Lessons learnt from a real-world operating Microgrid

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The Cell Controller Pilot Project

Dr.-Ing. Eckehard Tröster

Sevilla, 8th November 2017

3DMicroGrid
DESIGN, DEVELOPMENT AND DEMONSTRATION
OF A SMART MICRO GRID

Contents

Energynautics

Cell Controller Pilot Project

- Motivation
- Concept
- Modelling and Simulation
- Field Test
- Conclusion

Energynautics - Areas of Expertise

SUSTAINABLE DEVELOPMENT FOR POWER AND ENERGY

Renewable Energies	Distribution Systems	Electromobility
Smart Grids	Combustion Engine Power Plants	Electricity Markets
Grid Codes	Island & Microgrids	Transmission Systems

Energynautics - Clients International

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International Work Experience

This schema illustrates only a selection of clients.

Energynautics - Our Team

Dr. Thomas Ackermann

Founder and CEO of energynautics

Dipl.-Wi.-Ing. Economics and Mechanical Engineering, TU Berlin

Master of Science in Physics, Otago University (New Zealand)

Ph.D. from Royal Institute of Technology (KTH), Stockholm

Dr. Eckehard Tröster

CEO at energynautics

Dr.-Ing. Electrical Engineering, TU Darmstadt

Energynautics - Services by energynautics

- Grid Studies
- Smart Grid Development
- Power Generating Unit Modelling
- Grid Code Development
- Grid Optimization Software ENAplan
- Capacity Building
- Conference Planning

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SMART NETWORK CONTROL WITH COORDINATED PV INFEED
Snoopi

GOAL

- Analyse the effect of controllable reactive and active power from battery systems on low voltage networks

TASKS

- Build simulation models of network areas including battery systems and PV infeed
- Collect metered voltage data with PMUs in selected field areas
- Develop and test reactive power regulation algorithm for battery systems in simulation models and field test areas

PROCECT PARTNERS

ewr netze
sicher · intelligent · innovativ

KTH
VETENSKAP
OCH KONST

Fronius
SHIFTING THE LIMITS

Grid Absorption Capacity Study and Grid Code for Renewable Energy Systems on Seychelles (2014)

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- Indian Ocean islands of Seychelles currently cover 2% of their electricity consumption from wind
- Rest of generation from diesel generators (and a few PV units)
- Policy targets of 5% renewables by 2020, 15% by 2030
- In a study in 2014, financed by the World Bank, Energynautics showed how Seychelles can reach even higher RES integration using innovative technology
- RES included wind, PV, biomass, hydroelectricity and waste-to-energy
- Energynautics also developed a Grid Code to regulate the technical requirements for connection of renewable energy generators to the power systems
- Project partners Meister Consultants Group wrote a draft Feed-In Tariff and Power Purchase Agreements

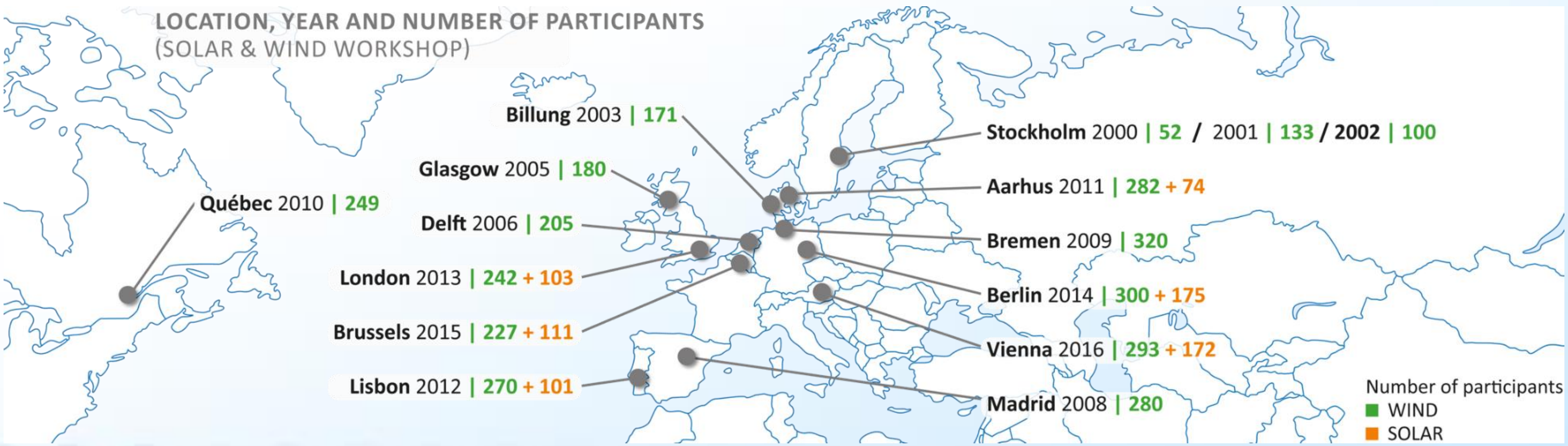
Workshops hosted by energynautics

WORKSHOPS, CONFERENCES AND SYMPOSIA ORGANIZED BY ENERGYNAUTICS

- 2008 – 2009 **International Workshop on Concentrating Pholtovoltaic Power Plants**
- 2013 **Renewables Intergration Symposium**
- 2014 **China Conference**
- 2017 **International Conference on Large-Scale Grid Integration on Renewable Energy** / India
- 2018 **International Hybrid Power Systems Workshops** / Tenerife

2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

- 2006 – 2018 … **International Wind Integration Workshop**
- 2011 – 2018 … **International Solar Integration Workshop**
- 2017 - 2018 … **E-Mobility Power Systems Integration Symposium**



This Year's Workshops by energynautics

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E-Mobility, Solar and Wind Workshops 2018 in Stockholm

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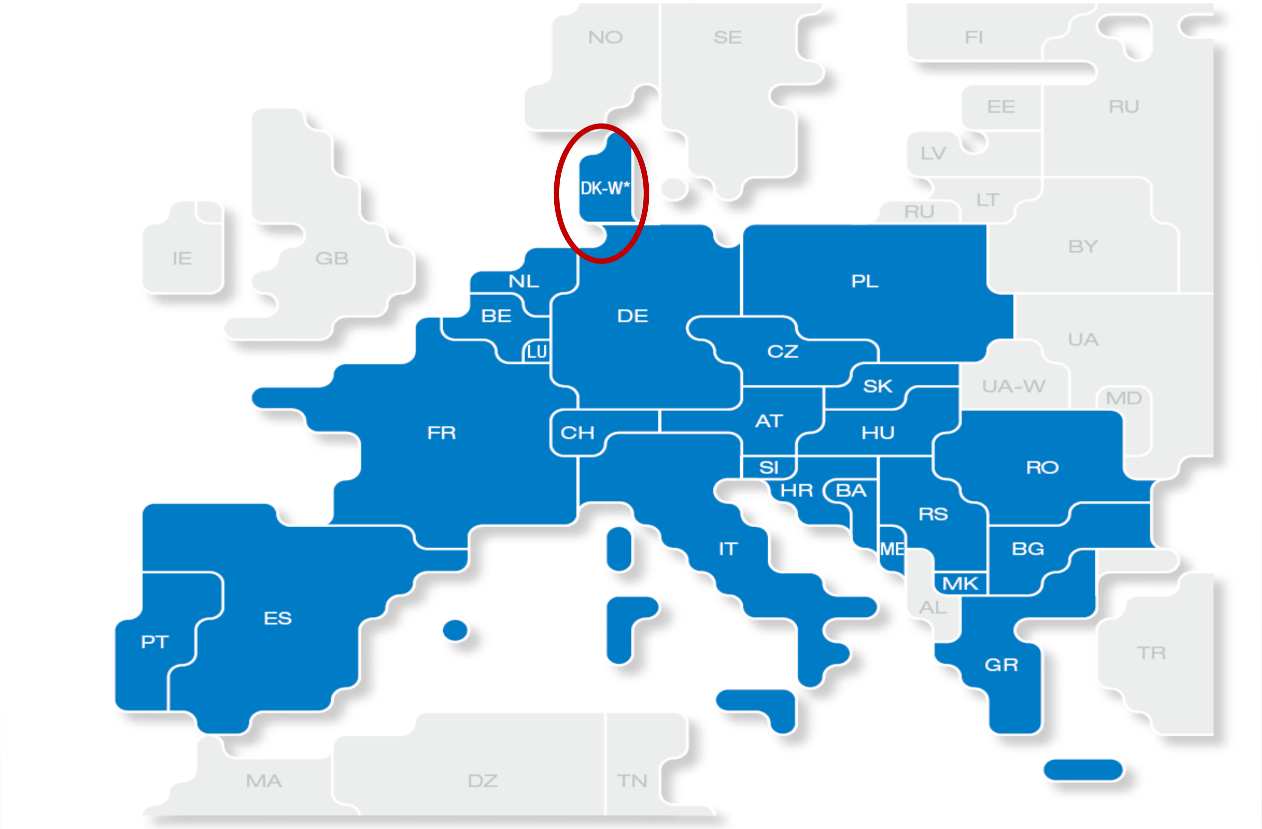
The Cell Controller Pilot Project

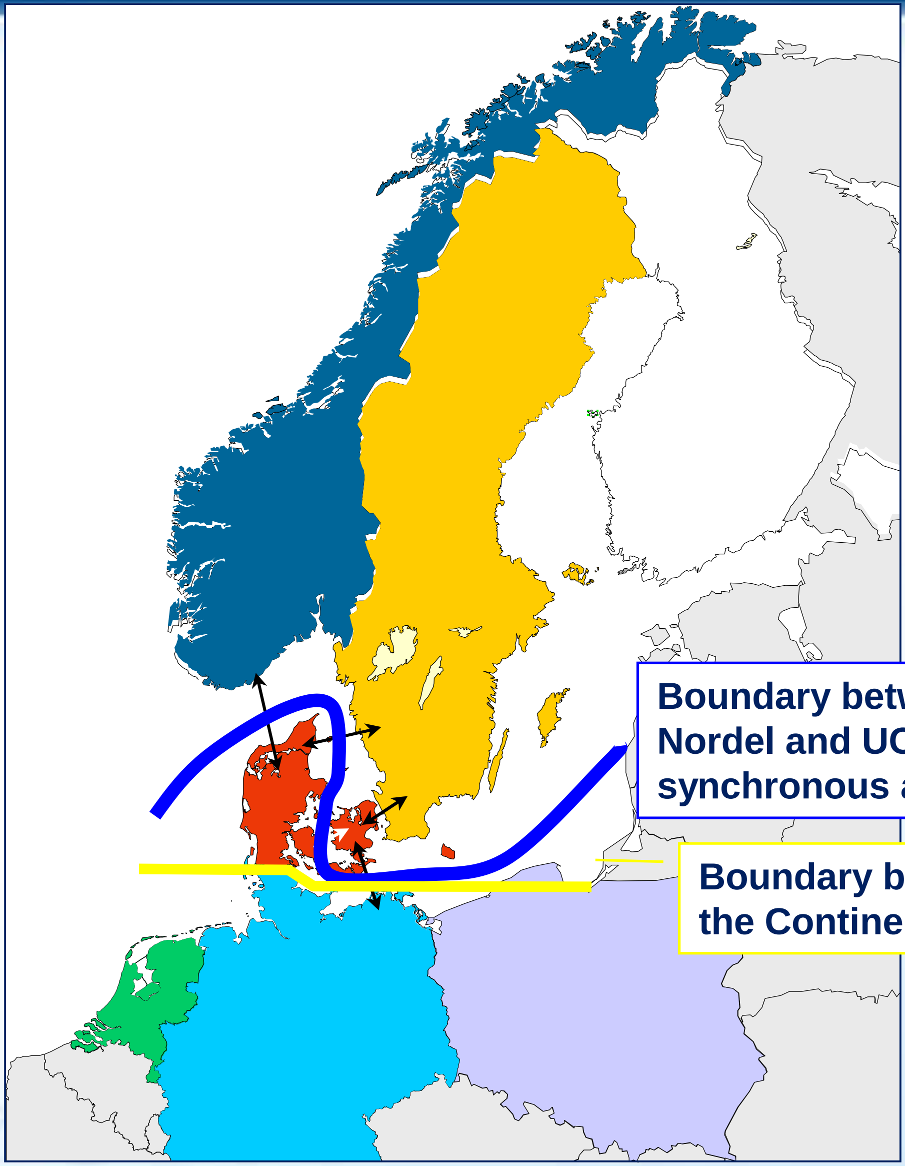
MOTIVATION

Energinet.dk
- Part of the European Transmission system -

The European area covered by UCTE



... Part of European System



Boundary between the Nordel and UCTE synchronous areas

Boundary between the NordPool and the Continental market systems

The Surroundings of the Western Danish Power System

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Extra 600 MW HVDC connection over Skagerrak (pol 4)

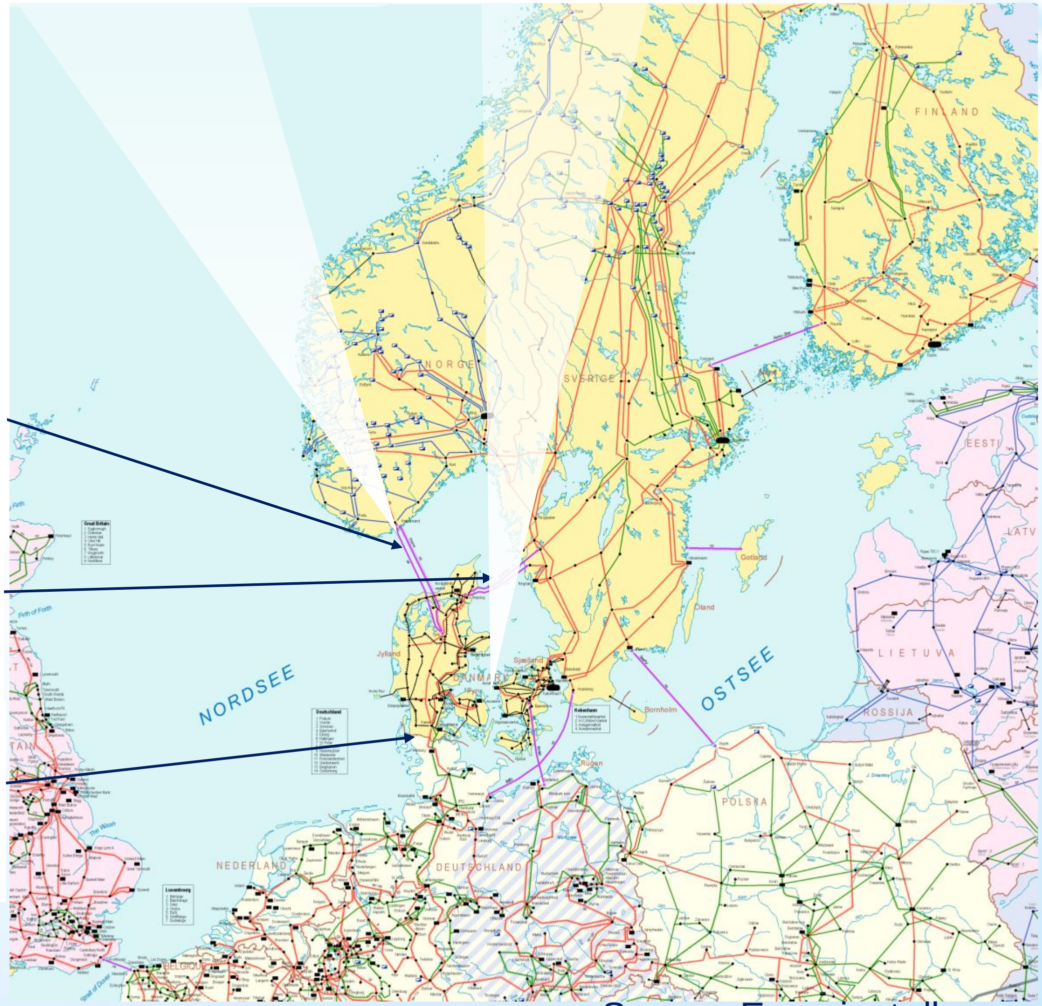
600 MW HVDC connection over The Great Belt

DK West is a regular transit area with large interconnections to the neighbouring areas:

Norway (HVDC ”Skagerrak”):
Capacity, import: 1,000 MW
Capacity, export: 950 MW

Sweden (HVDC ”KontiSkan”):
Capacity, import: 460 MW
Capacity, export: 490 MW

Germany (AC):
Capacity, import: 800 MW
Capacity, export: 1,200 MW

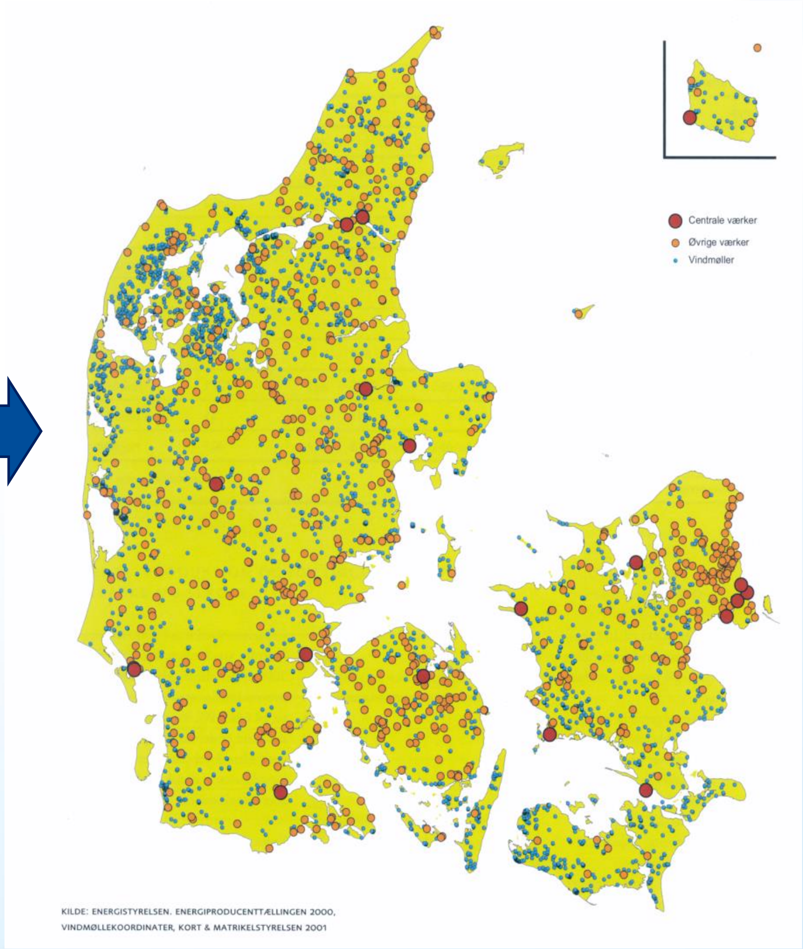


Source: Energinet.dk

Development from the 1980s to the 1990s

Primary generation

Local generation



Power Balance 2006

West:

Load	1.250 – 3.700 MW
Central power plants	3.400 MW
Local CHP units	1.700 MW
Windpower	2.400 MW

4100 MW

East:

Load	880 – 2.600 MW
Central power plants	3.800 MW
Local CHP units	650 MW
Windpower	750 MW

1400 MW

Many annual hours, where RE covers the entire demand

Source: Energinet.dk

Distribution of Production Capacity

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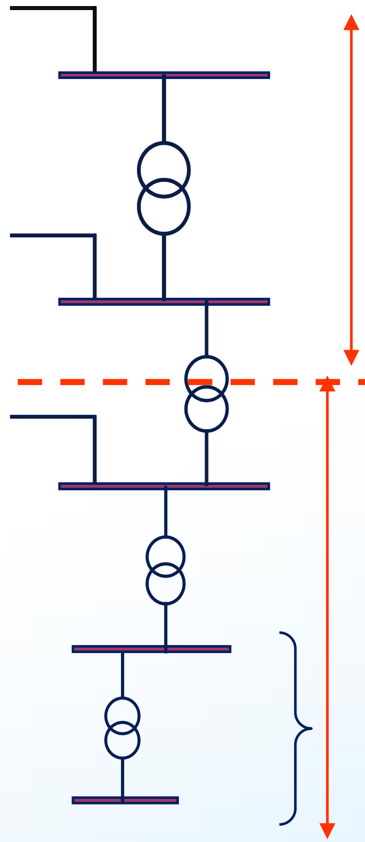
Range of central control



Interconnections 400 kV — 4 primary units: 1,488 MW

Interconnections 150 kV — 5 primary units: 1,914 MW; 80 wind power units: 160 MW

Interconnections 60 kV — 15 local CHP units: 569 MW

10-20 kV / 400 V — 545 local CHP units: 1,087 MW; 4,074 wind power units: 2,214 MW

Non-dispatchable and beyond central control

Source: Energinet.dk

The Western Danish "Wind Power Carpet"

By March 1st, 2004:

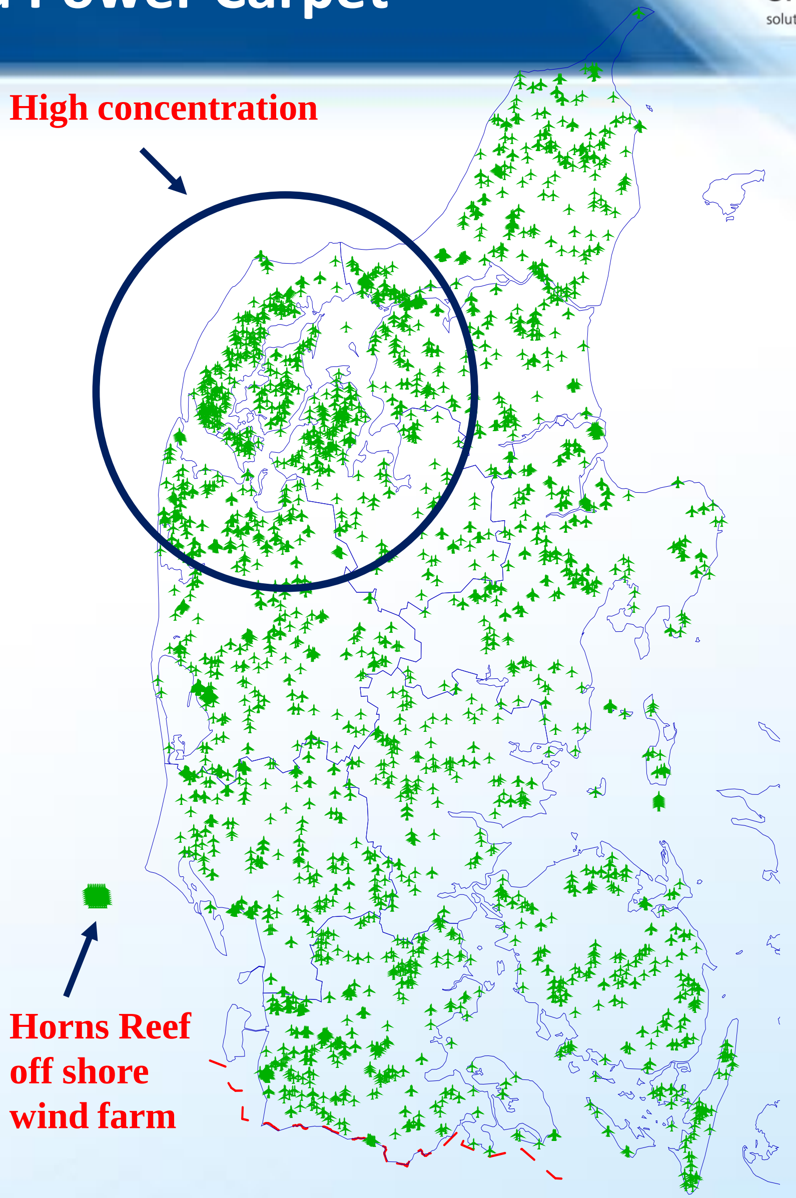
4,175 wind turbines: 2,374 MW

Average size of wind turbines:
approx. 570 kW

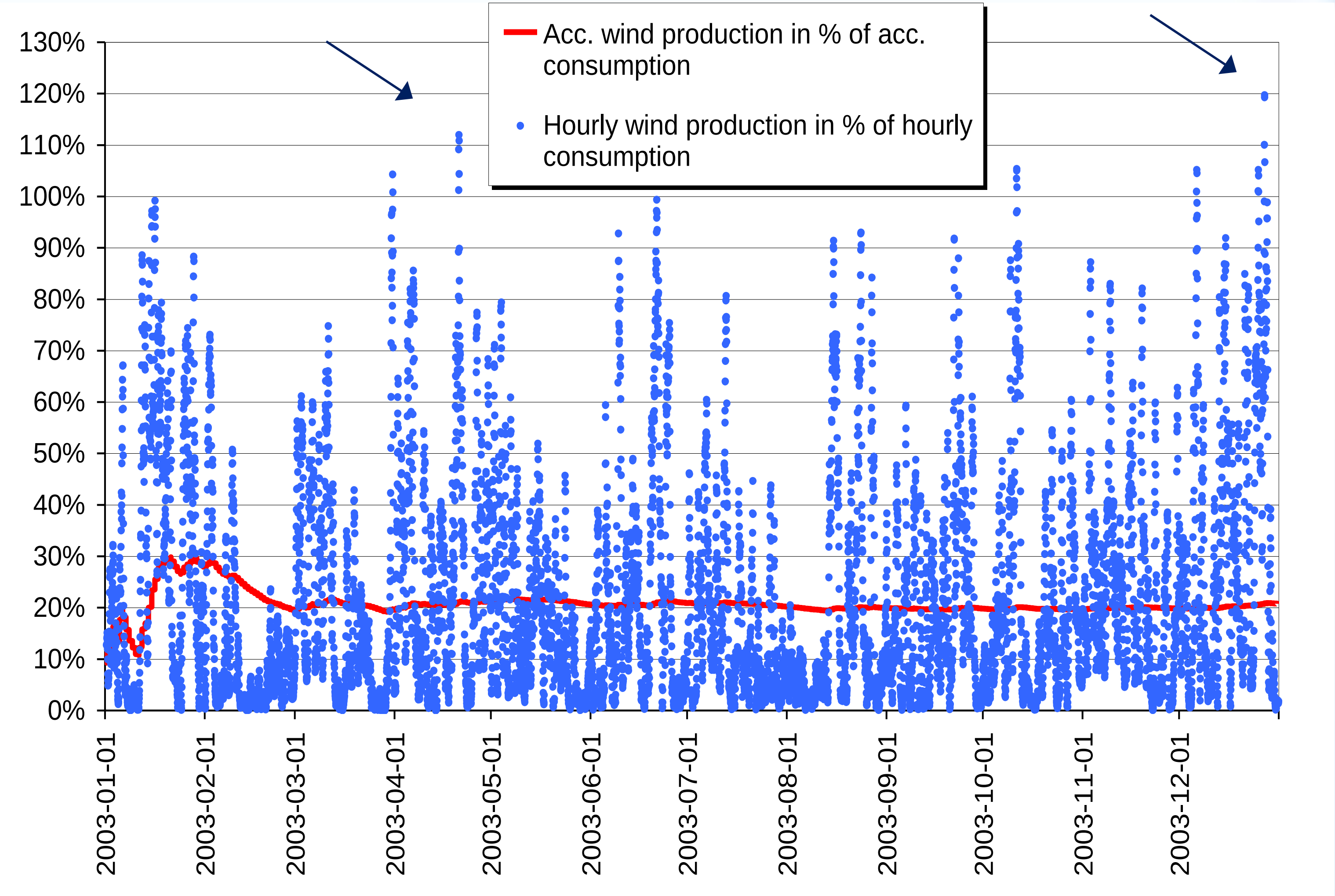
Average rotor diameter:
approx. 40 meters

Average hub height:
approx. 40,5 meters

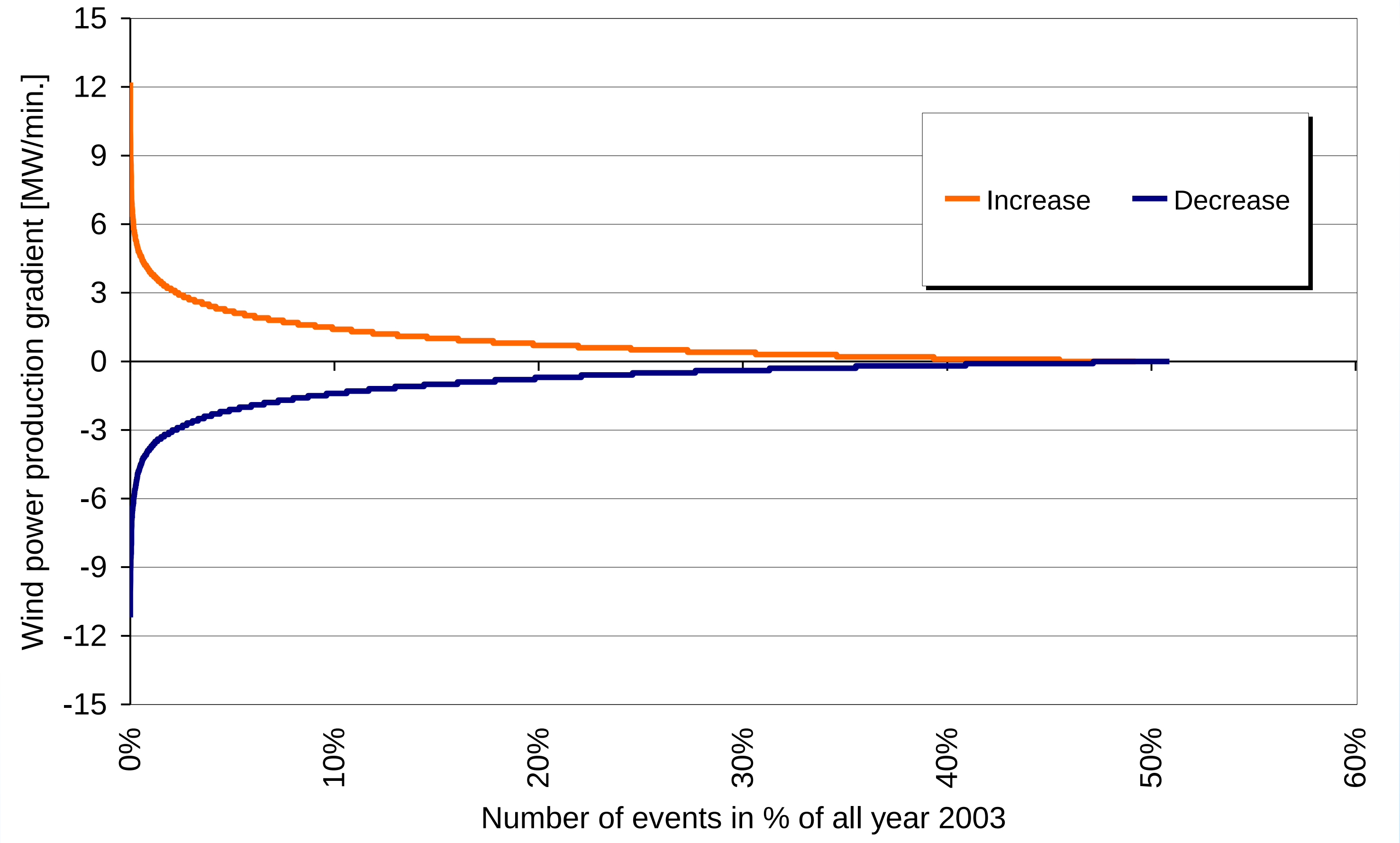
75 per cent of the installed wind capacity in Denmark.



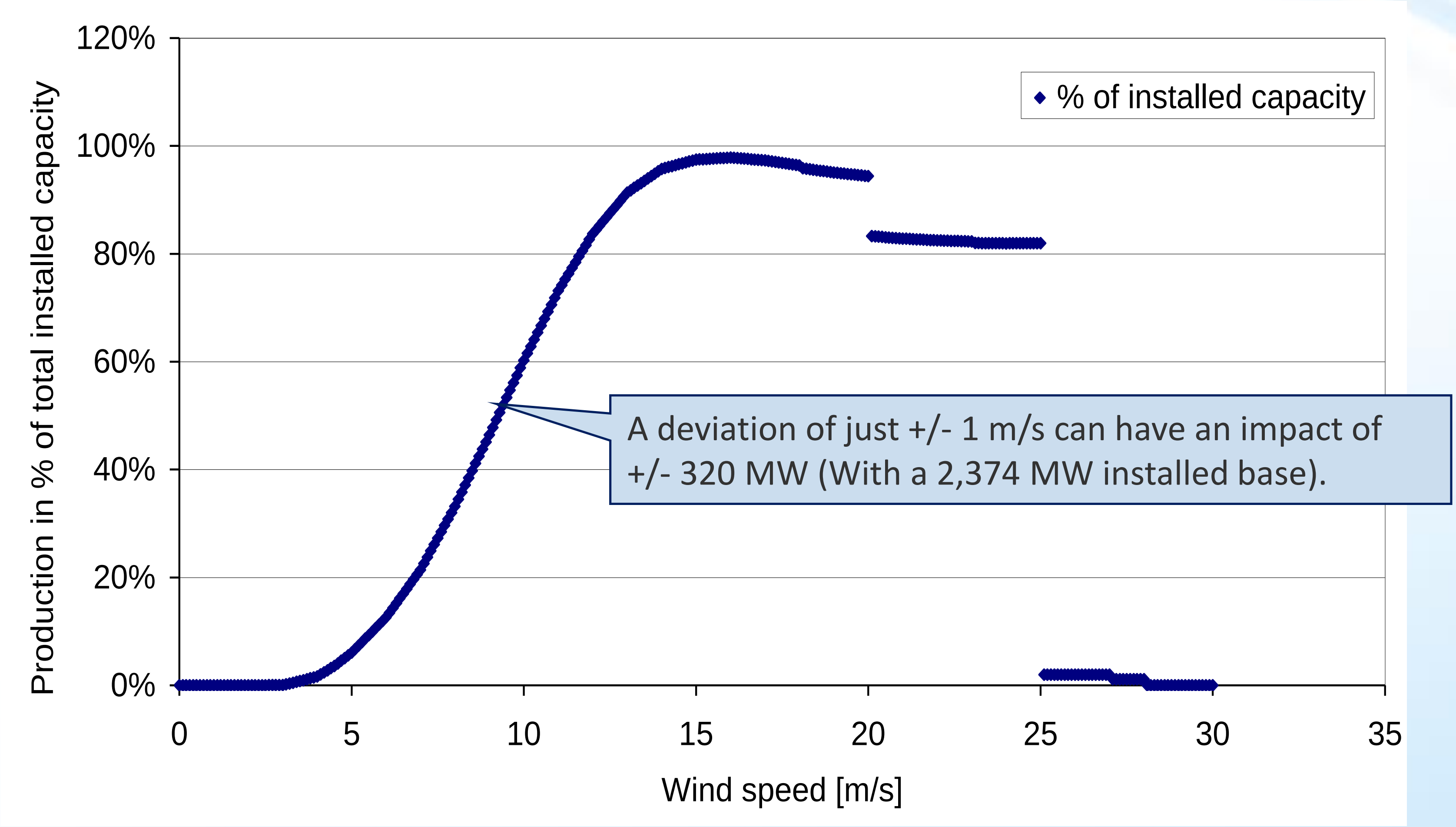
Wind Power Year 2003
(2004 max: 120 %)



Wind Power Year 2003



Aggregated Wind Production Curve (PC) for Western Denmark



Identified Security Problems in the Western Danish Power System

- Local grids cannot maintain normal n-1 security if local generation exceeds local demand and if separation of generation and consumption is insufficient
- Security analysis has become less accurate due to missing information on local generation and unpredictable wind power
- Protection relays trip local generators after distant faults on the high-voltage transmission grid
- Traditional under-frequency load shedding schemes will disconnect both load and generation
- Restoration after fault has become more complicated and more time consuming

CONCEPT

Cell Controller
for
Decentralized Grid Management

A project of

Energinet.dk, Energynautics and Spirae

The Cell Controller Pilot Project Time Schedule

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Phase

2004

A

Information gathering through 3 international workshops. Identification and selection of 60 kV Pilot Cell Area. Requirements spec and prelim design of Pilot Cell.

2005

B1 to B3

Implementation of measurement and monitoring system in Pilot Cell. Detailed modeling and simulation of Pilot Cell. Detailed design and laboratory-scale testing of Cell Controller in Colorado State University Diesel Engines Lab.

2009

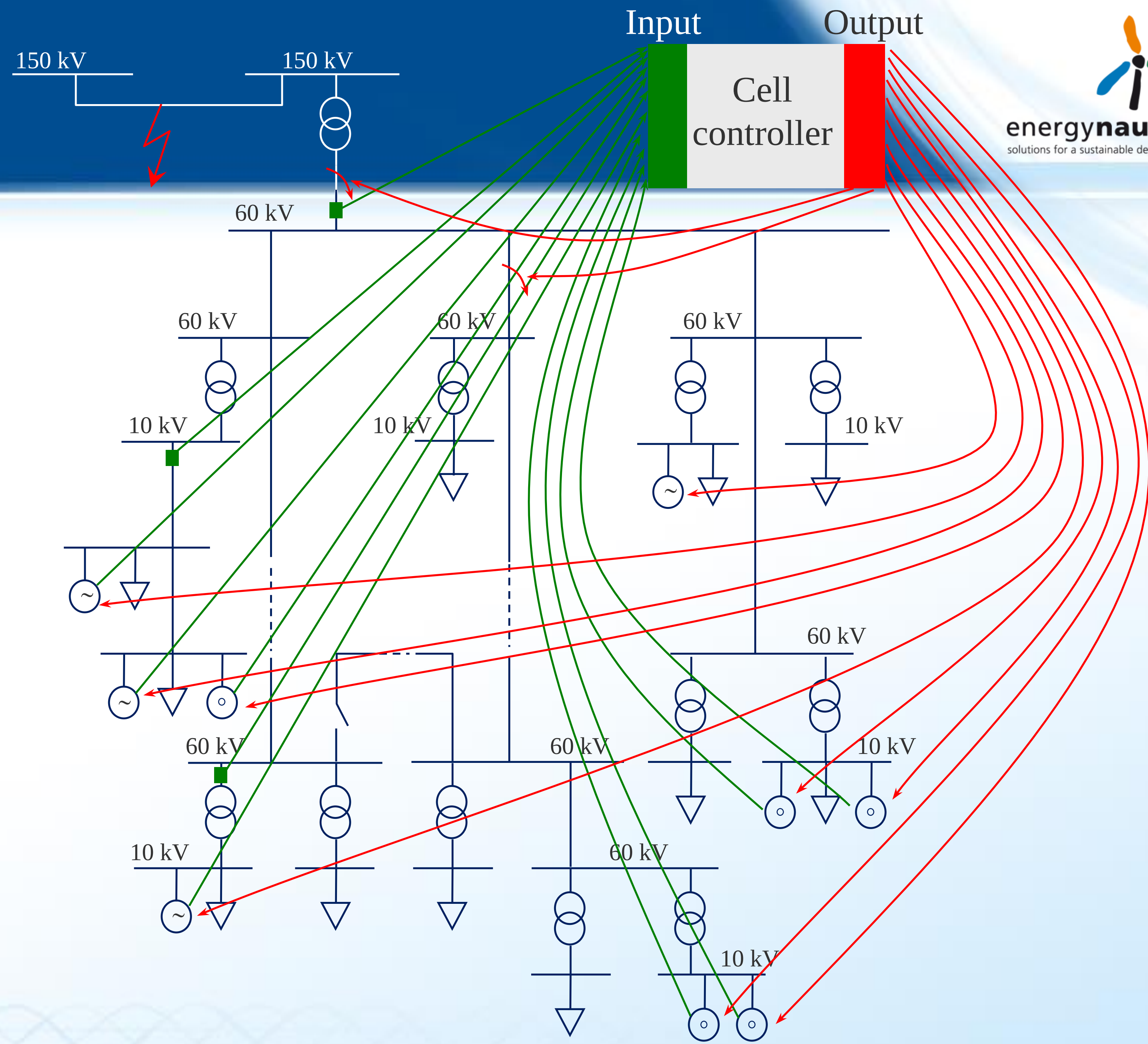
C1 to C3

Pilot implementation and testing of Cell Controller in test area 1, 2 and 3 of Pilot Cell.

2011

Identified Targets of the Redesign Process

- Increased security of supply
- Sufficient domestic resources must be available to maintain a balance between demand and generation
- Improved operator knowledge of actual system conditions both locally and centrally
- Efficient system control particularly during emergencies
- Active usage of distributed passive generators
- Black starting capabilities using distributed generators
- Organising distributed generators into controllable Virtual Power Plants



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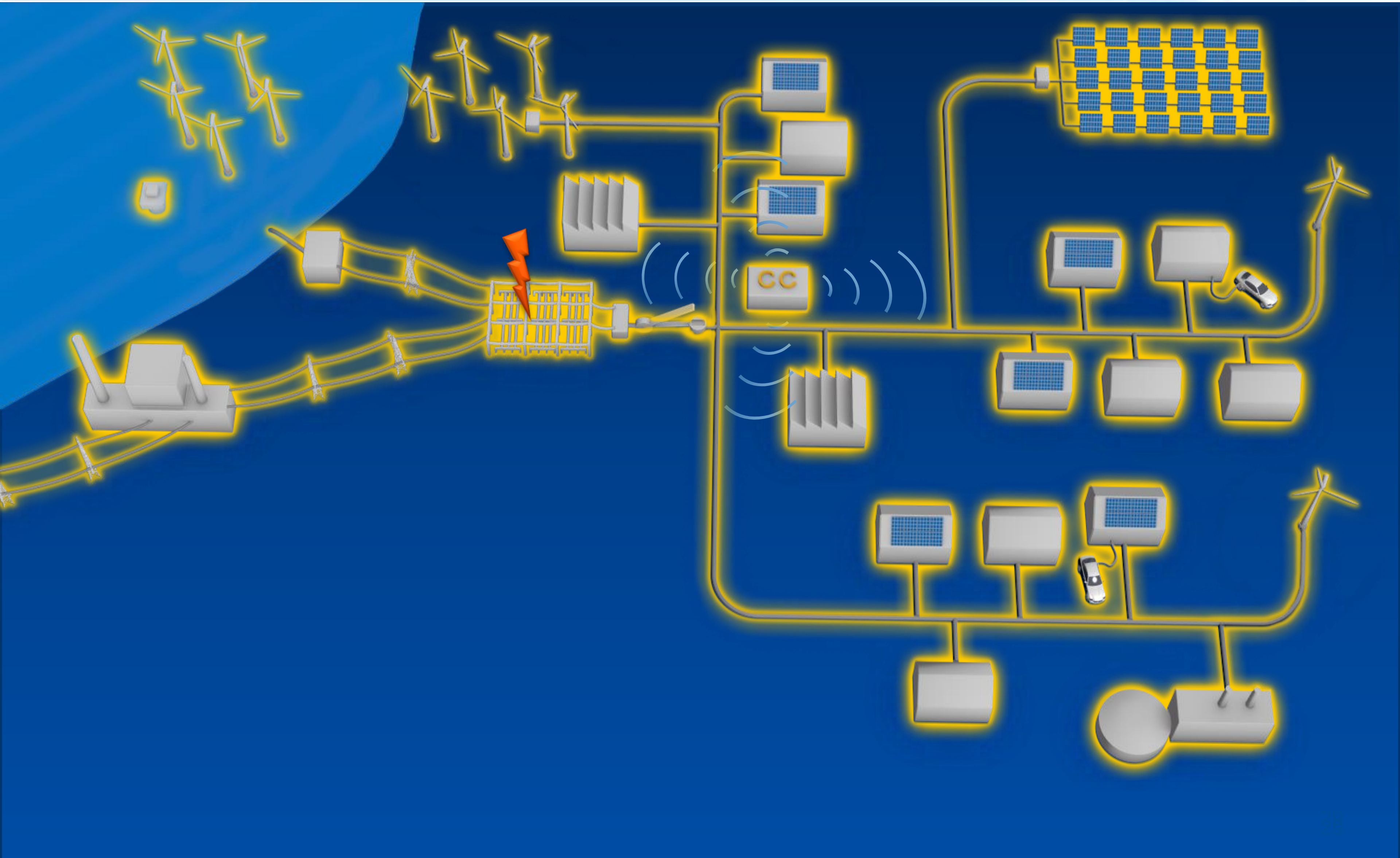
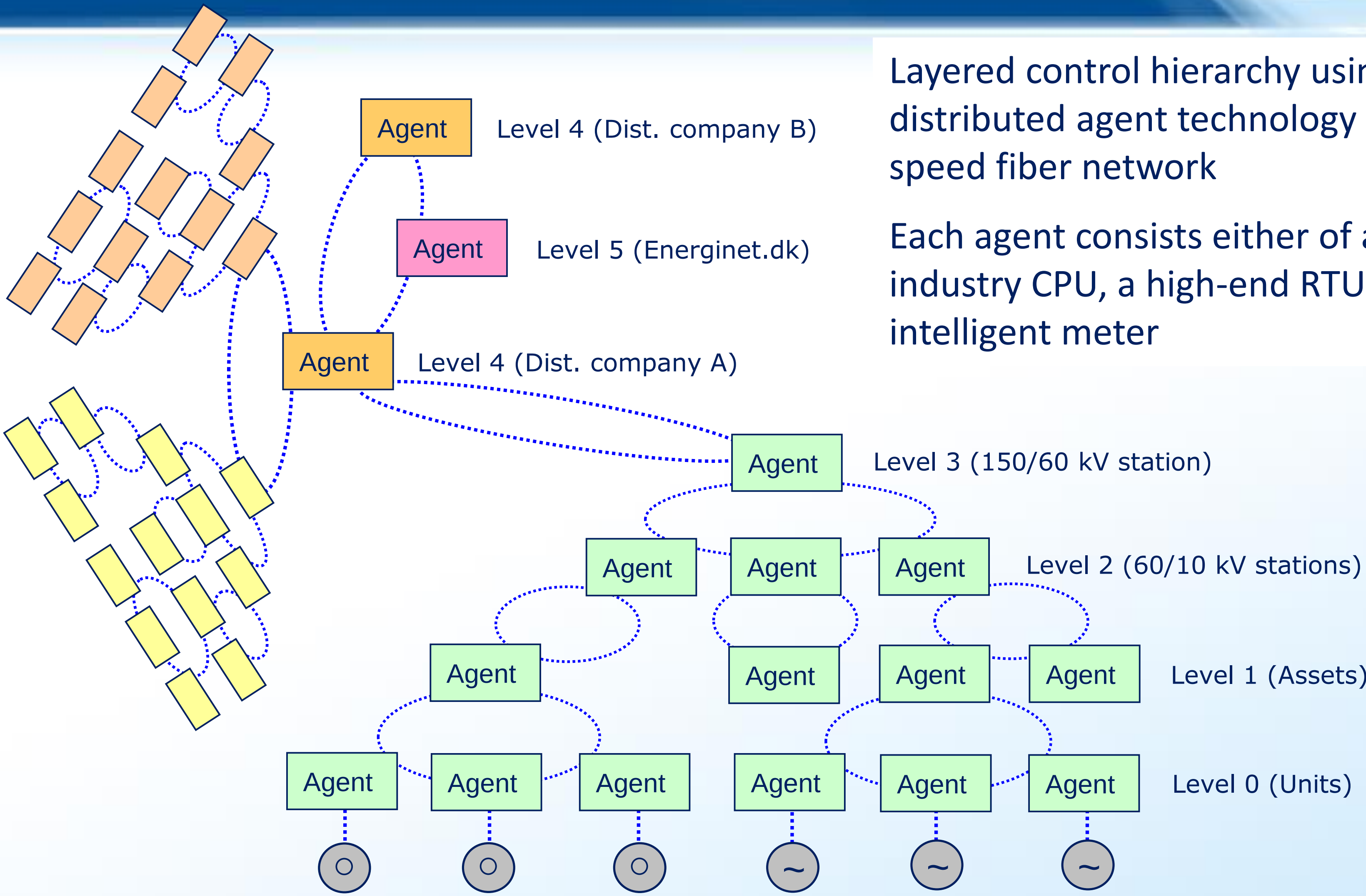
The Cell Controller



Cell Controller Architecture



Layered control hierarchy using distributed agent technology and high speed fiber network

Each agent consists either of an industry CPU, a high-end RTU or an intelligent meter

Primary Design Criteria Cell Controller Pilot Project

High Ambition:

In case of an emergency situation reaching the point of no return the Cell disconnects itself from the HV grid and transfer to controlled island operation

Moderate Ambition:

After a total system collapse the Cell black-starts itself to a state of controlled island operation

- **High Ambitions to ensure that new features can be implemented as pure software development without replacement or installation of new hardware**

Location of Demonstration Area

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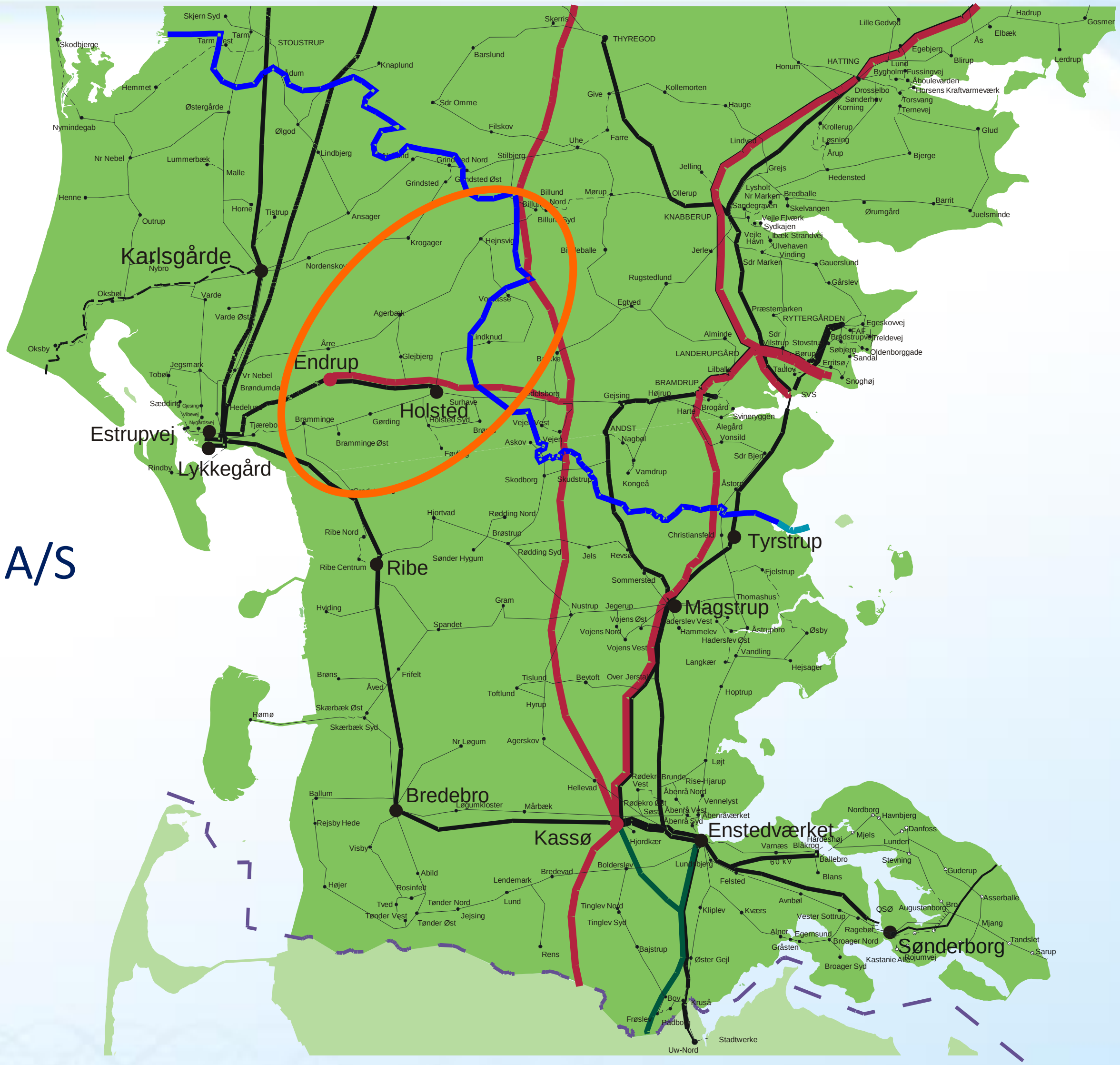
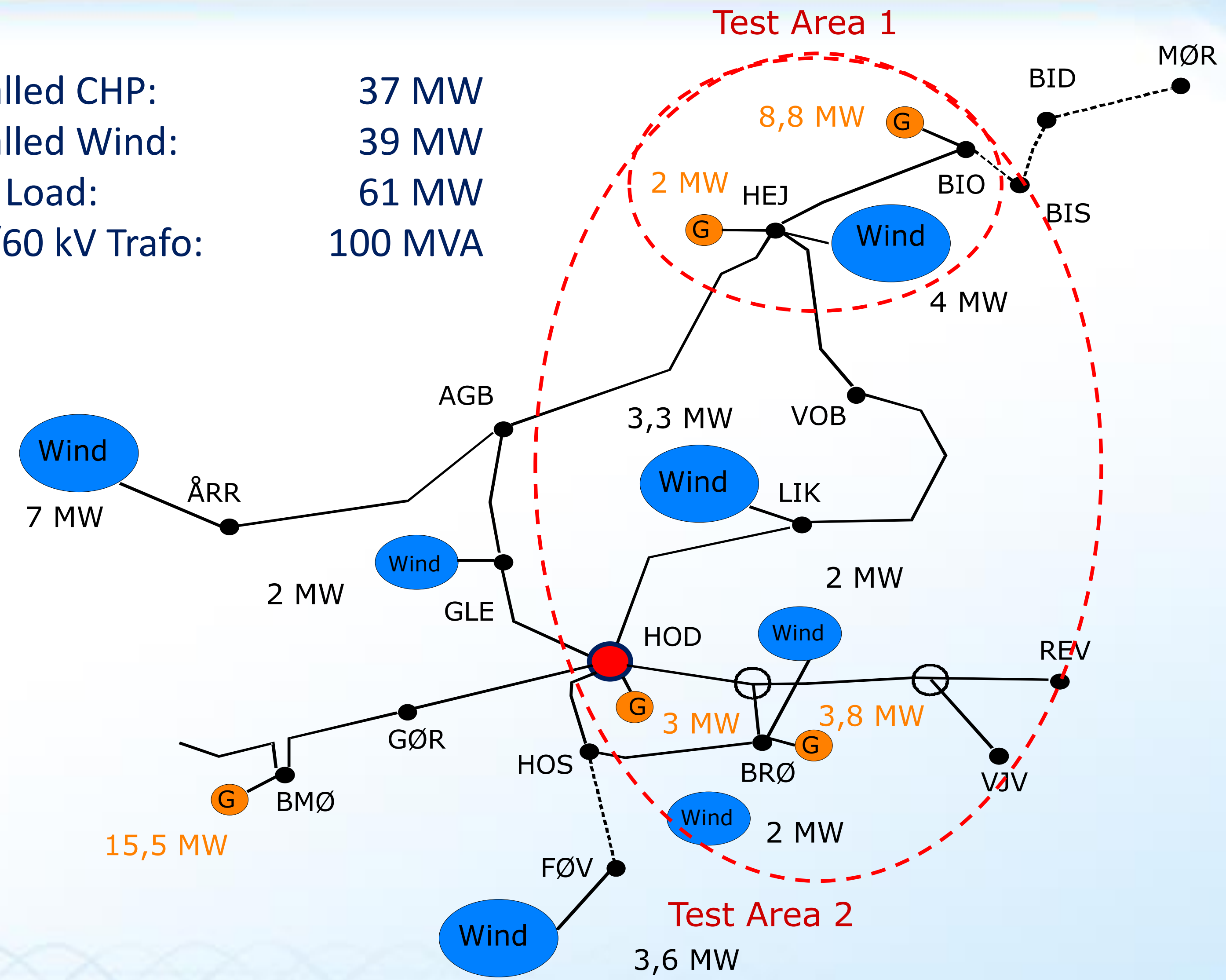
Syd Energi Net A/S



Pilot Cell:
Holsted 60 kV Grid Area

Installed CHP:	37 MW
Installed Wind:	39 MW
Max Load:	61 MW
150/60 kV Trafo:	100 MVA



Level of Functionality of the 150/60 kV Cell Controller

- ✓ Monitoring total load and production within the Cell
- ✓ Active power control of synchronous generators
- ✓ Active power control of wind farms and large wind turbines
- ✓ Reactive power control by utilising capacitor banks of wind turbines and grid
- ✓ Voltage control by activating AVRs on synchronous generators
- ✓ Frequency control by activating SGSs on synchronous generators
- ✓ Capability of operating 60 kV breaker on 150/60 kV transformer
- ✓ Capability of operating breakers of wind turbines and load feeders
- ✓ Automatic fast islanding of entire 60 kV Cell in case of severe grid fault
- ✓ Automatic fast generator- or load shedding in case of power imbalance
- ✓ Voltage, frequency and power control of islanded Cell
- ✓ Synchronising Cell back to parallel operation with the transmission grid
- ✓ Black-starting support to transmission grid in case of black-out

Cell Controller Concept Expectations

- Each Cell can be regarded as a Virtual Generator with same or better controllability compared to a traditional power station unit of equal size
- Local distribution companies attain strongly increased possibilities of distribution network on-line monitoring and active control
- Automatic Cell transition to controlled island operation in case of imminent transmission system break-down
- Black-start of transmission system
- Robust Cell Controller Concept designed to encompass all new types of DG units and controller functionalities

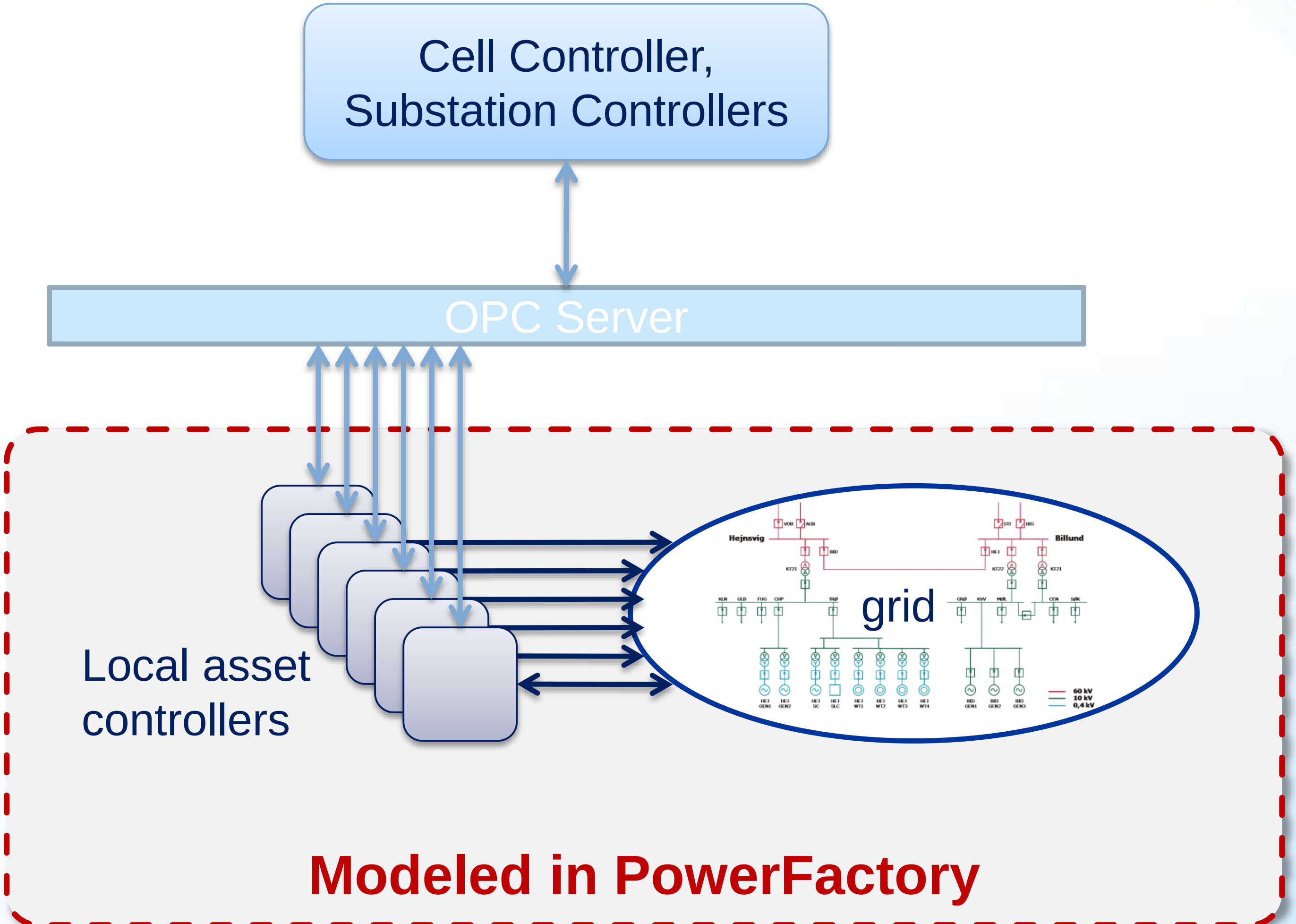
➡ Increase in security of supply

➡ Any new functionality as pure software development

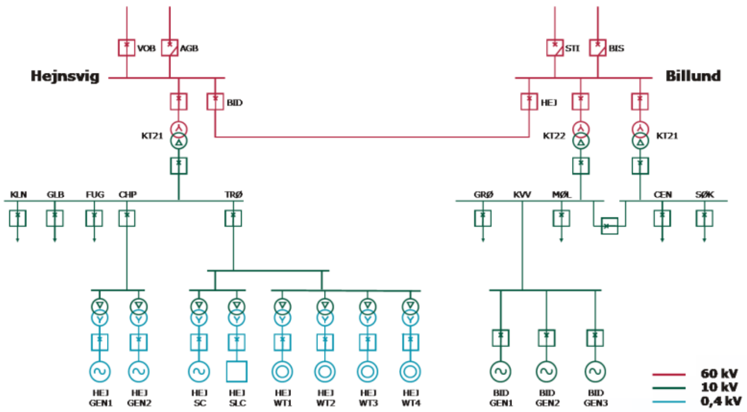
➡ Re-design for the future Danish electric power system

MODELIING AND SIMULATIONS

Simulation Setup



Cell Grid Simulation Model (1)



Topology: 60 kV lines, 60/10 kV transformers

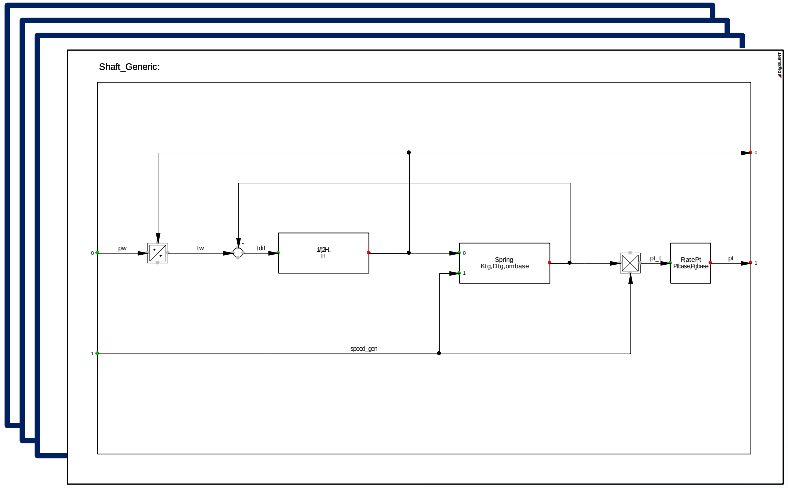
10 kV feeders: Aggregate model (one load per feeder), representing available data

Cell monitoring system: extensive data recording in the Cell Area grid

Analysis of hourly, daily and seasonal load variation

constant impedance characteristic for short term dynamic simulations

Cell Grid Simulation Model (2)



Wind turbines: Danish type constant speed turbines with induction generators and controlled capacitor banks. The simulation model includes a two-mass drive train model.

Asset Controllers:

Synchronous Condenser, and CHP plants (synchronous generators)

Secondary Load Controller (fast switching load)

Cell Grid Simulation Model (3)

PowerFactory provides built-in OPC interface

OPC interface must be configured by inserting “external data” interface objects into the model database tree, and connecting these objects to input and/or output signals.

User-defined models created to translate the raw input data into usable signals for control models

Time synchronization between dynamic simulation and Cell Controller software application

Cell Controller Test Planning

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Critical tests are islanding tests, because of risk of consumer black-out

Development of test scenarios

Gradually increasing complexity:

- Start with one generator and one load
- Increase number of involved load feeders
- Add generators
- Add wind turbines

Simulate tests in a real machine test laboratory with multiple loads and generators

Static calculations and dynamic simulations in the software environment

Simulation Testing

Simulate aspects of Cell Controller operation in different scenarios:

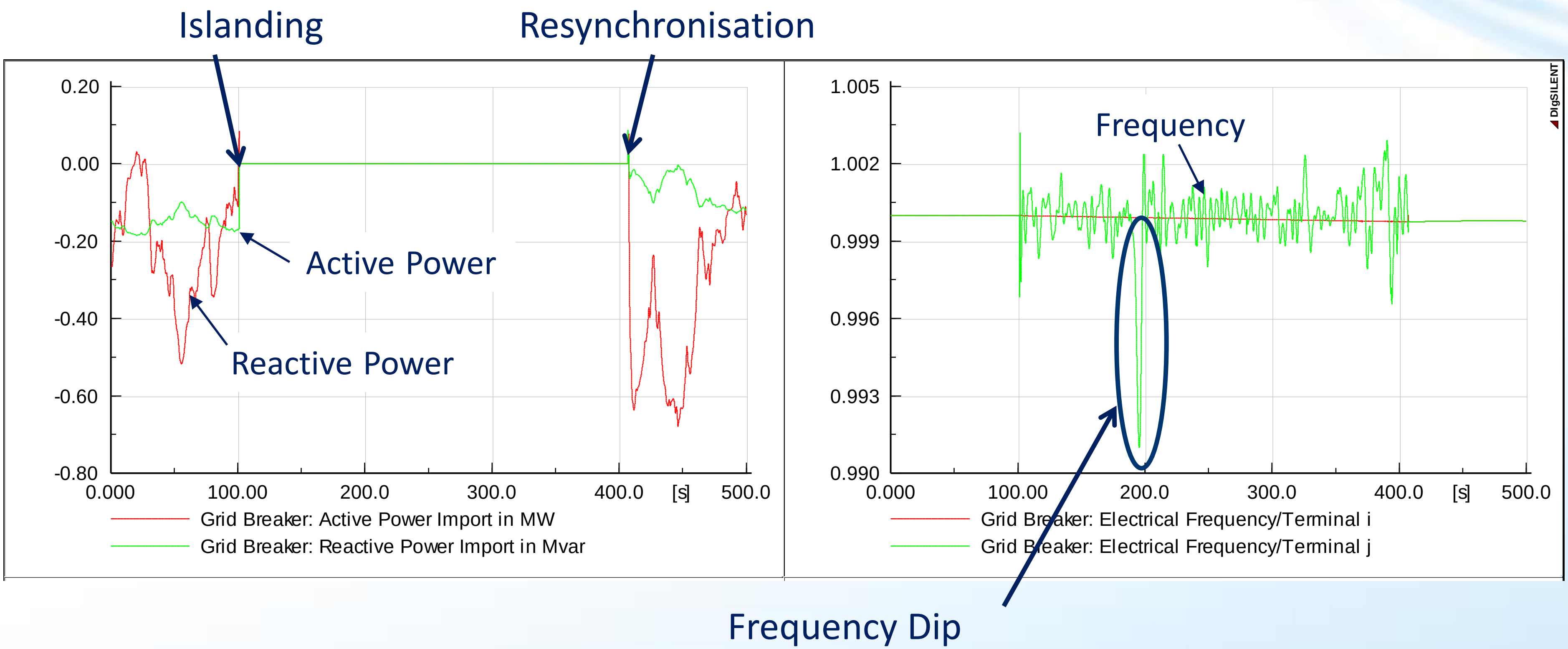
- Virtual generator operation
- Islanding under various conditions

Arbitrary load steps of increasing size to investigate stability margin of islanded system

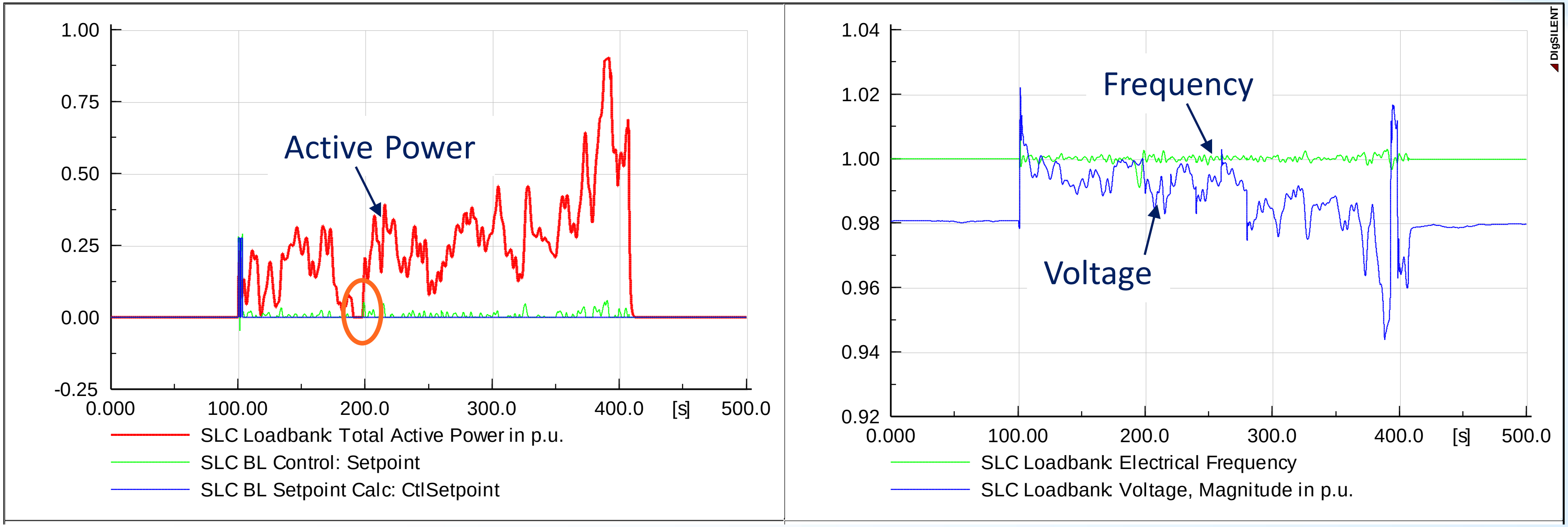
Validate simulation results against asset protection limits: over-/undervoltage, over-/underfrequency (automated result processing)

Visual inspection of simulation results plots to identify unexpected behavior

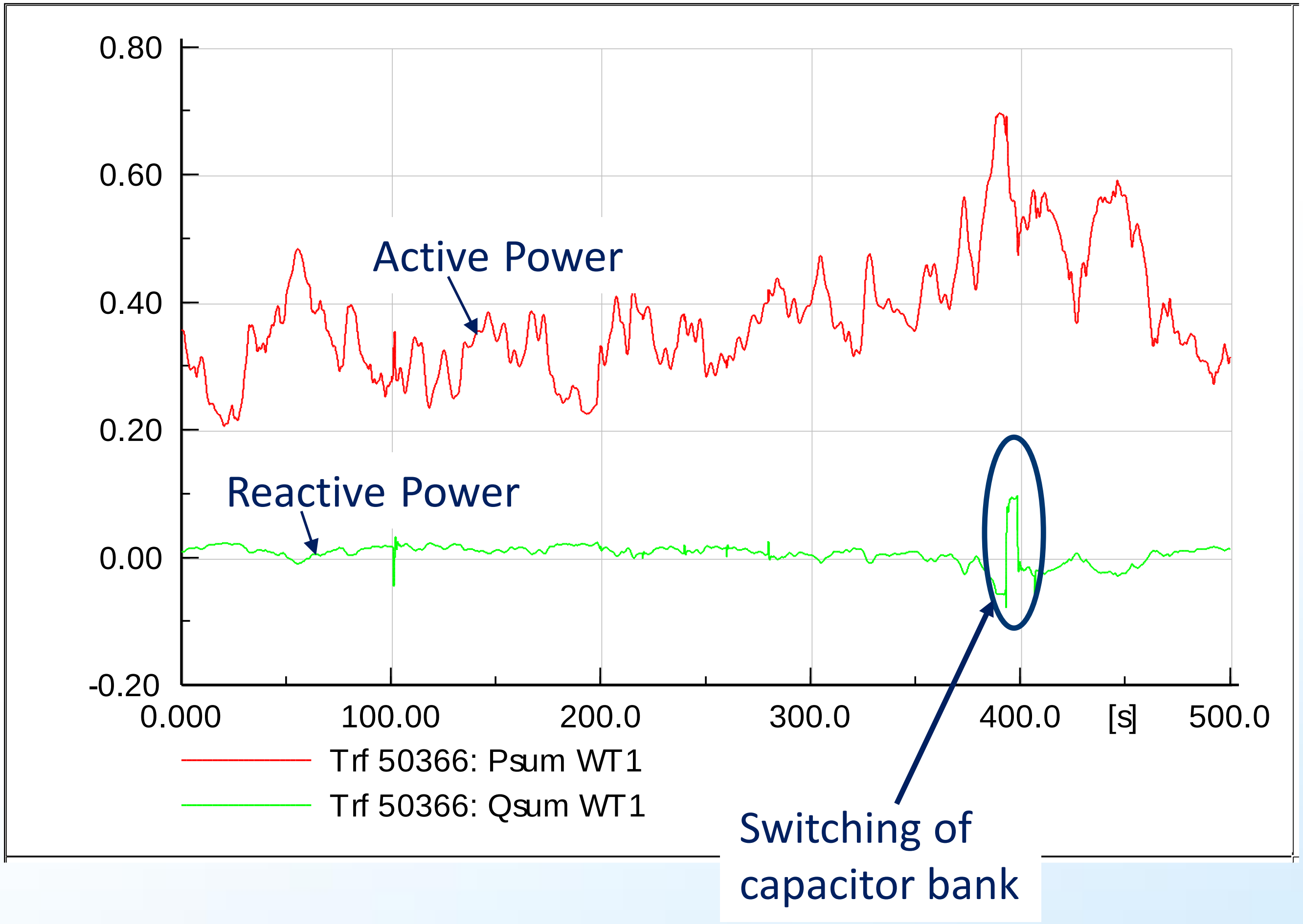
Simulation: Islandoperation with Windturbines



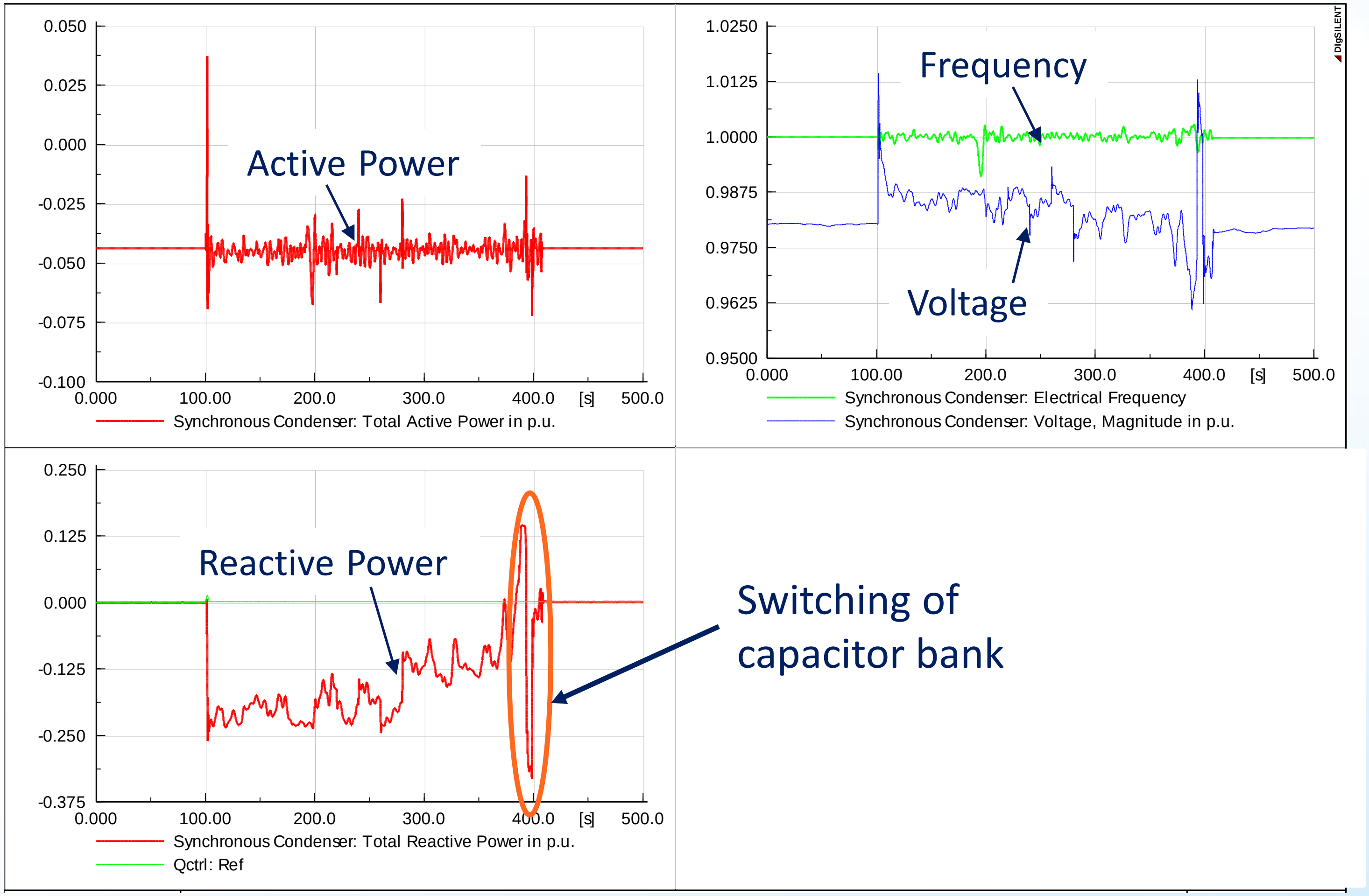
Simulation: Dump Load (SLC)



Simulation: Windturbine



Simulation: Synchronous Condenser



Simulation Results

Detect invalid operation conditions: Active/reactive power balance cannot be achieved

Adjust test scenarios

Dynamic stability margins for islanding and operation in island

General verification of Cell Controller functionality

Improved asset selection for individual scenarios

Tuning of Cell Controller configuration for given scenario to achieve smoothest possible transition to island

Identify high-risk scenarios

FIELD TESTS

CHPs in Test Area 1

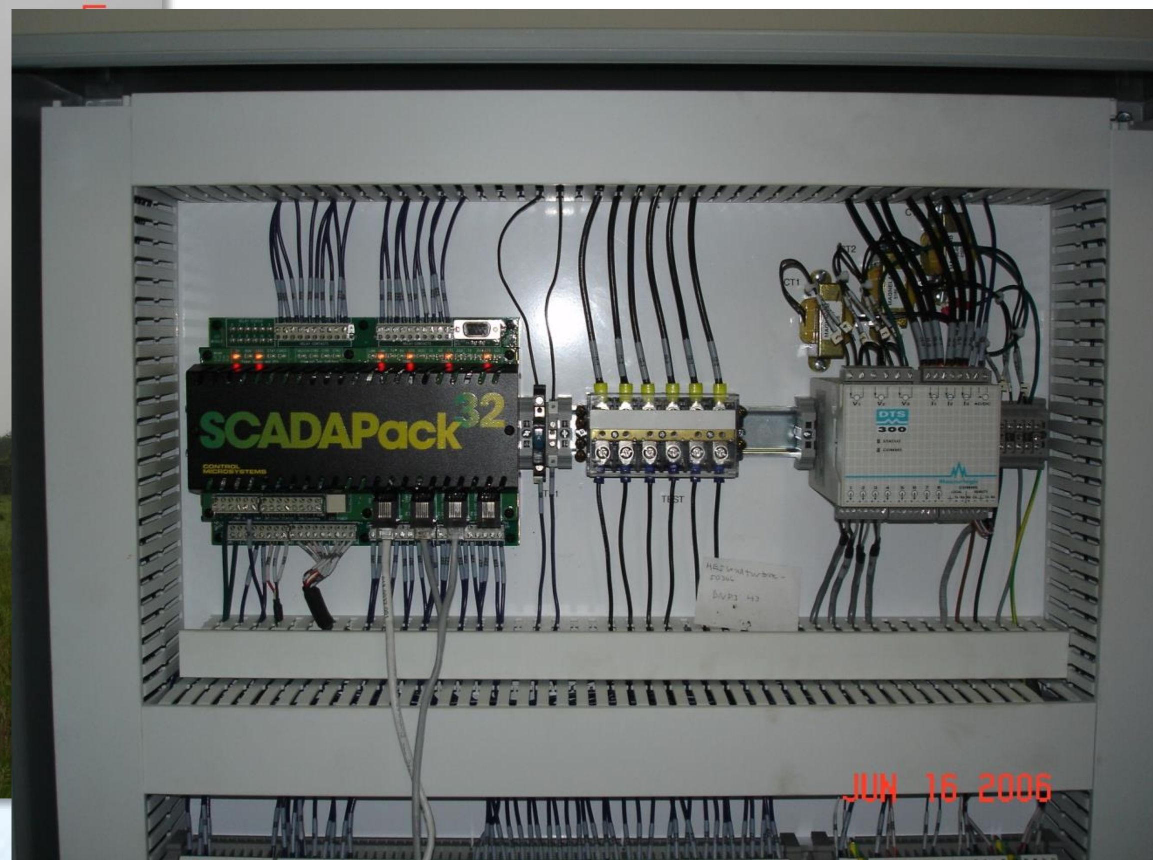
Billund: 3x 3.6 MVA

Hejnsvig：2x 1.3 MVA

Windturbines in Test Area 1

4x 1000 kW Windturbine
NEG Micon NM60/1000

Monitoring

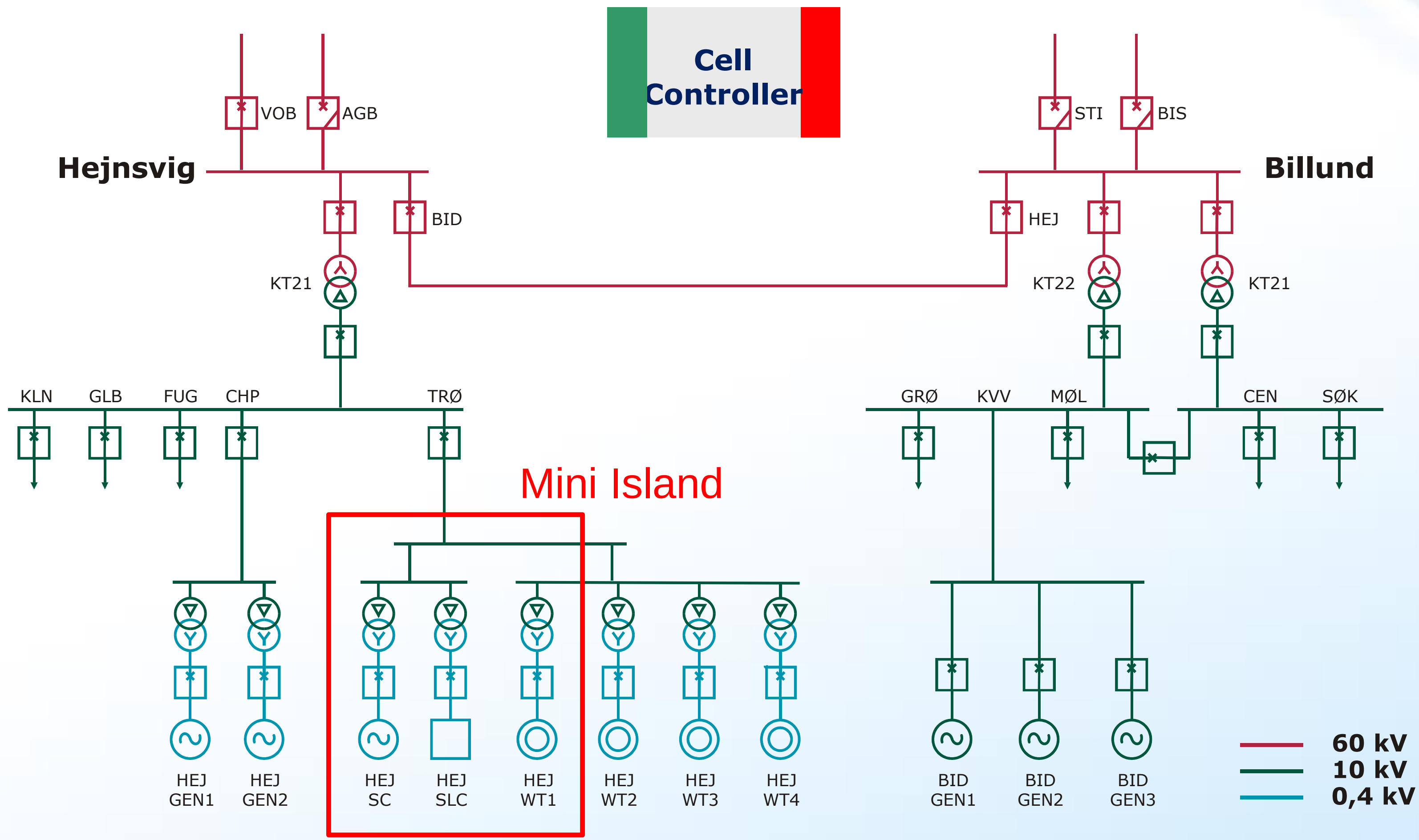


Synchronous Condenser and Dump Load (SLC)

1000 kW dump load for frequency control

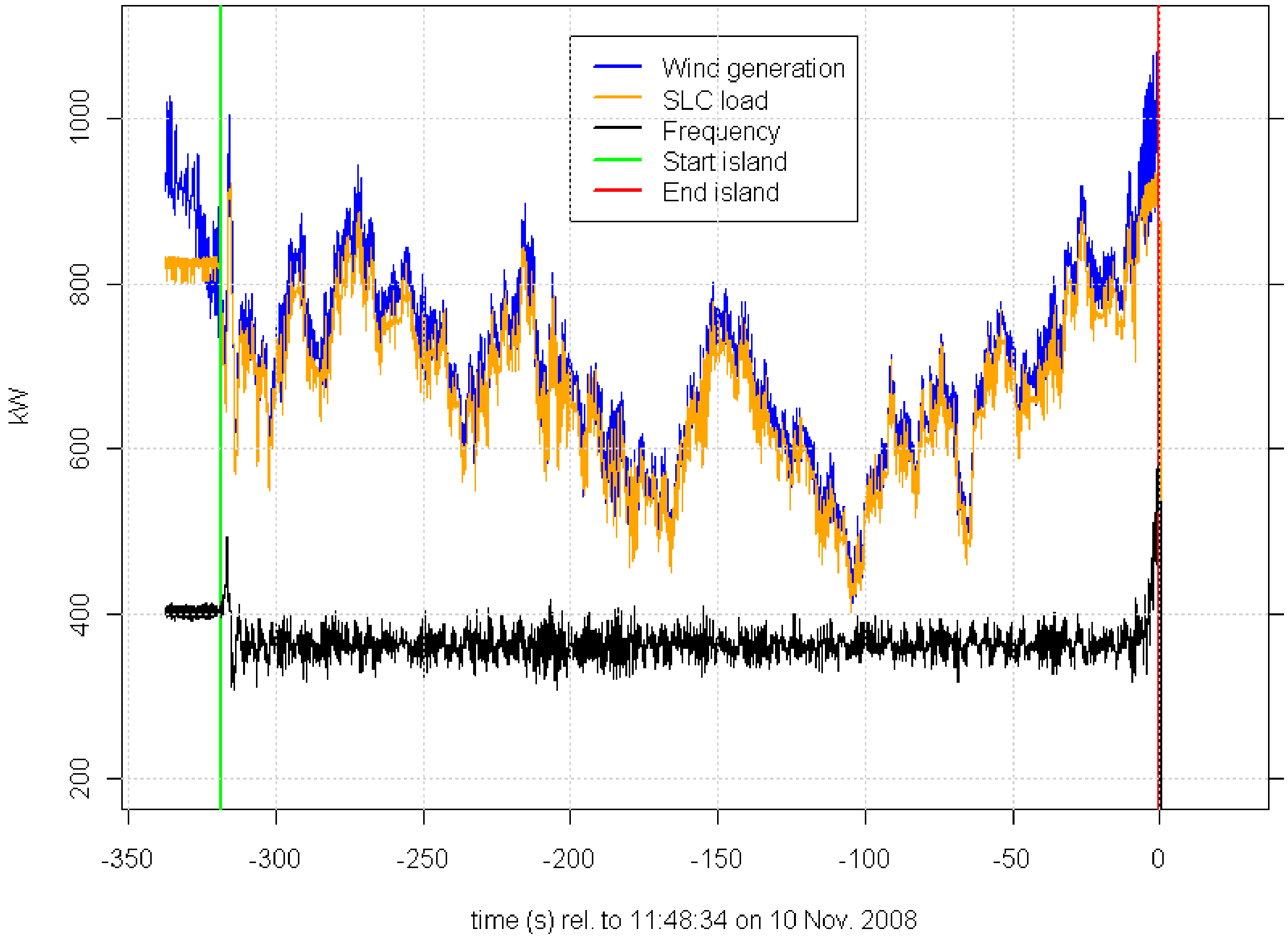
800 kVA synchronous condenser for voltage control

Measurement Results



Measurement Test 1: „Mini Island“ Frequency

10. November 2008, 11:43 – 11:48



Measurement Test 1: „Mini Island“ Voltage

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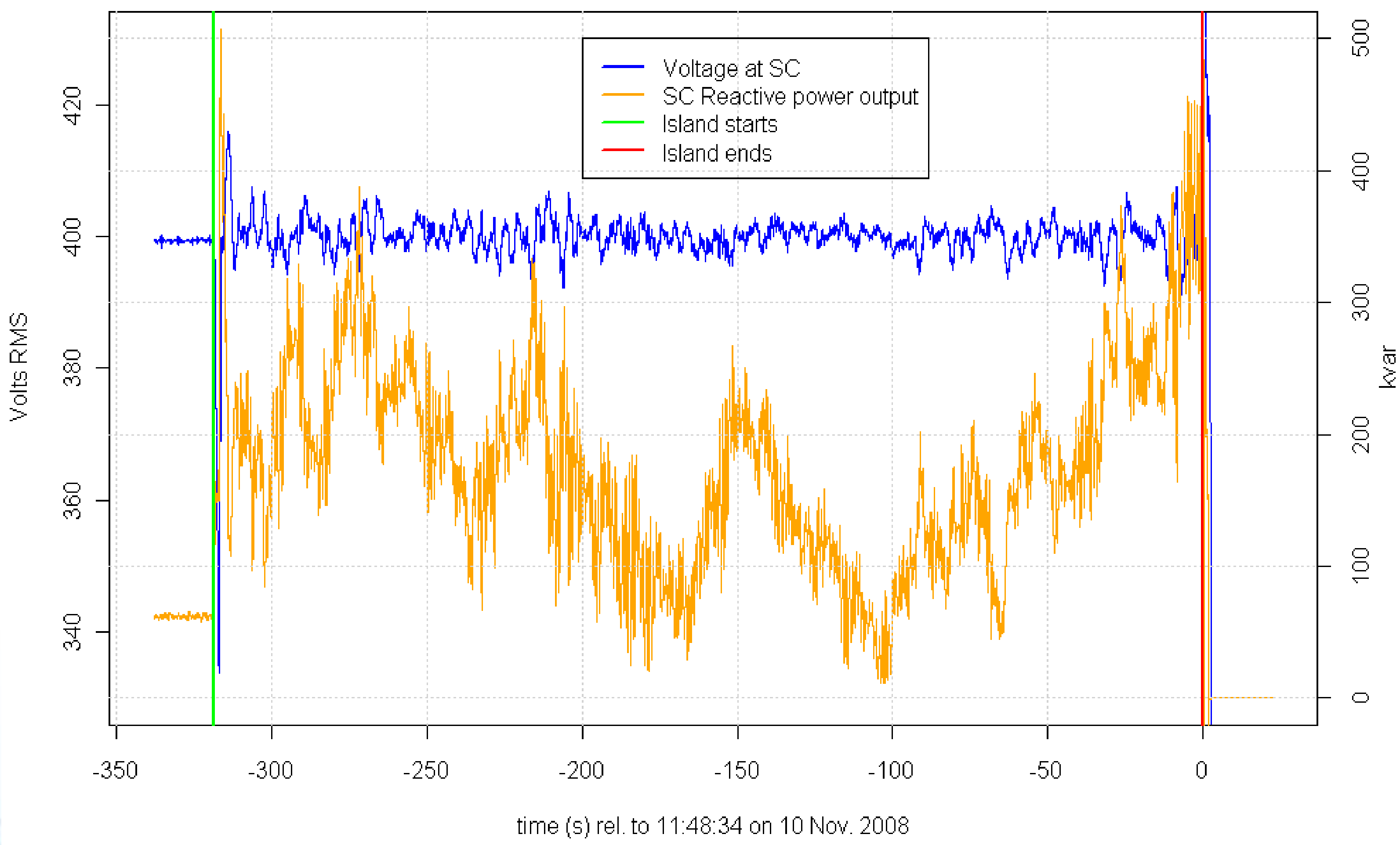
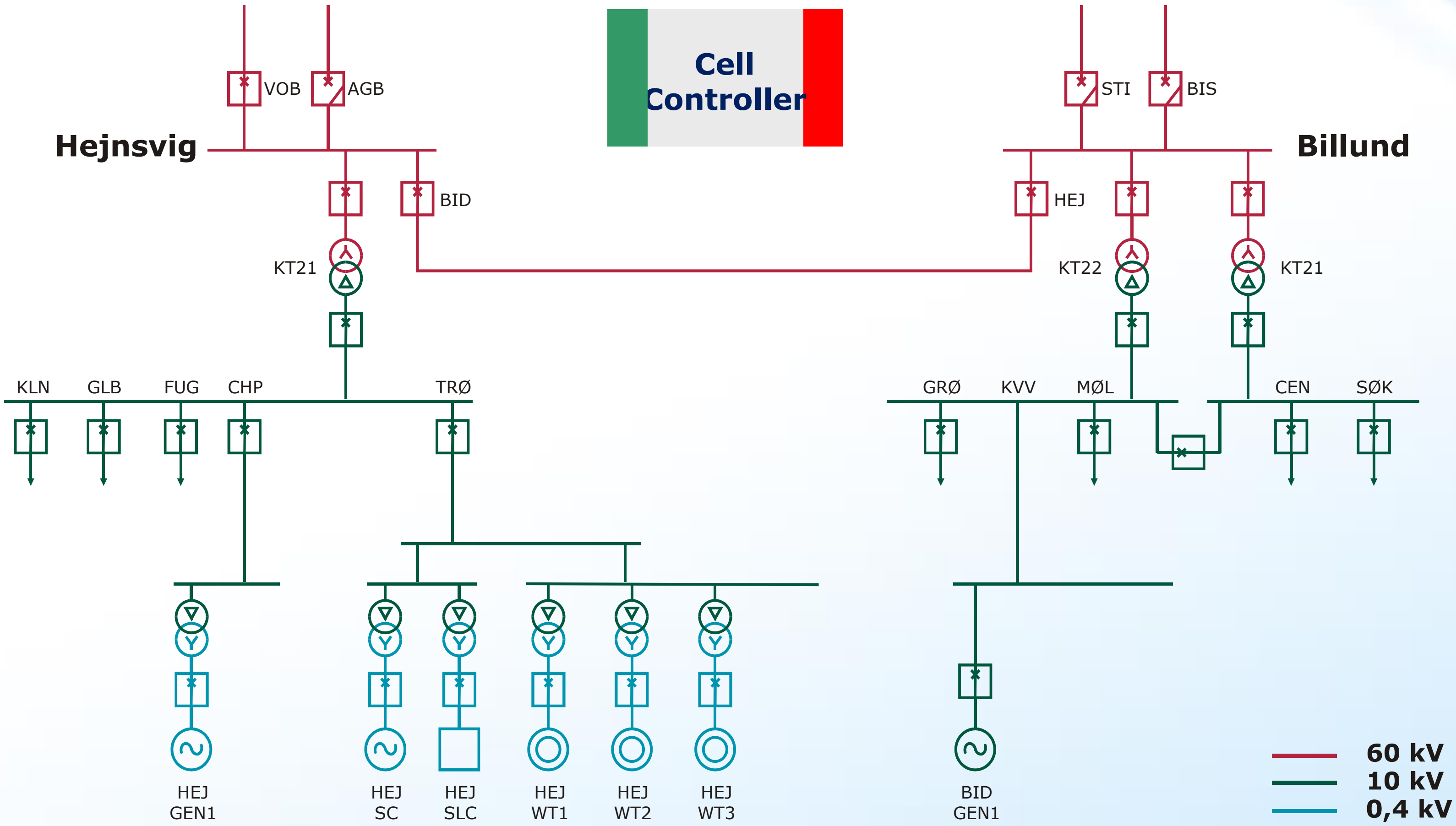
10. November 2008, 11:43 – 11:48



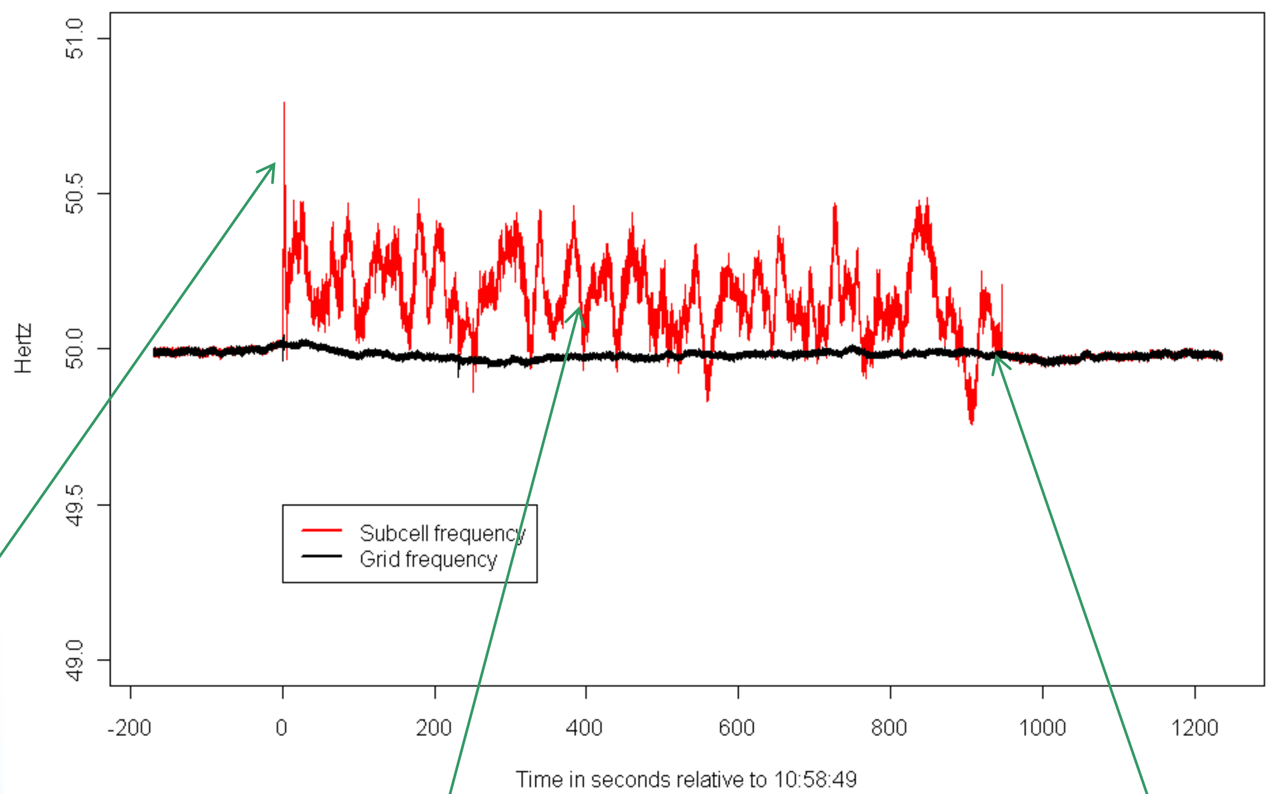
Measurement Test 2: Island Operation



Measurement Test 2: Island Operation Frequency

At time of island, cell generation (which includes over 1 MW of wind power) exceeds load by 470 kW.

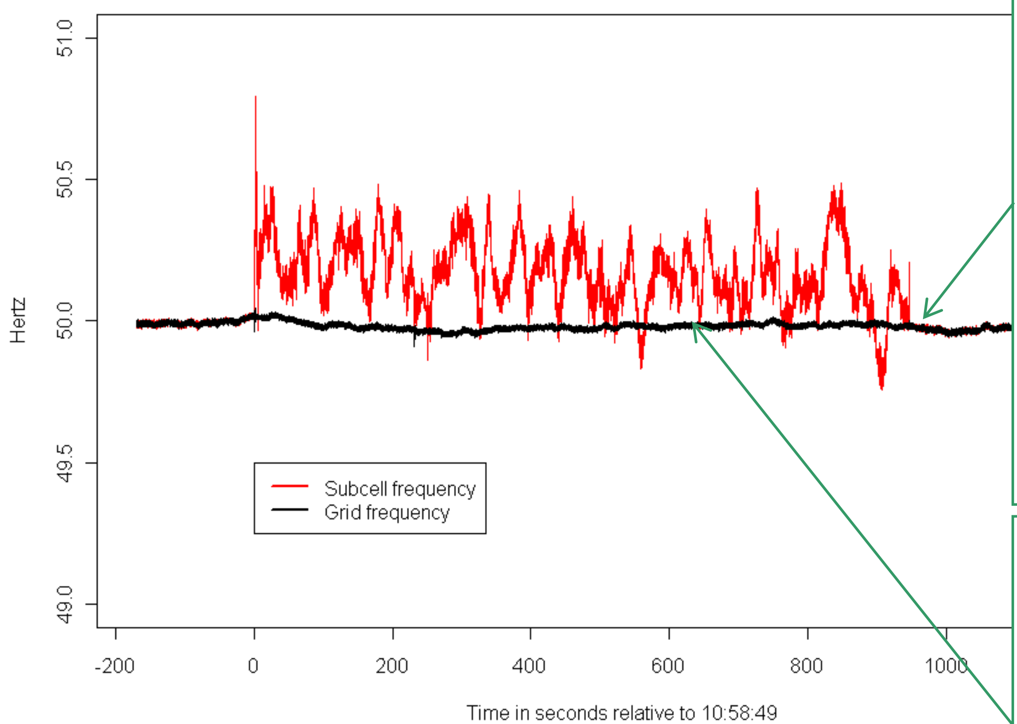
Frequency increases immediately, but SLC and CHP governors react to compensate.

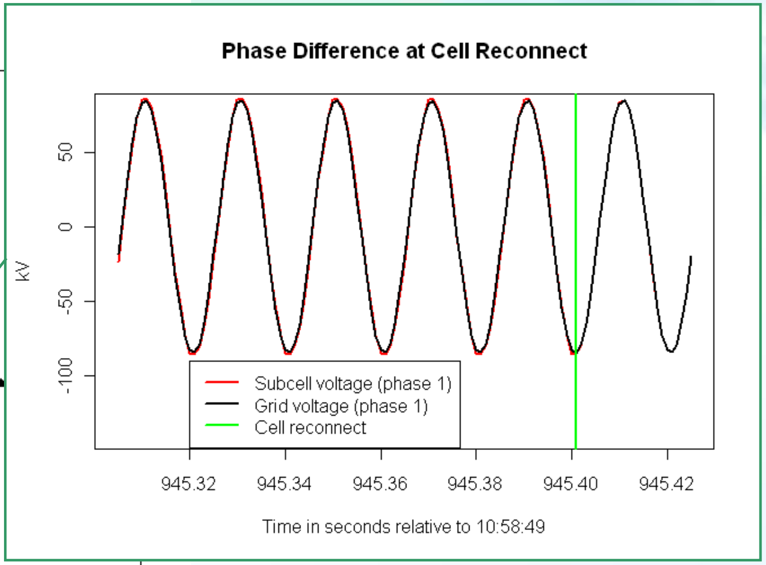


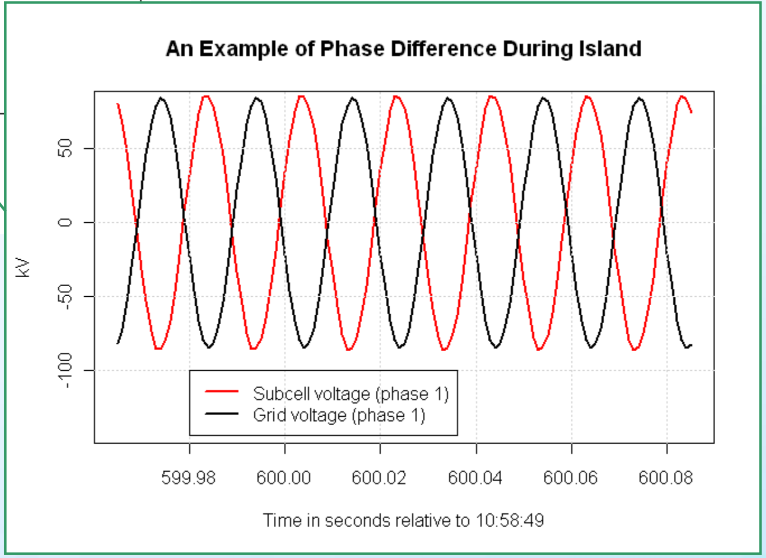
During island, cell frequency fluctuates as wind generation varies from 800 to 1350 kW. Cell Controller reacts and maintains cell within all grid code given boundaries.

Cell reconnected to grid.

Measurement Test 2: Island Operation Synchronization

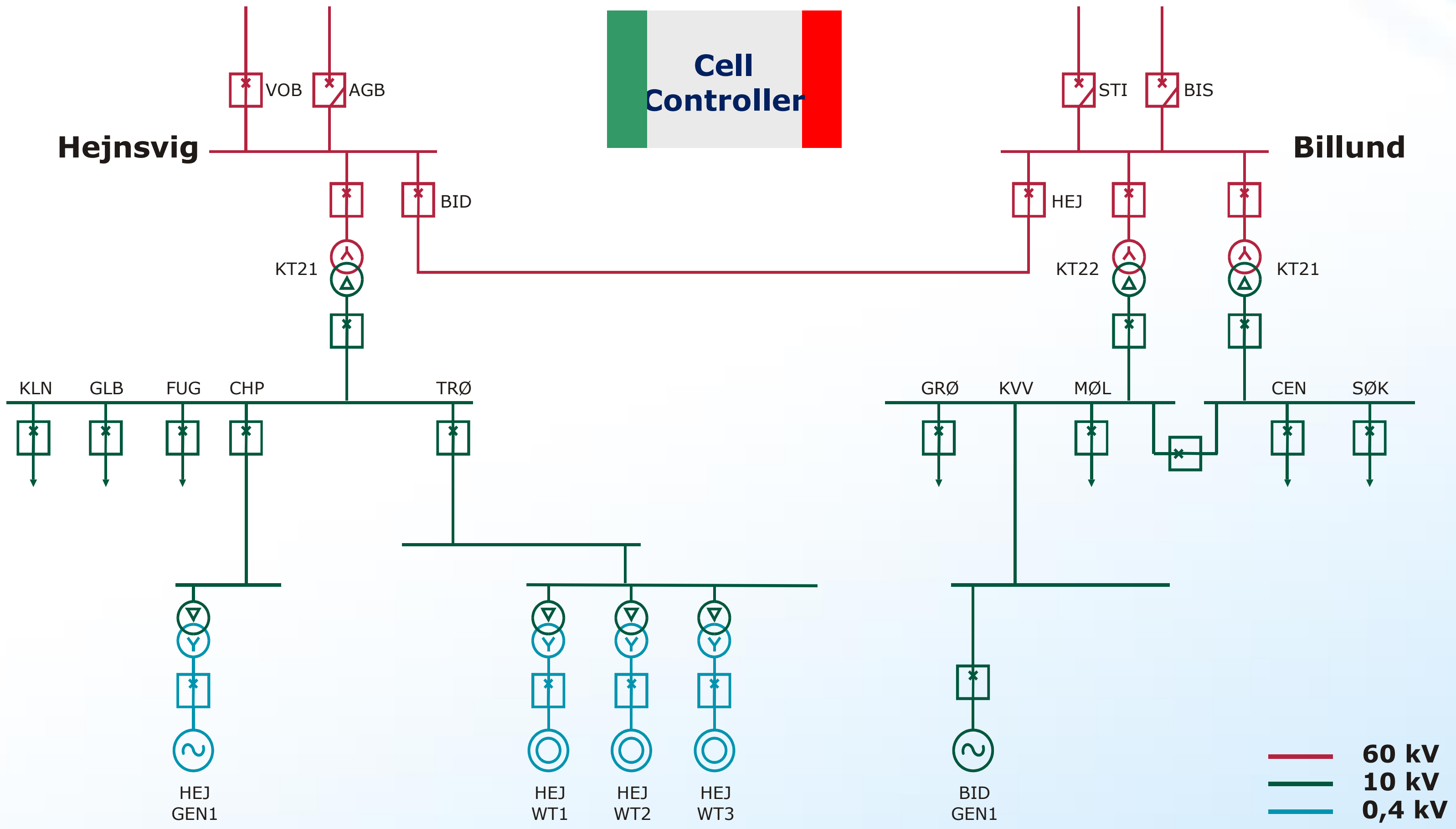






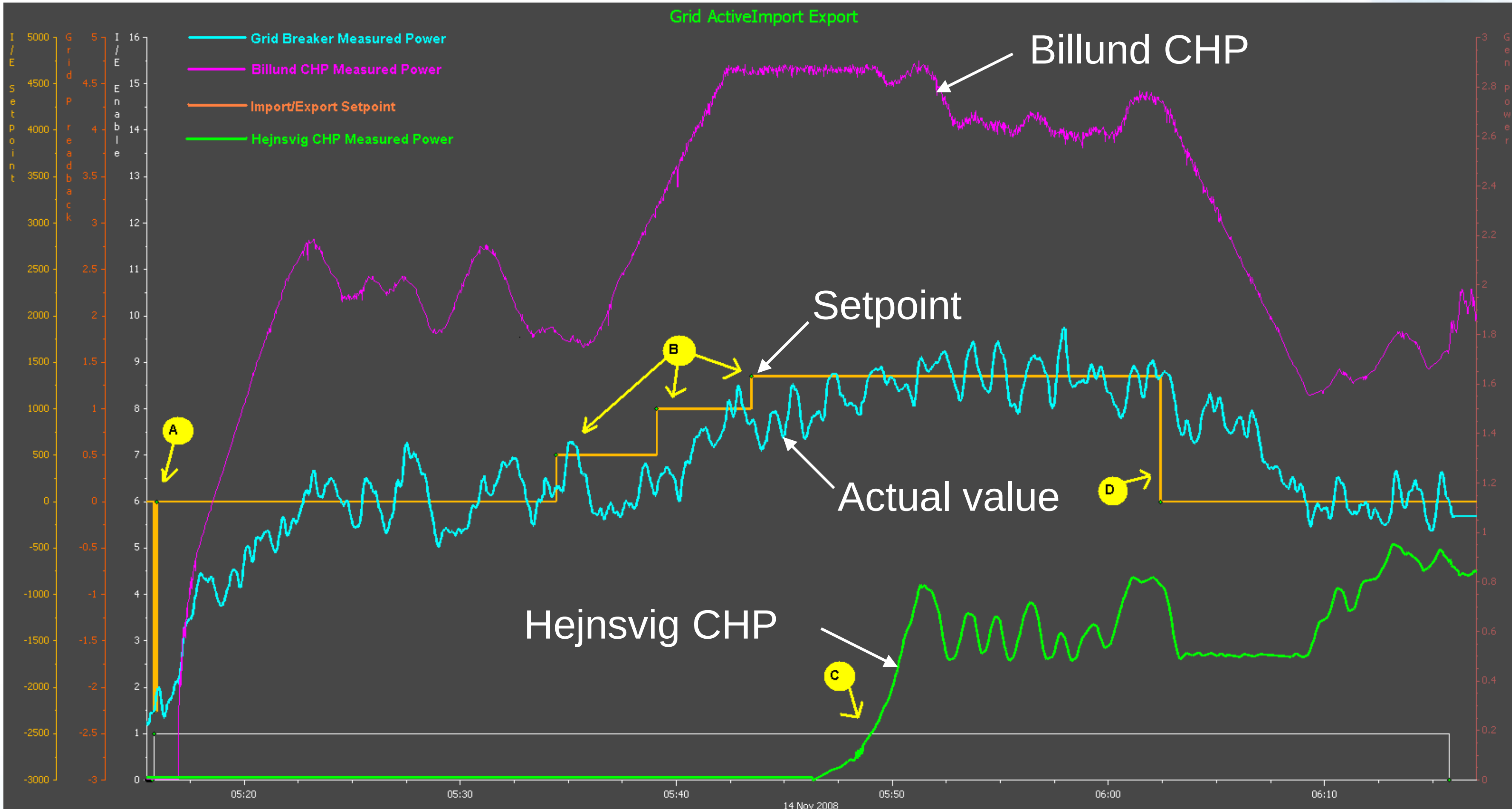
Once a reconnection to the grid is requested, the Cell Controller brings cell frequency and voltage phase within range of grid values. The Master Synchronizer reconnects only when cell frequency and voltage phase are sufficiently close to the grid values.

Measurement Test 3: Import/Export Control



Measurement Test 3: Import/Export Control

14. November 2008, 12:15 – 13:16



Trace	Type	Ruler Value	Minimum	Maximum	Mean	Std. Dev.
CC1.D.3.CC_.001.CMD.PSPc	Raw Historic	-	-2259.52	1350	98.41	1274.35
HEJ.A.2.VOB.000.PMR.P__h	Raw Historic	-	-2.41	1.87	0.41	0.81
CC1.D.3.CC_.001.CMD.PIEc	Raw Historic	-	0	1	0.06	0.24
BID.B.1.GEN.001.PMR.P__h	Raw Historic	-	0	2.9	2.29	0.55
HEJ.B.0.GEN.001.PMR.P__h	Raw Historic	-	-0	0.95	0.59	0.2
InternalPoints.TotalWindP	Raw Historic (*)	-	0.52	2.19	1.29	0.28

Cell Controller Field Test Results

Despite careful testing, a number of black-outs occurred during the field tests:

There were unknown details in the grid configuration (couplings between load feeders) that led to too high load changes on load shed/restore

The power supply of one CHP plant was provided via another load feeder. Shedding this feeder therefore also disconnects the CHP plant…

Intentionally risky scenarios with regard to power balance, involving very high contribution of wind generation.

No black-out due to Cell-Controller problems!

Achieved test results

- ✓ Grid connected import/export control (virtual generator operation)
- ✓ Emergency transfer to sustained hybrid island operation
- ✓ Islanded wind only operation with SC and SLC

➔ A utility scale „Micro“grid concept has been successfully demonstrated.

Lessons learnt

- By adding ICT to the system a higher security of supply can be achieved, however it also adds new sources of failure.
- Modelling and simulations are powerful tools to test new control strategies before going into the field. In case of island operation dynamic simulations are necessary!

Publications

The final report can be downloaded here:

- http://energynautics.com/content/uploads/2017/08/energynautics_energinetdk_report_cell_controller_pilot.pdf

Papers

- **P. Lund, S. Cherian, T. Ackermann, 2005, "A Cell Controller for Autonomous Operation of a 60 kV Distribution Area", *International Journal of Distributed Energy Resources*, vol.1, No.1, 83-100.**
- **P. Lund, 2007, "The Danish Cell Project – Part 1: Background and General Approach", *IEEE Power Engineering Society General Meeting*, Tampa, USA.**
- **S. Cherian, V. Knazkins, 2007, "The Danish Cell Project – Part 2: Verification of Control Approach via Modelling and Laboratory Tests", *IEEE Power Engineering Society General Meeting*, Tampa, USA.**
- **H. Kley, N. Martensen, P. Lund, S. Cherian, O. Pacific, 2009, "The Cell Controller Pilot Project: Testing a Smart Distribution Grid in Denmark", *Grid Interop 2009: The Road to an interoperable Grid, Proceedings*, Denver, USA.**
- **N. Martensen, P. Lund, N. Mathew, 2011, "The Cell Controller Pilot Project: From Surviving System Black-Out to Market Support", *CIRED 2011, Proceedings*, Frankfurt, Germany.**
- **N. Martensen, H. Kley, P. Lund, 2011, "Demonstrating DER-based Voltage Control in the Danish Cell Project", *CIGRÉ Symposium 2011, Proceedings*, Bologna, Italy.**

Thank you for your attention!