ANNEX XXI SEMINAR PRESENTATIONS
NREL, CO, USA, 11 NOVEMBER 2003

Dynamic models of wind farms for power system studies
Operating Agent: J O Tande, SINTEF Energy Research

Contents

- Scope of works for IEA Annex 21; John Olav Tande, SINTEF (NO)
- NREL's wind farm power monitoring; Yih-huei Wan, NREL (USA)
- Wind farm models and measurements; Ola Carlsson, Chalmers (SE)
- Wind farm modeling using PSCAD, Simulink and ADAMS; B Lemstrom, VTT (FI)
- NREL's wind farm model development; Ed Muljadi, NREL (USA)
- Transient events in large wind power installations; Poul Sørensen, Risø (DK)
- Dynamic wind farm models; Edwin Wiggelinkhuizen; ECN (NL)
- ERCOT's wind turbine model project; Bob Zavadil, Electrotek (USA)
- GE Wind Energy Technology and Dynamic Modeling; William W. Price (USA)
- Wind farm models for power system analysis; John Tande, SINTEF (NO)

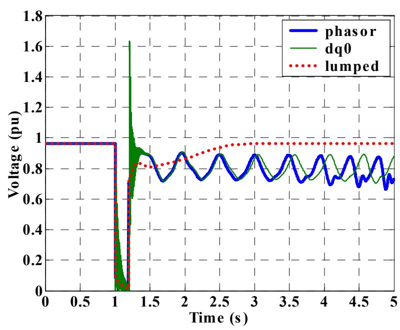
IEA R&D Wind Annex XXI
Dynamic models of wind farms for power system studies

John Olav Tande (SINTEF Energy Research)

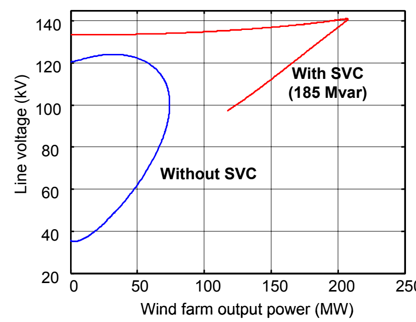
Motivation

- Large wind farms +100 MW are now being planned
- Power system dynamic studies are required
- Well developed models of “conventional components” (gas/coal fired power stations, cables/lines, transformers)
- Wind farm models need to be developed and verified
- IEA Wind R&D ideal framework for coordinated effort (cost effective, enhance know-how & confidence)
- IEA Topical Expert Meeting Newcastle, November 2001

Accurate modelling is important!

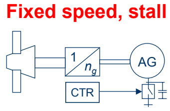


Accurate modelling save costs!

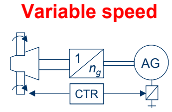


Accurate modelling is a challenge!

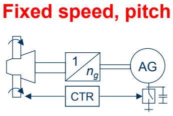
Fixed speed, stall



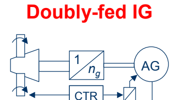
Variable speed



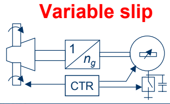
Fixed speed, pitch



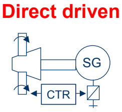
Doubly-fed IG



Variable slip



Direct driven



Objective

Overall:

Coordinated effort to develop wind farm models suitable for power system dynamic studies

Immediate:

- Establishment of an international forum for exchanging knowledge
- Development, description and validation of wind farm models
- Set-up and operation of a database for benchmark testing

Means & Results

- Work-shops and meetings
  (presentation of models, share know-how & experience)
- Common database
  (technical data & measurements)
- Bench-mark test
  (provide confidence in models)

Annex XXI Participants

Country	Contracting party	Participant
Denmark	Danish Energy Authority	Risø National Laboratory
Finland	VTT Energy	VTT Energy
Netherlands	NOVEM	ECN and TU Delft
Norway	NVE	SINTEF Energy Research
Sweden	Energimyndigheten	Chalmers University of Technology
USA	Department of Energy	NREL
Portugal	INETI	INETI

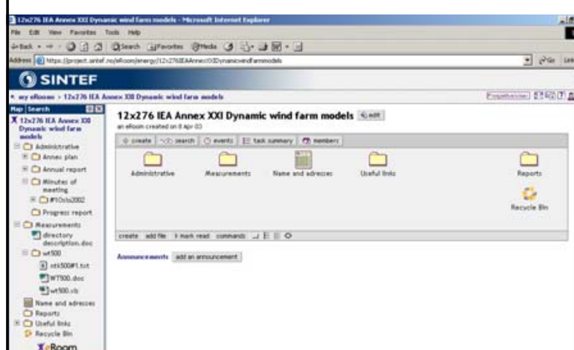
- Total participant works to Annex XXI: 237 man-months
- In addition: UK has recently announced that UMIST will participate, and further Canada and Ireland are expected to join soon and lately also Japan and Korea have taken interest

Time schedule

	2002		2003				2004				2005			
	3	4	1	2	3	4	1	2	3	4	1	2	3	4
IEA ExCo meetings		x		x		x		x		x		x		x
Meetings/workshops	x			x		x	x		x		x		x	
Data collection														
Model validation														
Database operation														

Target dates:

- Data collection
  - transfer and description of existing measurements is 31 Dec 03
  - data from ongoing/planned campaigns is 31 December 2004.
- Model validation
  - consensus on benchmark test procedures by 31 September 2004
  - model validation will be carried out until 31 June 2005.
- Database operation
  - start database operation by 31 June 2003
  - upload data shall be completed by 31 December 2004
  - database maintenance continues throughout the Annex duration



Conclusion

- Broad interest - important topic
- IEA Wind R&D ideal framework for coordinated effort
  (cost effective, enhance know-how & confidence)
- Progress is according to time schedule
- Annex participants are from Sweden, Finland, Norway, Portugal, Netherlands, Denmark, UK and USA, whereas Canada and Ireland are considering to join and lately also Japan and Korea have taken interest
- The OA suggests that the Annex may continue as planned expecting the works to provide for confidence in wind farm models enabling detailed grid connection assessments, saved costs and relaxing grid constraints so more wind power may be connected and operated

International Energy Agency Annex XXI Meeting

NREL Wind Farm Monitoring Program

Yih-huei Wan

November 11, 2003
National Wind Technology Center
Boulder, Colorado

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Wind Farm Monitoring Objectives

Have actual wind power data to

- Investigate output fluctuations from large wind power plants and its statistical properties
- Study frequency distribution of wind power plant output variations with long-term data
- Evaluate ancillary service impacts and costs for wind power
- Validate wind farm models

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Approaches

- Collaborate with wind farm owners, operators, utilities, and regional reliability council
- NREL owned and installed equipment
- Through subcontractor

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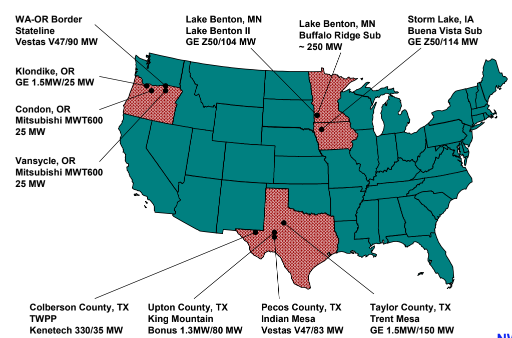
Wind Farm Monitoring Project

(Total capacity ~875 MW)



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Monitored Wind Farms

Midwest

- Lake Benton II (Lake Benton,MN) — GE Z50/104 MW
- Buffalo Ridge Substation (Lake Benton, MN) — 250 MW
- Buena Vista Substation (Storm Lake, IA) — GE Z50/113 MW

Texas (collaboration with ERCOT/Electrotek)

- King Mountain (Upton County, TX) — Bonus 1.3MW/80 MW
- Indian Mesa (Pecos County, TX) — Vestas V47/83 MW
- Trent Mesa (Taylor County, TX) — GE 1.5 MW/150 MW
- TWPP (Colberson County, TX) — Kenetech 330/35 MW

Northwest (through data sharing with BPA)

- Vansycle (OR) — Mitsubishi MWT600/25 MW
- Stateline (WA-OR border) — Vestas V47/90 MW
- Condon (OR) — Mitsubishi MWT600/25 MW
- Klondike (OR) — GE 1.5MW/25 MW

Total approximately 875 MW

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Wind Farm Data Collected

- Time-synchronized 1-second real and reactive power and line voltages (BPA data set contains only time-synchronized 2-second real power)
- Event-triggered, 10-second P, Q and V waveforms at sampling rate of 120 Hz from 4 monitored Texas wind farms

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Wind Farm Data Collected (cont.)

- More than 3 years of continuous data from Lake Benton II; 2 years of data from Buffalo Ridge and Storm Lake; data from Northwest starting 2002; Texas data starting 2003

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Program Status

- Lake Benton II monitoring will continue
- Subcontract for Buffalo Ridge and Storm Lake data collection has been extended until fund runs out; a new subcontract will be put in place afterward (FY2004 budget request)
- Subcontract for monitoring Texas wind farms in calendar year 2004 is under negotiation; ERCOT will continue the work in 2005
- Data sharing with BPA will continue

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What Have Been Learned

- Despite the stochastic nature of wind power, the power changes are not totally random, and fluctuations are within narrow ranges
- Analysis of output correlation among wind power plants shows significant spatial variations
- Wind power persistency and correlation between adjacent wind power plants suggest the feasibility of forecasting wind power
- Provide realistic wind power data for system operation and impact studies

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What Have Been Learned (cont.)

Data have been used for

- Methods and analytic studies
  - Regulation and metrics for allocating to generators/loads (Kirby and Hirst, ORNL)
  - Hirst's market and PJM studies
  - Milligan's Load following and imbalance study of Iowa
- Operating impact case studies
  - Electrotek's Xcel/Lake Benton II study for UWIG
  - Hirst's study for BPA
- Wind farm output forecasting studies
  - Milligan's statistical wind power forecast

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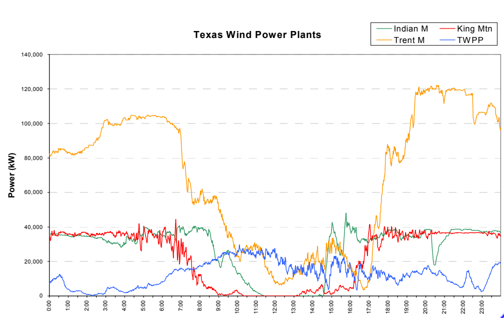

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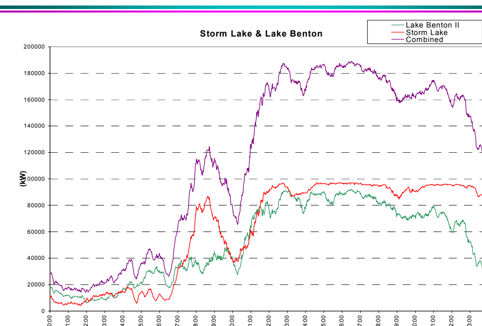
Midwest Wind Power Plants



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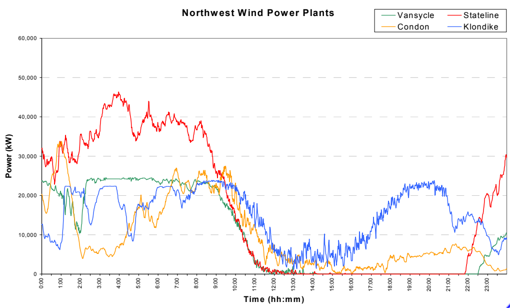
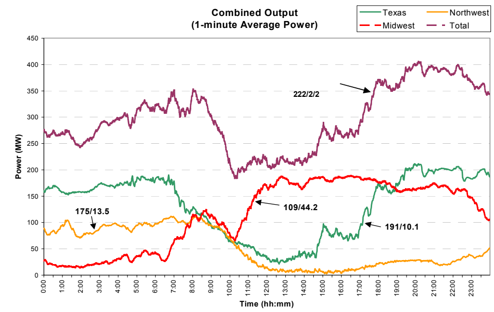
Northwest Wind Power Plants



Geographic Diversity of Wind Power

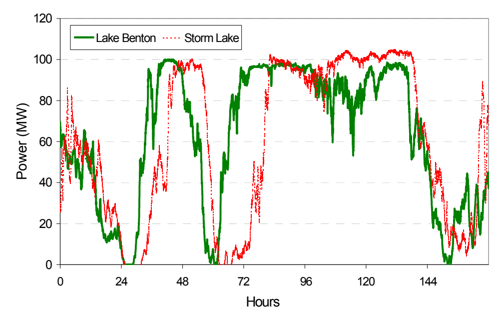


Correlation Coefficients

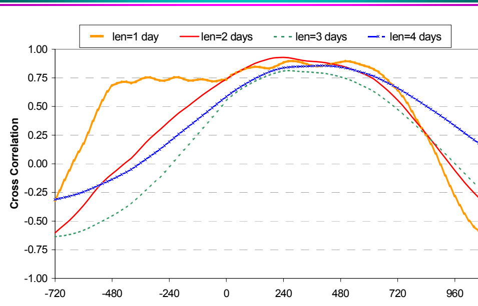
	STL	CON	KLN	LB II	SL	MW	IM	KM	TM	TWPP	TX
VNC	0.94	0.76	0.66	-0.05	-0.01		0.11	0.03	0.05	0.20	
STL		0.81	0.67	-0.05	-0.01		0.11	0.07	0.03	0.13	
CON			0.57	-0.03	-0.05		-0.05	-0.04	-0.14	0.14	
KLN				-0.05	-0.01		0.18	0.19	0.03	0.31	
NW						-0.09					0.07
LB II					0.81		0.10	0.05	0.10	-0.13	
SL							0.24	0.22	0.19	0.01	
MW											0.14
IM								0.76	0.50	0.05	
KM									0.49	-0.03	
TM										-0.01	

VNC: Vansycle
STL: Stateline
Con: Condon
KLN: Klondike
LB II: Lake Benton II
SL: Storm Lake
IM: Indian Mesa
KM: King Mountain
TM: Trent Mesa
TWPP: Texas Wind Pwr Proj
NW: Combined Northwest
MW: Combined Midwest
TX: Combined Texas

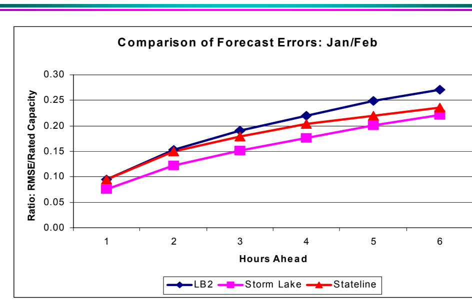
Weekly Output Power Example



Cross Correlation between Lake Benton and Storm Lake



Statistical Wind Power Forecasting



RMSE: Root Mean Square Error

FY2004 Plan

- Add wind power plants in the Rocky Mountain region and eastern states to the monitoring program
- Using data and power system simulation program to simulate the electric power operations and the impacts of wind power forecasting errors

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Wind Power Data Applications

Consultants

- United Technology Research Center: Wind power fluctuations
- EnerNex Corporation: collaborating with other data for Blackout analysis
- SSESCO: wind power forecasting
- Wind Utility Consulting: Midwest Cooperative purchase offset and storage analysis
- Platts Research Consulting/RDI: Integration of coal and wind for transmission
- AWS Scientific/TrueWind Solutions: Wind power forecasting

Utilities

- WAPA Rocky Mountain Region: rate analysis
- Electrotek/Great River Energy: Resources planning
- FPL
- TVA
- Alliant Energy

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Conclusions

- Continue to work with utilities and industry partners to expand the wind farm monitoring network (e.g., California, Rocky Mountains, Eastern wind farms)
- Support system impact and ancillary services analyses and wind farm model validation

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Selected References and Links

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- Kirby, B., Hirst, E. (2000) Customer-Specific Metrics for the Regulation and Load Following Ancillary Services. ORNL/CON-474. http://www.onrl.gov/~webworks/cpr/rpt/105927.pdf
- Wan, Y.; Bucaneg, D. (2002). Short-Term Power Fluctuations of Large Wind Power Plants; NREL Report No. CP-500-30747 http://www.nrel.gov/docs/fy02osti/30747.pdf
- Wan, Y. (2003) Output Power Correlation between Adjacent Wind Power Plants; NREL Report No. CP-500-33519.
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Modeling of Wind Turbines for Power System Studies

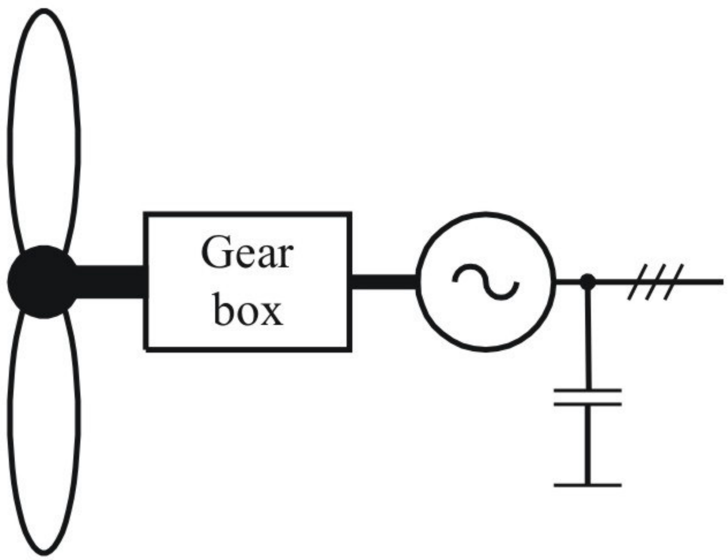
Ola Carlson

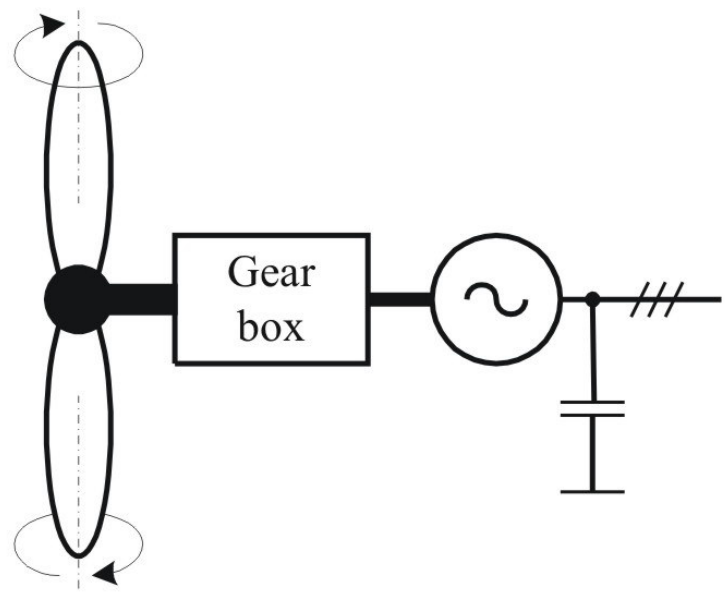
Tomas Petru, PhD-defence

Torbjörn Thiringer, Supervisor

Wind Turbine Systems

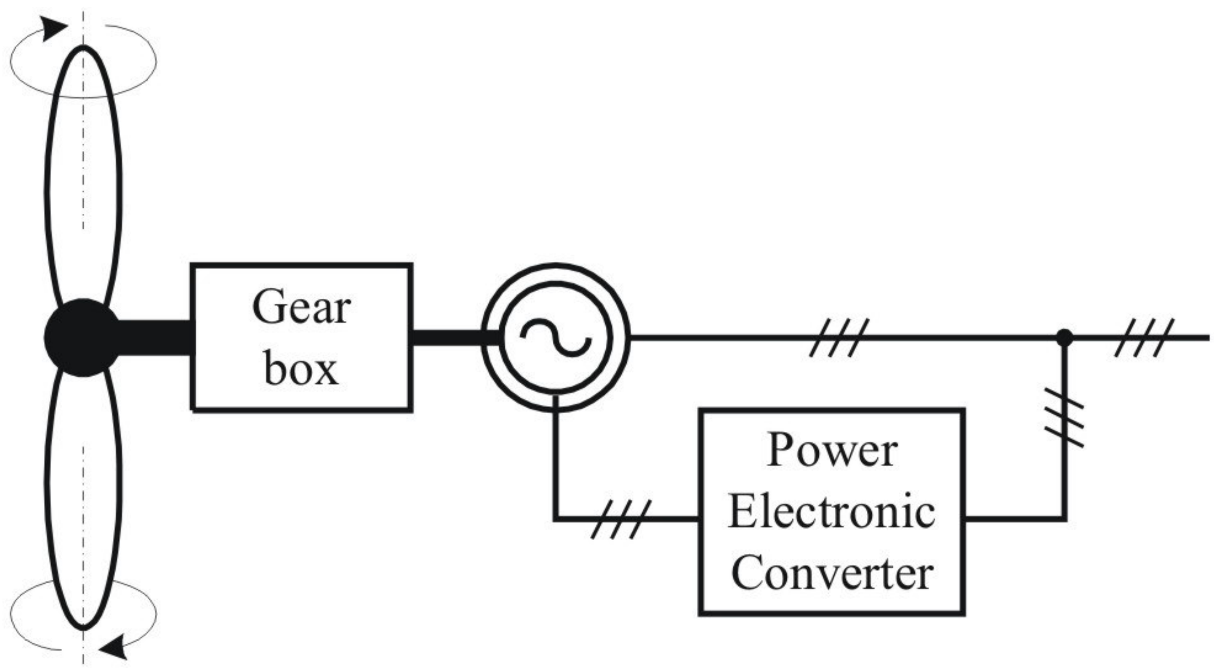
Fixed-speed, stall or active-stall controlled wind turbine induction generator





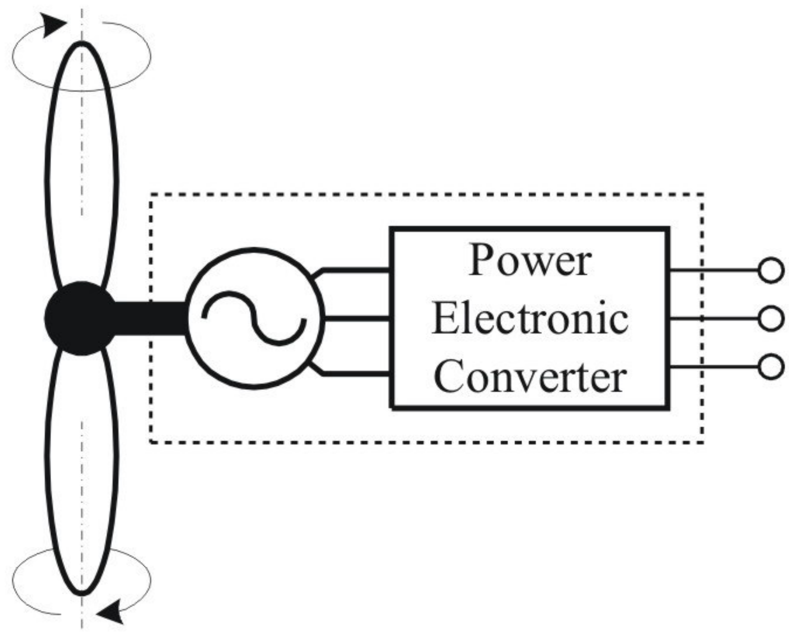
Wind Turbine Systems

Variable-speed, pitch-controlled wind turbine with doubly fed induction generator



Wind Turbine Systems

Variable-speed, pitch-controlled wind turbine with power electronic converter in the stator circuit



Possible components of a wind turbine model

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

Aerodynamic conversion: blade profile, dynamic hysteresis

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

Wind turbine structure: tower, nacelle

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

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

Grid connection: Transformer, line capacitance, resistance and inductance

Presentation of model

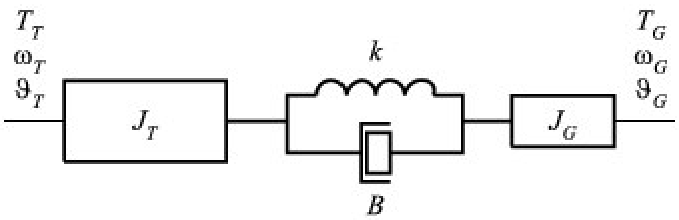
Aim:

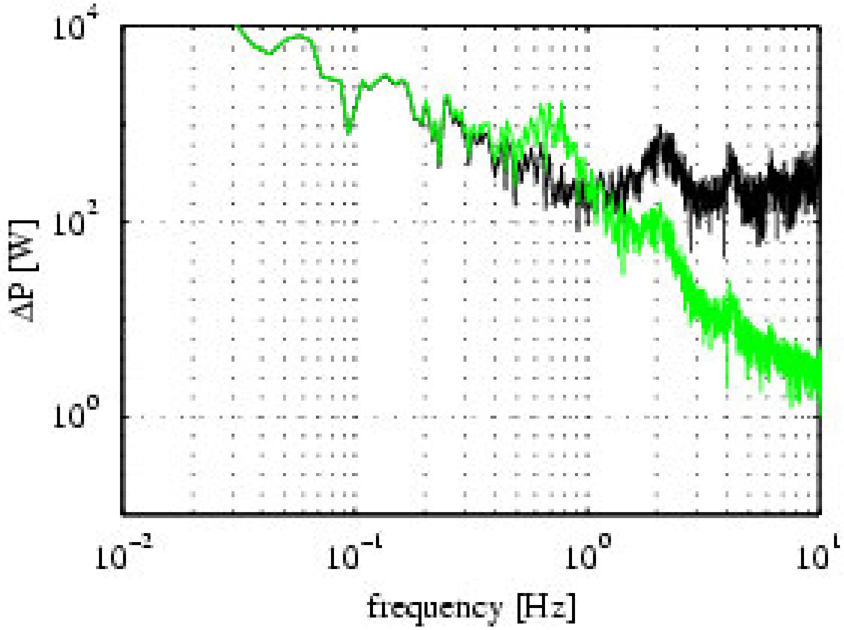
- Model shall be possible to implement in simulation programs
- Test operation with parameters from example
- Possible to compare result with an examples

Needs:

- Model description in words and equations
- Usage and limitations of model
- Data for an example and simulation results
- If possible, measurements to compare with
- If possible, Matlab/simulink code with data and result according to measurem.
- If possible, inform where the model is implemented

Soft shaft

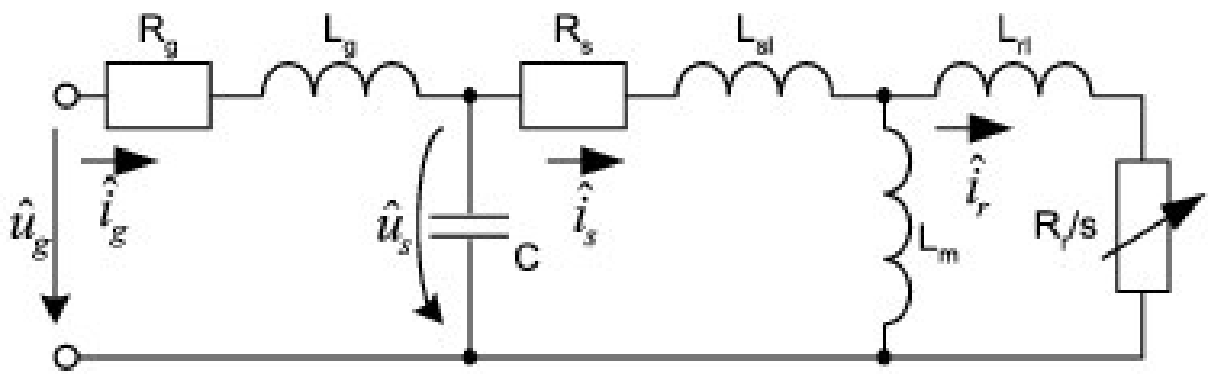




Power spectrum: Green:soft shaft

Black: stiff shaft

Model of induction generator with capacitor and grid



Grid and capacitor ought to be included

Models to deliver

5+4–order model of induction generator with capacitor, grid and soft shaft

5–order model of induction generator

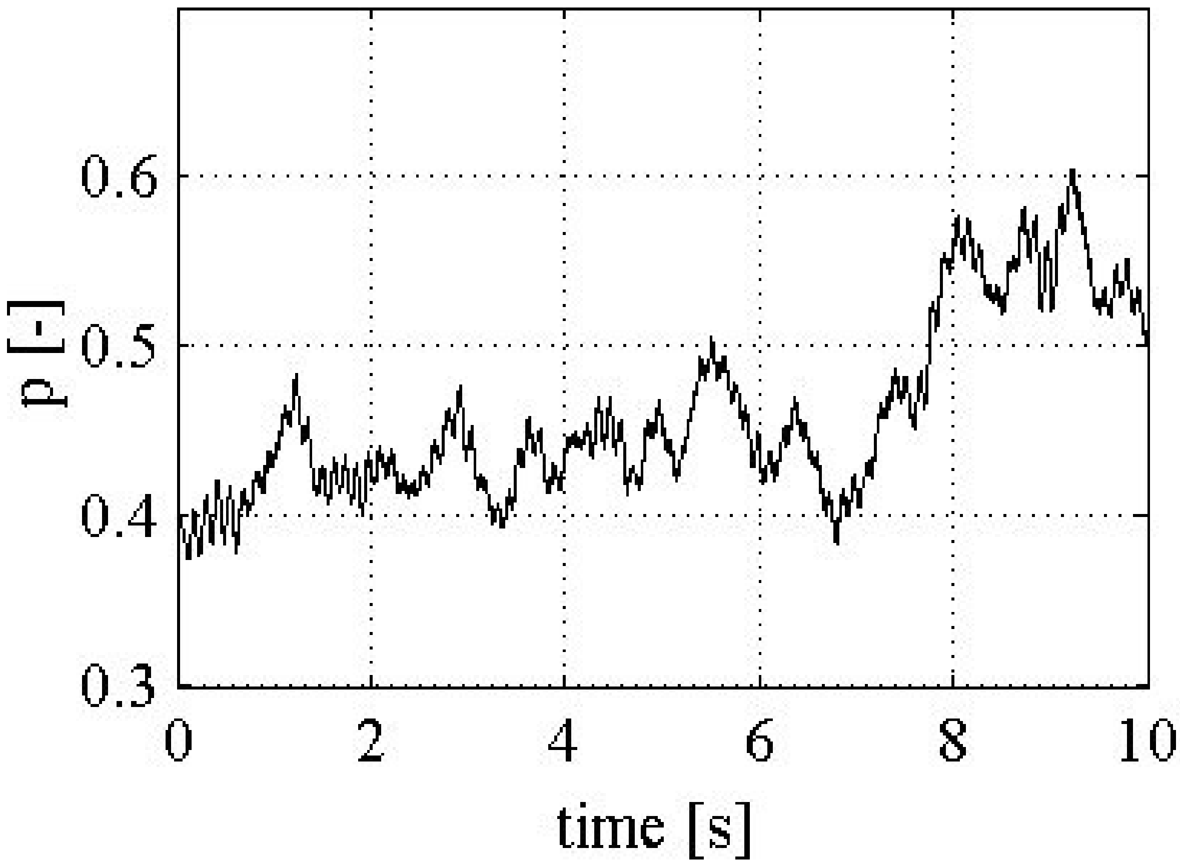
3–order model of induction generator (stator flux transient neglected)

1–order model of induction generator (stator and rotor flux transient neglected)

DFIG-coming years.

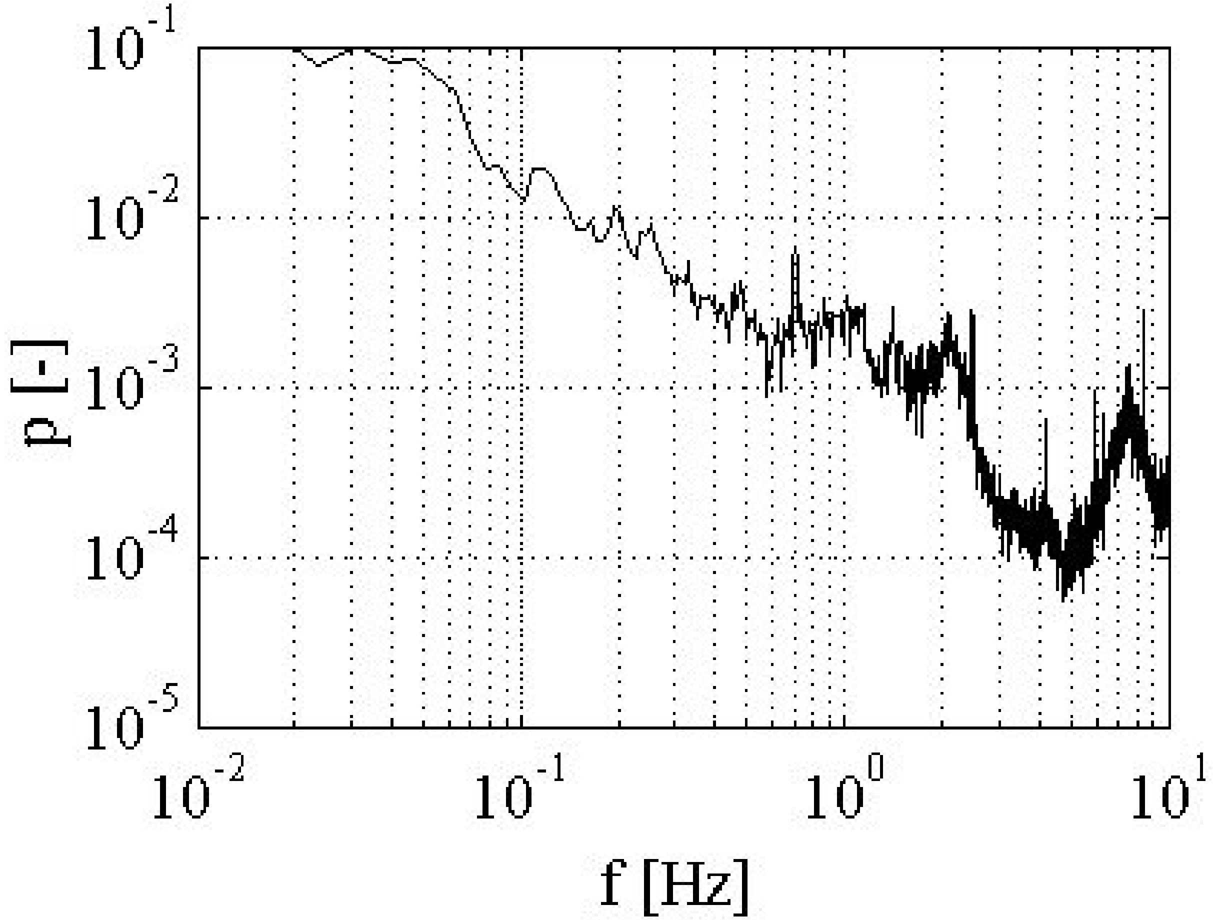
Full size converter wind turbine-coming years.

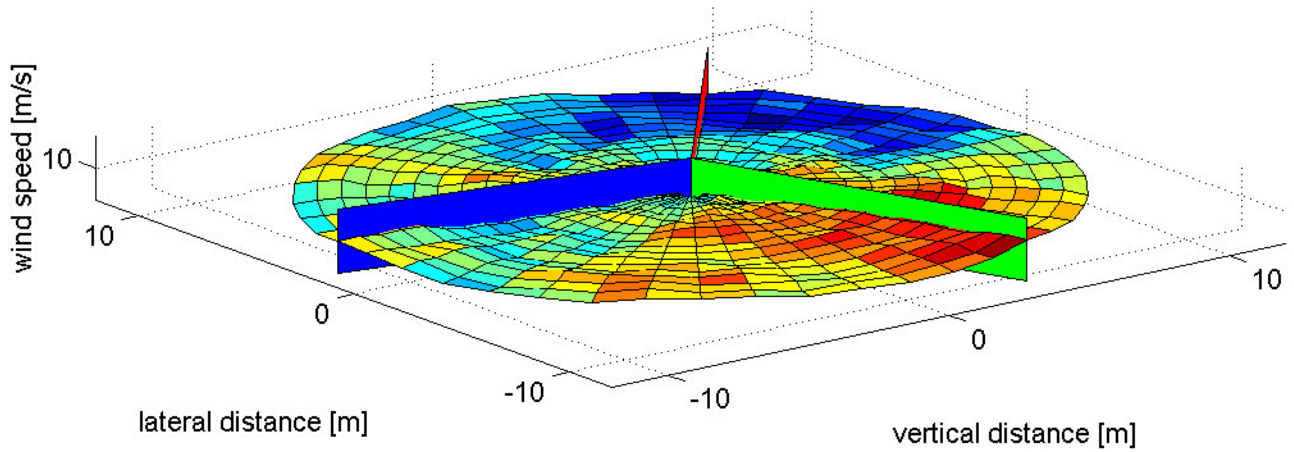
Output active power - Alsvik

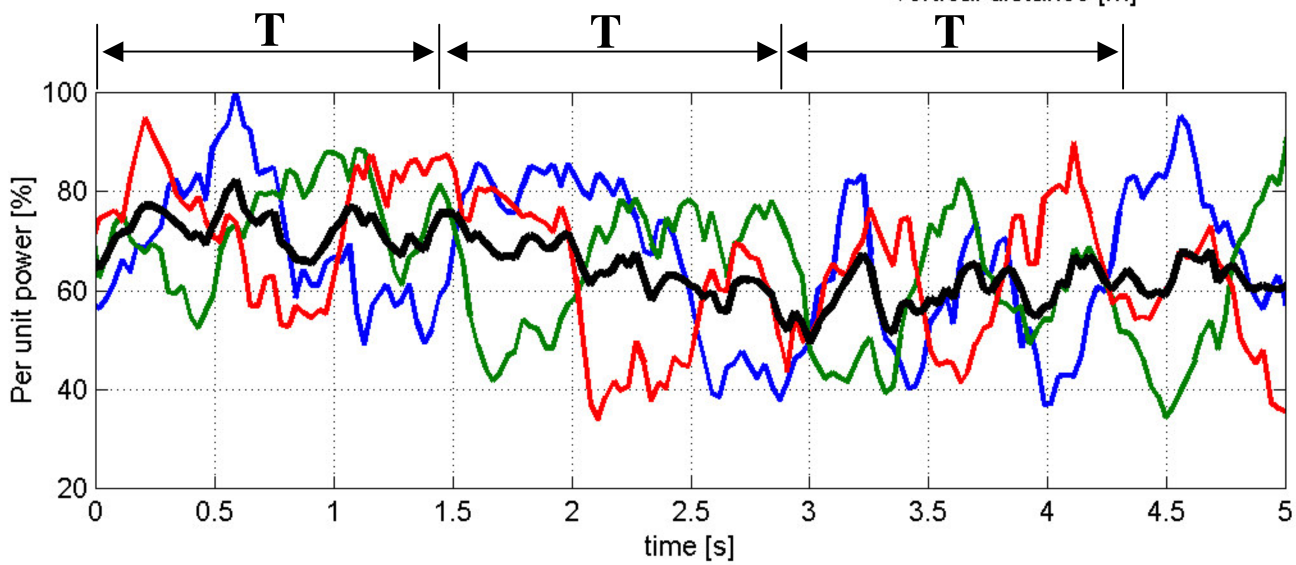


Output active power – Alsvik

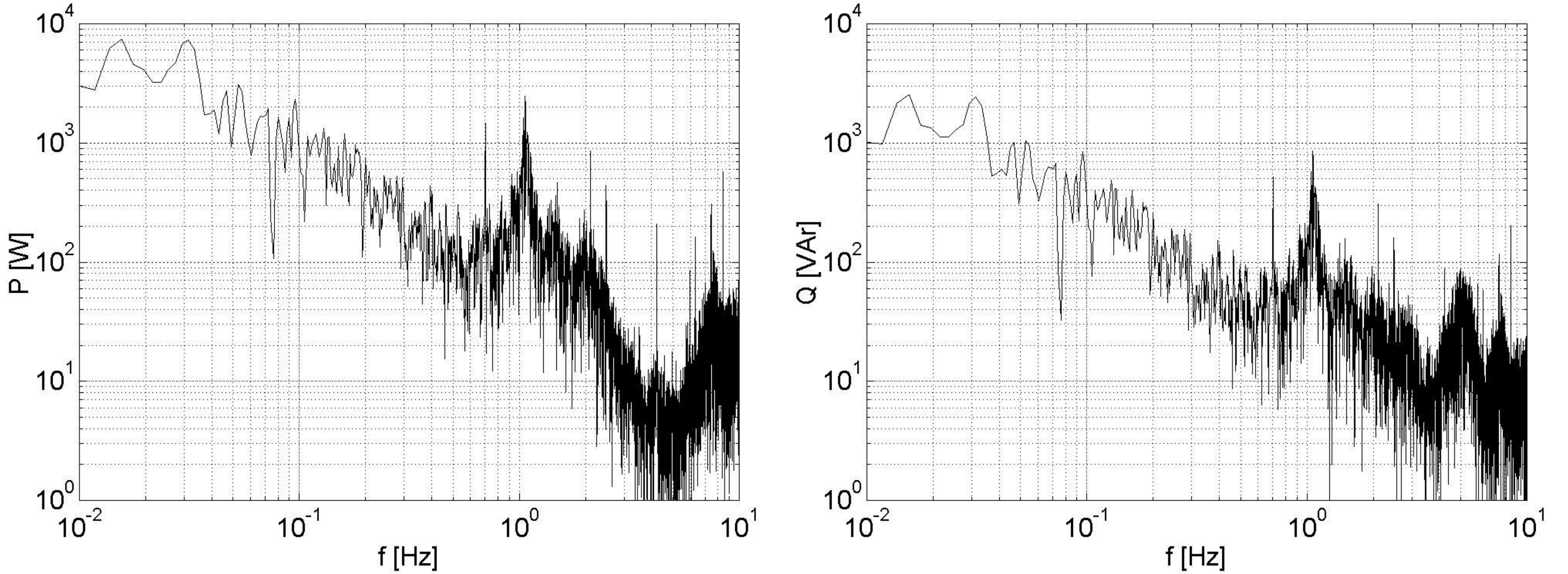
frequency content




wind speed [m/s]
10
10
0
-10
-10
0
10
lateral distance [m]
vertical distance [m]

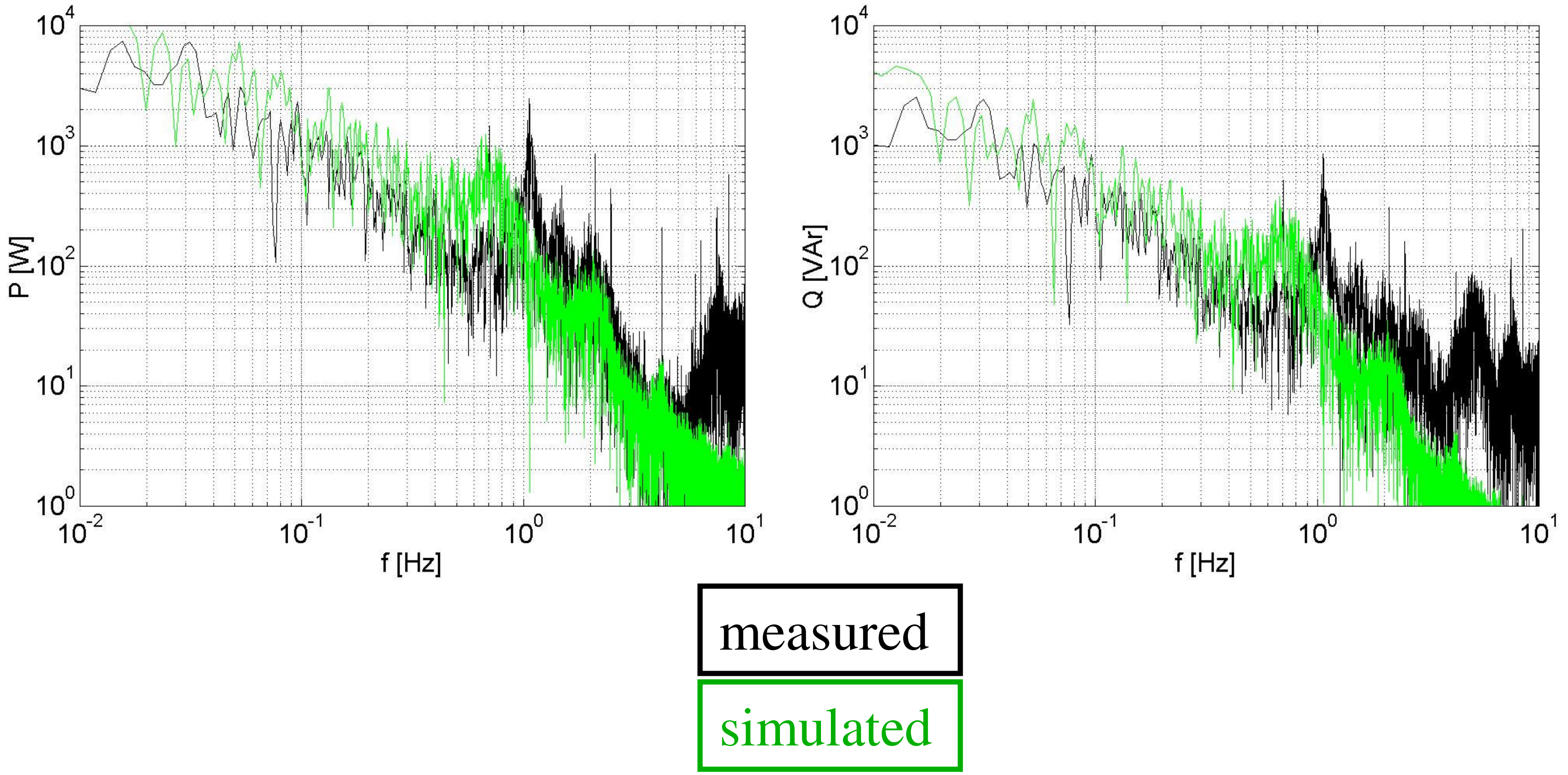

T
T
T
100
80
60
40
20
Per unit power [%]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
time [s]

Alsvik wind turbine – measured P and Q

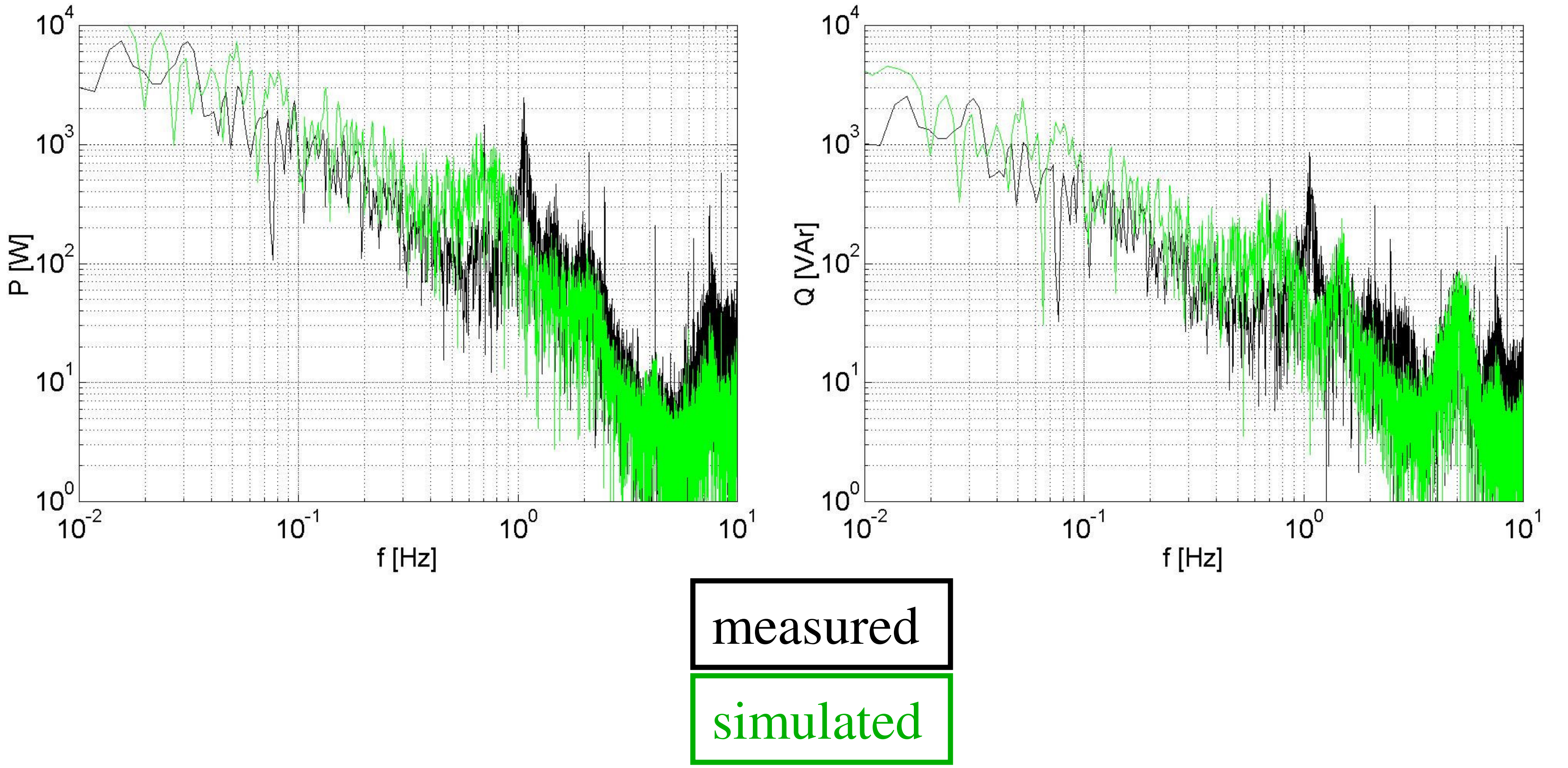


measured

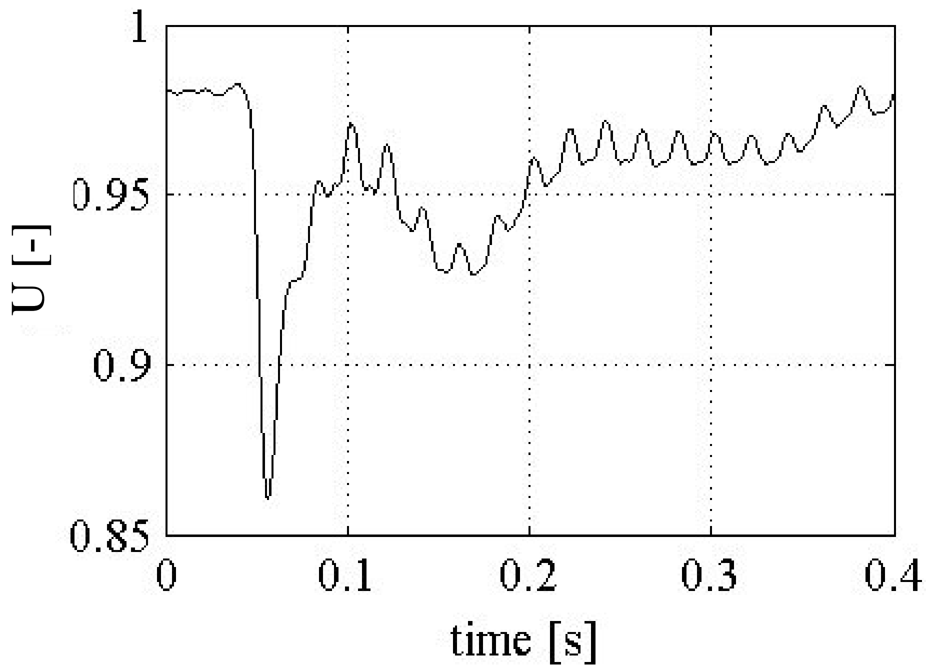
Alsvik wind turbine – stiff voltage supply

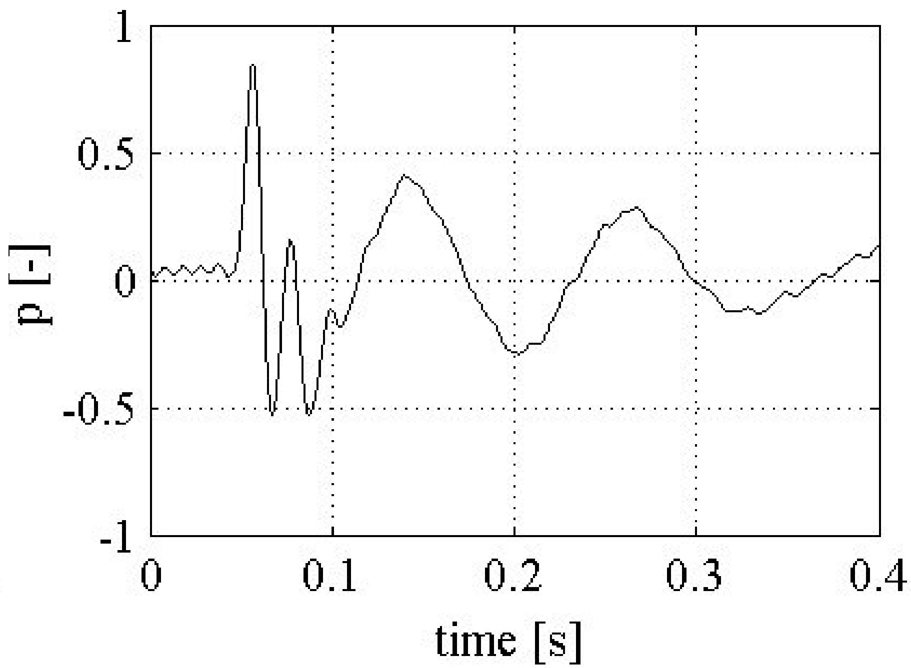


Alsvik wind turbine – grid voltage supply



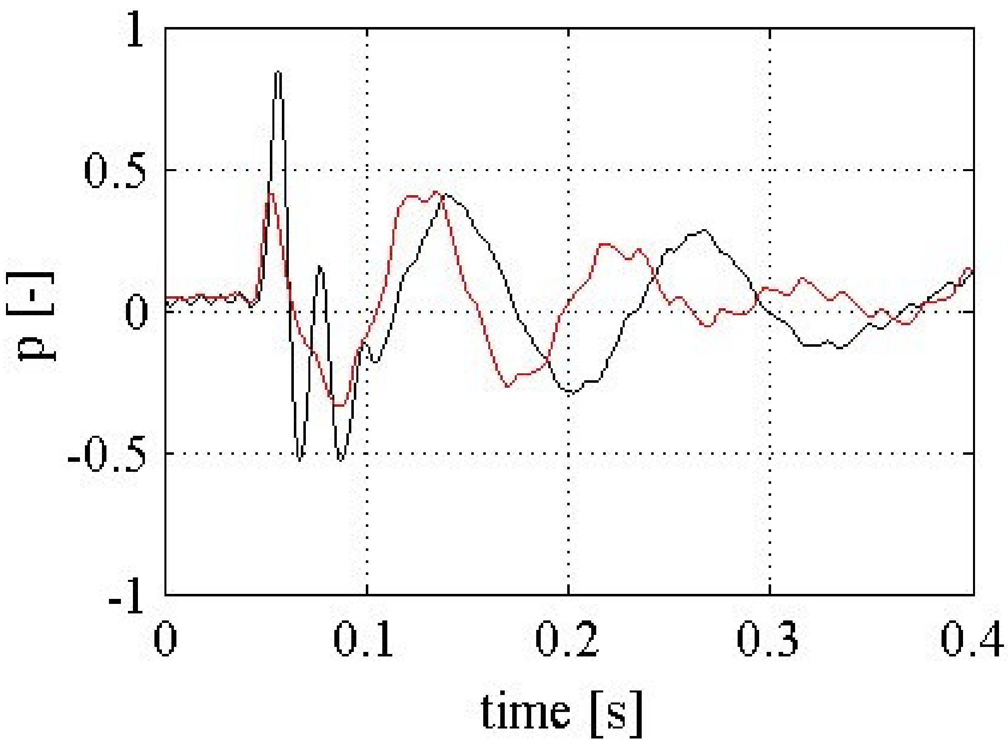
Fault response of Alsvik wind turbine





- measured data

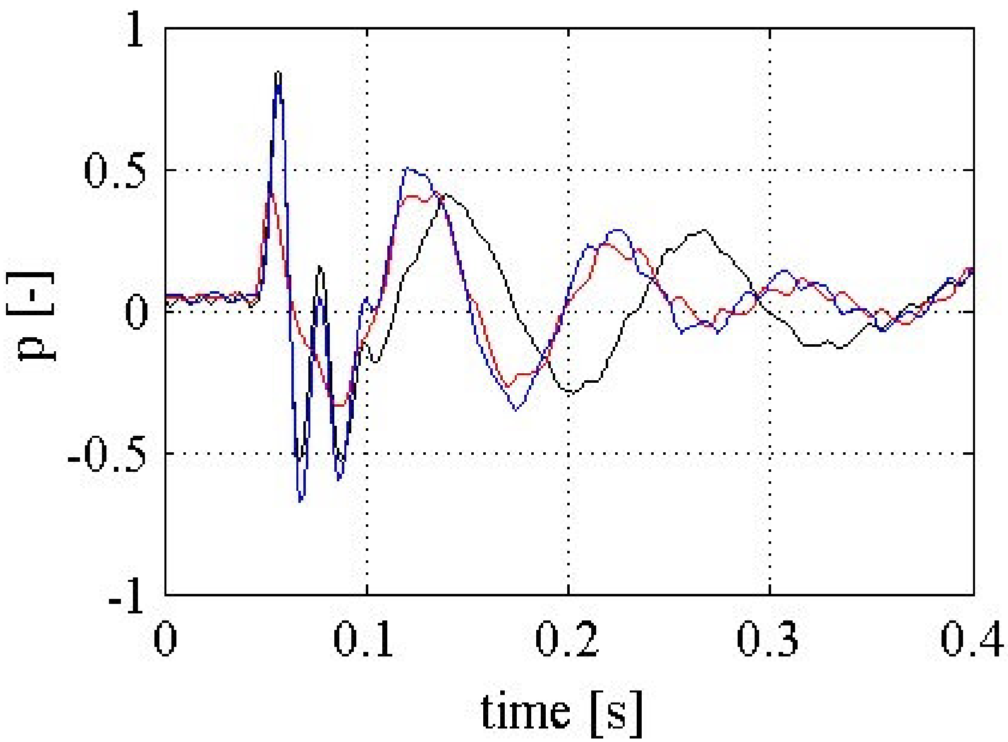
Fault response of Alsvik wind turbine



- measured data

- 3rd order model

Fault response of Alsvik wind turbine

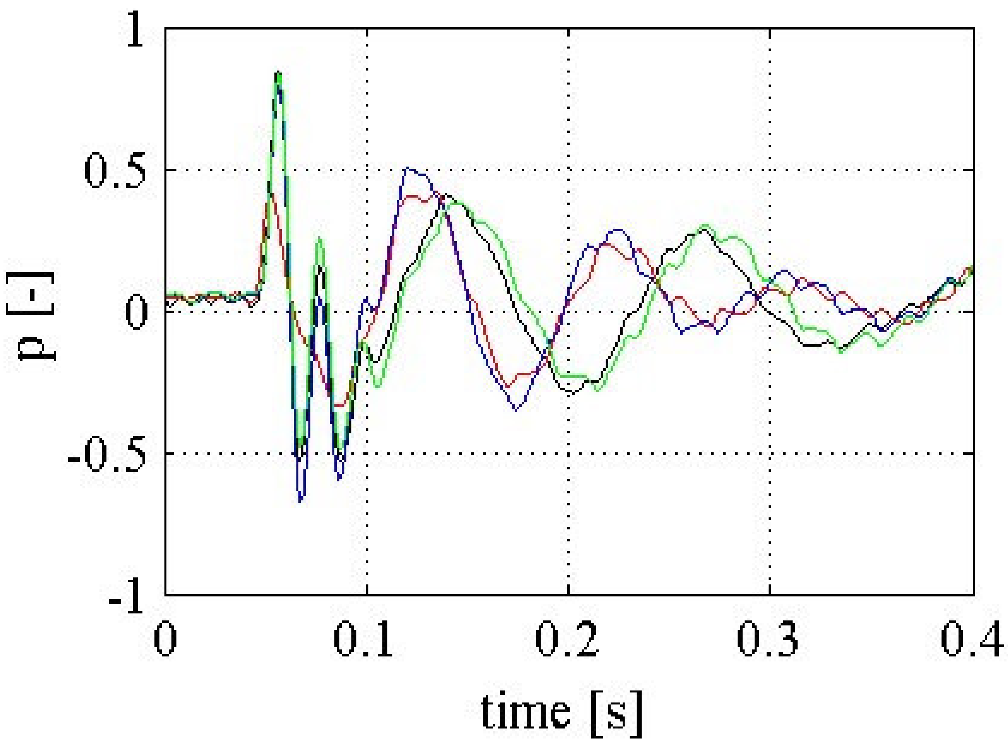


- measured data

- 5th order model

- 3rd order model

Fault response of Alsvik wind turbine



- measured data
- 3rd order model
- 5th order model
- 5th order model + soft shaft

Measurements

Description of: Site, wind turbine, measurement system

Signal list, sensors, signal gains, filter, sample rate,

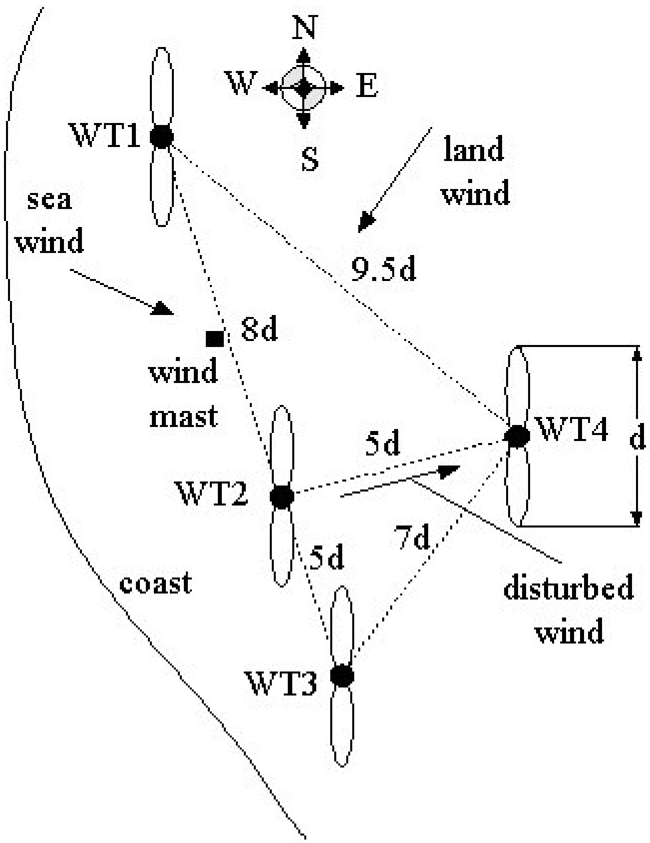
Type of operation: Normal, faults

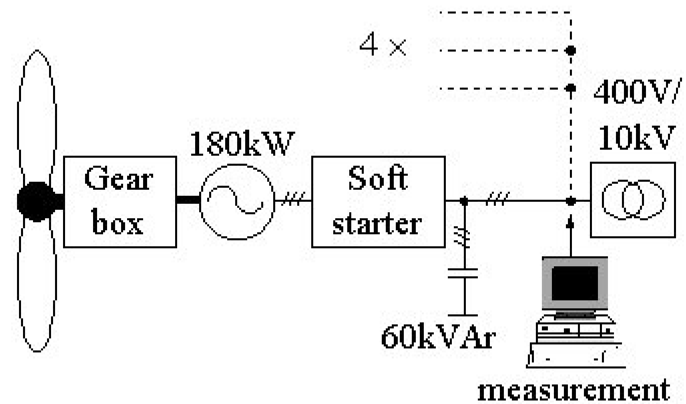
Example of reading Matlab-code or …..

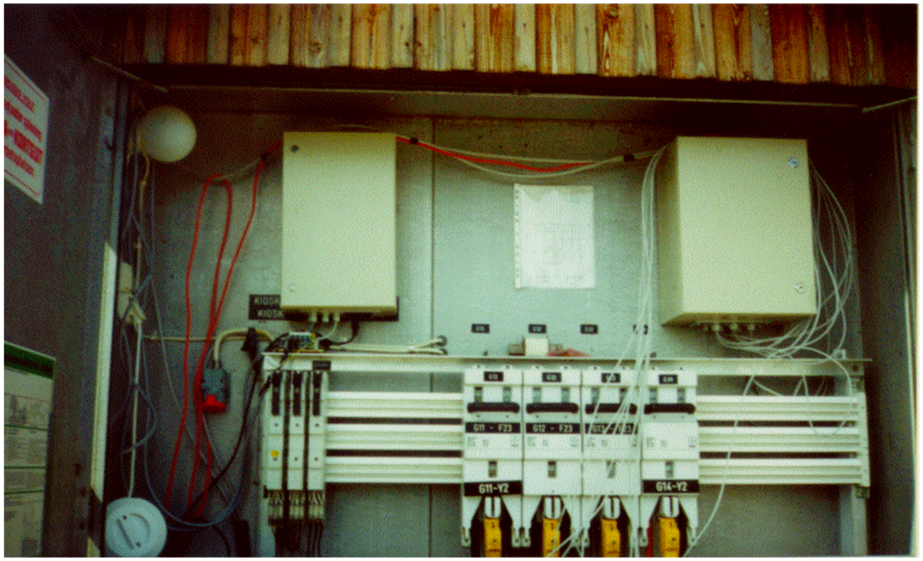
Example of plots

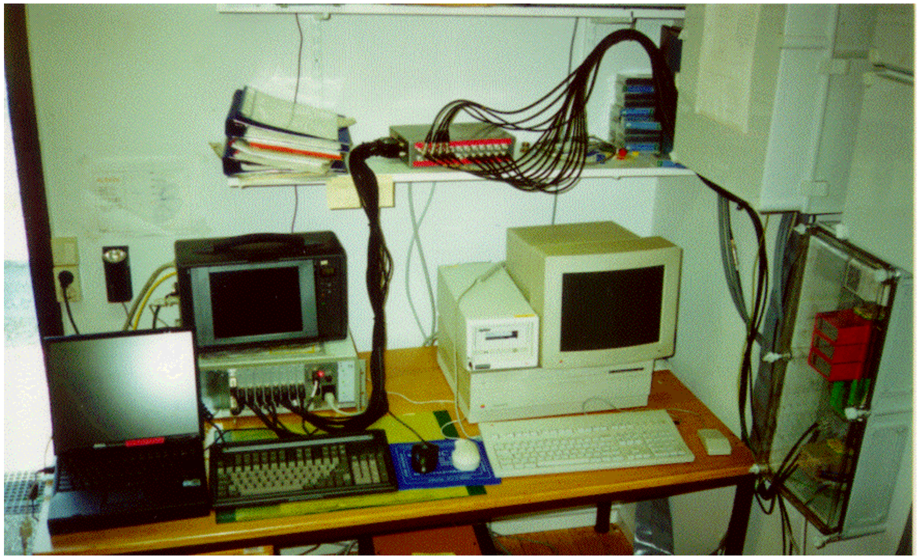
Alsvik wind farm

stall-regulated, fixed-speed system









Data 180 kW Danwind fixed speed stall-regulated wind turbine

General information:

Rated Power: 180 kW

Generator Type: Asynchronous

Number of Blades:3

Hub height 30 m

Rotor radius: 11.6 m

Gear-box ratio: 23.75

Rotor speed: 42 rev/min

Blade profile: NACA-63200

Shaft information (referred to high speed shaft):

J_t=103 kgm^2

J_m=4.5 kgm^2

k= 2700 Nm/rad

Generator:

U=415 V, f= 50 Hz,

Number of pole-pairs: 6

Rs=0.0092 Ω, Rr=0.0061 Ω

Xm=6.7 mH, Xsl=186 μH, Xrl=427 μH

Grid data (10 kV side):

R=6.5 Ω, X=7.1 Ω

Grid data (including transformer, 400 V side):

R=0.0076 Ω, X=0.0209 Ω

Data acquisition:

Sampling speed 62.5 Hz:

ACC1=Accelerometer signal in nacelle direction

ACC2= Accelerometer signal in edgewise direction

ACC3= Accelerometer signal in torsional direction

Pkort=Active power, high bandwidth

Pkortbinary= Active power, high bandwidth (special scaling)

Qkort= Rective power, high bandwidth

Qkortbinary= Reactive power, high bandwidth (special scaling)

edge=Shaft torque determined from blade-root signals;

flap1=flap-directional stress in blade 1

flap2= flap-directional stress in blade 2

flap3= flap-directional stress in blade 3

time1=62.5 Hz time vector

Sampling speed 31.25 Hz:

T1=Tower moment in nacelle direction 6.9 m below centra
T2= Tower moment in nacelle direction 4.9 m below centra
T3= Tower moment in cross nacelle direction 6.9 m below centra
T4= Tower moment in cross nacelle direction 4.9 m below centra
T5=Torsional moment, positive in clockwise direction (seen from above)
pow4=Power turbine 4 (2 Hz bandwidth)
WD=Wind direction
WS2=Wind speed at hub height
NacD=Nacelle direction
newangle=Rotor position
time2=31.25 Hz time vector

Sampling speed 2 Hz:

Pow1_slow= Power turbine 1 (2 Hz bandwidth)
Pow2_slow= Power turbine 2 (2 Hz bandwidth)
Pow3_slow= Power turbine 3 (2 Hz bandwidth)
Pow4_slow= Power turbine 4 (2 Hz bandwidth)
WD_slow= Wind direction)
WS1_slow= Wind speed at bottom of rotor disc
WS2_slow= Wind speed at hub height
WS3_slow= Wind speed at top of rotor disc
time3=2 Hz time vector

File names:

The wind direction and wind speed is indicated in the file name, in addition where more then one file existed for a specific direction and wind strength up to three files are stored which is marked with _1 to _3 at the end of the file. A file containing information using 8 degrees wind direction and 11.5 m/s is named:

WD008WS115_1

While a file with data from a situation of 5 m/s and 313 degrees wind direction is named :

WD313WS050_3

Matlab M-file read file program: READ_PROFILE.M

Used wind directions:

Five main wind directions were used:

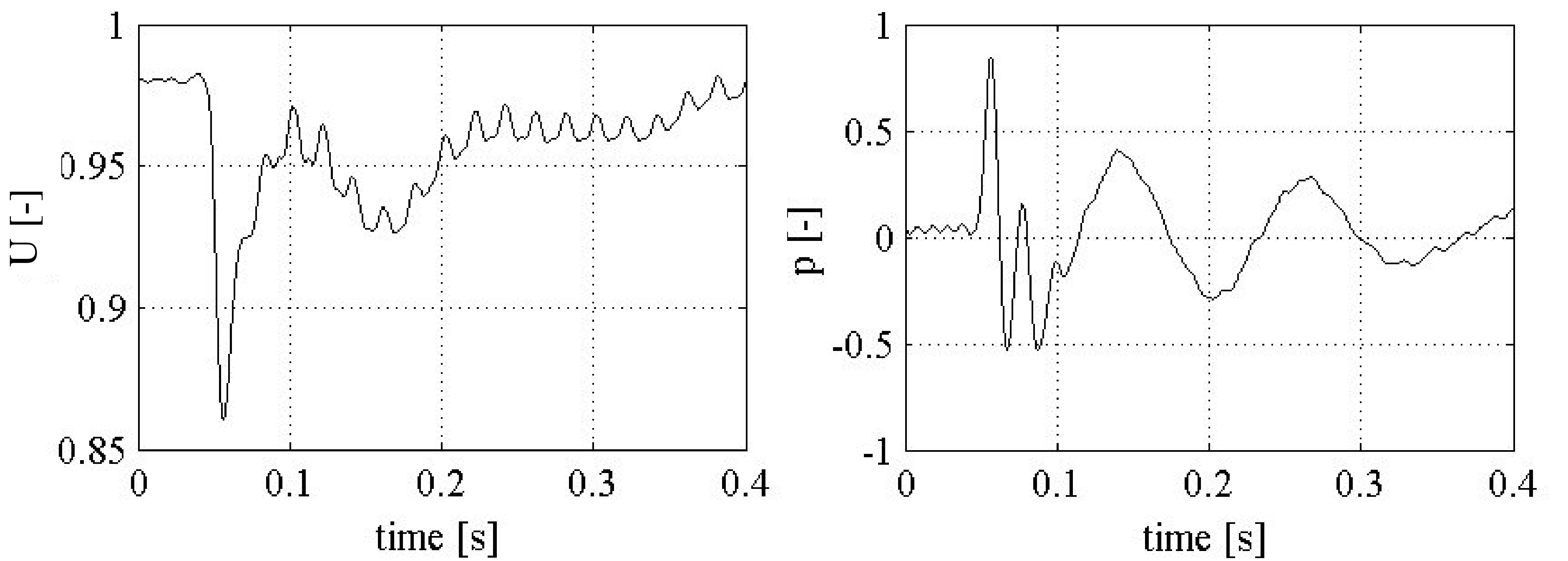
Name	Actual wind direction	Description	Number of files
WD075ws	70-80°	Forest winds (priority direction)	17
WD313ws	308-318°	Disturbed wind from turbine 1	68
WD008ws	0-15°	Free wind from north (shore)	43
WD65wws	50-80°	Forest winds (wider range)	20
WD135wws	120-150°	Wind passing over a 5 km forest after 10 km of sea	51
WD135ws	130-140°	As above, but with a minimum of disturbance on the wind mast	38
WD210ws	205-215°	Disturbed wind from turbine no. 3	87
WS255ws	250-260°	Disturbed wind from turbine no. 2	61
WD285ws	280-290°	Free wind	78

Contact information

Torbjörn Thiringer, Chalmers University of Technology,

torbjorn.thiringer(at)elteknik.chalmers.se (anti spam mail address)

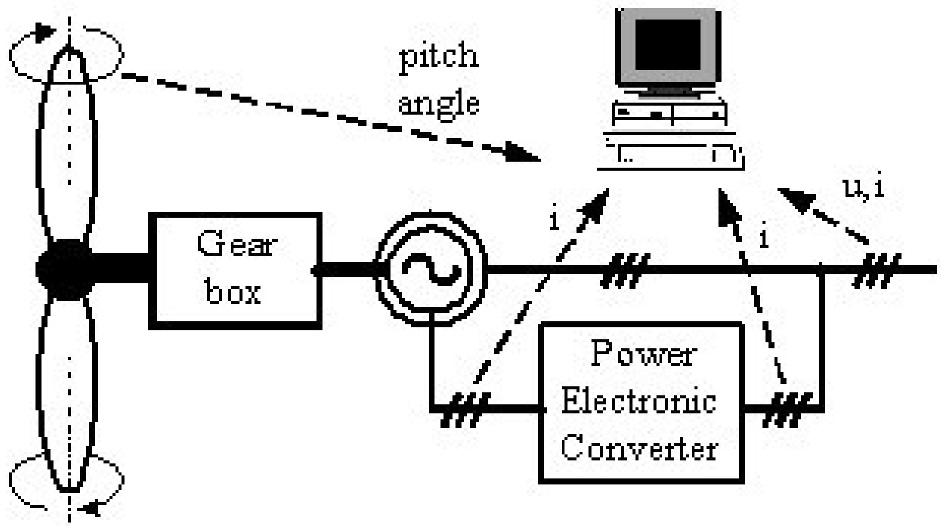
Fault response of Alsvik wind turbine



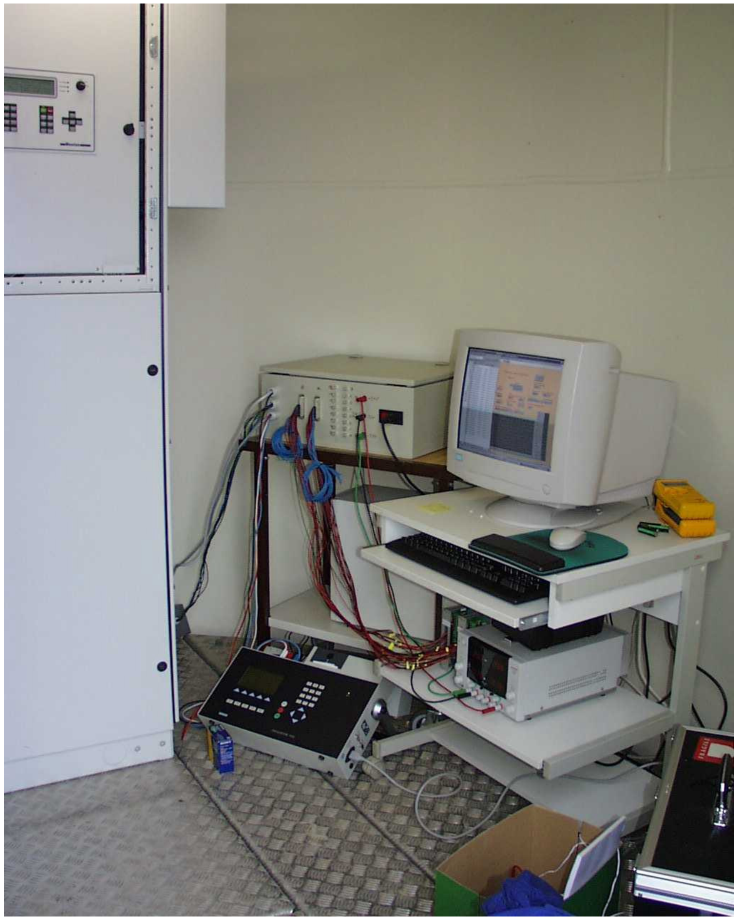
- measured data

Jung, Vestas V52 / 850kW

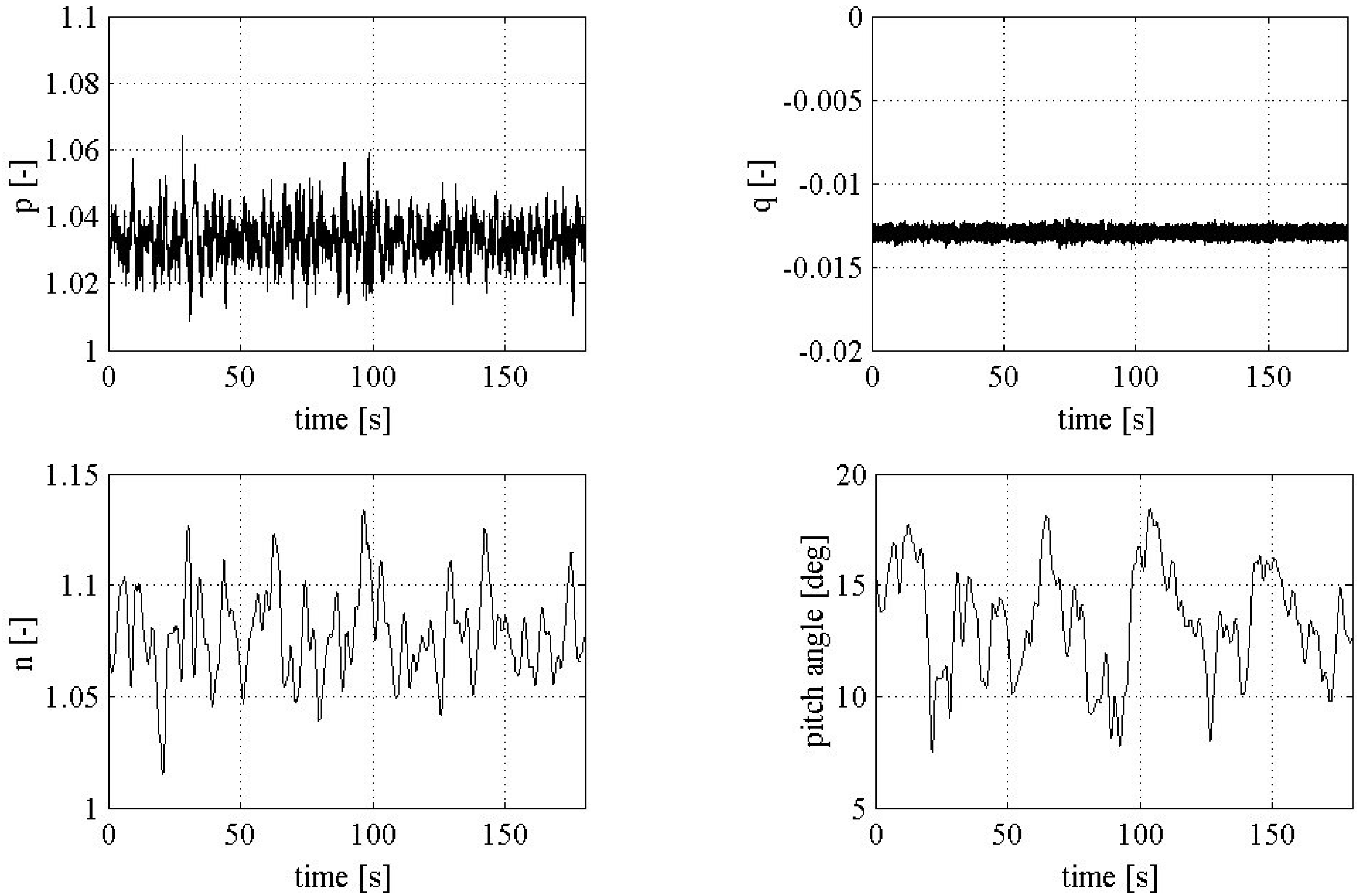
- pitch regulation - OptiTip®
- variable speed (DFIG) - OptiSpeed®



Jung – DAQ system



Jung – high wind speed operation

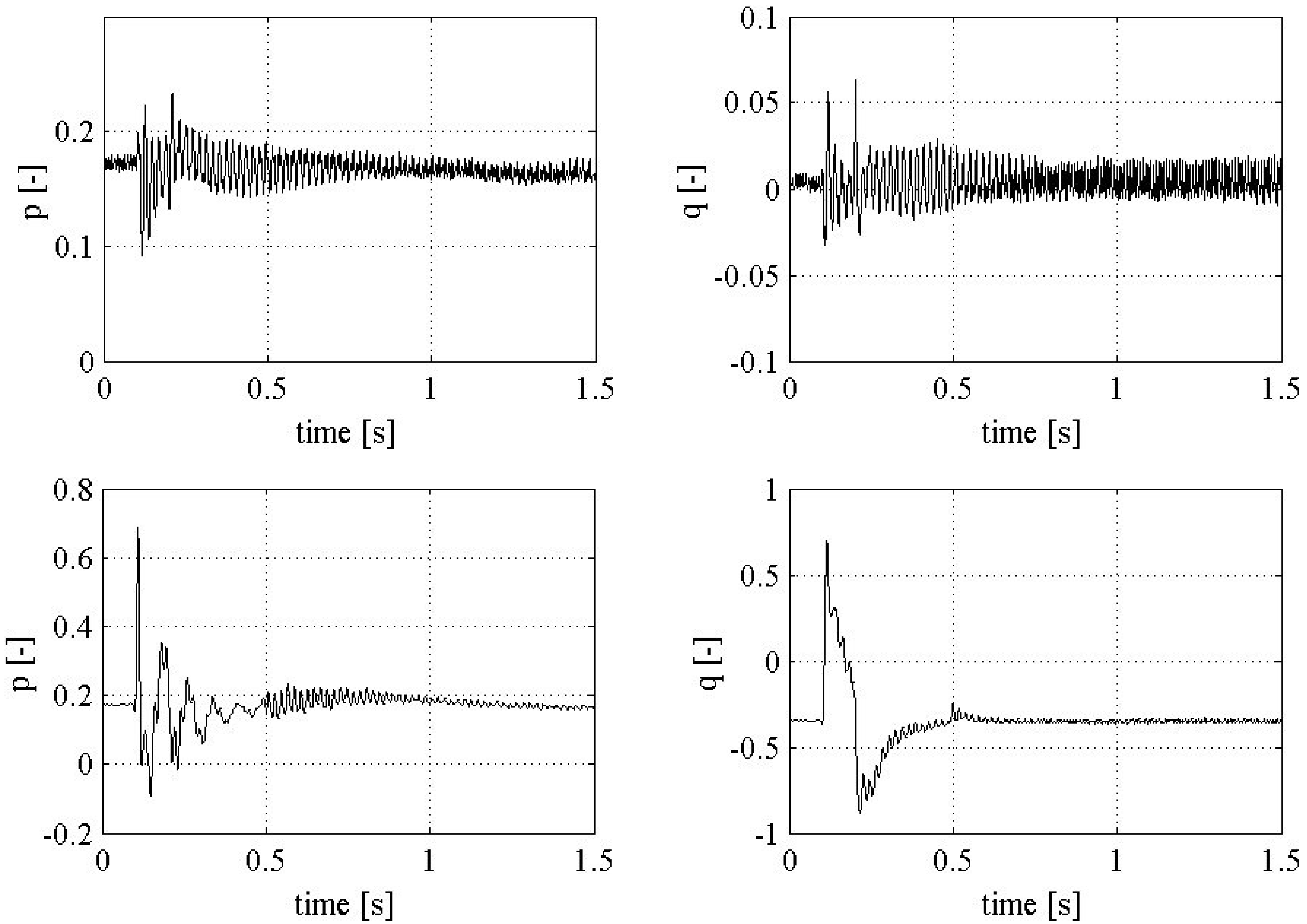


Response to smaller voltage dips

Jung DAQ

Vestas V52

Alsvik simulation



Conclusions

Continuous impact

- mainly fixed-speed systems are of interest
- model of FSS WT is suggested
- impact of grid is shown

Fault response

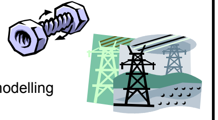
- FSS: 3rd or 5th order model of induction machine + soft shaft representation
- full power PEC: no dynamic description, programmed response
- DFIG: → small voltage dip ⇒ PEC like behavior
  ↘ big voltage dip ⇒ induction machine behavior

Wind turbine modelling using PSCAD, Simulink and ADAMS

Bettina Lemström
IEA Annex XXI meeting 12.11.2003

Background

ADAMS
- Detailed wind field, aerodynamic and mechanical modelling
- Versatile dynamic simulation tool
- but electrical side and network is lacking



PSCAD/EMTDC
- Detailed electrical component and network modelling
- Efficient dynamic simulation tool
- Aerodynamic and mechanical side is possible to model sufficiently detailed for network simulations, but not readily available

Simulink
- Very convenient for control system modelling

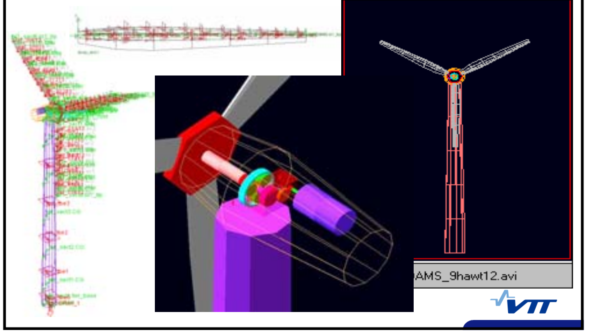
Objective

Different models & tools working simultaneous together enables to study
- what mechanical phenomena are transferred to the electrical side
- the influence of network disturbances to the mechanical side
- the impact of control actions and development of new control strategies

The purpose is not to use the three programs always together but to support
- development of mechanical models in PSCAD
- simple but correct modelling of network disturbances in ADAMS-Simulink

---

ADAMS/WT-simulation environment



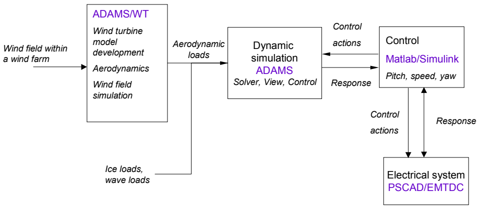
Turbine control modelling

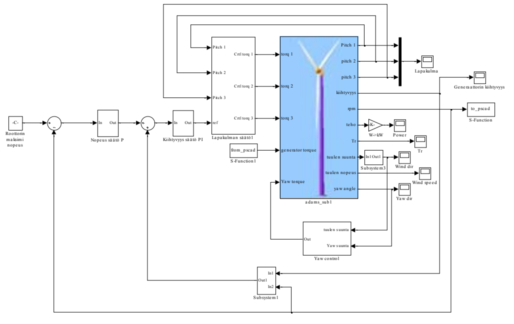
Controls
- pitch control
- yaw
- rotational speed
- in the future smart controls of f.ex. vibration

- Simulink is used to model the turbine control systems
- Simulink communicates with ADAMS Wind Turbine model through the ADAMS Control -module

---

Multidisciplinary simulation of wind turbines and wind farms





Features

- Simulink controls both PSCAD and ADAMS
- PSCAD and ADAMS communicate through Simulink

- ADAMS model is part of the Simulink model as an integrated block
- PSCAD runs as a separate program

- Simulink and PSCAD can be run on different computers in a local network
- In and out blocks for communication from PSCAD to Simulink and vice versa are developed by VTT
- Data analysis is possible in all three programs

Future work and thoughts

- To improve and test the modelling system further
- Make more detailed models in all three programs of real wind turbines
- Verification by measurements

- Same approach can be used in other electromotion systems
  - diesel generators
  - paper mills
  - etc.

NREL's Wind Farm Model Development

Eduard Muljadi

National Wind Technology Center
National Renewable Energy Laboratory
Golden, Colorado

IEA Annex XXI
Dynamic Models of Wind Farms for Power System Studies
November 10-11, 2003 at NWTC, NREL
Boulder, Colorado

Project Objectives

- Facilitate the integration of more wind power into the utility grid.
- Gain a better understanding of the technical barriers impeding the integration.
- Bridge the information gaps among our stakeholders (utilities, wind turbine manufacturers, transmission owners, wind farm operators, ISOs, wind farm developers).
- Provide tools and data to our stakeholders.

Wind Farm Model Development/Validation

Related Issues
- Aggregation effect on flicker and power quality
- Energy storage impacts
- Reactive power compensation
- Machine design configuration (control, generator, power converter, etc.) impacts on grid stability
- Self excitation, fault current contributions, and ride-through capability.

Collaborations
- ERCOT (review, model development, model testing)
- Southern California Edison (wind farm analysis)
- Oak Creek Energy (storage and reactive power compensation)
- Wind turbine manufacturers – testing, analysis, control design
- WAPA (large-scale fault and grid stability analysis).

Assumptions

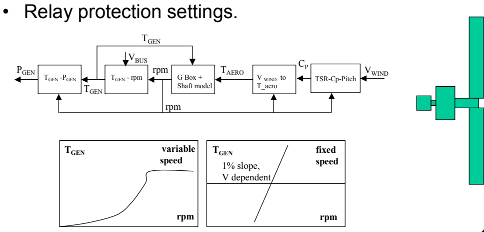
- Different turbine has different characteristics
- Wind turbine spread all over the large area of a wind farm
- No single turbine operates at the same exact operating condition
- Aggregation of the wind turbines tends to smooth out the output power of the wind farm
- Utilities are interested in the behavior of the entire wind farm at the point of common coupling
- Survivability of the wind farm and the power systems network is strongly determined by the interaction between the two.
- The prime concerns about the electrical supply occur during extreme conditions (high wind, faults, etc.).

Implementation

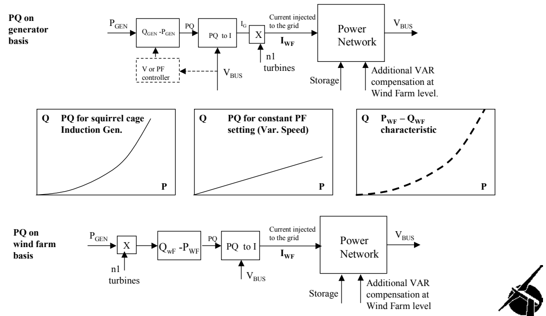
- Maintain characteristics of the WTG.
- Adapt the PQ characteristics of the wind farms to include compensations if any.
- Consider supervisory control (Wide Area Network).
- Adopt extreme conditions cases (typical faults, wind speeds, load changes, ramp-up/down rates) needed to test the WF/Power System for security and reliability.
- Make the modules comprising the turbine components to allow the choice of building a very complete model or to simplify model if necessary to speed up computing time.
- Adopt commonly used package program to implement the models.

Maintain Characteristics of the WTG

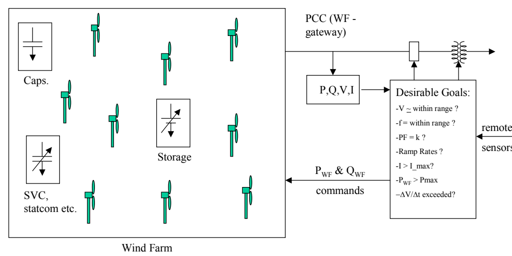
- Cp-TSR-pitch complete or simplified
- Torque-speed of the generator
- Torque shaft characteristic
- Relay protection settings.



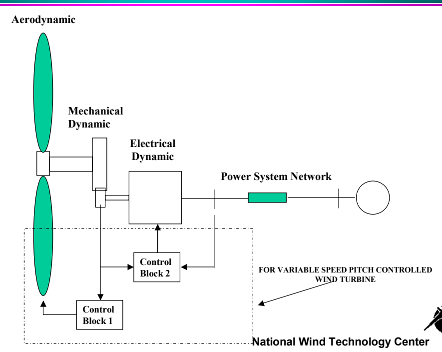
Adapt the PQ Characteristics of the Turbine and/or Wind Farm to Include Compensations



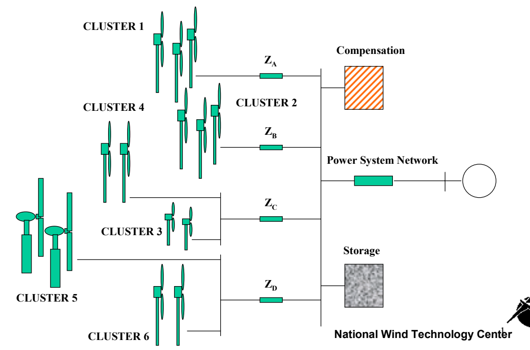
Consider Supervisory Control (Wide Area Network)



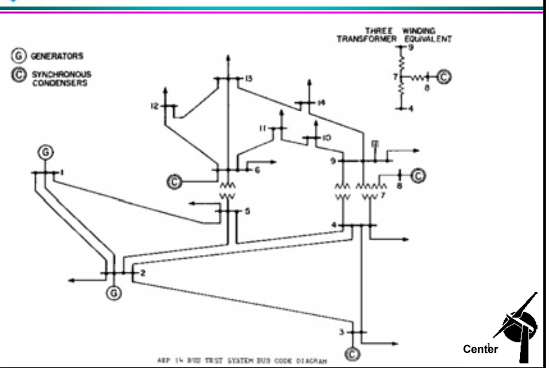
A Single Turbine Model (STM)



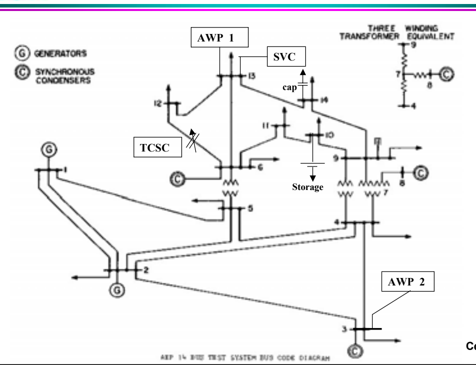
Aggregation of a Large Wind Power Plant (AWP)



Example of IEEE 14 Bus Test Case



Example of IEEE 14 Bus Test Case with Wind Farms, Reactive Power Compensations, and Storage



What are the Important Subjects?

STM:

- Mechanical survivability of the wind turbine during transients
- Electrical characteristics of the wind turbine during transients (power quality and stability)
- Mechanical-Electrical interaction (stiff/weak shaft effects on power system, and stiff/weak power system effects on mechanical system)
- Controllability of the wind turbine (runaway condition or dropping off the line).

AWP:

- Ride-through capability
- Is diversity of contribution from each cluster of wind turbines important to the power quality and stability of the power system?
- Is the computing time too slow if we have a complete model of STM? Or should we simplify the model?
- Is there any different between using single cluster (scaling up STM) and aggregation of multiple clusters (AWP) in terms of power quality and stability ?

Power System Network:

- How do transients in the power network affect the wind farms and the response of the wind farms affect the entire power network?
- How do the reactive power compensator and the energy storage affect the power systems?

Ride-Through Capability Under Different Transient Conditions

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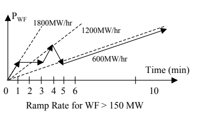
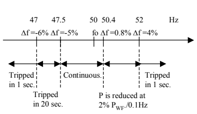
Example: Ramp Rates and Frequency Requirements.



Power Station Registered Capacity (MW)	Maximum Power Ramp Rate (MW per Hour)	Maximum Change Over 10 Minutes (MW)	Maximum Change Over 1 Minute (MW)
<15	60	10	3
15-150	4x Reg. Cap	Reg. Cap./1.5	Reg. Cap./5
>150	600	100	30



Frequency Range	Requirement
Less than 47 Hz	Wind farm should be tripped within 1 second.
47 Hz – 47.5 Hz	Operation for a period of at least 20 seconds is required each time the frequency is below 47.5 Hz
47.5 Hz – 50.4 Hz	Continuous operation is required.
50.4 Hz – 52 Hz	Power should be reduced at a minimum rate of 2% of Wind Farm output per 0.1 Hz deviation of system frequency above 50.4 Hz. No additional turbines may be started while frequency is above 50.4 Hz.
Above 52 Hz	Wind farm should be tripped within 1 second.

Derived from the " Guidance Note for the Connection Wind Farms"
A draft version prepared by Scottish Hydro.

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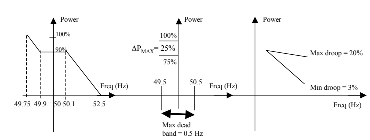
Example: Power Reduction versus Frequency.

Parameter	Set Value	Minimum Value	Maximum Value
Power Reduction	10%	0%	25%
Dead-band	0.1 Hz	0.0 Hz	0.5 Hz
Droop	5%	3%	20%



Derived from the " Guidance Note for the Connection Wind Farms"
A draft version prepared by Scottish Hydro.

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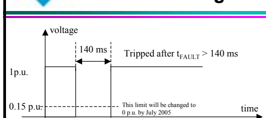
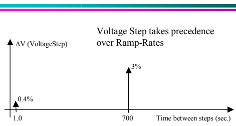
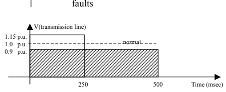
Example: Voltage requirements.

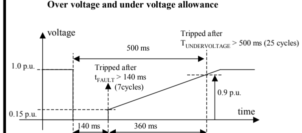






Over voltage and under voltage allowance

Derived from the " Guidance Note for the Connection Wind Farms"
A draft version prepared by Scottish Hydro.



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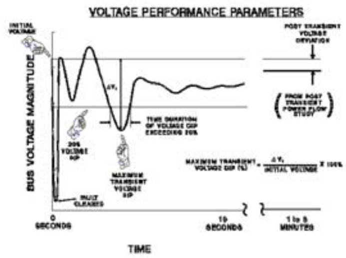
NERC/WSCC Planning Standards

I. System Adequacy and Security A. Transmission Systems

WSCC DISTURBANCE-PERFORMANCE TABLE OF ALLOWABLE EFFECTS ON OTHER SYSTEMS

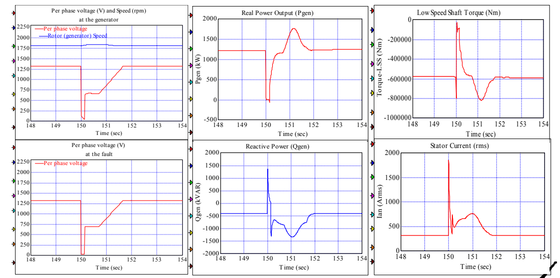
NERC and WSCC Categories	Outage Frequency Associated with the Performance Category (outage/year)	Transient Voltage Dip Standard	Minimum Transient Frequency Standard	Post Transient Voltage Deviation Standard (See Note 2)
A	Not Applicable	Nothing in addition to NERC		
B	≥ 0.33	Not to exceed 25% at load buses or 30% at non-load buses. Not to exceed 20% for more than 20 cycles at load buses.	Not below 59.6 Hz for 6 cycles or more at a load bus.	Not to exceed 5% at any bus.
C	0.033 - 0.33	Not to exceed 30% at any bus. Not to exceed 20% for more than 40 cycles at load buses.	Not below 59.0 Hz for 6 cycles or more at a load bus.	Not to exceed 10% at any bus.
D	< 0.033	Nothing in addition to NERC		



NERC/WSCC Planning Standards

Figure W-1

Example: Eon Voltage Profile



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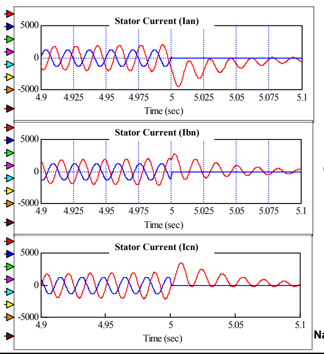
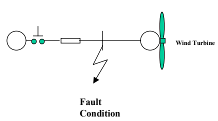
Example: Three Phase Short Circuit



Blue traces = per phase voltages

Red traces = line currents



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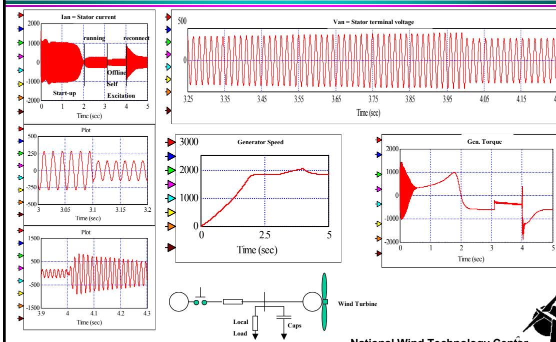
Example: Start-up, Running, Offline/Self-Excited, Reconnect



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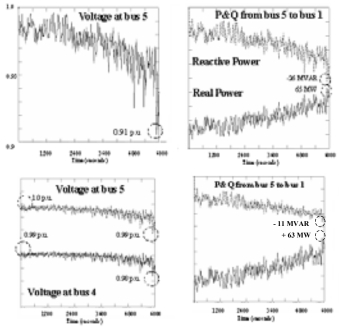
Example: Wind Farm Model w/o Reactive Power Compensation

Without Compensation

With Compensation



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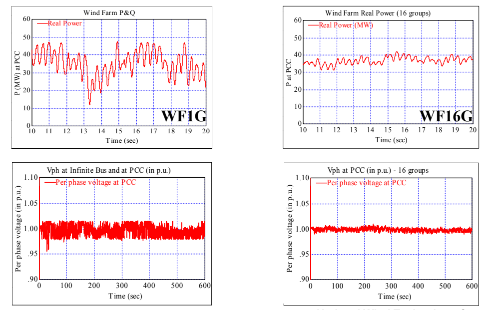
Example: Wind Farm Model Aggregation Impact

16 x1 group of turbines (no aggregation)

16 groups of turbines (with aggregation)



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Summary

Development of wind farm models:

- Generator level
- Wind farm level
- Supporting equipments (energy storage, reactive power compensation, etc.)
- Include relay protections.

Software used:

- Matlab, Mathcad, ACSL, PSSE, Vissim, RPMSim (Vissim based for hybrid system).

Case Studies:

- Dual speed WTG with induction generator
- San Clemente Island (Hybrid Diesel-Wind) project
- Self-excited induction generator for variable speed, and battery charging
- Permanent magnet generator WTG for battery charging, water pumping, grid connected
- Variable speed stall/pitch control WTG
- Aggregation impact on wind farm output
- Tehachapi wind farm
- Energy storage and reactive Power compensator.

NERC/WSCC Planning Standards

I. System Adequacy and Security — **A. Transmission Systems**

Table I. Transmission Systems Standards — Normal and Contingency Conditions

Category	Contingencies		System Limits or Impacts				
	Initiating Event(s) and Contingency Component(s)	Components Out of Service	Thermal Limits	Voltage Limits	System Stable	Loss of Demand or Curtailed Firm Transfers	Cascading[c] Outages
A - No Contingencies	All Facilities in Service	None	Normal	Normal	Yes	No	No
B - Event resulting in the loss of a single component.	Single Line Ground (SLG) or 3-Phase (3Ø) Fault, with Normal Clearing: 1. Generator 2. Transmission Circuit 3. Transformer Loss of a Component without a Fault.	Single Single Single Single	Applicable Rating[a] (A/R) A/R A/R A/R	Applicable Rating[a] (A/R) A/R A/R A/R	Yes Yes Yes Yes	No[b] No[b] No[b] No[b]	No No No No
	Single Pole Block, Normal Clearing: 4. Single Pole (dc) Line	Single	A/R	A/R	Yes	No[b]	No
C - Event(s) resulting in the loss of two or more (multiple) components.	SLG Fault, with Normal Clearing: 1. Bus Section 2. Breaker (failure or internal fault)	Multiple Multiple	A/R A/R	A/R A/R	Yes Yes	Planned[d] Planned[d]	No No
	SLG or 3Ø Fault, with Normal Clearing, Manual System Adjustments, followed by another SLG or 3Ø Fault, with Normal Clearing: 3. Category B (B1, B2, B3, or B4) contingency, manual system adjustments, followed by another Category B (B1, B2, B3, or B4) contingency	Multiple	A/R	A/R	Yes	Planned[d]	No
	Bipolar Block, with Normal Clearing: 4. Bipolar (dc) Line Fault (non 3Ø), with Normal Clearing: 5. Double Circuit Towerline	Multiple Multiple	A/R A/R	A/R A/R	Yes Yes	Planned[d] Planned[d]	No No
	SLG Fault, with Delayed Clearing: 6. Generator 8. Transformer 7. Transmission Circuit 9. Bus Section	Multiple Multiple	A/R A/R	A/R A/R	Yes Yes	Planned[d] Planned[d]	No No

NERC/WSCC Planning Standards

I. System Adequacy and Security — **A. Transmission Systems**

D[e] - Extreme event resulting in two or more (multiple) components removed or cascading out of service	3Ø Fault, with Delayed Clearing (stuck breaker or protection system failure): 1. Generator 3. Transformer 2. Transmission Circuit 4. Bus Section 3Ø Fault, with Normal Clearing: 5. Breaker (failure or internal fault) Other: 6. Loss of towerline with three or more circuits 7. All transmission lines on a common right-of-way 8. Loss of a substation (one voltage level plus transformers) 9. Loss of a switching station (one voltage level plus transformers) 10. Loss of all generating units at a station 11. Loss of a large load or major load center 12. Failure of a fully redundant special protection system (or remedial action scheme) to operate when required 13. Operation, partial operation, or misoperation of a fully redundant special protection system (or remedial action scheme) for an event or condition for which it was not intended to operate 14. Impact of severe power swings or oscillations from disturbances in another Regional Council.	Evaluate for risks and consequences. • May involve substantial loss of customer demand and generation in a widespread area or areas. • Portions or all of the interconnected systems may or may not achieve a new, stable operating point. • Evaluation of these events may require joint studies with neighboring systems. • Document measures or procedures to mitigate the extent and effects of such events. • Mitigation or elimination of the risks and consequences of these events shall be at the discretion of the entities responsible for the reliability of the interconnected transmission systems.

Footnotes to Table I.

a) Applicable rating (A/R) refers to the applicable normal and emergency facility thermal rating or system voltage limit as determined and consistently applied by the system or facility owner.
b) Planned or controlled interruption of generators or electric supply to radial customers or some local network customers, connected to or supplied by the faulted component or by the affected area, may occur in certain areas without impacting the overall security of the interconnected transmission systems. To prepare for the next contingency, system adjustments are permitted, including curtailments of contracted firm (non-recallable reserved) electric power transfers.
c) Cascading is the uncontrolled successive loss of system elements triggered by an incident at any location. Cascading results in widespread service interruption which cannot be restrained from sequentially spreading beyond an area predetermined by appropriate studies.
d) Depending on system design and expected system impacts, the controlled interruption of electric supply to customers (load shedding), the planned removal from service of certain generators, or the curtailment of contracted firm (non-recallable reserved) electric power transfers may be necessary to maintain the overall security of the interconnected transmission systems.
e) A number of extreme contingencies that are listed under Category D and judged to be critical by the transmission planning entity(ies) will be selected for evaluation. It is not expected that all possible facility outages under each listed contingency of Category D will be evaluated.

Transient events in large wind farm installations

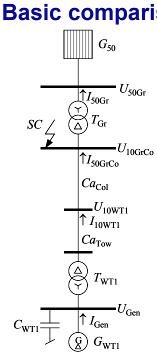
IEA Annex XXI

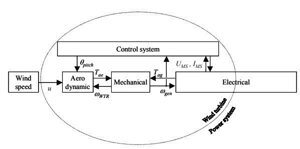
Poul Sørensen
Risø National Laboratory
Wind Energy Department

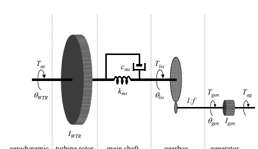
Outline

- **Comparisons of EMTDC and DIgSILENT simulations**
  - Basic comparison
  - Saturation
  - Stator flux transients
- **Validation based on measurements in Hagesholm wind farm**
  - Tripping of a wind turbine
  - Islanding of two wind turbines
  - Voltage steps
- **Report:** http://www.risoe.dk/rispubl/VEA/ris-r-1331.htm
- **Funded by (west) Danish TSO Elkraft System contract Bro-91.054 (FU 1103)**
- **Partners: NVE HVDC group, NEG Micon Control Systems and Aalborg University**

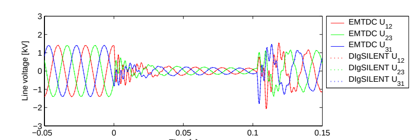
Basic comparison

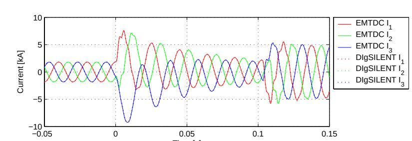






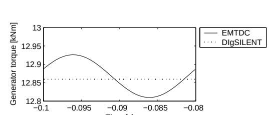
Basic comparison – generator U,I



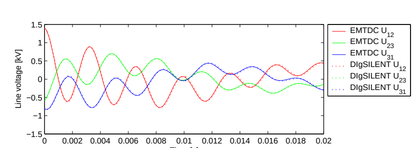


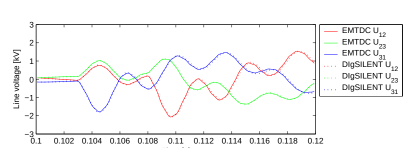
Basic comparison – steady state

- **Compares steady state before short circuit**
- **EMTDC sinusoidal variation (fundamental frequency) of powers and generator torque**
- **DC in currents cause the variation**

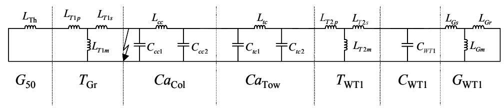


Basic comparison - resonances





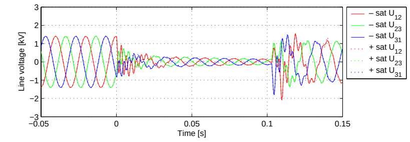
Basic comparison - resonances

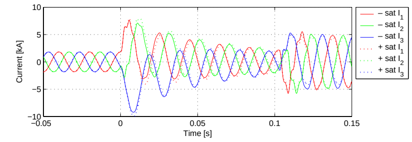


$$f = \frac{1}{2\pi\sqrt{LC}}$$

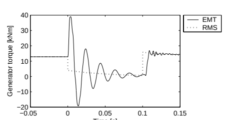
- **During short circuit $L \cong (L_{T2s}+L_{T2p}+L_{tc}+L_{cc}) || (L_{Gs}+L_{Gr})$: f=302 Hz**
- **Short circuit cleared $L \cong (L_{T2s}+L_{T2p}+L_{tc}+L_{cc}+L_{T1s}+L_{T1p}+L_{Th}) || (L_{Gs}+L_{Gr})$: f = 280 Hz**

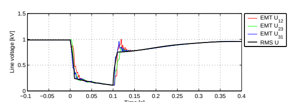
Saturation – generator U, I

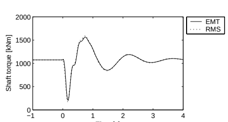


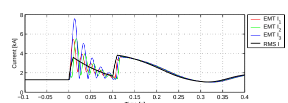


Stator flux transients (EMT)



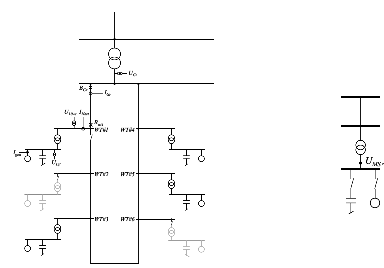




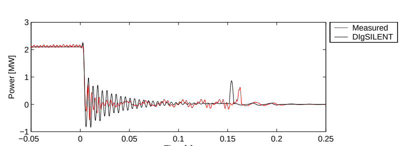


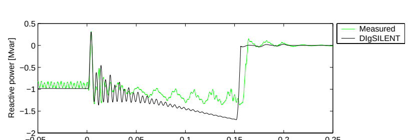
- **Generator voltages and currents**

Tripping of a wind turbine

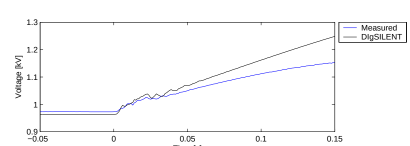


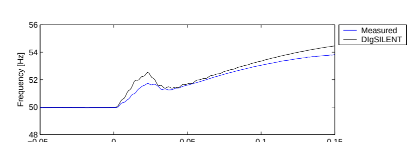
WT trip – generator power



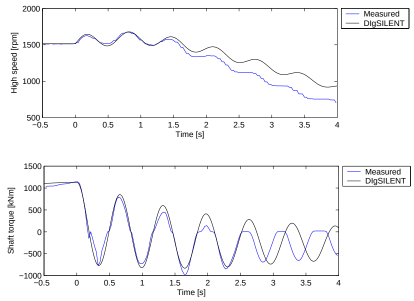


WT trip - generator voltage – and frequency

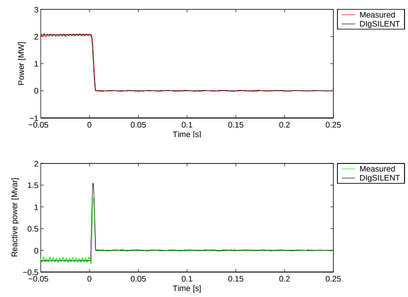




WT trip - generator speed and LS shaft torque

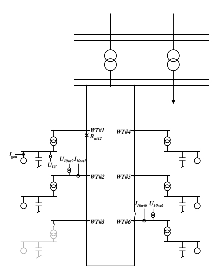


WT trip – 10 kV power

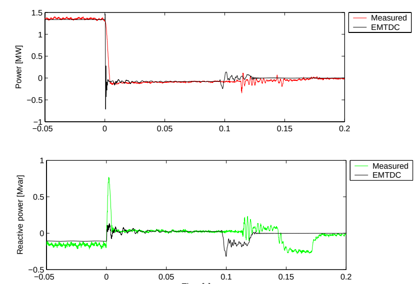


Fast arc (opened at first zero crossing)

Islanding of two wind turbines

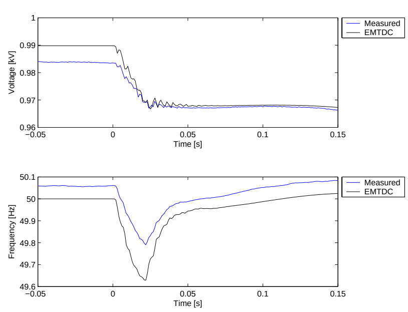


Islanding 2 wt (EMTDC simulations)

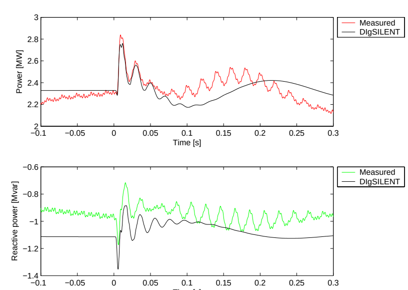


No arc in simulation (opened immediately)

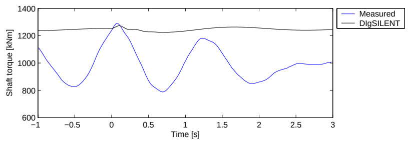
Voltage change on wt1



Voltage change on wt 1



Low speed shaft torque



- Simulated without 3p effect
- Trip happened at instant when turbulence 3p was high
- 2 % voltage change has marginal influence on shaft torque

Conclusion

- Very good agreement between basic EMTDC and DIgSILENT simulations
- Stator flux transients important for instantaneous currents, but not influence on long – term stability (if relays not tripped!!)
- Saturation in generator not available in DIgSILENT, probably reason for "over-simulated" voltage increase during islanding.
- Backlash should improve mechanical model (important because of torque zero-crossing)
- Dynamic inflow should improve aerodynamic model (important because of fast pitching)
- Validations (measurements) of short-circuit simulations missing

IEA Annex XXI meeting

Dynamic models for power system studies

Jan Pierik, Edwin Wiggelinkhuizen
ECN-Wind Energy

Johan Morren, Sjoerd de Haan
TU Delft

Jan Bozelie
Neg-Micon

NREL, 10-11 nov 2003

ECN

energy innovation

Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

ECN-TUD projects on models for power system studies:

1. Erao-2 project: model development
   - Component models
   - Current status
   - Example: Near Shore Windfarm Egmond
   - Next steps
   - 1-5-2002 — 31-12-2003
2. Erao-3 project: model verification
   - 1-1-2003 — 31-6-2006

ECN

energy innovation

Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

ERAO-2 project

- Objective:
  - development of dynamic models of wind farms with:
    - ∗ Double Fed Induction Generator (DFIG);
    - ∗ Permanent Magnet Generator (PMG);
    - ∗ Cluster Controlled Induction Generator (CCIG);
    - ∗ Induction Generator IG (reference case);
  - non-electrical part:
    - ∗ Constant Speed Stall (CSS);
    - ∗ Variable Speed Pitch (VSP).

- Tasks:
  - compare normal operation and response to grid faults
    in a case study:
    Near Shore Wind farm (20 km from NL coast near Egmond)

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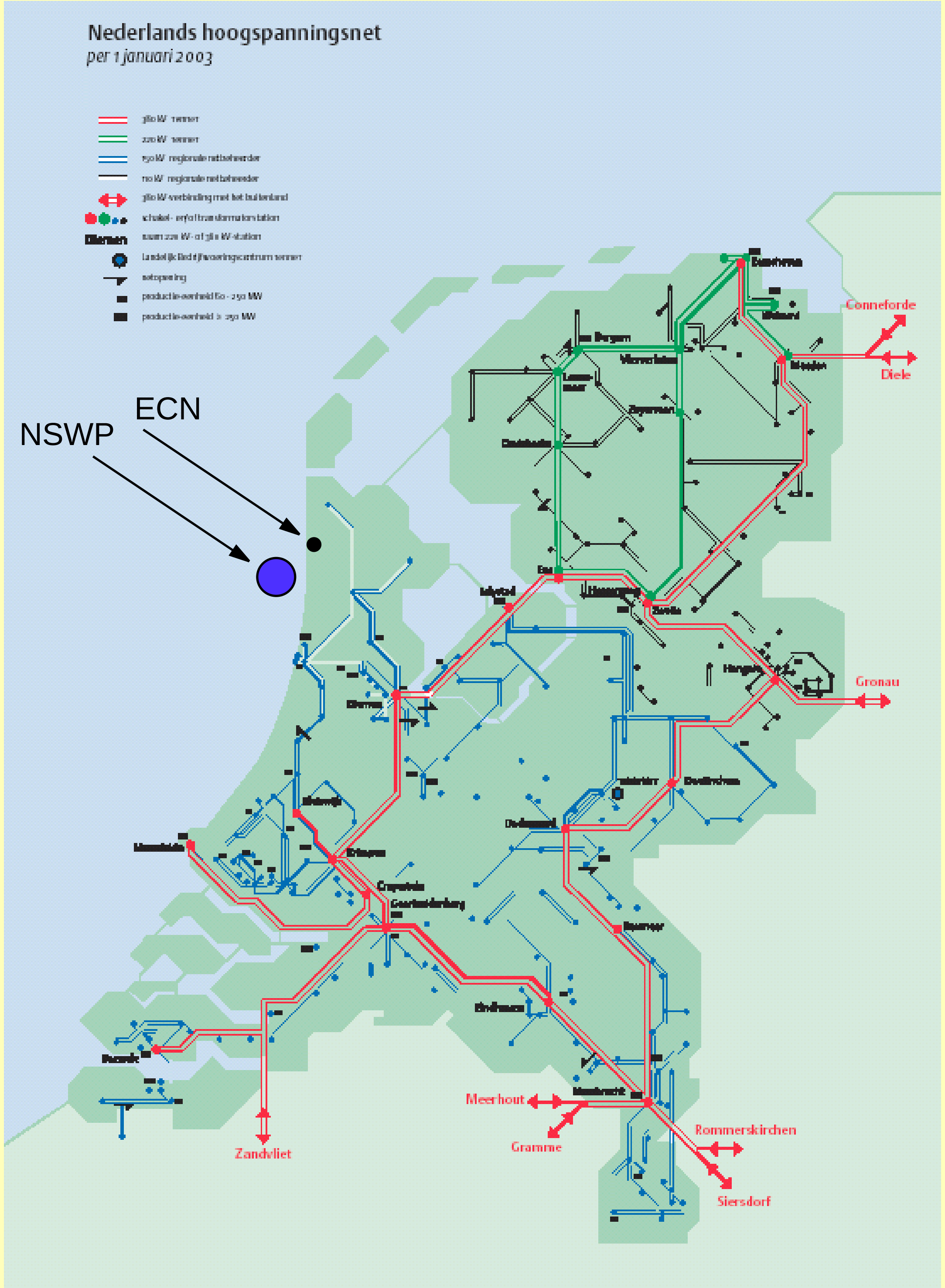
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl



ECN

energy innovation

Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Component Models (1):

- Wind farm model includes:
  - aerodynamic wake model of wind farm (pre-processor)
  - full dynamic model of turbine, including:
    * rotor effective wind (rotational sampling)
    * pitch control (if present)
    * speed control (if present)
    * tower motion
    * drive train dynamics
- two turbine types:
  - **Constant Speed Stall**
  - **Variable Speed Pitch**

ECN

energy innovation

Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Component Models (2):

- Electrical models include:
  - generators: IG, DFIG, PM;
  - IGBT converters;
  - converter control;
  - transfomers;
  - cables;
  - a simple grid model: controlled synchronous machine
- all electrical components are modelled in Simulink;
- converters are modelled as controllable V-sources;
- all electrical components are modelled in dq0 reference frame.

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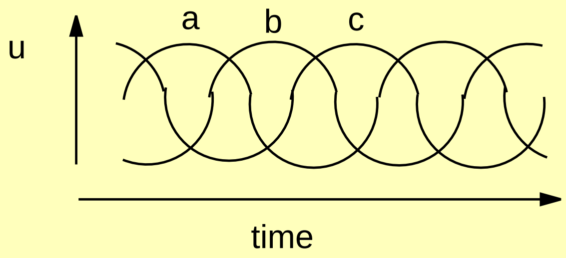
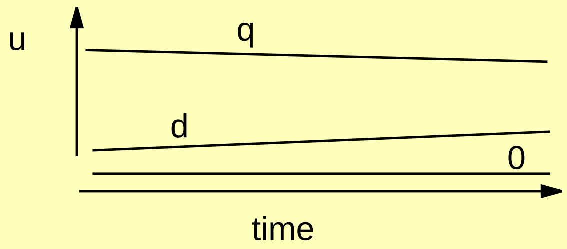
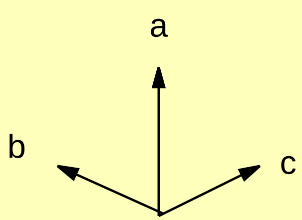
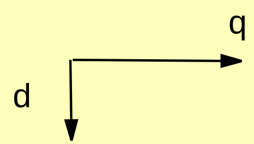
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

abc versus dq0 variables









sinusoidally changing
voltage and current

quasi constant

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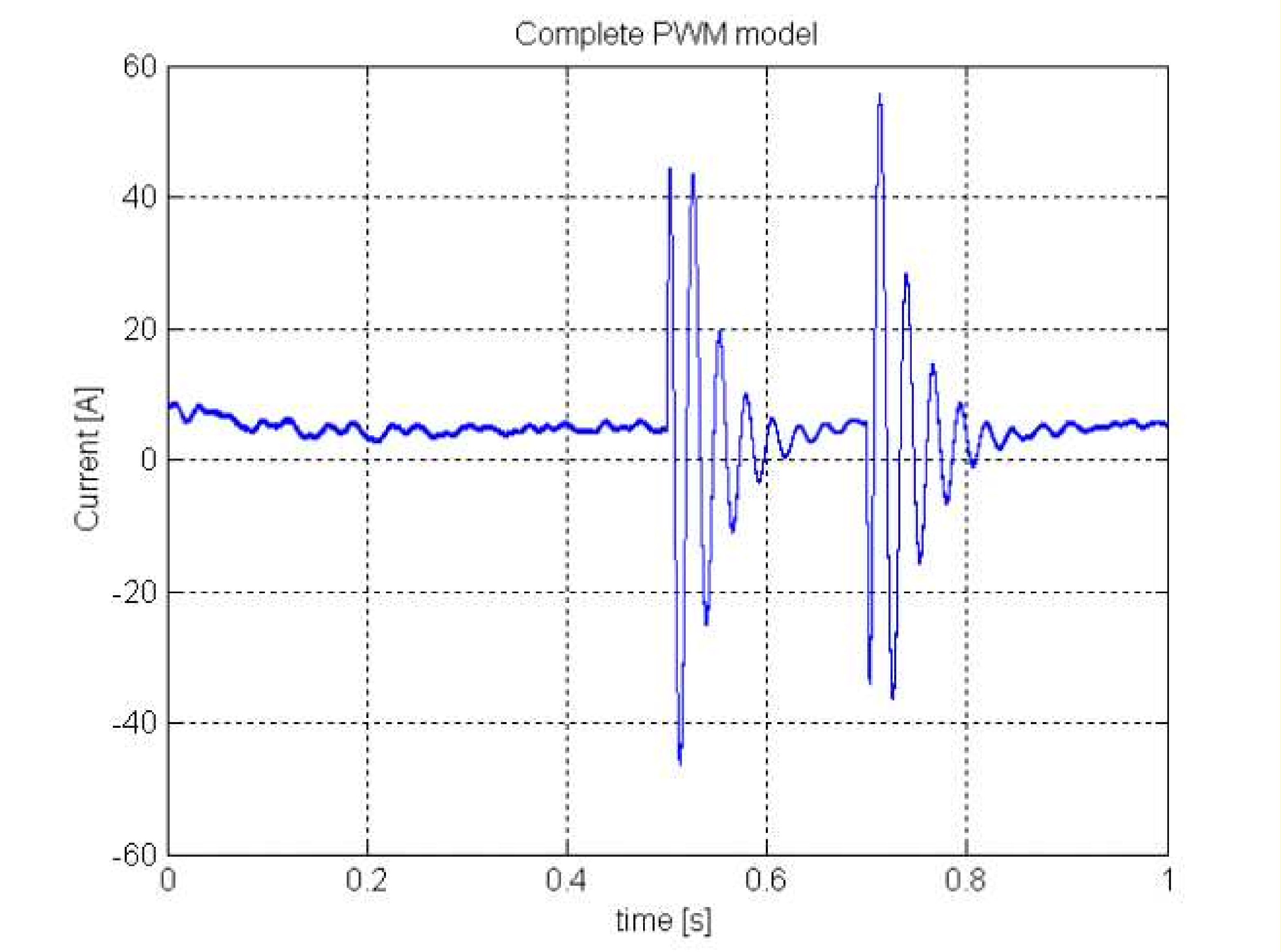
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Full model (switching converter) versus voltage source model

Voltage dip on DFIG model



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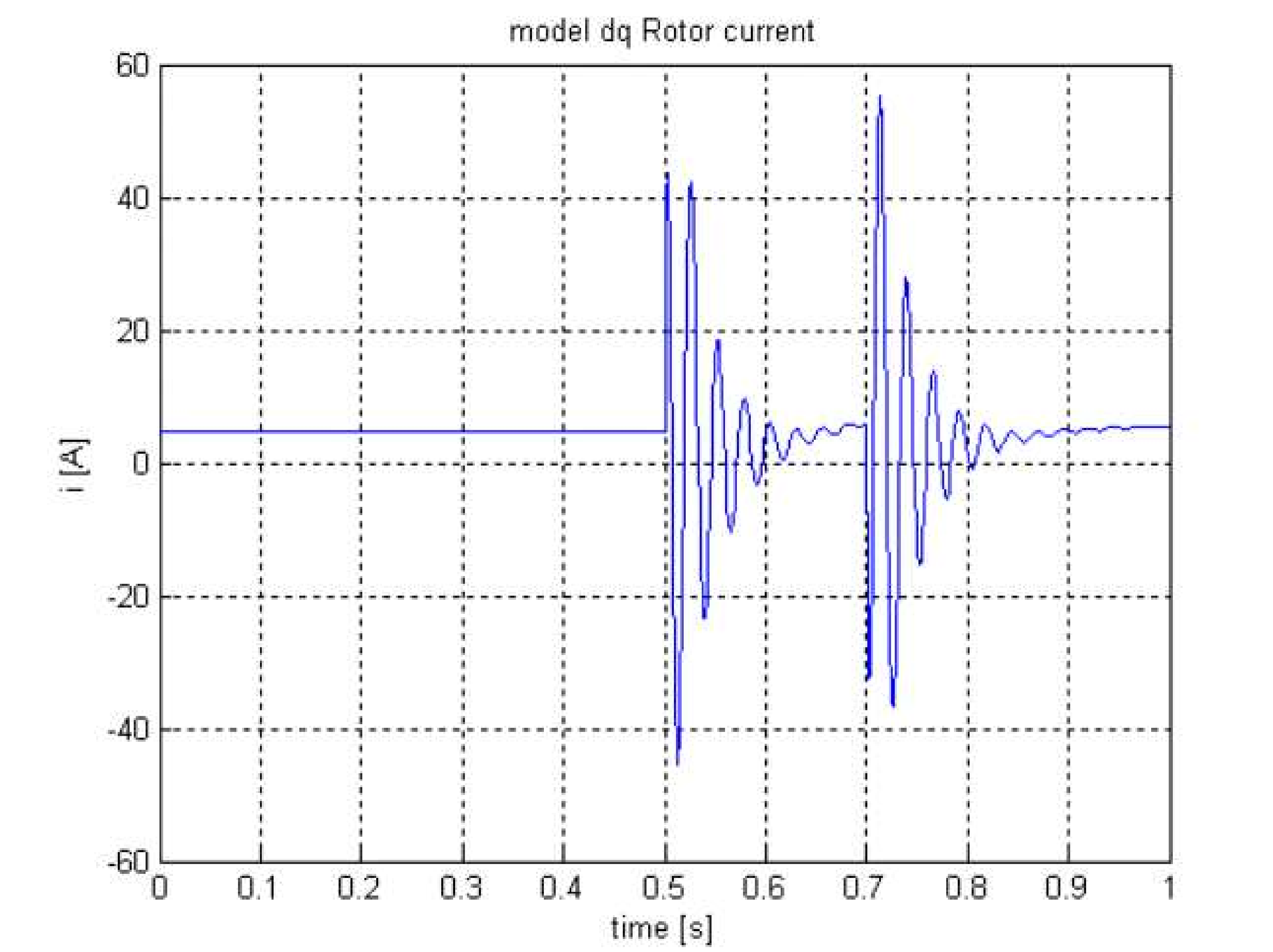
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Full model (switching converter) versus voltage source model

Voltage dip on DFIG model



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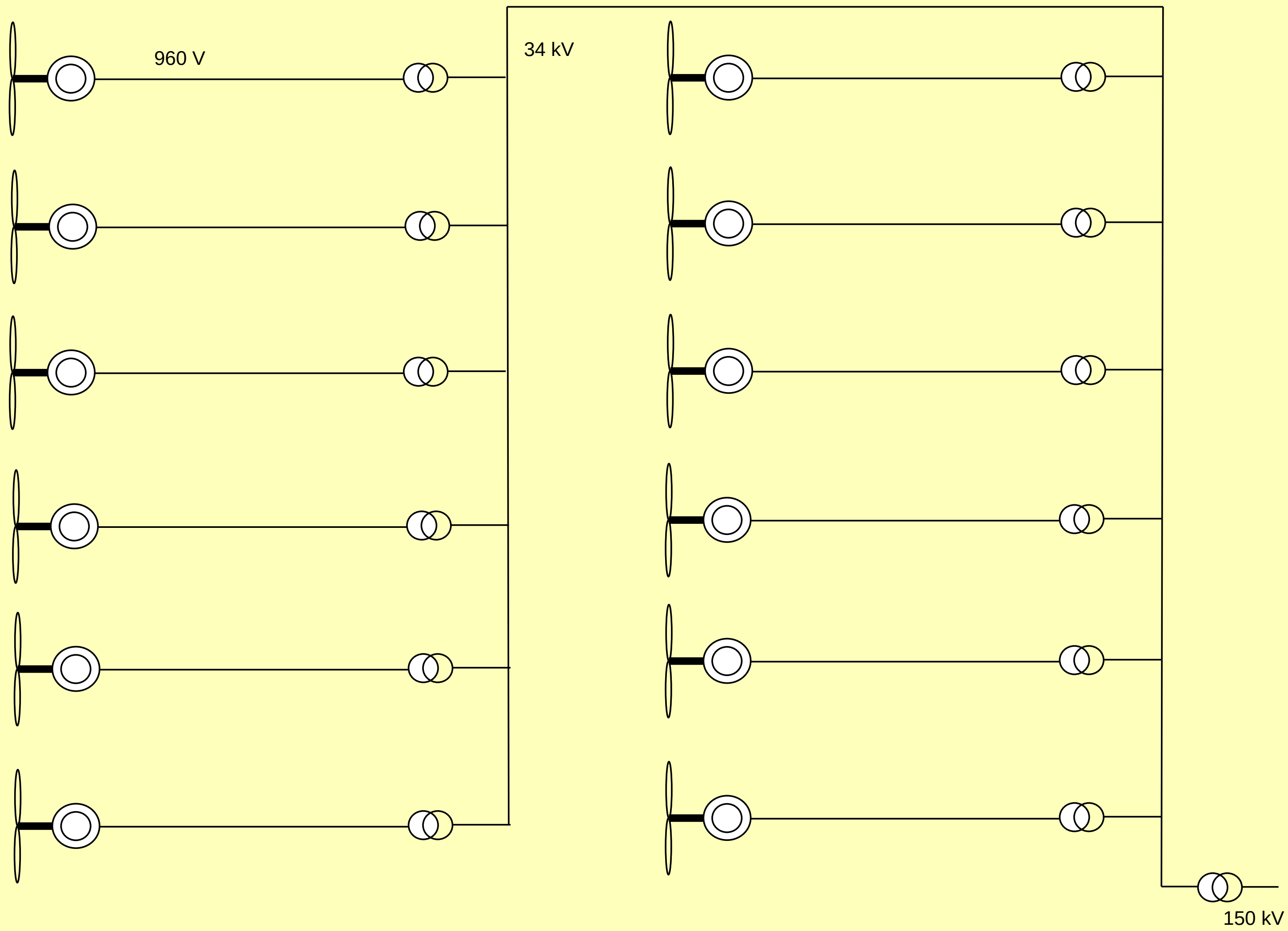
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Near Shore WF - 1 string of 12 turbines - Option 1: CSS-AM



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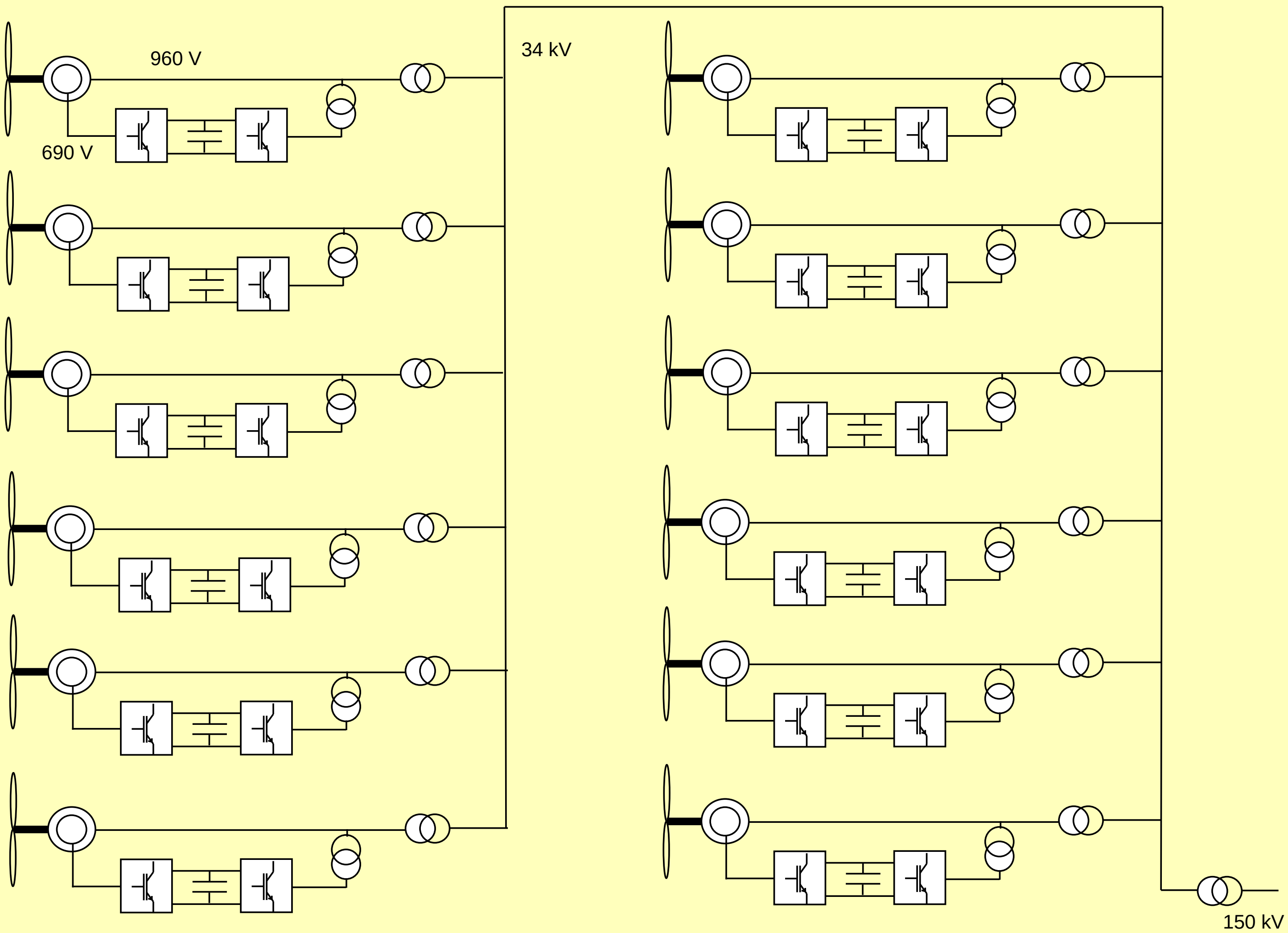
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Near Shore WF - 1 string of 12 turbines - Option 2: VSP-DFIG



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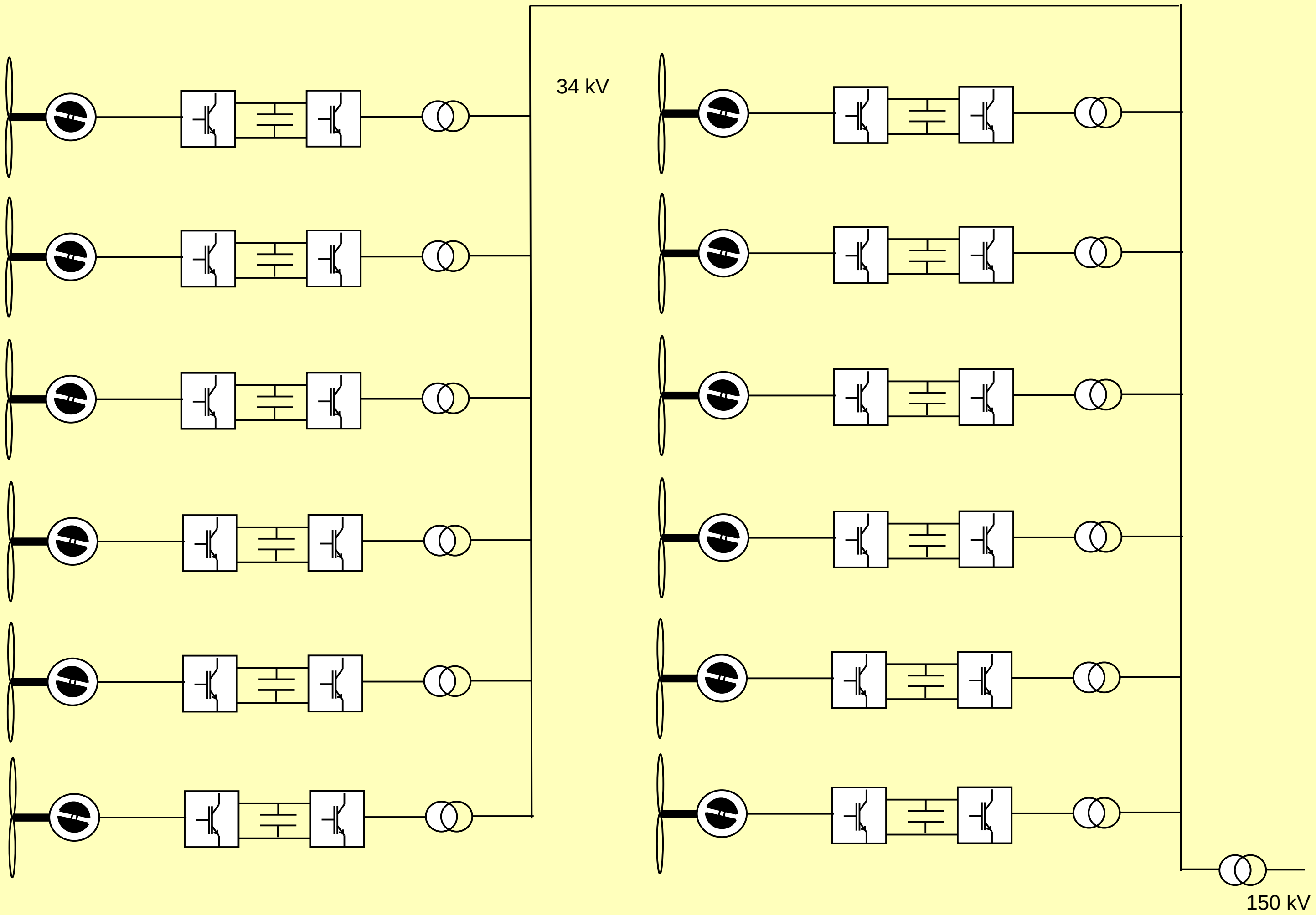
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Near Shore WF - 1 string of 12 turbines - Option 3: VSP-PM



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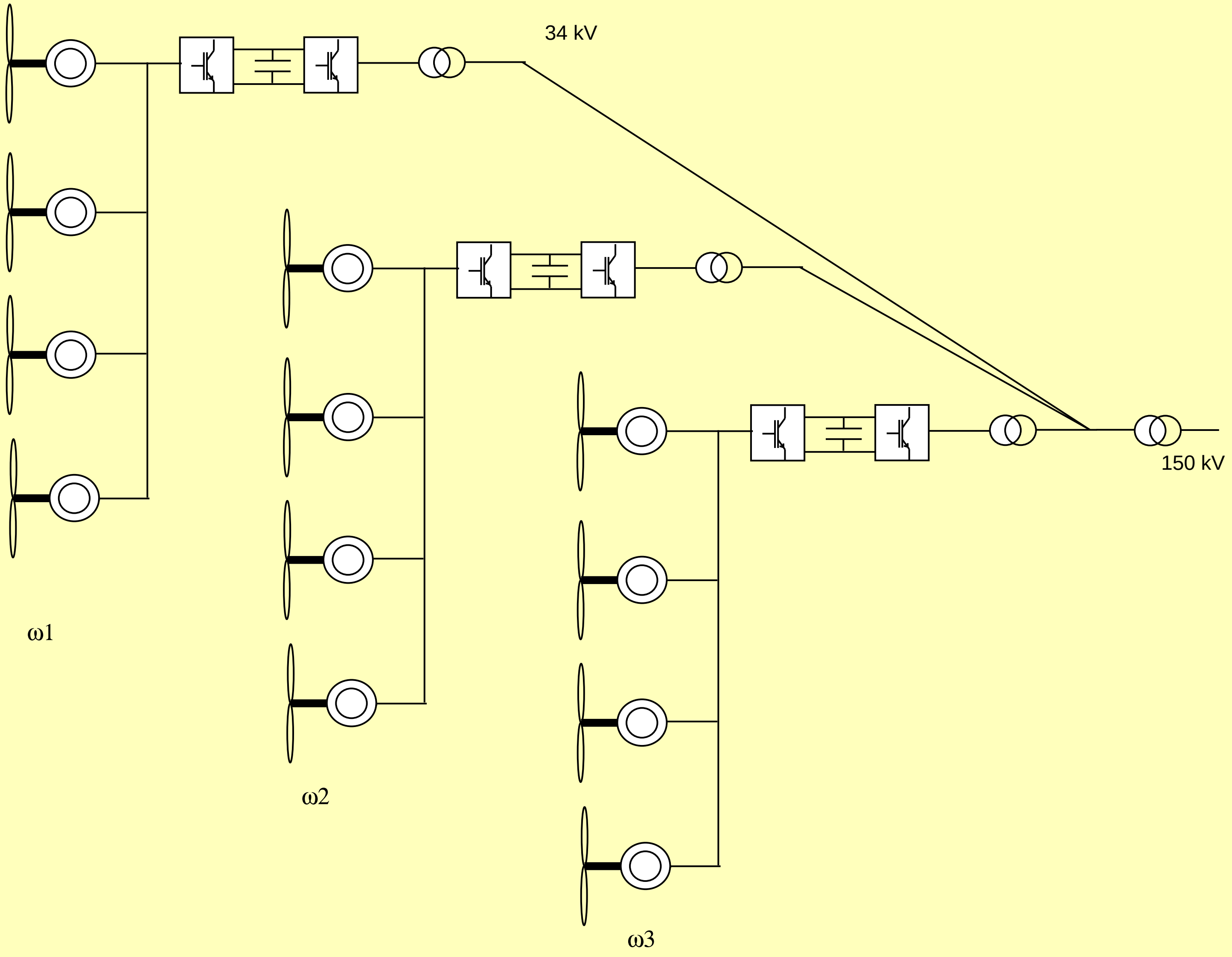
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Near Shore WF - 1 string of 12 turbines - Option 4: CSS-CC



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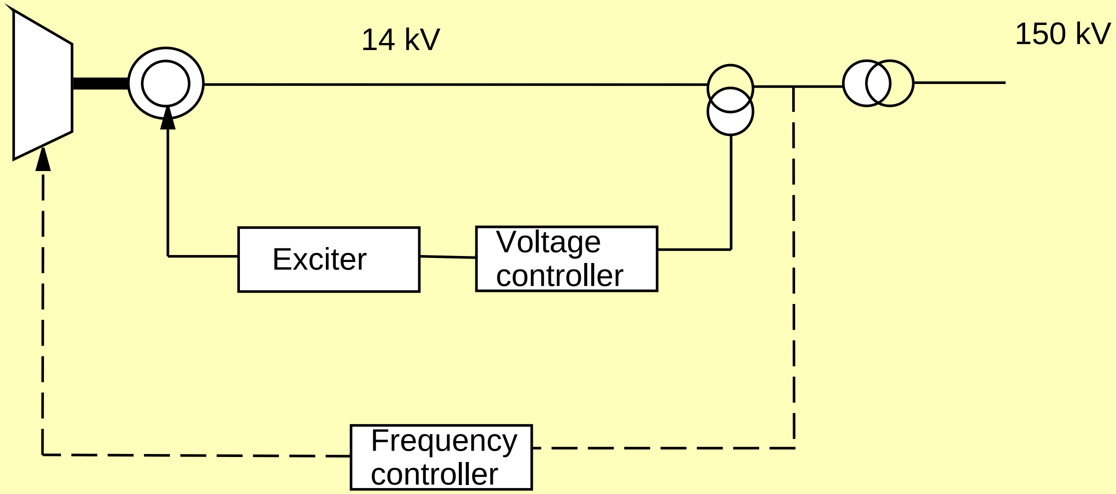
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Grid model: controlled synchronous machine



Purpose:

- compare performance of four WF options
  with interaction from the grid
  especially for frequency and voltage support

Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Current status

Component models:

Generators	DFIG PMG CCIG IG	completed completed completed completed
Grid components	cable transformer controlled SM	completed completed completed
Turbine	CSS VSP	completed completed

Near Shore WF models (1 string, 12 turbines):

VSP + DFIG WF	completed
VSP + PMG WF	completed
VSP + CCIG WF	completed (4 turbines)
CSS + IG WF	completed

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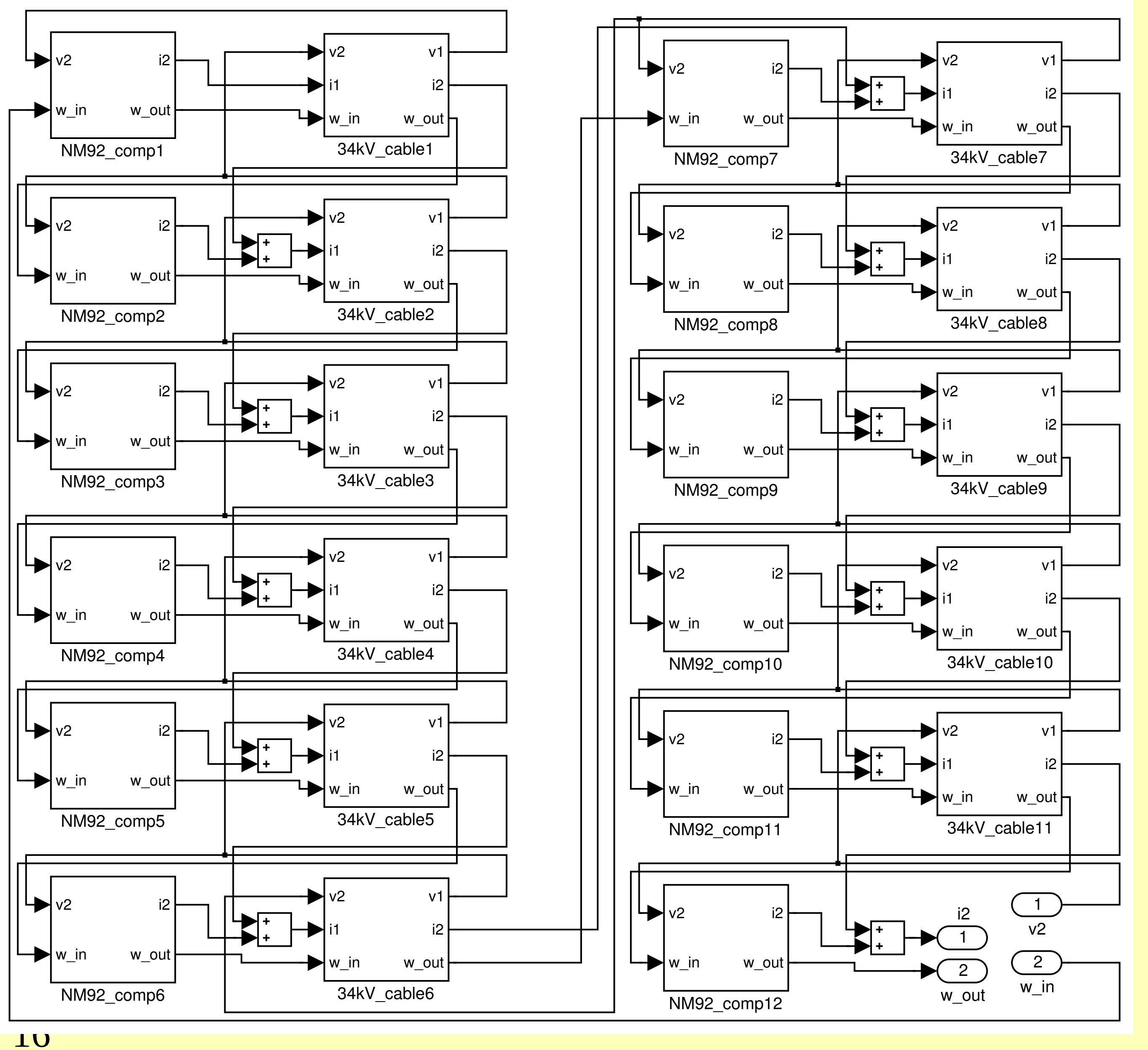
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Example of NSWF Simulink model - 1 string of 12 turbines:



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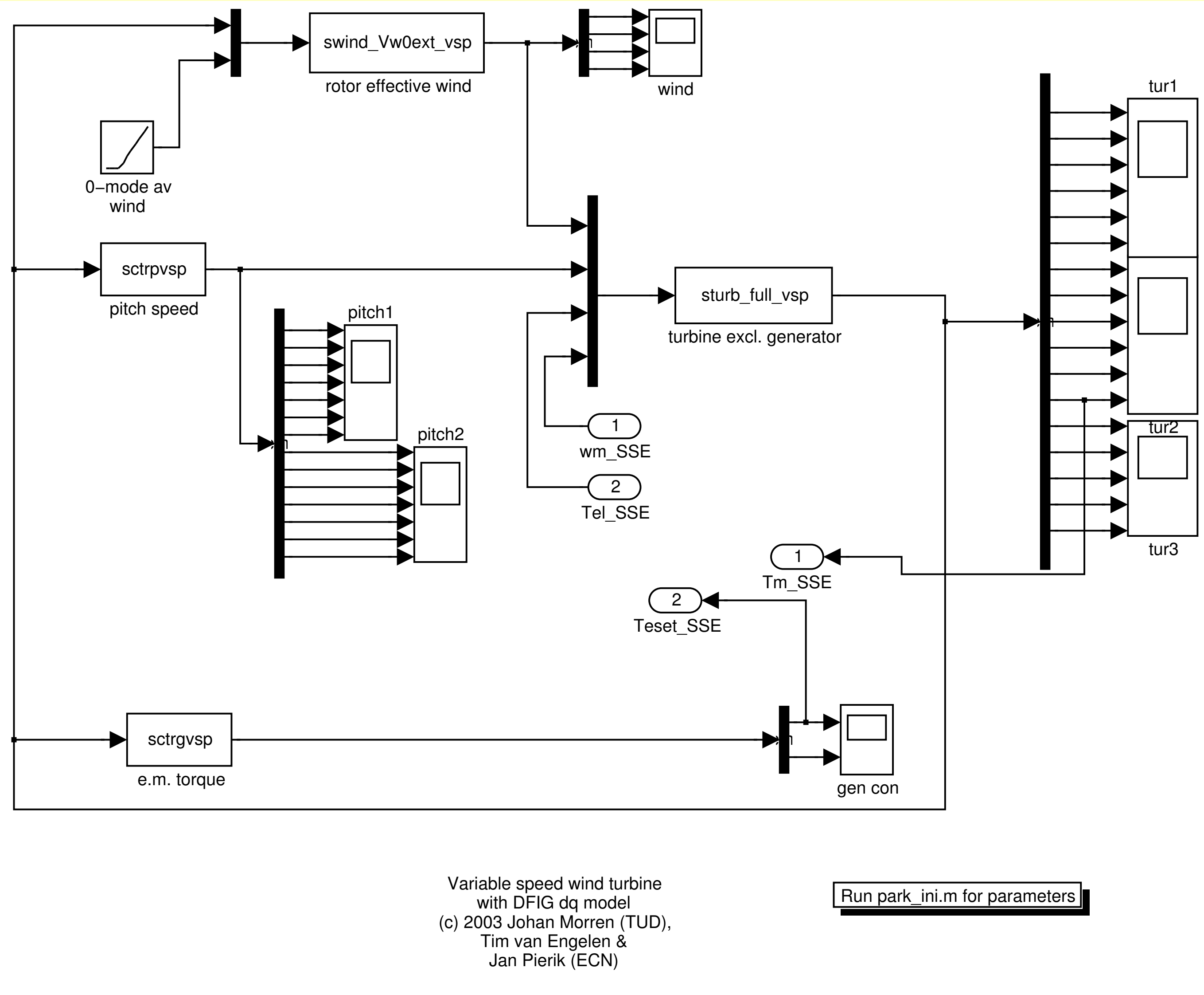
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Near Shore WF model - VSP Turbine:



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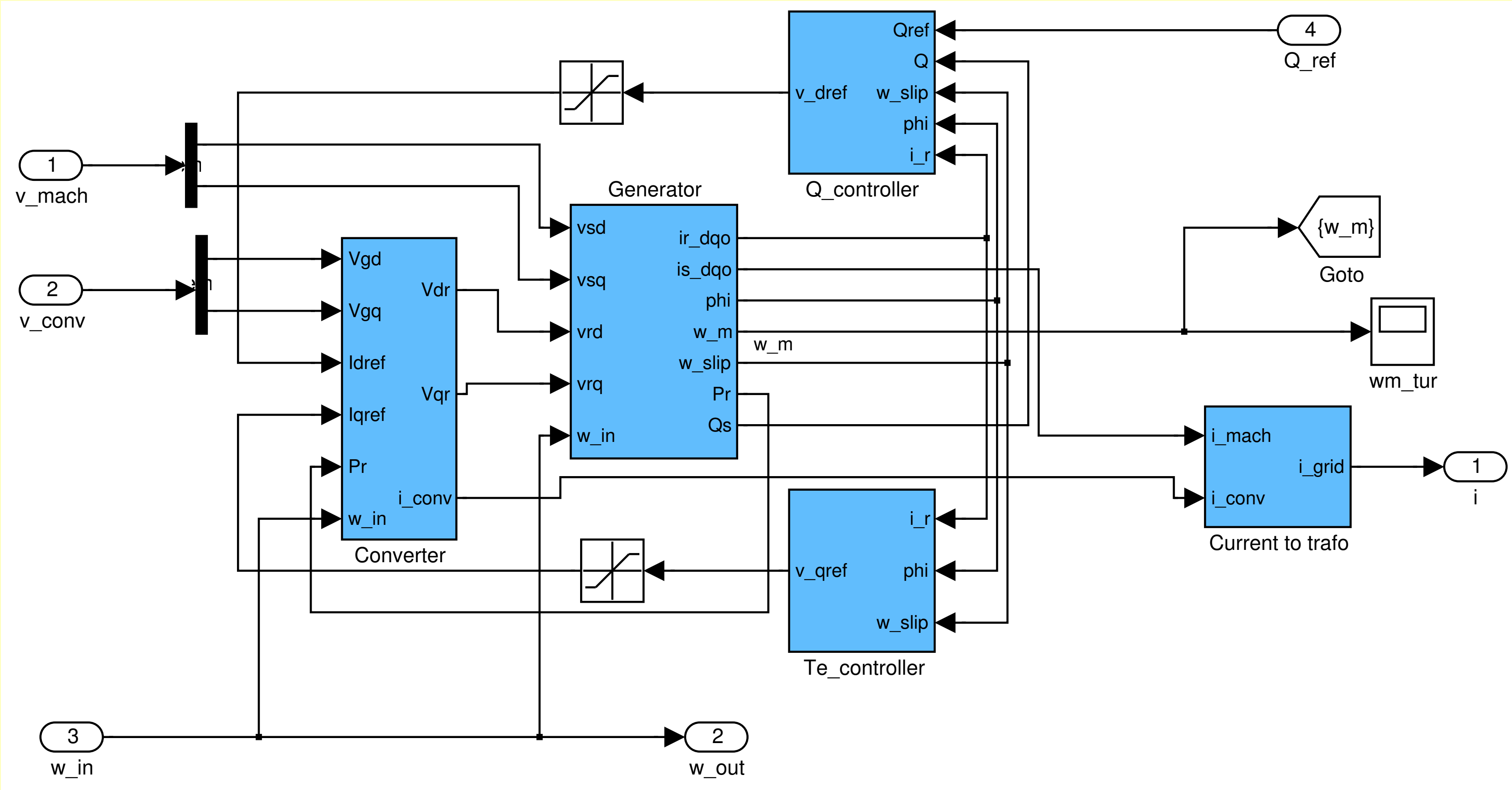
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Near Shore WF model - DFIG:



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Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Simulation example: NSWF - 1 string of 12 turbines: CSS-AM

- reference model, string of 12 constant speed stall turbines (one third of the NSWF);
- WF connected to a grid modelled as a single 220 MW synchronous generator;
- two constant loads: 75 MW total;
- response to a wind gust from 4 to 10 m/s;
- WF production from 0 to 16 MW;

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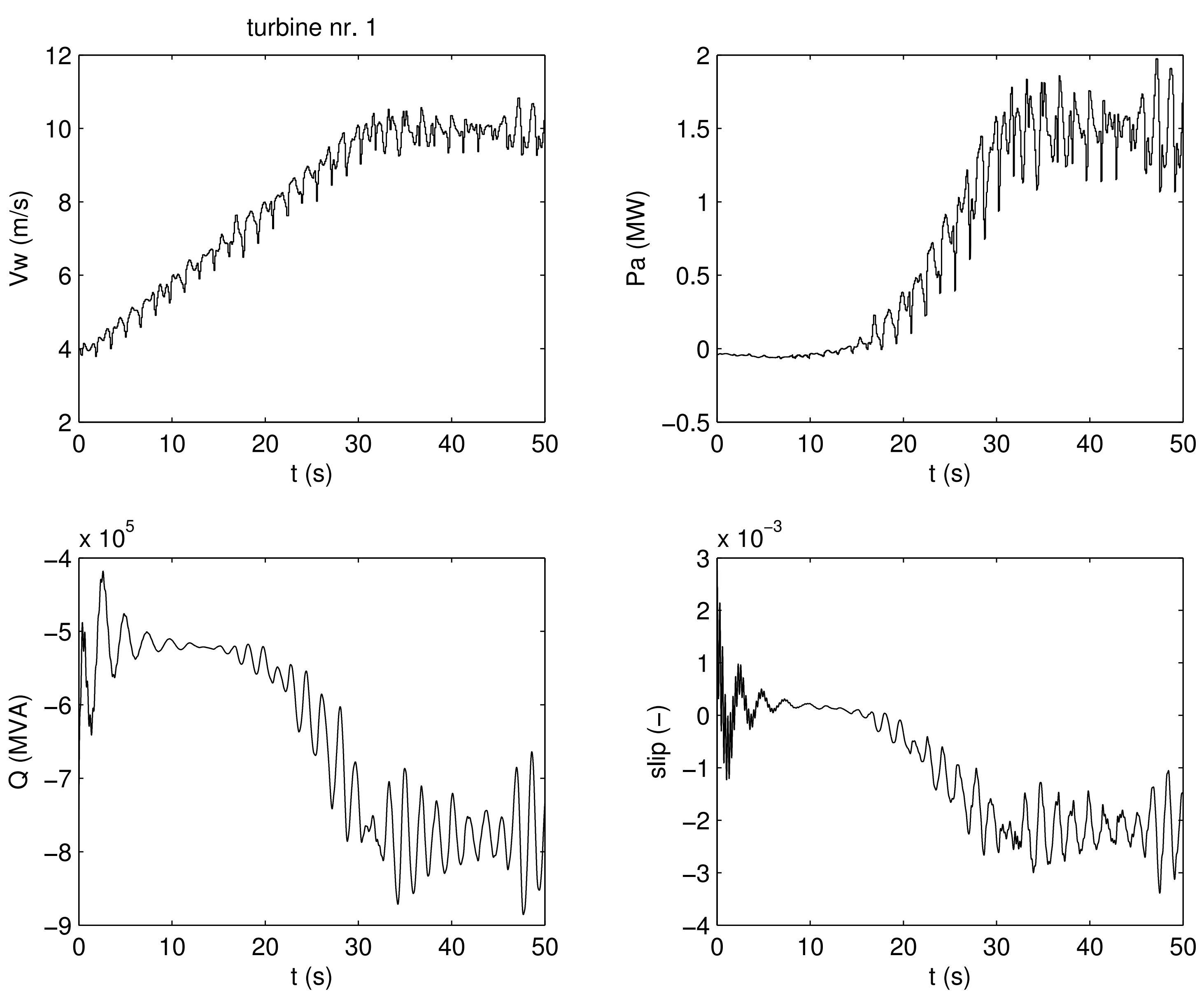
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Simulation example: NSWF - 1 string of 12 turbines: CSS-AM



ECN
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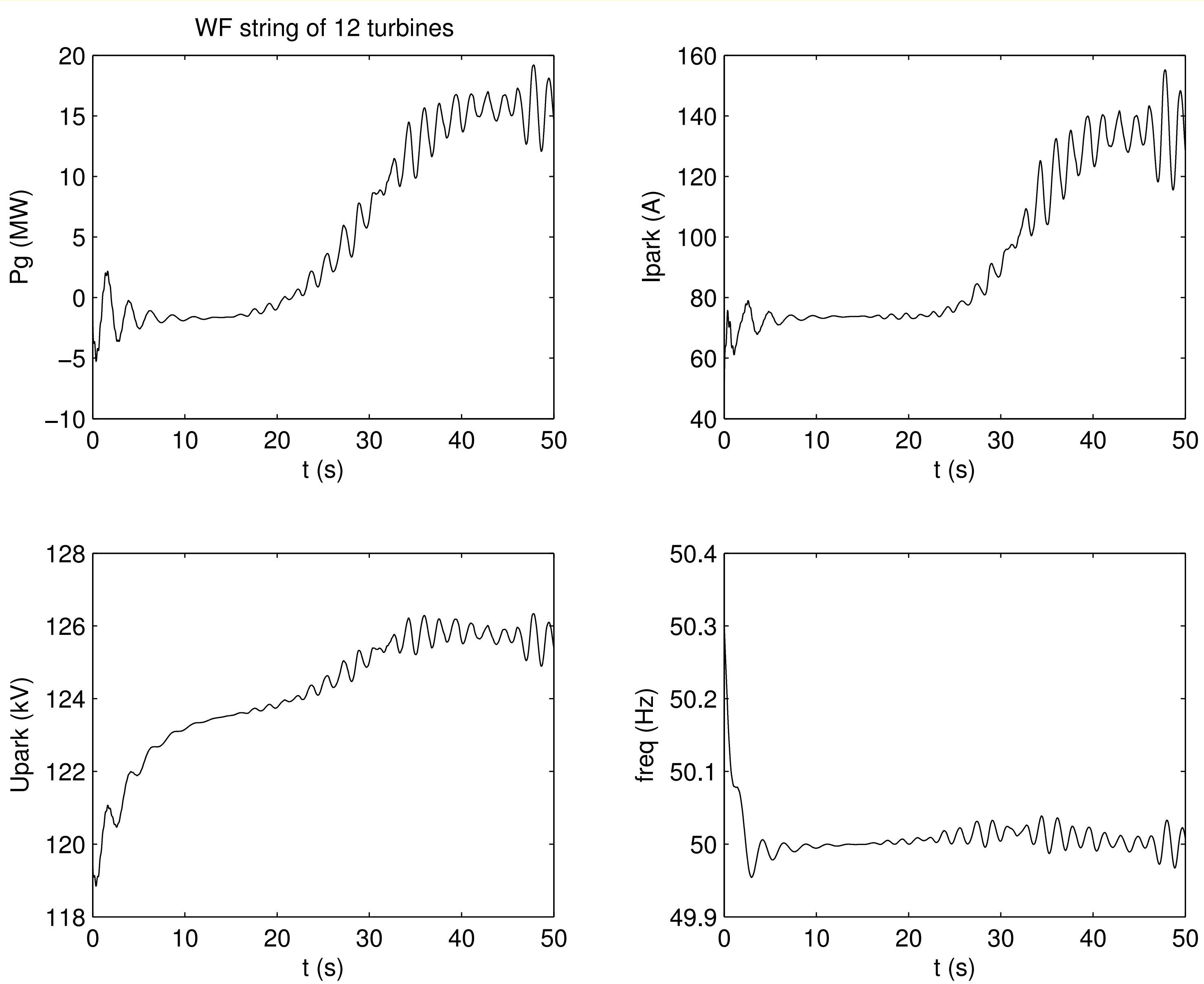
Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Simulation example: NSWF - 1 string of 12 turbines: CSS-AM



Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

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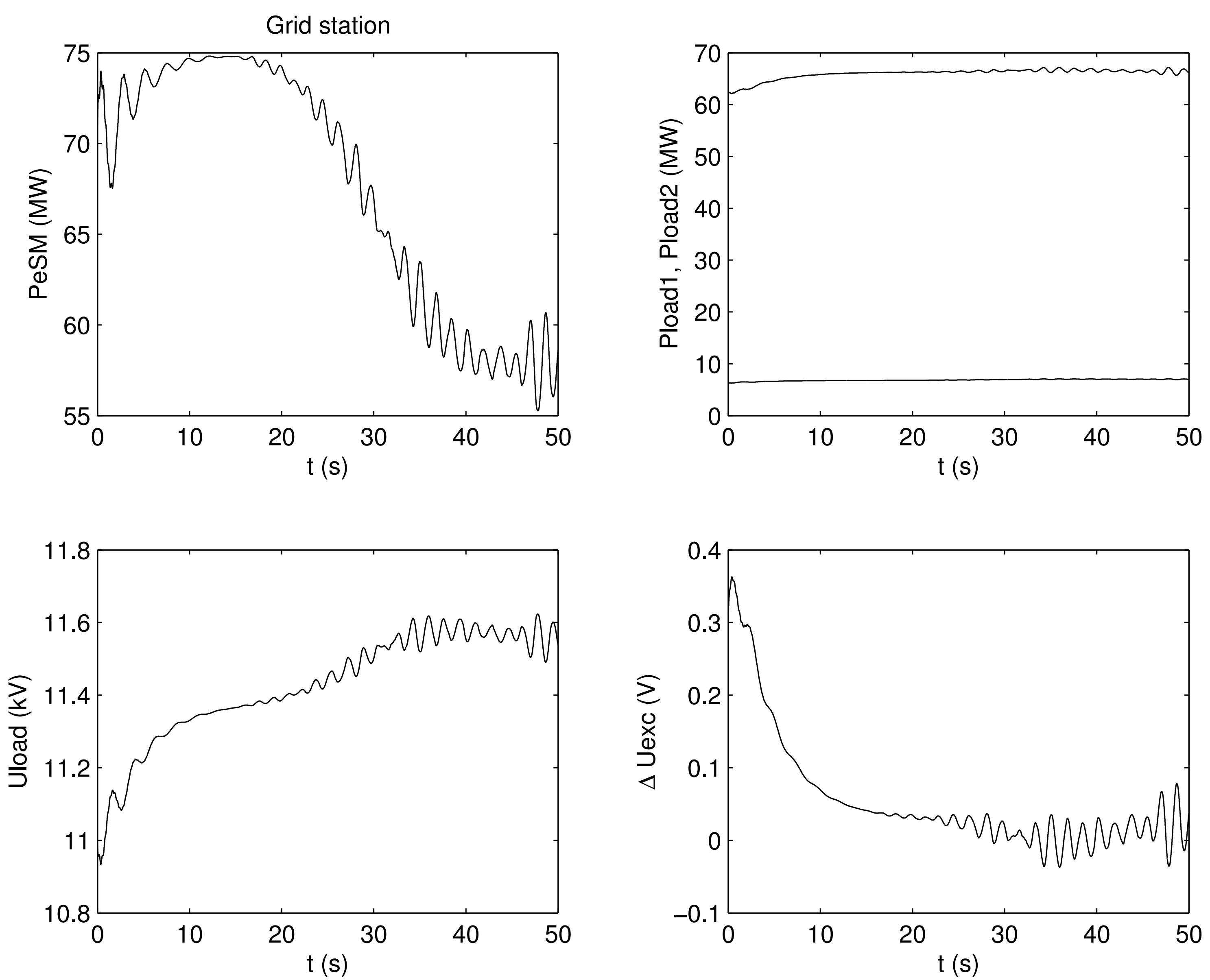
Simulation example: NSWF - 1 string of 12 turbines: CSS-AM



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Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

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Next steps Erao-2:

- compare WF dynamics during normal conditions and grid faults;
- improve WF control (especially for cluster controlled option);
- investigate grid frequency and grid voltage support.

Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Grid condition cases to be investigated:

Condition	CSS	VSP-DFIG	VSP-PM	CC-CSS
Normal operation				
Flicker	X	X	X	X
Frequency dip				
49 Hz	X	X	X	X
51 Hz	X	X	X	X
Voltage dip				
70-80%	X	X	X	X
60-70%	X	X	X	X
0-60%	X	X	X	X
3-phase short	X	X	X	X
Grid support				
Frequency	-	X	X	X
Voltage	-	X	X	X

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Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

Erao-3:

Objective:

- Verification of dynamic models of wind farms developed in Erao-2. For verifiation the measurement database of IEA Annex XXI will be used.
- Contribution of existing measurements to the IEA Annex database.

Tasks:

1. Inventory of available wind farm measurements in the Netherlands;
2. Model verification and where needed modification;
3. Documentation of results.

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Jan Pierik
ECN
Unit Wind Energy
tel. +31 224 564235
fax. +31 224 568214
pierik@ecn.nl

IEA Annex XXI Meeting

November 10-11, 2003
NREL – NWTC
Golden, Colorado

Development of Wind Plant Models for ERCOT

Robert Zavadil
Vice President & Principal Consultant
EnerNex Corporation
448 N. Cedar Bluff Road
Suite 349
Knoxville, TN 37923
Tel: (865) 671-6650
bobz@enernex.com
www.enernex.com

US Wind Integration Stuies: Primary Technical Tools

- Power Flow
  - Determines voltages, element loading for specified generation and deman
  - Most basic power system engineering tool
  - A variety of tools are used, but PSS/E and PSLF most common
- Dynamic Simulation
  - Used to show how large power system moves from state to state
  - Requires detailed models of dynamic elements
  - Suitable for simulations of very large power systems
  - **PSS/E, PSLF** are the standards for U.S. transmission entities
- Electromagnetic Transients
  - Detailed studies of electrical, mechanical, and control interactions
  - Very detailed models of all power system elements
  - Detailed nature of modeling prevents application to large power systems
  - Examples: EMTP, ATP, PSCAD

ERCOT Model Development Project - History

- Discussions of need for better wind plant models in system studies at least as far back as August, 2001
  - Ongoing issues with forced curtailment
  - Recognition that curtailments have linkage to models
- Project scope developed in early 2002
- RFP issued April, 2002
- Project awarded June, 2002
- Project kick off August 1, 2002
- Project completion September, 2003

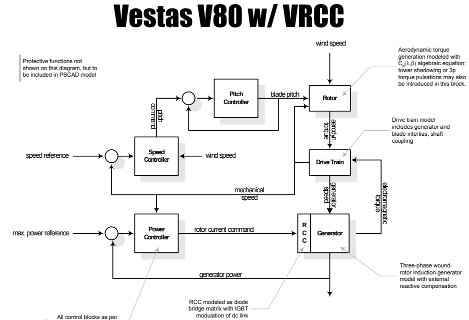
Project Objectives

- Develop models for four categories of commercial wind turbines appropriate for:
  - Steady state analysis (power flow)
  - Transient stability
  - Small signal stability
  - Stabilities studies including long and short-term dynamics
- Validate models with available event data from field measurements
- Document and deliver as "User Models" for PSS/E

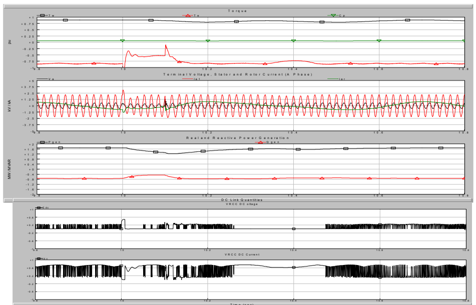
General Approach

1. Develop detailed models for individual wind turbines in PSCAD/EMTDC
2. Execute cases with detailed models and analyze results
3. Use simulation results to reduce the order of the turbine models for the types of events to be studied
4. Construct reduced-order models in PSS/E
5. Compare PSS/E and PSCAD/EMTDC results; refine models if necessary
6. Validate PSS/E models against field measurements

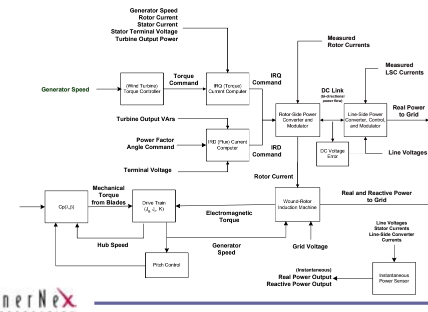
Vestas V80 w/ VRCC



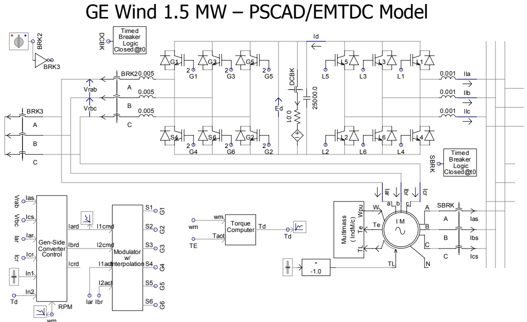
V80 VRCC Response to Fault



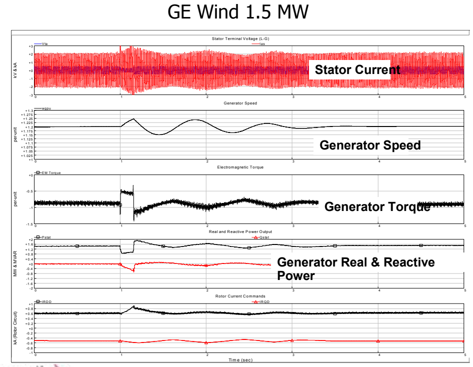
GE 1.5 MW Turbine – Block Diagram



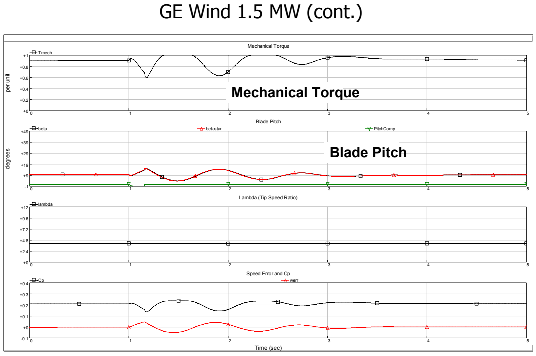
GE Wind 1.5 MW – PSCAD/EMTDC Model



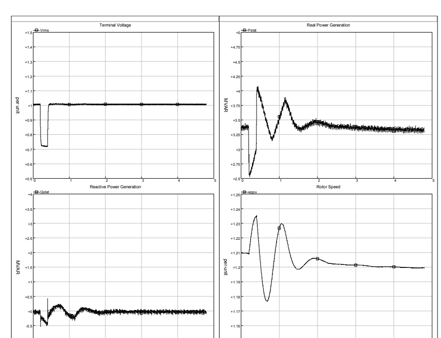
GE Wind 1.5 MW



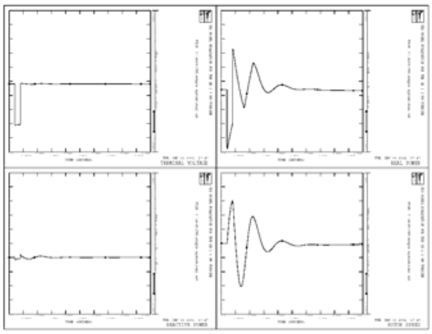
GE Wind 1.5 MW (cont.)



PSCAD Results for Comparison w/ PSS/E



Prototype PSS/E Model Results



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Validation of ERCOT Dynamic Models

- Actual measurements are ultimate measure of model validity
- Quantities of interest
  - Terminal characteristics – voltage current, P, Q
  - Mechanical – speed, pitch
  - Wind speed
- Challenges
  - Both individual turbine and plant level measurements desirable for computer model validation
  - Not feasible to collect both here due to budget and logistical constraints
  - Individual turbine measurement data hard to come by, even from vendors
- Electrical data from interconnect bus best compromise in terms of value and cost

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Data Collection

- Dranetz-BMI Signature System installed at each site
  - 1 InfoNode and 2 DataNodes
  - Installed at interconnect substation
- Data Types
  - 1-sec resolution average voltage, current, power quantities
  - 5-min resolution of Min/Max/Avg of every cycle for all steady-state quantities
  - Event-triggered disturbance data including 10-second rms voltage and current for rms voltage variations (1/2 cycle values)
- Collection period
  - Instruments installed at 3 sites in Dec 2003 and 4th site Mar 2004
  - Data collection through end of 2003 on current project and likely extension for 2004 (NREL) and 2005 (ERCOT)

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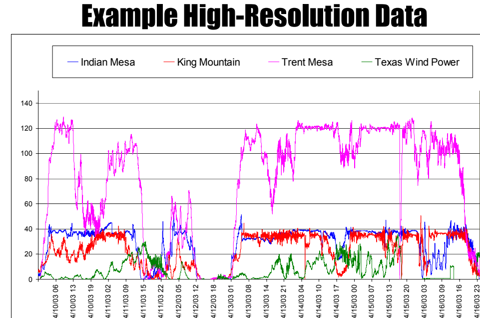
Example High-Resolution Data



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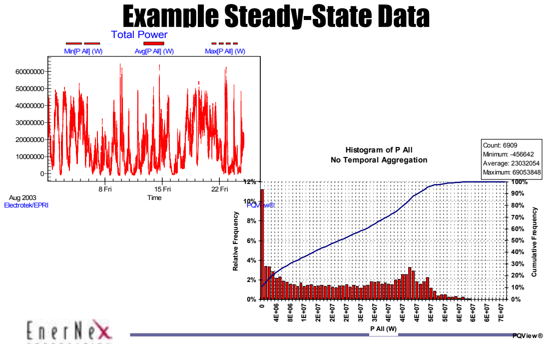
Example Steady-State Data



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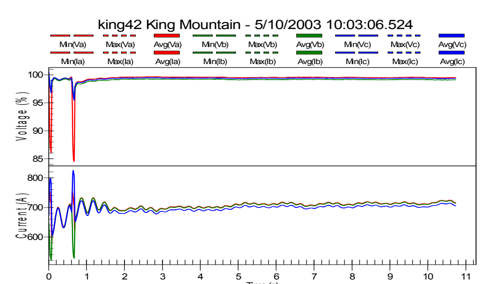
Example Disturbance Data



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Project Status

- 8 months of monitoring completed
- Detailed PSCAD and reduced-order PSS/E single turbine models completed for all 4 turbine types
- Analytical validation of PSS/E turbine models against detailed models completed for all 4 turbine types
- ERCOT wind plant models completed with finalization of TWPP remaining
- Plant model validation against measurements completed
- Presentation

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Ongoing Needs

- Model application expertise
- Continuing model validation
- Keeping up with new wind energy technology developments
- Addressing related issues
  - Short-circuit behavior
  - Advanced wind turbine technologies
  - Advanced wind plant designs

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Looking ahead...

- Enlisting others in the process
  - Other transmission providers, operators
  - Turbine vendors / customers
  - Industry working groups (e.g. IEEE PES)
- Addressing other power system engineering needs related to wind energy
  - Short-circuit models
  - Operations models
  - Wind plant design
  - Turbine and wind plant requirements/standards
- UWIG Role?

EnerNex CORPORATION

GE Power Systems Energy Consulting

GE Wind Energy Technology and Dynamic Modeling

IEA Annex XXI
Boulder, Colorado

November 11, 2003
William W. Price

GE Wind Technology

GE WIND - 1.5 / 1,5s / 1.5sl Series

Main Data:

- **Tower options:**
  GE Wind 1.5 — 67,4/80/85 m.
  GE Wind 1.5s — 67,4/80/85/100 m.
  GE Wind 1.5sl — 61,4/80/85/100 m.
- **Rotor diameter options:**
  GE Wind 1.5 — 65,0 m.
  GE Wind 1.5s — 70,5 m.
  GE Wind 1.5sl — 77,0 m.
- **Generator capacity:** 1500 kW, 50/60 Hz
- **Control:** Pitch
- **Rotor Speed:** Variable 11-20 rpm
- **Swept area:** 3.318/3.902/ 4.657 qm

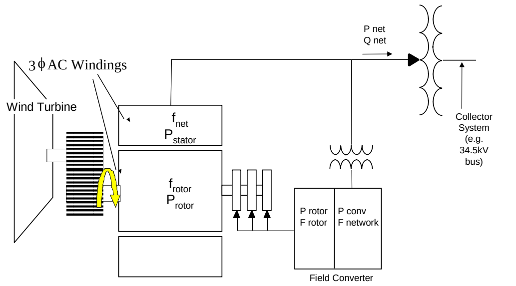
GE Wind Technology

GE WIND - 3.6 Offshore

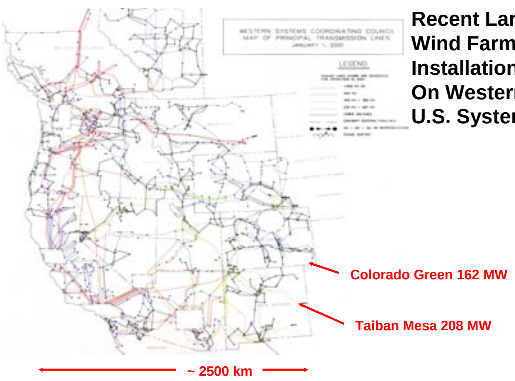
Main Data:

- **Tower options:** **100-140m**
- **Rotor diameter:** 104 m.
- **Generator capacity:** 3600 kW
- **Control:** Pitch
- **Rotor speed:** 8,5 - 15,5 Rpm
- **Swept area:** 7.854 sq.m

GE Wind Technology



Basic Components of a GE Wind Turbine Generator



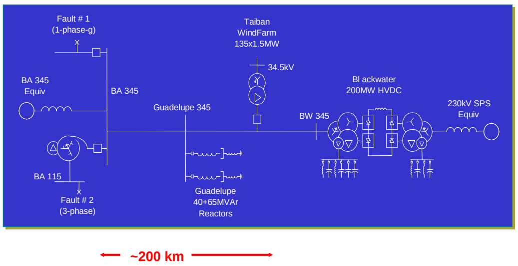
Recent Large Wind Farm Installations On Western U.S. System

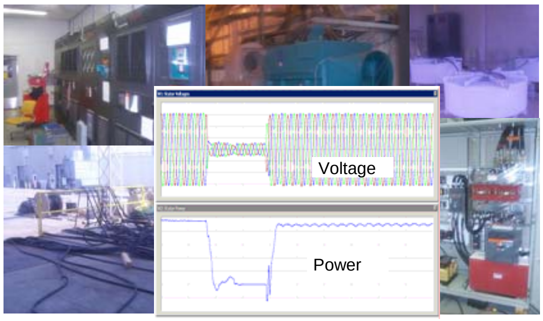
Interconnection Issues – Dynamic Performance

- **Voltage Regulation**
  - **Steady-state reactive power capability**
  - **Dynamic voltage response**
  - **Flicker**
- **Stability**
  - **Maintaining Synchronism**
  - **Damping**
- **Fault Tolerance/Low-Voltage Ride-Through**
- **Variable Power**

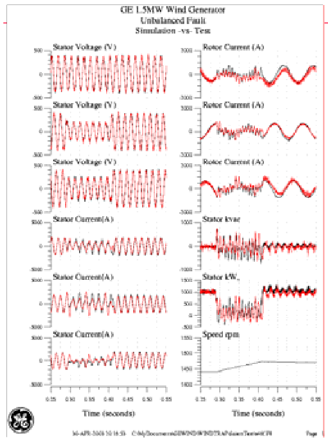
Problems are different and challenging for geographically large and weak (low short-circuit ratio) systems

Low Voltage Ride-Through
- Requirements driven by system needs





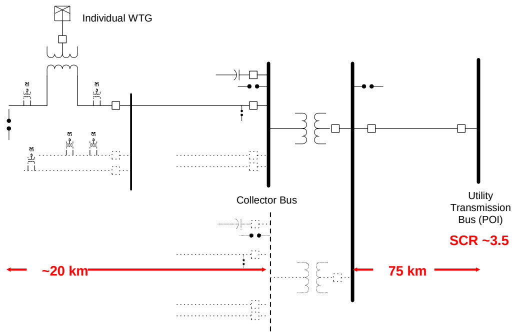
Low Voltage Ride-Through Factory Test

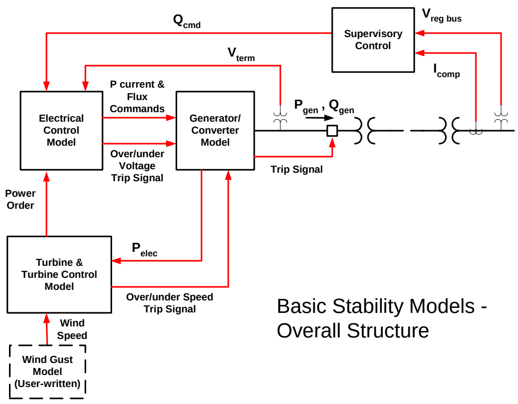


Unbalanced faults present equipment design and simulation challenge:

- **Good dynamic performance for severely unbalanced fault**
- **High fidelity simulations**

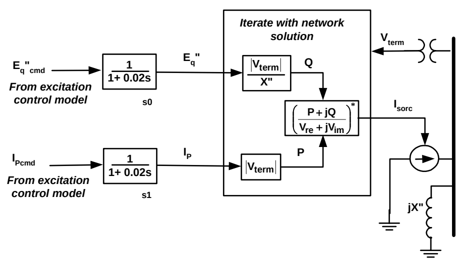
Crisp voltage regulation in weak systems is essential





Basic Stability Models - Overall Structure

Generator & Field Converter Model



Essentially instantaneous response to control commands

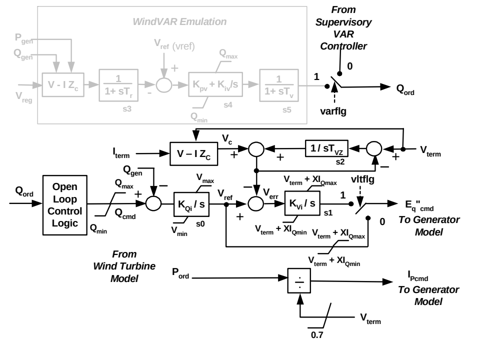
Typical Generator/Converter Trip Levels

ΔV_{trip} (p.u.)	T_{trip} (sec.)
-0.15	10.0
-0.25	1.0
-0.30	0.10
-0.70	0.02
+0.10	1.0
+0.15	0.10
+0.30	0.02

Low-voltage Ride-through

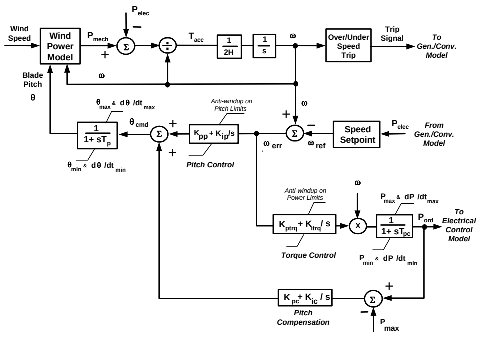
Values are application dependent

Excitation (Converter Control) Model



Model is evolving with the technology

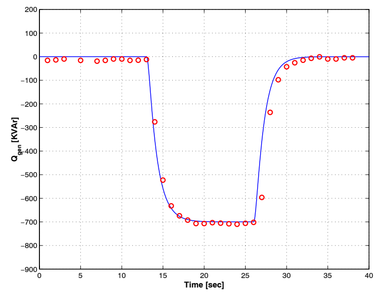
Wind Turbine and Turbine Control Model



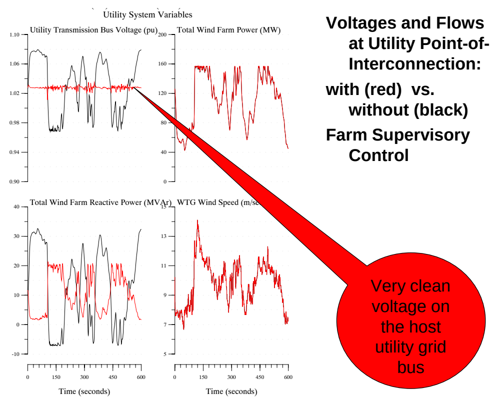
Two-mass torsional model may be used

Response to step in Q order

Red – measured
Blue - model



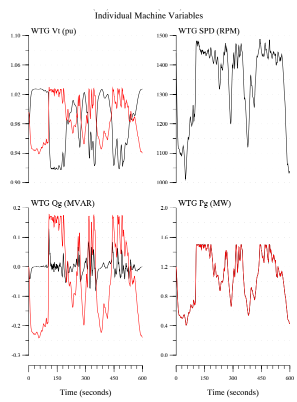
Close match with field measurements



Voltages and Flows at Utility Point-of-Interconnection:

with (red) vs. without (black)

Farm Supervisory Control



Response of Individual WTG electrical and mechanical variables:

with (red) vs. without (black)

Farm Supervisory Control

Summary:

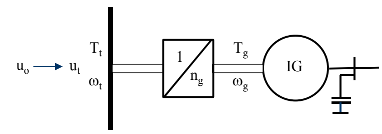
– Integration of wind generation into weak systems presents challenges
– A windfarm is an engineered system, and each application has particular characteristics which drive system requirements
– Successful design depends on systemic analysis beyond consideration of the performance of individual WTGs

Modeling must provide flexibility for evolving technology and application-specific designs

Wind farm models for power system analysis

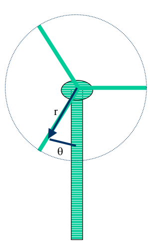
John Olav Giæver Tande
SINTEF Energy Research
7465 Trondheim. Norway
Phone: +47 73 59 74 94; Fax: +47 73 59 72 50
john.o.tande@sintef.no

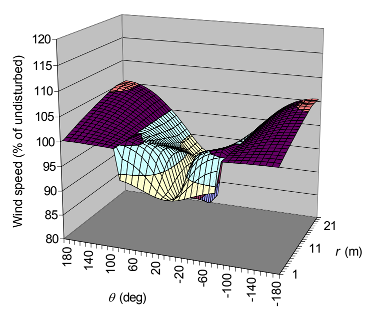
Fixed speed wind turbine/wind farm model



- Scope of model:
  user-model in power system simulation tools (PSSE, SIMPOW)
- Input:
  time-series of wind speed, Cp(λ,β), turbine radius, turbine inertia, shaft stiffness, gearbox ratio, generator inertia and electrical characteristics, pitch control data, capacitor bank and number of WT in wind farm

Wind speed variations (deterministic)





Torque providing wind speed

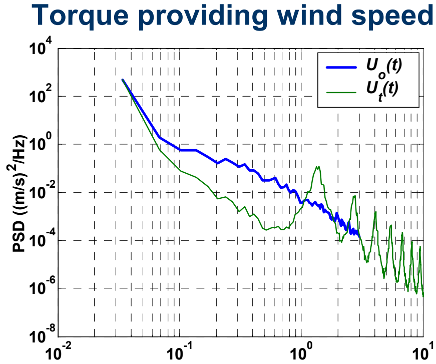
$$u_t(t) = L^{-1}\{u_o(s)H_o(s)\}$$
$$+\sqrt{2}\sum_{k=1}^{\infty} L^{-1}\{u_{ak}(s)H_{3k}(s)\}\cos 3k\theta_1(t)$$
$$+\sqrt{2}\sum_{k=1}^{\infty} L^{-1}\{u_{bk}(s)H_{3k}(s)\}\sin 3k\theta_1(t)$$

$$H_o(s) \approx \frac{0.99 + 4.79cs}{1 + 7.35cs + 7.68(cs)^2}$$

$c=R/u_{avg}$

$$H_{3k}(s) \approx \frac{0.0307 + 0.277cs}{1 + 1.77cs + 0.369(cs)^2}k^{-2}$$

Torque providing wind speed



Aerodynamic torque

Relation approximated by steady-state equation:

$$P_t = 0.5\rho A u^3 C_p(\lambda,\beta)$$

⇩

$$T_t = 0.5\rho A u_t^3 C_p(\lambda,\beta)\omega_t^{-1}$$

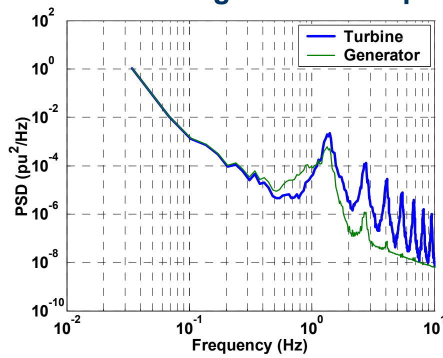
Mechanical Drive Train

Approximated by two-mass model
(in pu with ref to generator):

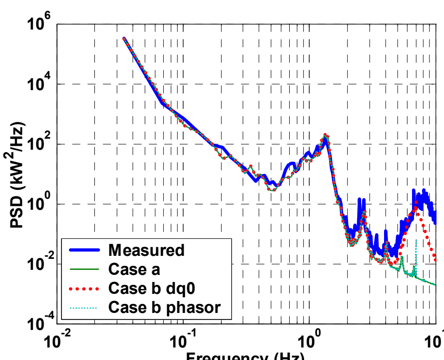
$$\frac{d\omega_t}{dt} = \frac{\omega_b}{2H_t}\left(T_t - d_m\left(\omega_t - \omega_g\right) - k\theta_t\right)$$

$$\frac{d\omega_g}{dt} = \frac{\omega_b}{2H_g}\left(d_m\left(\omega_t - \omega_g\right) + k\theta_t - T_g\right)$$

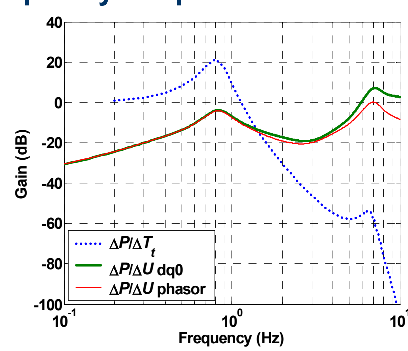
Turbine and generator torque



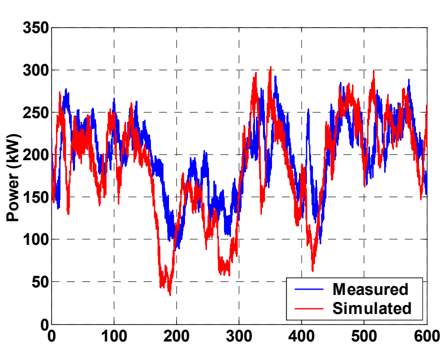
Measured vs simulated power



Frequency Response



Measured vs simulated power



Wind farm model - aggregation

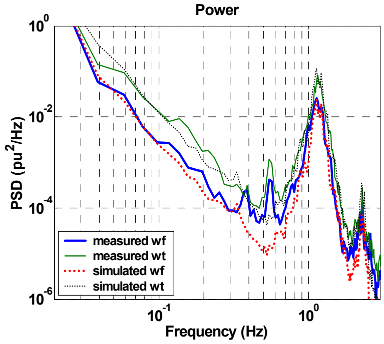
A wind farm with N_{wt} wind turbines is represented by one wind turbine model.

The aerodynamic torque is calculated assuming that the wind speed fluctuations at each of the wind turbines are uncorrelated.

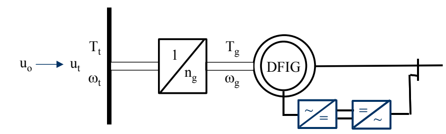
$$T_{t,wf} = N_{wt}\, 0.5 \rho A u_{t,wf}^3 C_p \omega_t^{-1}$$

$$u_{t,wf}(t) = u_{avg} + (u_t(t) - u_{avg}) N_{wt}^{-0.5}$$

Measured and simulated power



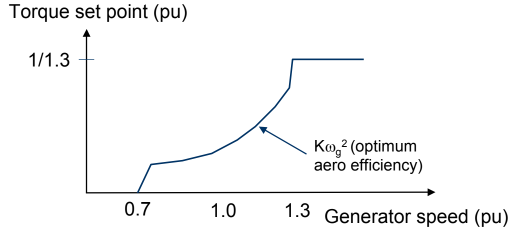
DFIG wind turbine/wind farm model



- Scope of model:
  user-model in power system simulation tools (PSSE, SIMPOW)
- Input:
  time-series of wind speed, Cp(λ,β), turbine radius, turbine inertia, shaft stiffness, gearbox ratio, generator inertia and electrical characteristics, pitch and speed control data, converter rating and number of WT in wind farm

DFIG control

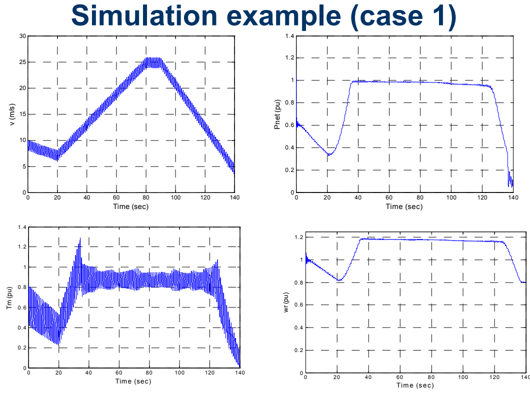
- Torque set point is controlled according to generator speed to obtain optimum aerodynamic efficiency below rated power
- Pitch control is applied to maintain generator speed at rated power



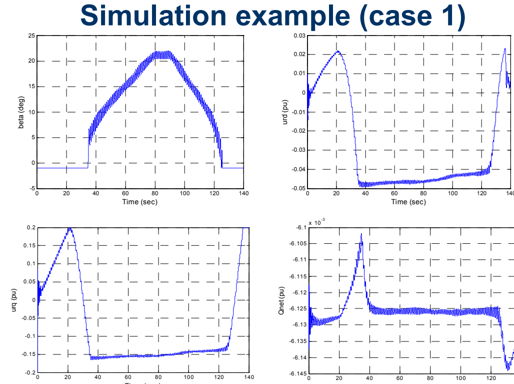
Simulation CASE 1

- Up and down ramping of the wind speed and with superimposed 1 Hz sinusoidal variation
- The grid is stiff and the terminal voltage of the wind turbine is 1.0 in the q-axis and 0.0 in the d-axis
- The reactive power exchange between the grid and the wind turbine is controlled to be zero
- The speed is controlled to maximize the efficiency of the wind turbine below rated power, whereas the pitch angle is controlled to limit the speed at rated power

Simulation example (case 1)



Simulation example (case 1)



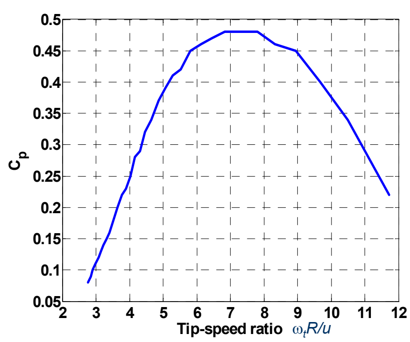
Conclusion

- Broad interest - important topic
- Initial developments constitute a good start
- Need for further development
- IEA Annex XXI forms framework for coordinated effort

Fixed speed wind turbine (WT500)

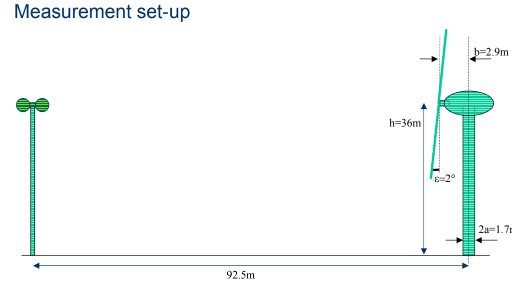
Nominal power, P_n (MW)	0.5
Nominal voltage, U_n (kV)	0.69
Nominal apparent power, S_n (Mvar)	0.557
Nominal frequency, f_n (Hz)	50
Number of pole pairs, p	2
Stator resistance, R_1 (pu)	0.0098
Stator leakage reactance, X_{1S} (pu)	0.1168
Rotor leakage reactance, X_{2S} (pu)	0.1691
Magnetizing reactance, X_M (pu)	3.9568
Magnetizing resistance, R_M (pu) (in series with X_m)	0.0999
Rotor resistance, R_{2S} (pu)	0.0096
Shunt-capacitor, Q_c (Mvar)	0.125
Generator inertia, H_g (s)	0.33
Turbine inertia, H_t (s)	2.99
Shaft stiffness, k (pu torque/el. rad.)	0.61
Mutual damping, d_m (pu torque/pu speed)	0.0017
Gearbox ratio, n_g	55.814
Turbine radius (m)	20.5

Fixed speed wind turbine (WT500)

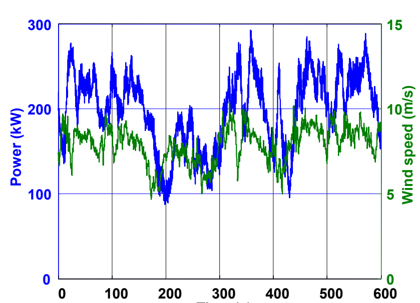


Fixed speed wind turbine (WT500)

Measurement set-up



Measurements (WT500)



Measurements (WT500)