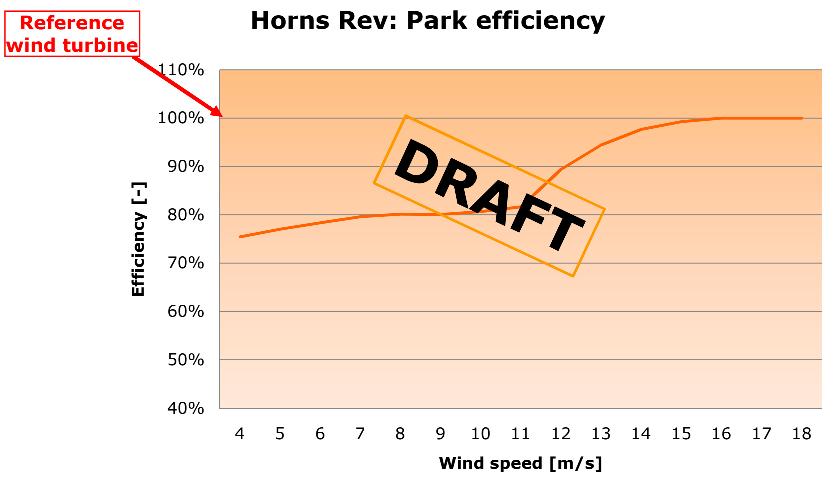

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Horns Rev: Park efficiency - preliminary

$4 \leq U_{hub} \leq 24$ m/s	Park efficiency
All recordings	90%

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Conclusion

- Power deficit along wind turbines;
- Park polar for 0 – 360 degree inflow;
- Park efficiency estimation;

Perspectives by introducing [active] wind farm control

Before implementing:

- To identify the potential benefit (AEP and fatigue life consumption);

After implementing [active] wind farm control:

1. Validate - if the expected efficiency improvement has been obtained;
2. Validate the future fatigue life consumption.

Acknowledgement

The research has been performed in part by EUDP 64010-0462 which is funded by the Danish Energy Agency.

We acknowledge Vattenfall AB and DONG Energy A/S for using the SCADA data from the Horns Rev offshore wind farm.

We acknowledge Vattenfall AB for using the SCADA data from the Lillgrund offshore wind farm.

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References:

The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm, by Kurt S. Hansen et al.;we.512 (2012), Wiley

Validation of the dynamic wake meander model for loads and power production in the Egmond aan Zee wind farm by Torben J. Larsen et.al; we.1563 (2012), Wiley

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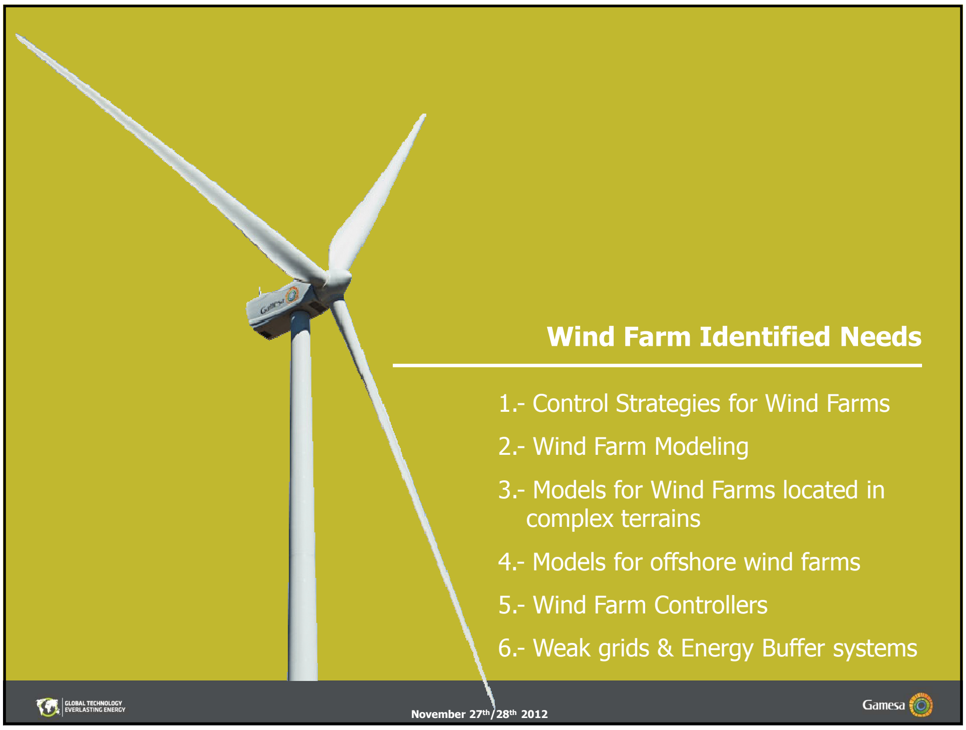
Technology Development
Needs of Gamesa
Gamesa
November 27th and 28th of 2012

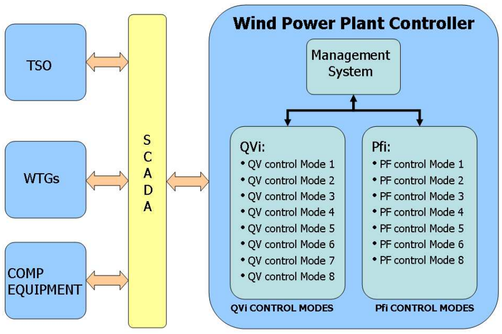

Wind Farm Identified Needs
1.- Control Strategies for Wind Farms
2.- Wind Farm Modeling
3.- Models for Wind Farms located in complex terrains
4.- Models for offshore wind farms
5.- Wind Farm Controllers
6.- Weak grids & Energy Buffer systems
November 27th/28th 2012
Gamesa

Gamesa Technological Needs related with Wind Farm Control

CONTROL STRATEGIES FOR WIND FARMS

- Gamesa have worked in the last two years in a Wind Farm Control oriented at:
  - Improving the quality of the electric power at the connection point.
  - Complying with the specific requirements of the Grid Codes.

3



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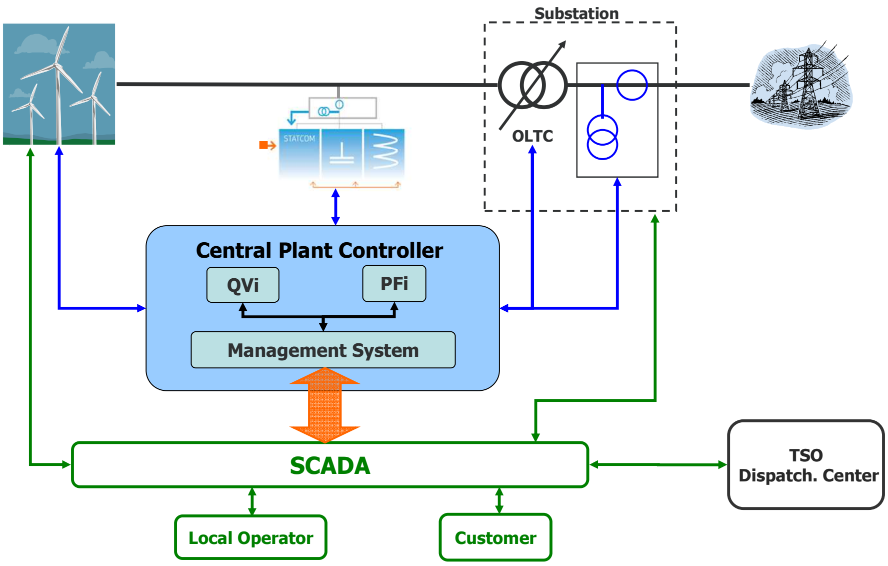

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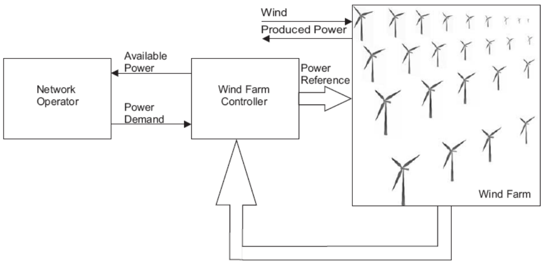
CONTROL STRATEGIES FOR WIND FARMS

- Gamesa wants to add a second layer to this control aimed at increasing the energy yield of the whole WF rather than letting each WTG to act on its own.



Key information of WTs status and operation

5

Gamesa Technological Needs related with Wind Farm Control

CONTROL STRATEGIES FOR WIND FARMS

- Therefore WF control strategies that use the information gathered from each WTG to return individual action commands for each turbine or group of turbines are of high interest for our company in terms of:
  - Developing a fast calculation module to predict with some anticipation the propagation of wind characteristics throughout the site.
  - Study of wake propagation on the WF.
  - Use of additional specific sensors, which would not be economically feasible at WTG level, but would be at WF level (e.g. with some sensors distributed along the perimeter of the Wind Farm)
  - Identifying faulty operation caused by malfunctioning sensors. The use of the signal of adjacent WTGs could avoid triggering alarms or WTG stops, increasing the global availability of the WF.
  - Load reduction and power optimization

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Gamesa Technological Needs related with Wind Farm Control

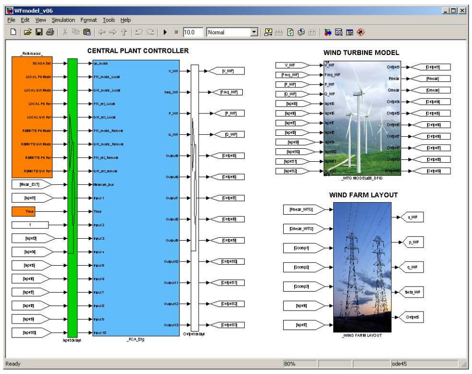
WIND FARM MODELLING (Electrical variables)

Gamesa has developed an Electric model of a Wind Farm in order to simulate the behavior of the Wind Farm as a whole from an electric point of view.

The model needed for this purpose does not require excessive computational effort because in this case, WT dynamics can be modeled in a relatively simple way:

- WF controller (Simulink)
- WTG model (Simulink)
- Park model (SimPower Systems)

Handy design & validation



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WIND FARM MODELLING (site and environment variables)

When it comes to design and validate Wind Farm Control strategies oriented to manage the performance of a Wind Farm as a whole but taking into account site-dependent variables, the required dynamics to be evaluated make the WTG model and hence the WF model more complex.

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The following points should be taken into account:

- Variation of wind characteristics throughout the site.
  1. Propagation of wakes.
  2. Propagation of noise.
- WTG aeroelastic model
- Commitment of accuracy versus computational time requirements.

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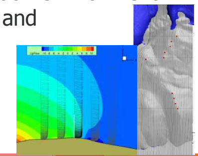
MODELS FOR WIND FARMS LOCATED IN COMPLEX TERRAINS

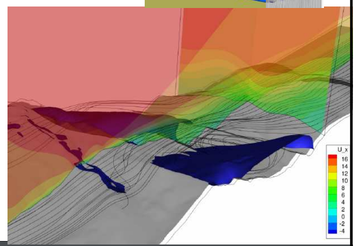
On-shore sites evaluated in site assessment department are progressively becoming orographically more complex and current tools cannot accurately predict flow phenomena such like: shear, upflow, yaw and TI vertical profiles, flow separated areas…

Several CFD methods to develop and validate and advanced CFD simulation environment are currently being evaluated to get the best balance between accuracy and computational time.



Objectives:

1. Accurate prediction of the wind profile (critical for load evaluation of the most complex terrains and an essential input for power production optimization at farm level).
2. Wake characterization
3. Predict and anticipate unconventional wind conditions that may affect machine integrity for wind farm optimization



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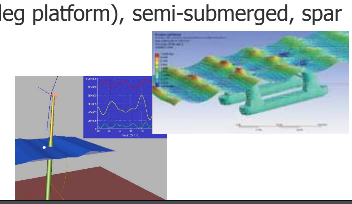
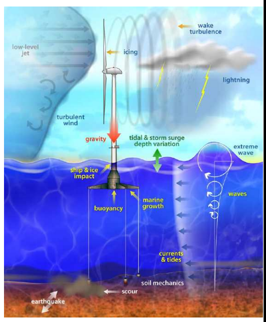
MODELS FOR OFFSHORE WIND FARMS

Design and evaluation of off-shore wind farms must take into account:

- Sea characteristics (waves, tides, water currents) and their influence on the dynamics of the coupled system (wind turbine + substructure)
- New DOF must be added to the WTG in order analyze the stability of the sea-WTG structure-soil interaction for different topologies:
  - Fixed: monopile, jacket, GBS…
  - Floating: TLP (Tension leg platform), semi-submerged, spar buoy, etc





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MODELS FOR OFFSHORE WIND FARMS

Gamesa are currently improving our in-house aeroelastic analysis tools to be applied for off-shore WTG design and analysis.

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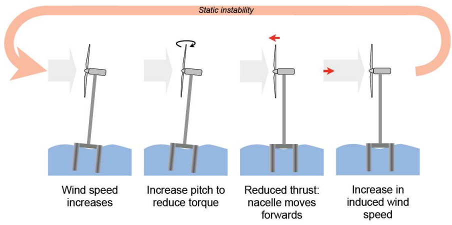

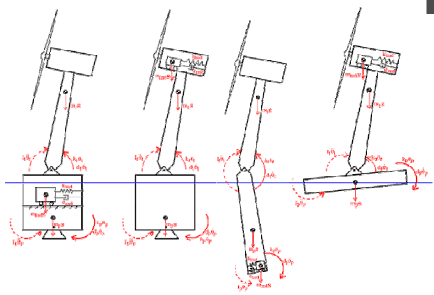

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WIND FARM CONTROLLERS

- Wind Farm Control Architecture:
  - Response times for electrical variables: The requirements coming from the strictest worldwide grid codes regarding reaction and response times should be fulfilled.
  - Response times for site variables are not as demanding as for electrical variables
- Discussion
  - Is it enough a WF control architecture based in SCADA?
  - Is it needed a totally new concept to fulfill the high demanding grid code requirements? Real Time applications, industrial fieldbus…

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Gamesa Technological Needs related with Wind Farm Control

EXPERIMENTAL DATA AND DYNAMIC STUDIES OF WF CONNECTED TO WEAK GRIDS

- Gamesa Services has already identified the most frequent problems in Wind Farms connected to Weak Grids.
- We are highly interested in obtaining Weak Grid experimental data in order to analyze in detail those problems and develop solutions.

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ENERGY BUFFER SYSTEMS

- Gamesa has been working in the past in the development of a massive storage system based on Redox Flow Batteries.
- We are participating together with Iberdrola in a demonstration Wind Farm in the Canary Island. This Wind Farm includes an hybrid system with:
  1. A flywheel used for voltage dips and start up.
  2. Diesel engines for back-up and secondary power supply (e.g. grid frequency variations).

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LIDAR measurements for wind farm control

D. Schlipf,
J. Anger, O. Bischoff, F. Haizmann, M. Hofsäß,
A. Rettenmeier, I. Würth, P. W. Cheng

Stuttgart Wind Energy (SWE), Germany

WindForS
The Southern German Wind Energy Research Alliance

SWE
Endowed Chair of Wind Energy at the Institute of Aircraft Design

University of Stuttgart
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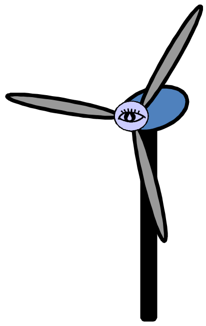
Motivation

SWE expertise

- wake measurements with LIDAR
- LIDAR assisted control

LIDAR measurements can be

- used to validate/improve wake models
- integrated in Model Predictive Control of wind farms



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Content

- wake measurements with LIDAR
  - at Bremerhaven
  - at alpha ventus
  - at DTU-Risø Campus
  - at Baltic I
- LIDAR assisted control
  - Proof-of-Concept at NREL
  - Nonlinear Model Predictive Control
- Conclusions and Outlook

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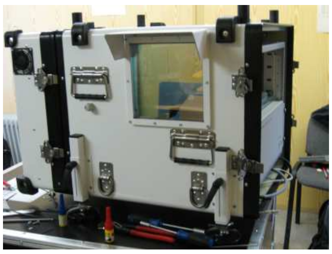
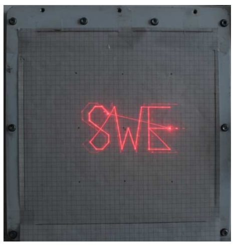
Wake Measurements with LIDAR at Bremerhaven

Adaptation of a Standard Windcube for Horizontal Scanning



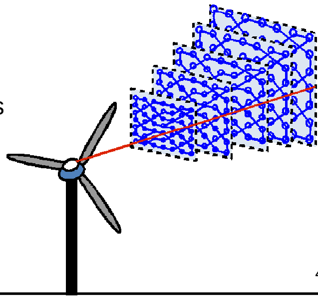
Scanner Unit

Web cam



Validation with visible laser

- High flexibility in trajectories with one mirror
- Real 3D figures through 5 adjustable range gates
- e.g. optimized Lissajous figure with 5x7x7 points in ~8s



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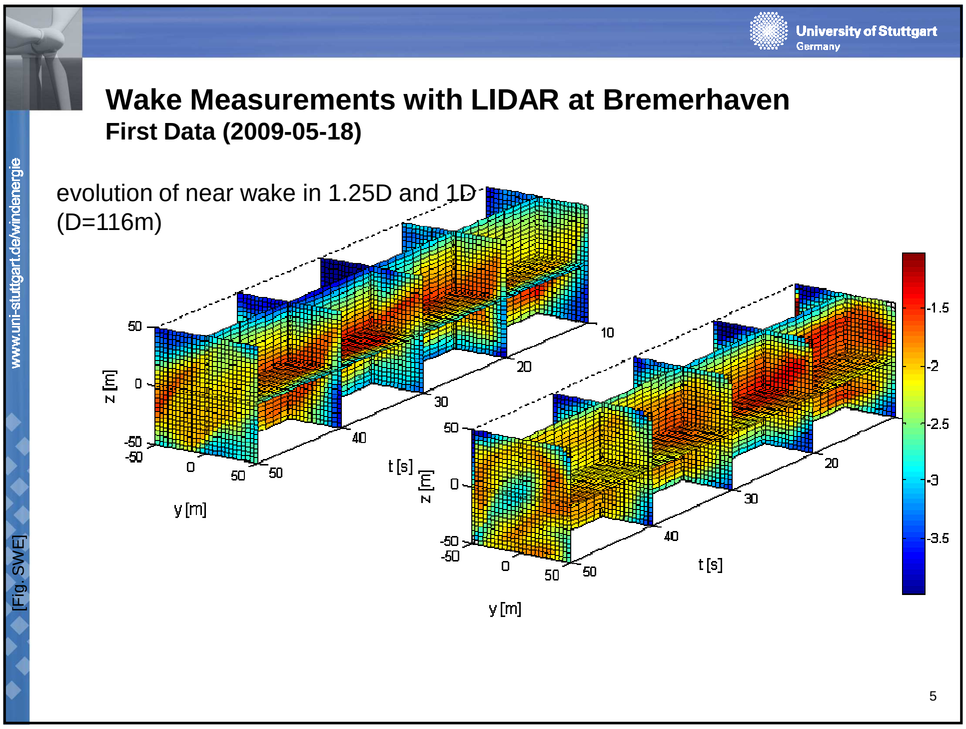
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Wake Measurements with LIDAR at Bremerhaven
First Data (2009-05-18)
evolution of near wake in 1.25D and 1D
(D=116m)
z [m]
y [m]
t [s]
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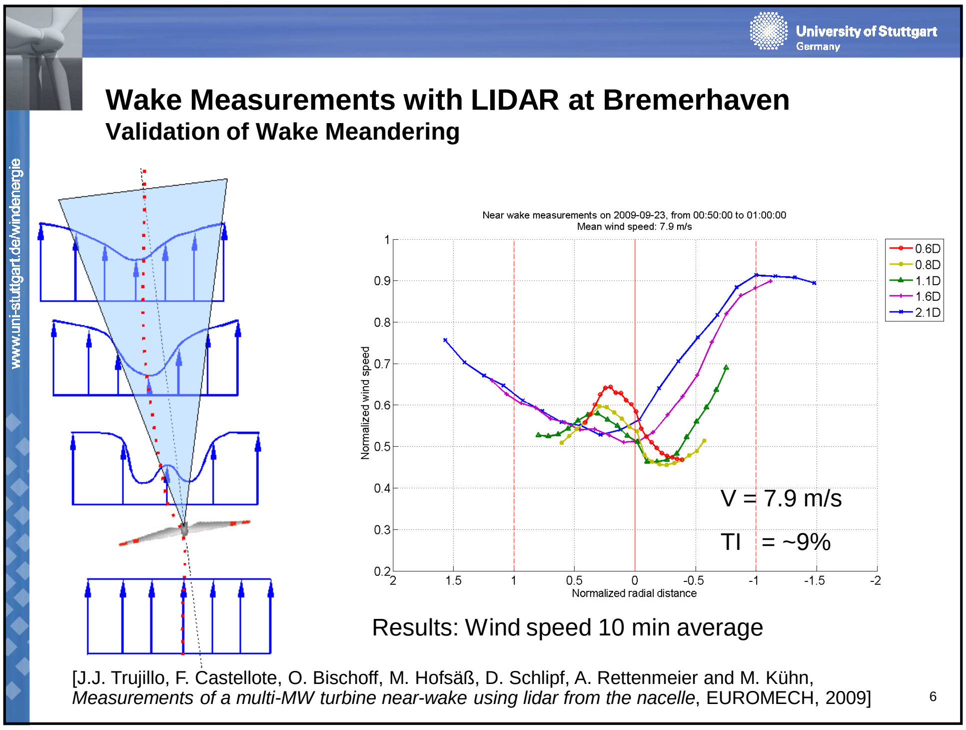
[Fig. SWE]
5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Wake Measurements with LIDAR at Bremerhaven
Validation of Wake Meandering
Near wake measurements on 2009-09-23, from 00:50:00 to 01:00:00
Mean wind speed: 7.9 m/s
Normalized wind speed
Normalized radial distance
0.6D
0.8D
1.1D
1.6D
2.1D
V = 7.9 m/s
TI = ~9%
Results: Wind speed 10 min average
[J.J. Trujillo, F. Castellote, O. Bischoff, M. Hofsäß, D. Schlipf, A. Rettenmeier and M. Kühn,
Measurements of a multi-MW turbine near-wake using lidar from the nacelle, EUROMECH, 2009]
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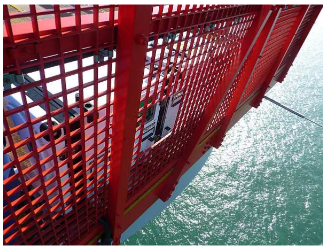
Wake Measurements with LIDAR at alpha ventus



Videos

- turbine
- fast motion

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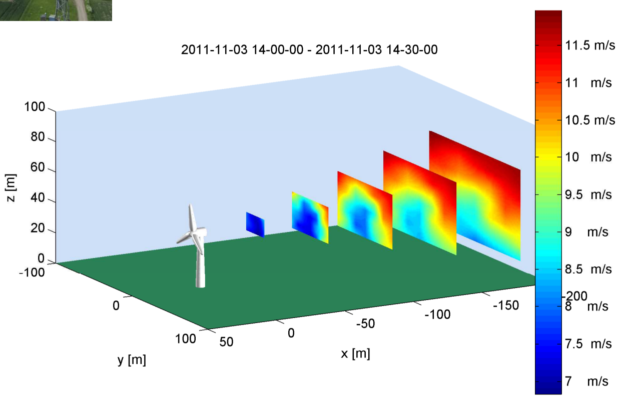
Wake Measurements with LIDAR at DTU-Risø Campus

- installed on the small Nordtank turbine
- measuring the wake at 1 to 5 rotor diameter



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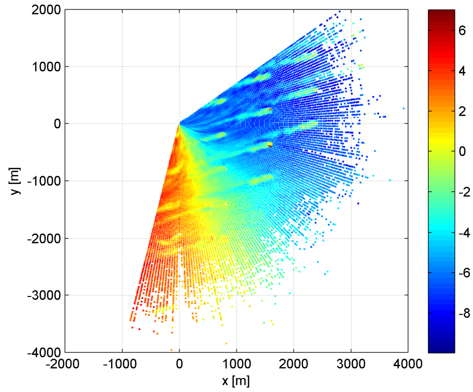
Wake Measurements with LIDAR at Baltic I

- Galion long range installed on transformer station
- ongoing measurement of the whole wind park



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Why should you control a wind turbine with lidar?

- wind is a disturbance
- knowing the disturbance, control can be improved
- used in daily life, e.g. bicycle
- for wind turbines several possibilities

SWE Simulation Study	Benefits	Potential	Complexity
Collective Pitch Feedforward	less loads	+ +	–
Direct Speed Control	more energy	o	– –
Nonlinear Model Predictive Control	more energy less loads	+ + + +	– – –
Lidar Assisted Yaw Control	more energy	+	–
Cyclic Pitch Feedforward	less loads	+	– –

Test the most promising!

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Lidar Assisted Collective Pitch Control

First Field Testing Results

[Schlipf et al. Torque 2012]

- cooperation with NREL
- proof of concept
- 2 campaigns
  - CART3: commercial lidar
  - CART2: SWE-Scanner
  - basically independent
  - modular controller
- started in March/April 2012
- direct control goal: reduction of rotor speed variation

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Controller Design

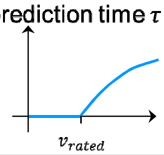
Feedforward Controller

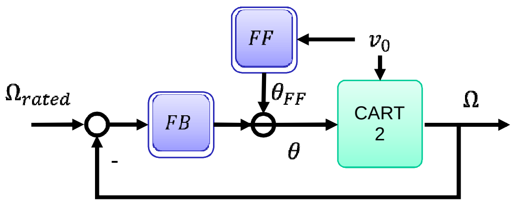
Control Goal

minimizing rotor speed variation

Feedforward Controller

- static pitch curve
- prediction time τ





Advantages

- simple update
- guaranteed stability
- 1 design parameter τ
- few model information

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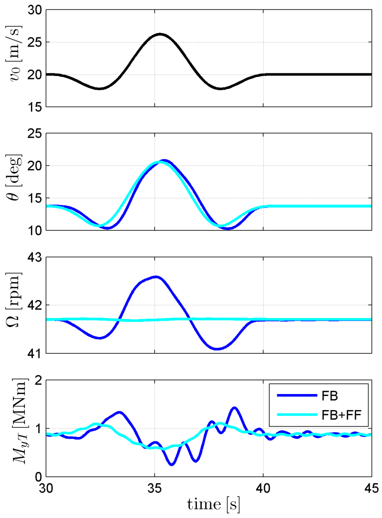
Controller Design

Simulated Extreme Loads



- FAST CART2
- perfect lidar measurement
  - only small preview necessary to compensate the pitch actuator
  - reduction overspeed from 2% to 0.02%
  - "side effect": less loads

But not realistic, because

- wind is much more complex disturbance
- wind cannot be measured perfectly

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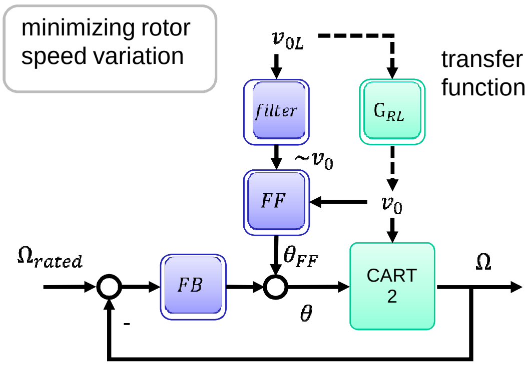
Controller Design

Feedforward Controller + Adaptive Filter

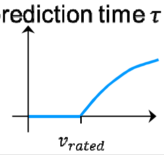
Control Goal

minimizing rotor speed variation



Feedforward Controller

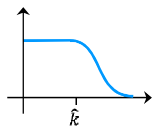
- static pitch curve
- prediction time τ



+

Adaptive Filter

- fitted $filter \approx G_{RL}$
- cutoff at maximum coherent wavenumber



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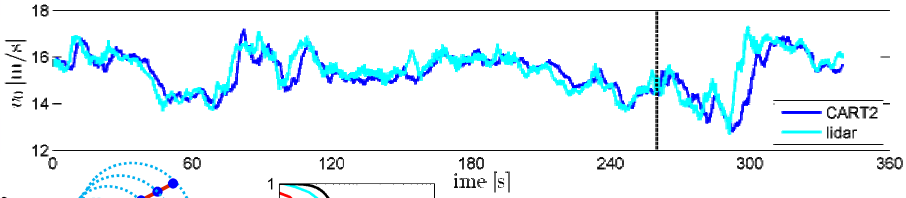
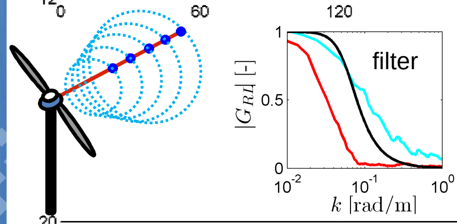
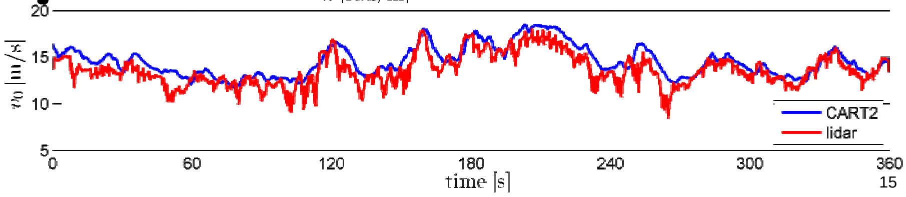
Lidar Assisted Collective Pitch Control

First Field Testing Results – CART2 Feedforward





- maximum coherent wavenumber mostly detected at $\hat{k}$ =0.06 rad/m
- but sometimes worse due to hard targets



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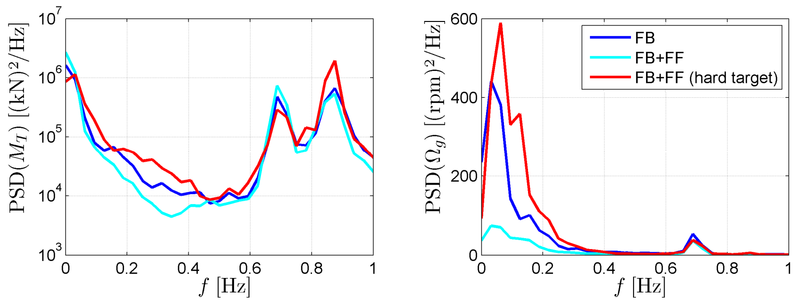
Lidar Assisted Collective Pitch Control

First Field Testing Results – CART2 Feedforward

data divided in blocks of 32 s



- similar wind distribution
- reduction in standard deviation of the generator speed of 30% at low frequencies
- but increase of 30% before solving the hard target problem
- similar behavior for the tower base bending moment and other loads
- in total only 15 min due to low wind conditions and technical problems

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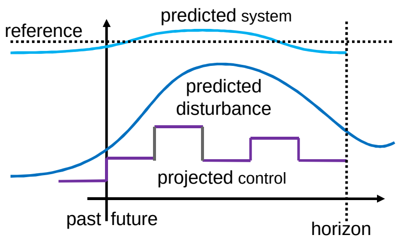
Model Predictive Control

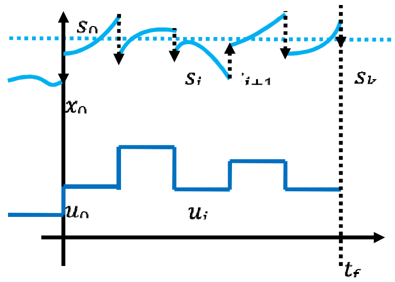
NMPC (Direct Multible Shooting)

[Schlipf et al. WE Journal 2012]



- Solves optimal control problem: Optimizes control inputs over a finite horizon
- Closed loop by iteration:
  - application of short control sequence
  - update of initial conditions
- Can handle multivariable control tasks
- Considers actuator and system constrains

- Can use nonlinear models, trade-off between performance and computational effort
- Can use predicted disturbances



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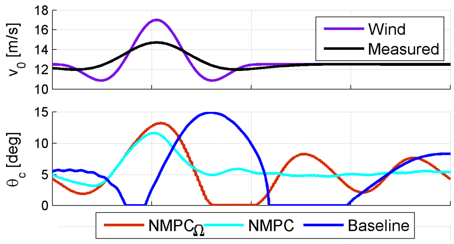
Model Predictive Control Results – Extreme Loads



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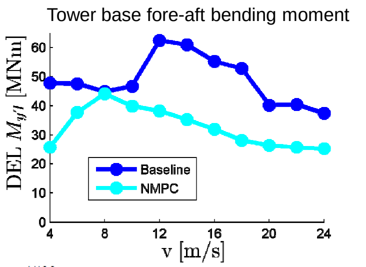
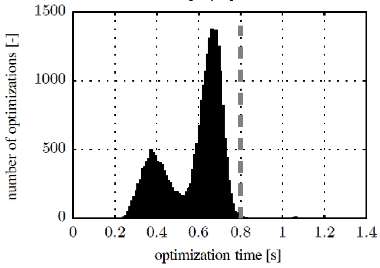
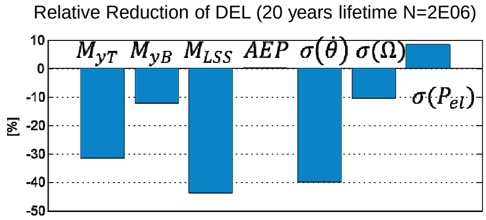
Model Predictive Control

Results – Fatigue Loads





- Overall high load reduction on tower (M_{yT}), blades (M_{yB}) and shaft (M_{LSS})
- standard deviation of pitch speed $\sigma(\dot{\theta})$ and rotor speed $\sigma(\Omega)$ reduced
- Small increase in AEP (+0.30%)
- Increase of power fluctuation $\sigma(P_{el})$
- Real time application seems to be feasible



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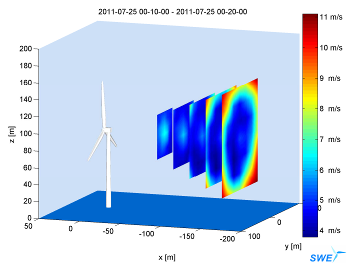
Conclusions

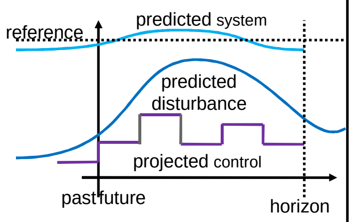
Lidar is a valuable tool to

- measure the near wake from the nacelle
- measure the flow and wakes in a wind farm
- improve the control of individual turbines



For wind farm control it can help to

- validate wake models
- monitor the improvement of control strategies
- give online information for a wind farm controller



Nonlinear Model Predictive Control could be used

- for a hierarchic controller for the wind farm
- with underlying NMPC for each individual turbine

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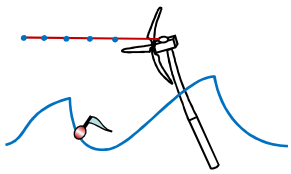
Outlook

- wake measurements with LIDAR
  - continue using data to evaluate wake models
  - measuring simultaneously the inflow and wake at alpha ventus

- LIDAR assisted control
  - controlling a 5MW turbine in alpha ventus
  - investigation for floating wind turbines
- LIDAR assisted wind farm control
  - set up a simple model and test NMPC



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Thanks for you attention!

Acknowledgement

Thanks to all persons from NREL, DTU and SWE involved in the campaigns.

Part of this research is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) in the framework of the German joint research project "**LIDAR II**" .

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RESEARCH AT ALPHA VENTUS
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Reactive Power Control of Wind Parks Connected to Weak Grids

IEA R&D Task 11 - Wind Farm Control Methods – 27./28.11.2012

Melanie Hau

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Reactive Power Control of Wind Parks Connected to Weak Grids

- Background
- Basic Controller Concept
- Challenges at Weak Grids
- Simulation Study
- Future Steps

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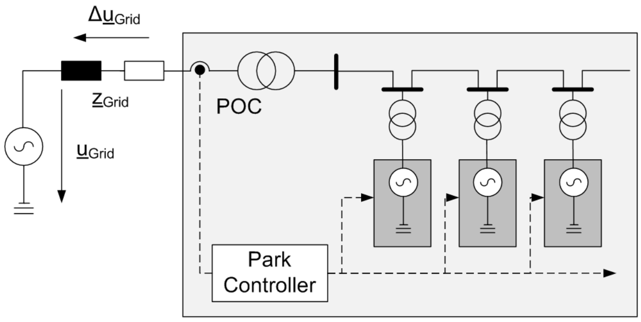
Background



Weak grids:

Low SCR -> large x
Often large r/x-ratio

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Background

Aim at Weak Grid Connections

- Keep POC voltage close to a given setpoint
- Respect voltage limits within wind park

- Voltage variations at POC due to
  - grid source voltage changes
  - fluctuating loads
  - fluctuating wind power

$$\Delta u_{POC} \approx \frac{r_{grid}}{u_{grid}} \cdot \Delta p_{POC} + \frac{x_{grid}}{u_{grid}} \cdot \Delta q_{POC}$$

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Background

Possible Grid Code Requirements

- Direct Setpoint for Q, U or cosρ
- Alternatively: Q feed-in according to Voltage or active power, e.g. Q(U), cosρ(P)
- Dynamics: 1 sek … 1 min

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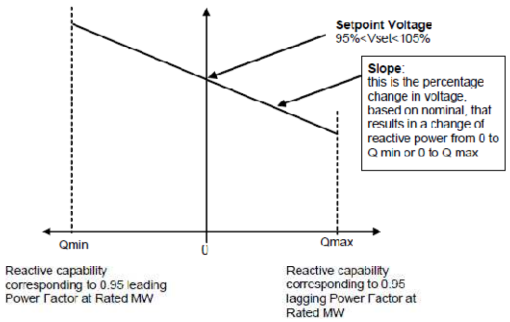
Basic Controller Concept

Example of Q(U) Control (UK Gridcode)



Advantage: Voltage is regulated

Disadvantage: Can cause oscillations when improperly designed NGET, The Grid Code, 2010

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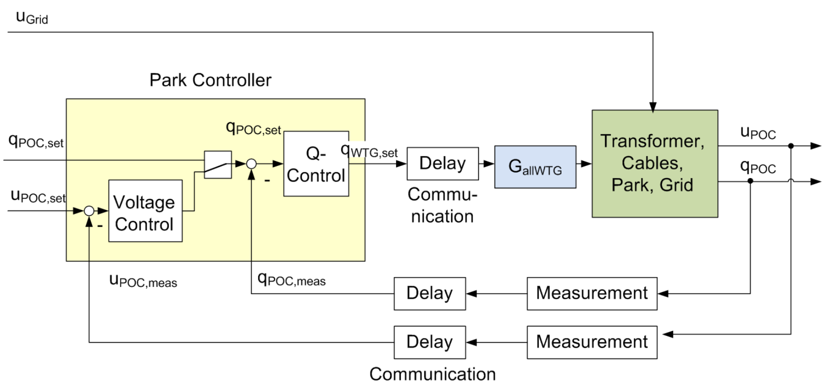
Basic Controller Concept



- Focus on Q(U) Control
- Nonlinear System

Basic Controller Concept

Controller Design:

- Consider couplings reactive power/voltage -> related to x_{grid}
- Linear controller design for full operating range of the park
  - Nonlinear behaviour covered by robust controller design. Includes:
    - Variation of gains with p, q
    - Variations of x_{grid} (up to which x_{grid} do we need smooth behaviour? Stability!)

  -> large deviations from linearity lead to conservative controller design

Fast & smooth response is possible if

- Small deviation from linearity (strong grid)
- Fast communication within the loop (small total delay)

Challenges at Weak Grids

- Large x_{grid} -> strong couplings q->u at POC
- large r/x -> high influence of p on reactive power and voltage
- Significant nonlinearities
  - Variation of x_{grid}
    - Which x_{grid} variations to be expected?
  - Model gain variation with operating point p, q

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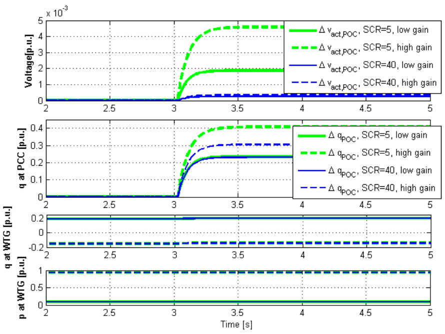
Challenges at Weak Grids

Nonlinearities of the gains due to p, q - operating points

- Open Loop Simulation:
  - Q-Step at WTG -> Reaction of POC Voltage and Reactive Power
  - For weak and strong grid



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Simulation Study

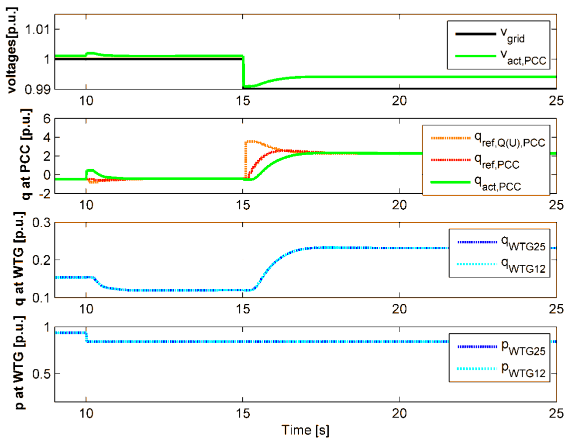
Q(U) – Controller for strong and weak grid

Example:

- Wind park 25 WTG
  - Strong grid: SCR = 40, r/x=0.1
  - Weak grid: SCR = 5, r/x=0.2
- Controller Design without considering variations of x_{grid}
- Operating Point: Full active Power
- Total Delay in Control Loop: 300 ms
- Steps in
  - p
  - u_{grid}

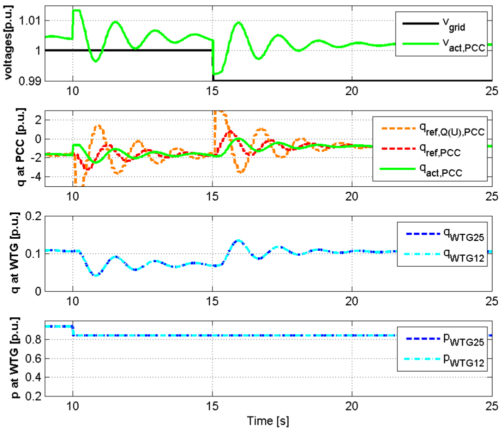
Simulation Study

Strong grid



Simulation Study

Weak grid, same controller parameters



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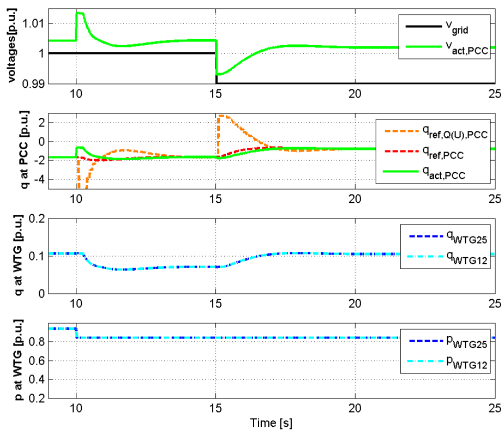
Simulation Study

Weak grid, adapted controller parameters



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Simulation Study

Turbulent Wind

- Weak grid, two Modes
  - Q(U)
  - Q
- Parameters as used before

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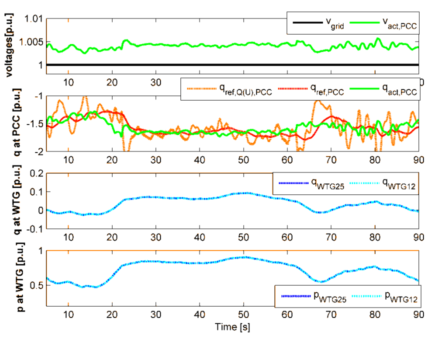
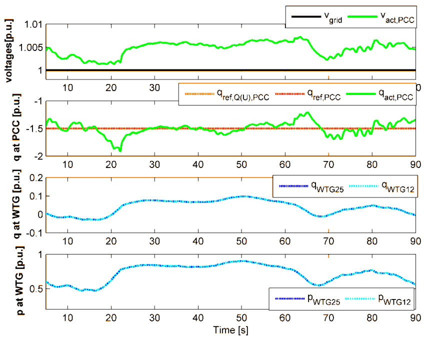
Simulation Study

Turbulent Wind



Q(U)- Mode



Q-Mode (Q-Setpoint = -1.5 p.u.)

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Conclusions and Outlook

- Q(U) Control is convenient for weak grid
- Controller works for weak grids after redesign
- With linear design approach: Nonlinearities lead to slow controller
  For dynamic behaviour -> nonlinear approach
- Test on HIL Platform

Open questions:

- Which dynamics are required for weak grid connections?
- Which variation of x_{grid} should be considered for
  - Smooth behaviour
  - Stable behaviour

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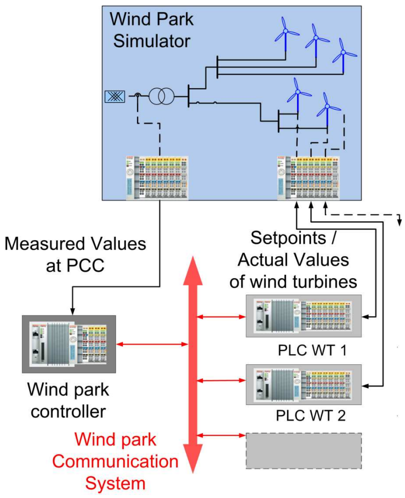
Realtime Test Bed for Park Controller and Communication

HIL-Simulator for wind field, wind park grid and WT

-> reproducable tests of controller software and hardware under realistic conditions

Test cases for controller software:

- Setpoint changes
- Changes in grid voltage (symmetrical / unsymmetrical)
- Frequency changes



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Thank You

for your attention

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Wind Farm Technologies

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Outlines

- **Wind Power Development in China**
- **Wind power prediction**
- **Unit commitment Optimization in wind farm**
- **CPFF method for modeling of the flow in wind farm**
- **Condition monitoring and health management**

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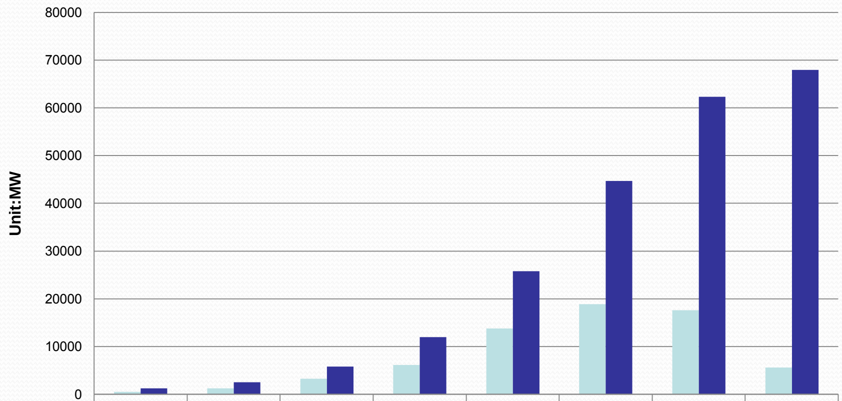
Wind Power Development in China



	2005	2006	2007	2008	2009	2010	2011	2012H1
新增装机	506. 9	1287. 6	3311. 3	6153. 7	13803. 2	18928. 0	17630. 9	5609. 3
累计装机	1249. 5	2537. 1	5848. 4	12002. 1	25805. 3	44733. 3	62364. 2	67973. 6

Source: CWEA

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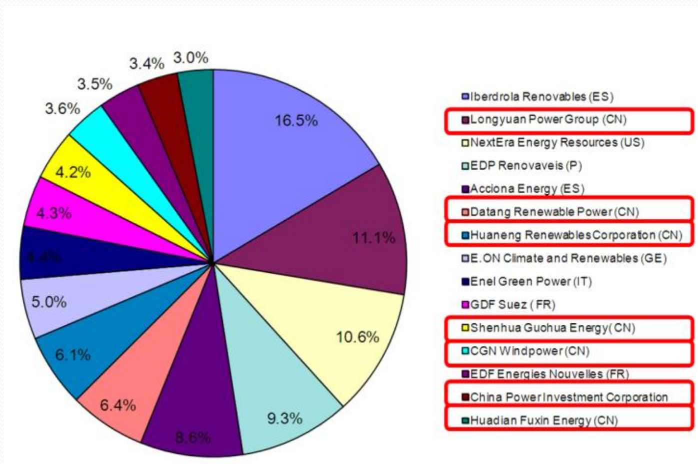
Top 15 Wind Power Developers in the world in 2011



Source: BTM Consult-A Part of Navigant-March 2012

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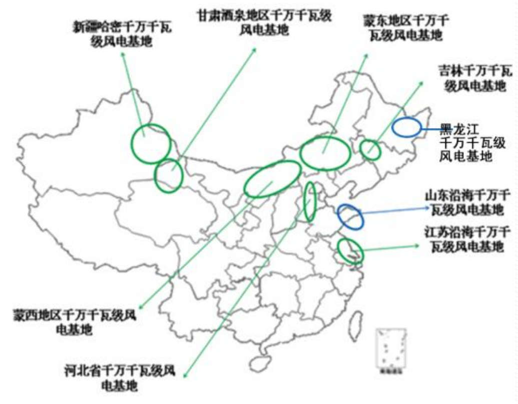
中国风电十二五规划：有序推进大型风电基地建设

河北基地	1000万千瓦
蒙东基地	700万千瓦
蒙西基地	1300万千瓦
吉林基地	600万千瓦
甘肃基地	1000万千瓦
新疆基地	1000万千瓦
江苏基地	600万千瓦
	（海上风电200万千瓦）
山东基地	800万千瓦
	（海上风电100万千瓦）
总计	7000万千瓦



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Features of Wind Power Industry in China

- **Largest wind power market in the world.**
  Accumulated capacity in China: 47.8GW in 2011, 100GW in 2015, 200GW in 2020
- **Large scale wind farms and wind power bases.**
  244 wind farms has the capacity over 100MW in China end of September 2012. Before 2020 China will have 7 large wind power bases with average capacity of 10 GW
- **Long distance transmission of wind power.**

Source：CWEA

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Challenges of wind farm technologies in China

- **Dynamic properties of large wind farms:** Modeling the coupling relations of metrological, fluid, electrical factors.
- **Coping with variability:** Wind power prediction, energy storage, demand response.
- **Grid friendly wind farms:** actively participating the power system operations, including power regulation based on wind power prediction, maintain system stability and electric energy quality, etc.
- **Optimal operation and maintenance:** unit commitment optimization, condition monitoring and health management, etc.

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Wind power forecasting

- Ultra short term wind power forecasting (0-4hours)
  - Based on historical data and NWP (Numerical Weather Prediction) data
    - Auto Regressive Integration Moving Average （ARIMA） model
    - Artificial Neural Network （BP、RBF） model
    - Piecewise Support Vector Machine （PSVM） model
    - Genetic Algorithm and Piecewise Support Vector Machine （GA-PSVM） model
    - Wavelet and Support Vector Machine model
    - Hilbert-Huang Transform and Artificial Neural Network （HHT-ANN） model

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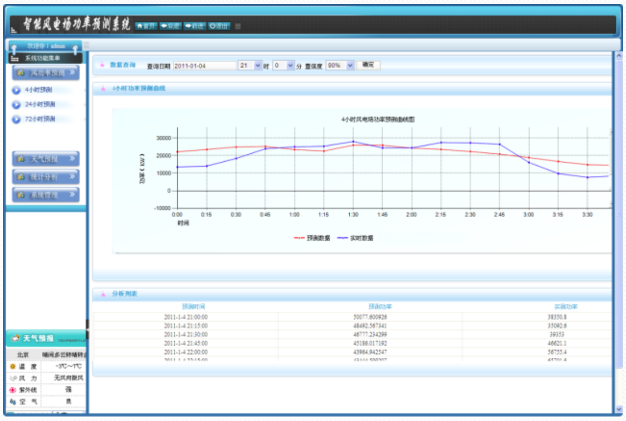
Wind power forecasting

- **Ultra short term wind power forecasting （0-4hours）**



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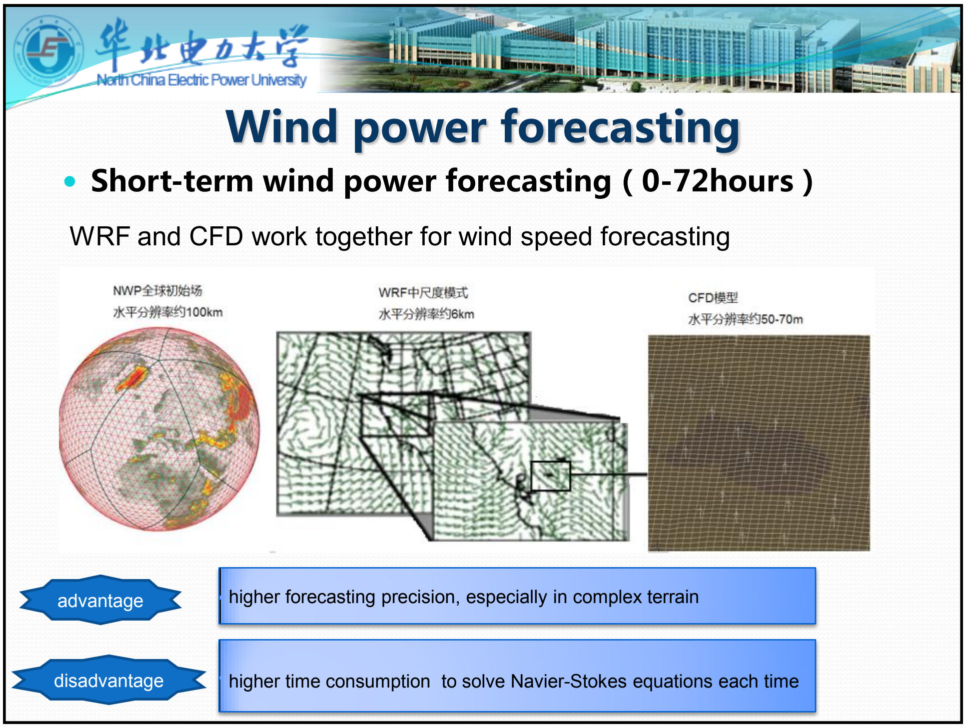
Wind power forecasting

- **Short-term wind power forecasting（0-72hours）**

Short-term wind power forecasting
- Statistical model
  - BP ANN model based on GA（GA-BP）
  - Relevance Vector Machine model (RVM)
- Physical model → CFD based model
- Statistical model + Physical model → Hybrid model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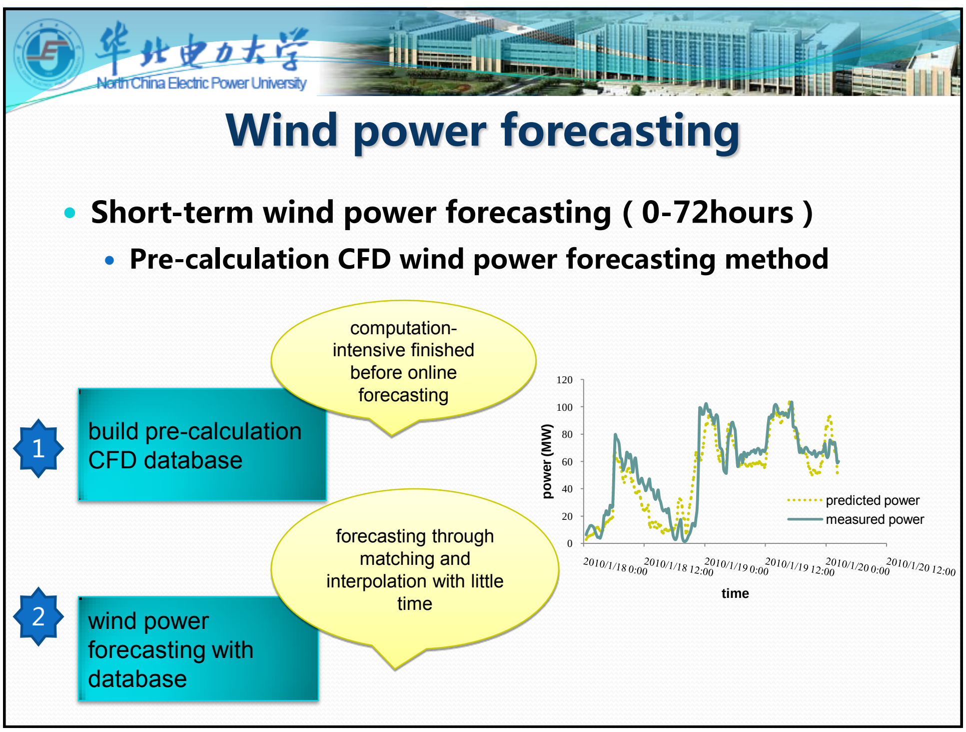
Wind power forecasting
Short-term wind power forecasting (0-72hours)
WRF and CFD work together for wind speed forecasting
NWP全球初始场
水平分辨率约100km
WRF中尺度模式
水平分辨率约6km
CFD模型
水平分辨率约50-70m
advantage
higher forecasting precision, especially in complex terrain
disadvantage
higher time consumption to solve Navier-Stokes equations each time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Wind power forecasting
Short-term wind power forecasting (0-72hours)
Pre-calculation CFD wind power forecasting method
computation-intensive finished before online forecasting
1
build pre-calculation CFD database
forecasting through matching and interpolation with little time
2
wind power forecasting with database
power (MW)
120
100
80
60
40
20
0
2010/1/18 0:00
2010/1/18 12:00
2010/1/19 0:00
2010/1/19 12:00
2010/1/20 0:00
2010/1/20 12:00
time
predicted power
measured power

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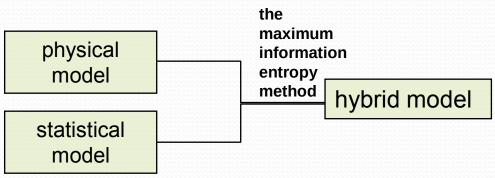
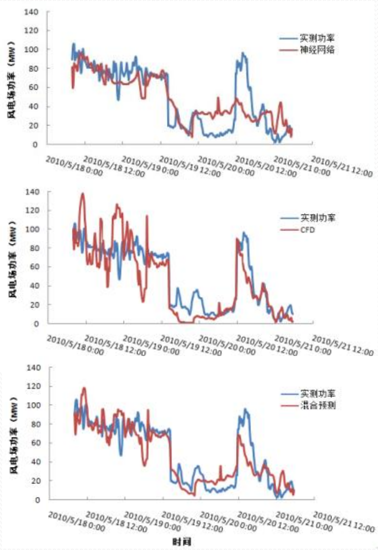
Wind power forecasting

- Short-term wind power forecasting





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Wind power forecasting

- Uncertainty analysis for wind power forecasting
  - wind power forecasting uncertainty model with Quantile-Regression method
  - wind power forecasting uncertainty model with conditional probability method
  - wind power forecasting uncertainty model based on forecasting error distribution

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Wind power forecasting

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Wind power forecasting

- **System development-**Funded by ‘863’ Program from Ministry of Science and Technology of China

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Wind power forecasting

- **Publications**

1. Yongqian Liu, Jie Shi, Yongping Yang, Shuang Han. Piecewise support vector machine model for short term wind power prediction. International Journal of Green Energy, 2009, 6(5): 479-489. (SCI)
2. Yang Zhiling, Liu Yongqian, Li Chengrong. Interpolation of missing wind data based on ANFIS, Renewable Energy, v 36, n 3, p 993-998, March 2011. (SCI)
3. Jie Shi, Wei-Jen Lee, Yongqian Liu, Yongping Yang. Forecasting Power Output for Photovoltaic System Based on Weather Classification and Support Vector Machine. 2012, IEEE Transactions on Industry Application, 48(3): 1064-1069. (SCI)
4. Han Shuang, Liu Yongqian, Yang Yongping. Ultra-Short Term Wind Power Prediction and Uncertainty Assessment. Acta Energiae Solaris Sinica, 2011, 32 (8): 1251-1256. (EI)
5. Jie Shi, Yongqian Liu, Yongping Yang, Wei-Jen Lee, "Short-term Wind Power Prediction Based on Wavelet Transform-Support Vector Machine and Statistic Characteristics Analysis", 2011 IEEE Industrial & Commercial Power Systems (I&CPS) Technical Conference, Newport Beach, CA, U.S.A., May 1-5, 2011. (EI)
6. Liu Yongqian, Wang Fei, Shi Wengang, Zhuo Yue. Operation condition classification method for wind turbine based on support vector machine. Acta Energiae Solaris Sinica, v 31, n 9, p 1191-1197, September 2010. (EI)

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Wind power forecasting

- **Publications**

7. Jie Shi, Wei-Jen Lee, Yongqian Liu, Yongping Yang, Peng Wang, "Short Term Wind Power Forecasting Using Hilbert-Huang Transform and Artificial Neural Network", The Fourth International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, Weihai, China, July 6-9, 2011. (EI)
8. Liu Yongqian, Tian Zichan, Li Fenhua, Xing Jian. The research on the wind energy distribution over complex terrain of wind power plant. Advanced Materials Research, v 143-144, p 1186-1189, 2011. (EI)
9. Shuang Han, Yongqian Liu, Jie Yan. Neural Network Ensemble Method Study for Wind Power Prediction. Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific, Wuhan, 25-28 March 2011, 1-4. (EI)
10. Shuang Han, Yongqian Liu. The Study of Wind Power Combination Prediction. Asia-Pacific Power and Energy Engineering Conference (APPEEC2010) Chengdu,China.March 28-31,2010. (EI)
11. Shi Jie,Liu Yongqian,Yang Yongping,Han Shuang, Wang Peng.The research and application of wavelet-support vector machine on short-term wind power prediction, Proceedings of the World Congress on Intelligent Control and Automation (WCICA), p 4927-4931, 2010. (EI)

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Wind power forecasting

- **Publications**

12. Shi Jie, Yang Yongping, Wang Peng, Liu Yongqian, Han Shuang. Genetic algorithm-piecewise support vector machine model for short term wind power prediction .Proceedings of the World Congress on Intelligent Control and Automation (WCICA), p 2254-2258, 2010. (EI)
13. Han Shuang, Liu Yong-qian, Yang Yong-ping, Wang Yu-yong. Wind-Hydrogen Hybrid Energy System[J]. Electric Power Construction, 2009, 30(4): 15-18.
14. Han Shuang, Yang Yongping, Liu Yongqian. Application study of three methods in wind speed prediction. Journal of North China Electric Power University, 2008, 35(3): 57-61.
15. Jie Shi, Yongqian Liu, Yongping Yang, Shuang Han, Wei-Jen Lee, "Multistage Model For Short Term Wind Power Forecasting", ASME Power 2011, Denver, CO, U. S. A., July 12-14, 2011.
16. Yang Zhiling, Liu Yongqian, Lichengrong, Dong Xinghui. Wind power prediction algorithm. High Performance Computing Technology, 2011, (1): 43-48.

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Unit commitment optimization in wind farm

Objectives

- **To reduce the fatigue damage of the wind turbine and lower the cost of maintenance.**
- **Maximize the wind energy production.**

Means

- **Optimal dispatching the load in the wind farm.**
- **Optimizing the start and shutdown plans of the wind turbines in the wind farms.**

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Unit commitment optimization in wind farm

Main difficulty: quantitative relations between operation conditions and the fatigue damages.

The damage value of wind turbine blades under different conditions for a 1.5MW turbine through load calculation:

operation conditions	Power (kW)	Damage value
Idling	0	1 /(1.3*10^8)/min
power production	0-1400	12/(1.3*10^8)/ min
	1400-1500	17/(9 *10^7)/ min
	>1500	17/(5.4*10^7)/ min
start-up	<=1500	12/(1.3*10^8)/start
	>1500	4/(1.3*10^8)/start
normal stop	0	2.5/(1.3*10^8)/stop

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Unit commitment optimization in wind farm

Objective function: minimize the life lost of the blades

$$\min F = \sum_{j=1}^{T}\sum_{i=1}^{N}(a_i^j u_i^j \Delta t) + \sum_{j=1}^{T}\sum_{i=1}^{N} b_i^j u_i^j (1 - u_i^{j-1}) + \sum_{j=1}^{T}\sum_{i=1}^{N} c_i^j u_i^{j-1}(1 - u_i^j) + \sum_{j=1}^{T}\sum_{i=1}^{N}(d_i^j u_i^{j-1}(1 - u_i^j)\Delta t)$$

F: total life lost of the blades,
T: total time period
N: number of the turbines
a, b, c, d: life lost under different operation conditions
u : operation conditions of the turbine
t: time
i: turbine No.
j: time interval No.

Unit commitment optimization in wind farm

Constraints:

1.Power output range

$$P_{i,\min} \le P_{i,j} \le P_{i,\max}$$

2.Power limit from the grid

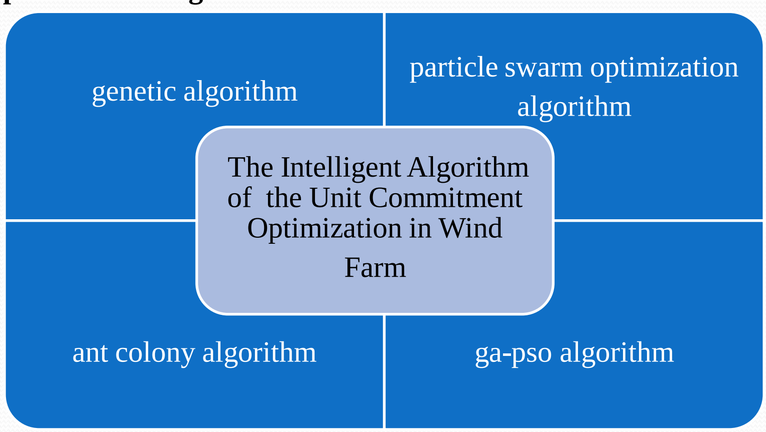
$$\sum_{i=1}^{N} u_{i,j} P_{i,j} \le P_{Dj}$$

3.Wind power prediction constraint

$$P_{ij}^{\min} \le P_{yuce}^{i} \le P_{ij}^{\max}$$

Unit commitment optimization in wind farm

Optimization Algorithm



Unit commitment optimization in wind farm

Case 1

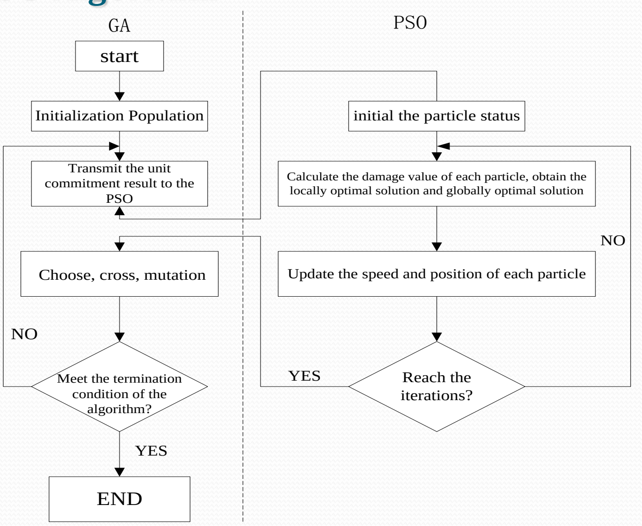
- **Wind farm : 33 wind turbines, Rated power 1.5MW.**
- **4 operation conditions: stop, generated output :**
  p<1400kW, 1400kW<=p<=1500kW, p>1500kW.
- **Power limits in the next 4 time intervals:**
  p[1]=20000kW; p[2]=18000kW; p[3] =18000kW; p[4]=22000kW.

The wind power prediction

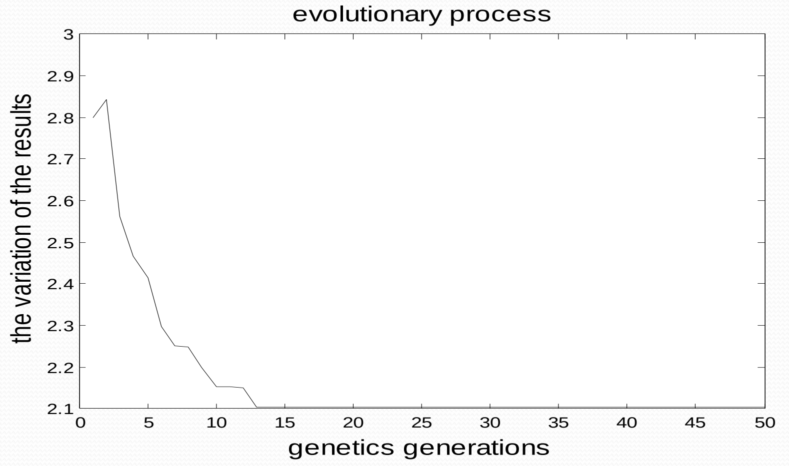
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	833.8	1009.2	203.5	625.3	600.2	951.2	737.3	889.5	928.1	674.5	850.0	920.3	731.7	1003.9	809.7	1130.6	1122.4
2	1525.2	1522.0	218.9	1519.6	1301.8	1505.0	1487.1	1268.7	1140.9	1317.9	954.7	1426.3	1299.4	1191.2	1237.5	661.6	596.0
3	1507.5	1438.5	331.8	1511.7	1512.2	1507.9	1438.7	1522.2	1546.9	1370.9	1379.2	1527.9	1501.5	1504.4	1530.7	930.0	1364.9
4	1020.2	942.5	254.3	1339.1	1310.1	1410.2	1129.0	1505.3	1515.6	1397.9	1502.6	1445.7	1458.4	1449.8	1494.3	1489.4	1495.1

Time	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	1065.1	1177.9	1106.4	1249.6	1188.1	1309.0	1004.1	1327.6	1500.6	1513.6	1353.0	1318.4	1500.8	1539.1	1523.0	1495.1
2	727.9	659.6	517.1	894.2	604.4	749.2	713.0	972.2	1184.3	1190.2	891.1	883.4	1311.0	1352.2	1237.8	1162.8
3	1266.4	1275.9	1164.4	1457.3	1388.8	1409.1	1384.0	804.2	712.2	606.8	653.7	483.9	689.4	644.1	734.9	555.9
4	1502.1	1536.6	1524.3	1528.6	1525.9	1536.9	1513.6	1355.0	1403.7	1357.2	1250.2	955.2	1225.2	1224.6	1261.9	930.1

GA-PSO Algorithm



Convergence of the GA-PSO hybrid algorithm



As we can see from the convergence graph, GA-PSO Algorithm is equipped with good convergence and optimization ability.

The optimal unit commitment

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0	0	0	1	1	1	1	0	1	1	0	1	1	0	1	0	1
2	1	1	0	0	0	0	0	0	1	1	0	1	0	0	1	0	0
3	1	1	0	1	1	0	0	0	0	1	0	0	1	1	0	0	0
4	1	1	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0

Time	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	1
2	0	0	1	0	0	0	0	0	0	1	1	0	0	1	0	0
3	0	1	0	0	0	0	0	0	1	0	0	0	1	0	1	0
4	1	0	1	0	0	0	0	0	1	1	1	0	0	0	0	1

Conclusion from the test case

As shown in the table above, the optimization apparently decreased times of start/stop, and maximized the wind farm power output under the power limit from the gird.

- **Start from period 1, 19 wind turbines are shut down due to the power limit .**
- **In the 2nd period, the load is decreased by 2000kW, and 23 wind turbines are shut down.**
- **In the 3rd period, the load limit remains the same while predicted power changes, and 22 turbines are shut down.**
- **In the last period the load limit is increased by 4000KW,and 21 turbines are shut down.**
- **During the whole time scale, 7 turbines are kept in the shutdown condition.**

Wind farm flow field modeling method: CPFF (CFD Pre-calculated Flow Fields)

Basic idea:

➢On the assumption that the inflow wind is steady, theoretically, the wind speed distribution is determined by the inflow wind condition as well as the local topography and roughness, and the wind power is determined by the wind speed distribution. Namely, a specific inflow wind condition results in the unique local wind and the unique wind power.

➢ For each of all the inflow wind conditions, the steady wind distribution could be obtained by the CFD model simulation and then the wind power could be gained by the power curve.

➢If the flow fields and wind power were pre-calculated for all the inflow wind conditions, while prediction, the wind power should be obtained by referring to the pre-calculated wind power data instead of by CFD simulating again.

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A physical approach of wind power prediction is established which is based on CFD Pre-calculated Flow Fields (CPFF)

The prediction approach is divided into two parts:

➢**Part Ⅰ:** to simulate the flow fields under all the discrete inflow conditions and establish the pre-calculated flow field and wind power database

➢**Part Ⅱ:** to do power prediction according to the pre-calculated database by coupling the NWP input data to the reference mast

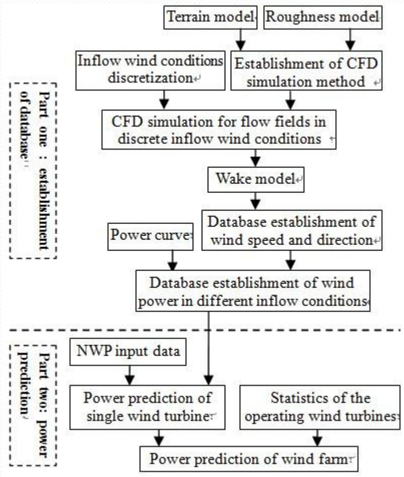

Fig.3 Structure diagram of wind power prediction

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A physical approach of wind power prediction based on CFD Pre-calculated Flow Fields (CPFF)

Part Ⅰ (1): Discretization of inflow wind conditions

➢The two parameters of wind speed and wind directions were chosen to discretize the inflow wind conditions.

➢In order that the speed at wind turbines' hub height from the cut-in speed 4m/s to the rated speed 13m/s could be covered at least, the discrete inflow speeds are set every other 1m/s from 3m/s to 20m/s.

➢The discrete inflow wind directions are divided into 16 sectors evenly, by setting a direction every other 22.5° from 0° to 337.5°.

➢The combination of each wind speed and each wind direction makes up a discrete inflow wind condition, and it sums up to 288 discrete inflow wind conditions.

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A physical approach of wind power prediction based on CFD Pre-calculated Flow Fields (CPFF)

Part Ⅰ (2): CFD pre-calculation for all the discrete inflow wind conditions

➢**Boundary conditions**:

Inlet: velocity boundary, set to be the wind speed profiles

$$u_n = u_1 \left(\frac{Z_n}{Z_1} \right)^{\alpha}$$

Outlet: pressure boundary

Ground: wall, non-friction boundary condition

➢**Turbulence model:** the standard *K*-*ε* equation model

➢**Pressure-velocity coupling:** SIMPLE algorithm

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A physical approach of wind power prediction based on CFD Pre-calculated Flow Fields (CPFF)

Part Ⅰ (2): CFD pre-calculation for all the discrete inflow wind conditions

➢**Judgment of convergence:** by monitoring both the residuals and the variable values at a specific spot. The iteration can be regarded convergence when the variable values are almost constant and the residuals are adequately small.

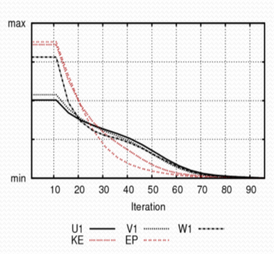


Fig.4 the curve of residuals with iteration

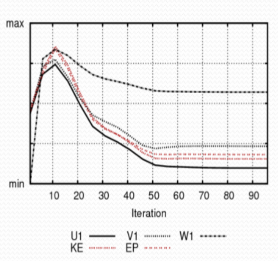
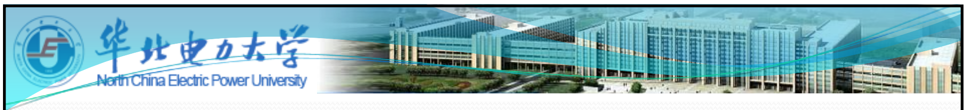


Fig.5 the changing curve of variable values with iteration

A physical approach of wind power prediction based on CFD Pre-calculated Flow Fields (CPFF)

Part Ⅰ (3): Establishment of CPFF and wind power database

- To extract the wind speed and direction at all the hubs from each of the 288 wind fields
- Speed correction of Wake effect: Larsen wake model
- To pre-calculate the wind power of each wind turbine according to the corrected speed and the power curve
- To establish the pre-calculated database, including the parameters of inflow wind condition, air properties, wind speed at each wind turbine's hub, wind power of each wind turbine and so on.



A physical approach of wind power prediction based on CFD Pre-calculated Flow Fields (CPFF)

Part Ⅱ (1): The NWP input data

- Origin : the GFS（Global Forecasting System） 1° ×1° pattern forecasting field released by NCEP at 6 o'clock every day
- The WRF model is adopted to downscale the initial field to the horizontal resolution of 6km×6km
- To meet the requirement of short-term wind power forecasting in China, the time-serial result from 24 o'clock today to24 o'clock next day is extracted as NWP input data for power prediction.
- According to the demand for wind power prediction, the time resolution is 15 minutes.

A physical approach of wind power prediction based on CFD Pre-calculated Flow Fields (CPFF)

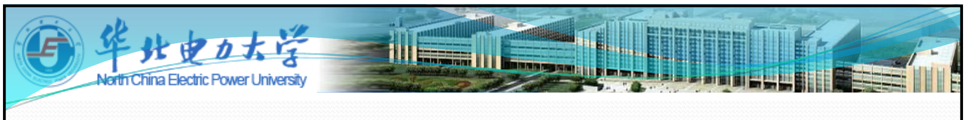
Part Ⅱ(2): to predict the wind power

- By coupling the time-series NWP wind speed and direction to the position of reference mast, the four adjacent inflow wind conditions were queried and the corresponding wind power of each wind turbine were read in the database.
- The wind power of every wind turbine could be predicted by invoking and linear interpolating of the queried wind powers.

$$P_k(V, d) = \frac{V - V_i}{V_{i+1} - V_i}(P_{i+1} - P_i) + P_i$$

$$P_i = \frac{d - d_j}{d_{j+1} - d_j}(P_{i,\ j+1} - P_{i,\ j}) + P_{i,\ j}$$

$$P_{i+1} = \frac{d - d_j}{d_{j+1} - d_j}(P_{i+1,\ j+1} - P_{i+1,\ j}) + P_{i+1,\ j}$$



A physical approach of wind power prediction based on CFD Pre-calculated Flow Fields (CPFF)

Part Ⅱ(2): to predict the wind power

- In China, because of the maintenance of wind turbines or the scheduling measures of restricting the wind farms' generating power capacity by the Grid Company, the amount of the operating wind turbines in a wind farm often changes with time. This is the problem of the wind turbine availability.
- After judging that which wind turbines are on operation, the wind power of the whole wind farm can be predicted by adding the power of all the operating turbines:

$$Y_i^{'} = \sum_{j=1}^{m} P_{i,j}$$

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Example wind farm

- The prediction approach will be verified by taking a wind farm located in the north China as example.
- The wind farm covers an area of about 45 square kilometers, which has some villages and farmland among the wind turbines.
- The installed capacity is 183MW. It consists of 122 GE 1.5 serial 1.5MW wind turbines whose hub height is 67meters.

Fig.6 Layout of the wind turbines

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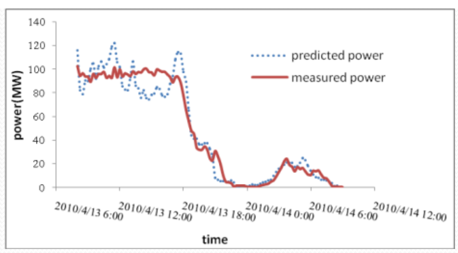
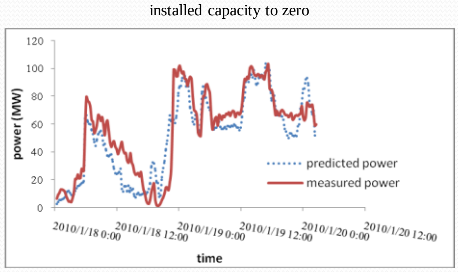
Results: time-series power

- It has a good performance on the prediction of wind power's changing trend.
- It is difficult to predict the slightly power fluctuating with time.
- Generally speaking, the forecasting power is slightly less than the measured power.



（a）Prediction result when power output decreases from installed capacity to zero



（b）Prediction result when power output changes drastically

Fig.7 Comparison of predicted and measured power

•table 1 the statistics of monthly error

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Results: Error statistics

- The RMSE of all months are less than 20%, which meet the requirements of engineering application in China

Table 1 the statistics of monthly error

time	RMSE (%)	MAE (%)	time	RMSE (%)	MAE (%)
Jan	14.73	10.82	Jul	8.97	5.79
Feb	16.97	12.44	Aug	11.96	7.95
Mar	16.66	12.29	Sep	15.94	9.67
Apr	18.69	14.19	Oct	13.80	9.42
May	16.88	12.36	Nov	15.68	11.99
Jun	10.30	6.75	Dec	18.34	14.46

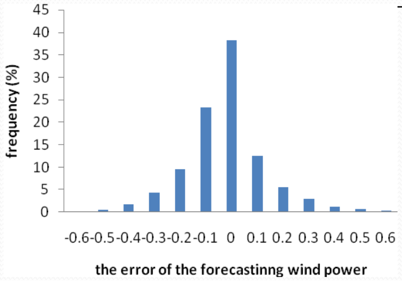

Fig .8 Frequency distribution histogram of forecasting wind power error

- The diagram shows a normal distribution ;
- The predicted power with the absolute error of almost zero has the highest appearing probability;
- The larger the absolute error of predicted power, the smaller its appearing probability.

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Advantages and disadvantages of the CPFF wind power prediction approach

- **Advantages:**

1. It is short time consuming because the complicated CFD calculations is in part Ⅰ and it has been completed before power prediction;

2. It has higher precision than physical approach based on analytic method;

3. It predicts the power of wind farms by adding every single operating wind turbine's power together, easily solving the problem of wind turbine availability .

- **Disadvantages:**

1. The physical terrain and roughness model of wind farm is required to be accurate;

2. The precision of the predicted power is sensitive to the accuracy of NWP input data.

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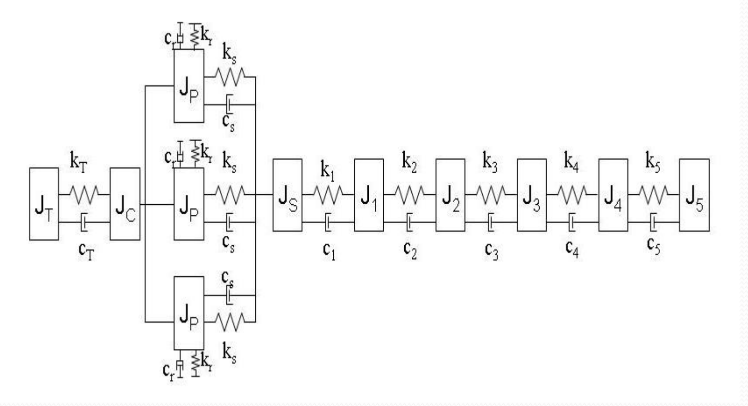
Modeling of wind turbine gear drive system



The equivalent dynamic model of the wind turbine gear drive system

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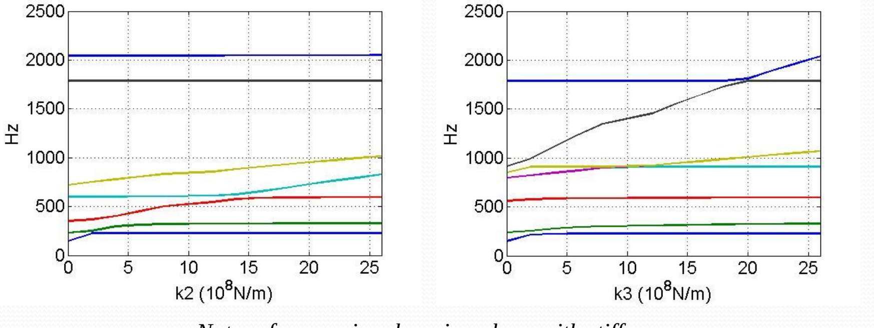
Modeling of wind turbine gear drive system

Natural characteristic and sensitivity analysis

- Set up differential equations of torsional vibration
- Calculate natural characteristic
- Sensitivity analysis of system



Nature frequencies changing along with stiffness

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Modeling of wind turbine gear drive system

Vibration response analysis

- ➢ Parameters calculation
- • Meshing Stiffness
- • Damp Coefficient
- • Error Excitation

- ➢ Numerical simulation of vibration system

  Numerical simulation of the vibration system in time domain can be carried out by the method of the 4-steps Runge-Kutta.

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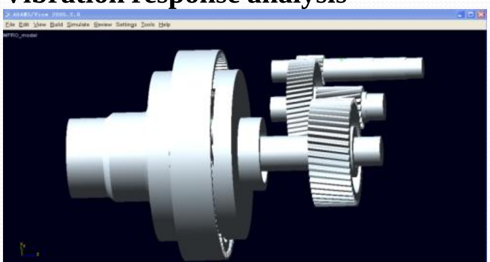
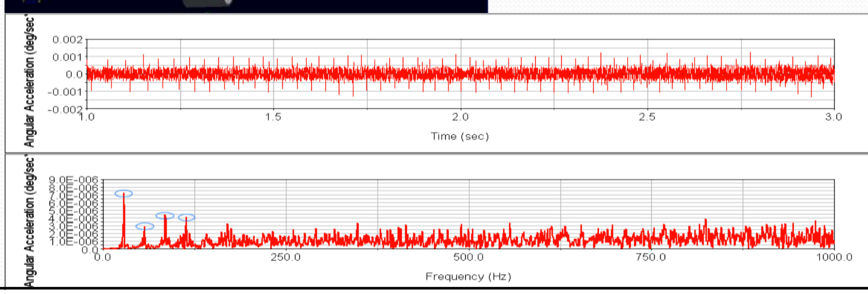
Modeling of wind turbine gear drive system

Vibration response analysis



Dynamic simulation of gear drive system can be made based on virtual prototyping technology and frequency response is also analyzed.



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Modeling of wind turbine gear drive system

Publications

1. Long Quan, Liu Yongqian, Yang Yongping. Applications of Condition Monitoring and Fault Diagnosis to Wind Turbines. Modern Electric Power, 2008, 25(6): 55-59.
2. Liu Yongqian, Long Quan, Yang Yongping. Sensitivity analysis of natural frequency for gear driven system of wind turbine. 2010 International Conference on Computer, CMCE 2010, v 2, p 559-562, 2010. (EI)
3. Yongqian Liu , Quan Long,Yongping Yang. Dynamic analysis of multistage gear driven system of wind turbine .Applied Mechanics and Materials, v 29-32, p 1706-1710, 2010. (EI)

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Modeling of wind turbine gear drive system

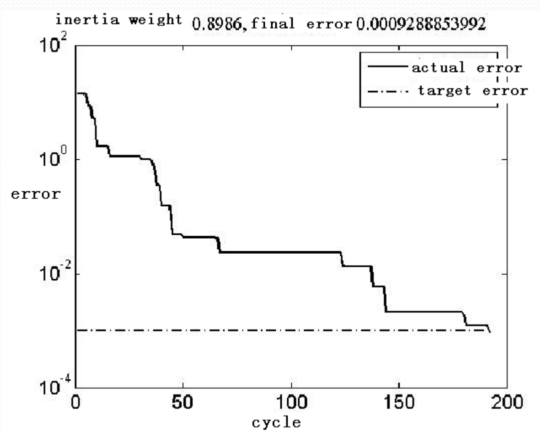
Publications

4. Long Quan , Liu Yongqian, Yang Yongping. Vibration response analysis of gear driven system of wind turbine. 2010 IEEE International Conference on Intelligent Computing and Intelligent Systems (ICIS 2010), p 380-3, 2010. (EI)
5. Liu Yongqian, Long Quan, Yang Yongping. Modal Analysis of High-Speed Helical Gear of Wind Turbine Driven System, Proceedings of 2009 International Conference on Information, Electronic and Computer Science, Vols I and II . Pages: 351-354, Qingdao, China.

Fault diagnosis of wind turbine gear drive system

- A method based on BP neural networks trained by particle swarm optimization (PSO) algorithm was proposed for fault diagnosis of wind turbine gearbox.
- Power spectral entropy, wavelet entropy, kurtosis, skewness, correlation dimension and box dimension were extracted as fault feature for gearbox of wind turbine considering uncertainty, non-stationarity and complexity of vibration signal.

Fault diagnosis of wind turbine gear drive system



Error change curve of particle swarm optimization

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Fault diagnosis of wind turbine gear drive system

	Power spectral entropy	wavelet entropy	kurtosis	skewness
normal	1.0021	0.3611	-0.3884	1.5167
	correlation dimension	box dimension		
	2.5897	1.4603		
Wear	0.7932	0.2696	-0.7131	1.4332
	2.6263	1.4906		
Tooth breaking	2.4346	1.3853	2.4629	2.014
	2.6906	1.5201		

Test samples of fault eigenvalue of wind turbine gearbox

NO.	Y1	Y2	Y3	State
1	0.0000	0.0236	0.0001	Normal
2	0.0123	0.9579	0.0000	Wear
3	0.0000	0.0000	1.0000	Tooth breaking

Results of states recognition

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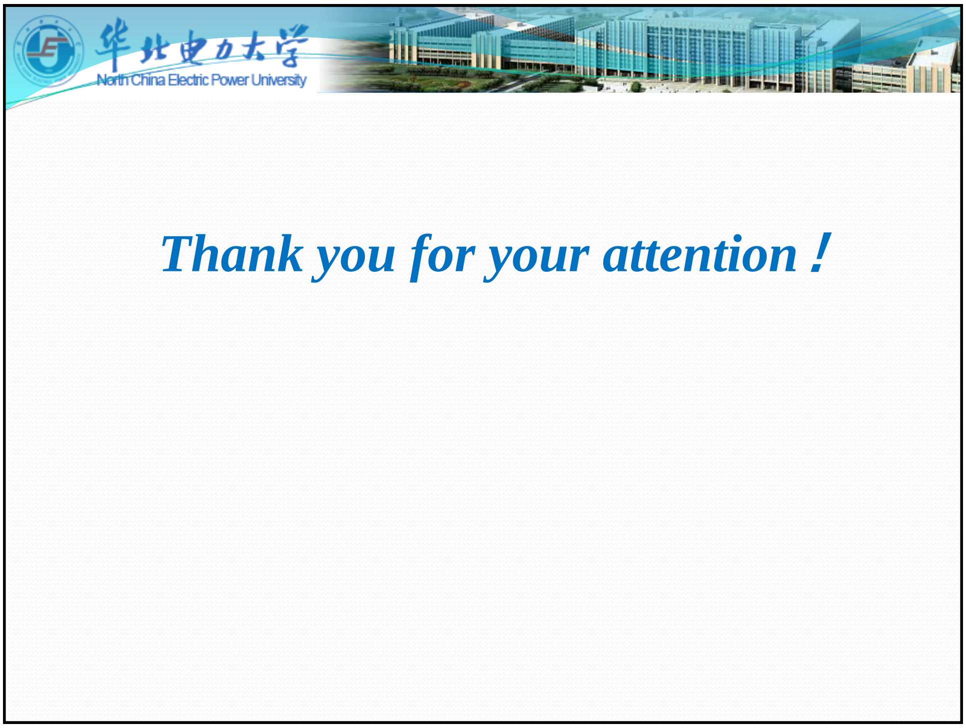
Fault diagnosis of wind turbine gear drive system

Publications

1. Long Quan, Liu Yongqian, Yang Yongping. Fault diagnosis method of wind turbine gearbox based on neural network trained by particle swarm optimization algorithm. Acta Energiae Solaris Sinica, 33 (1): 120-125. (EI)
2. Qiang Xu, Yongqian Liu, De Tian, D.G. Infield. Towards more reliable wind turbines: models for gear condition monitoring. International Conference on Sustainable Power Generation and Supply (SUPERGEN), 2012. (EI)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Thank you for your attention !