Secure Operation of Sustainable Power Systems

Systmod Seminar at the University of Liege

Hjörtur Jóhannsson
Assistant Professor

Center for Electric Power and Energy

26-04-2013

DTU

The
Danish Council for
Strategic Research

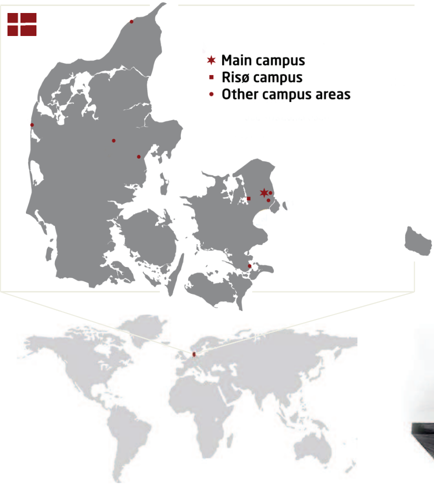
Center for Electric Power and Energy
Department of Electrical Engineering

Outline

Technical University of Denmark

Technical University of Denmark

(founded 1829; first rector H.C. Ørsted)



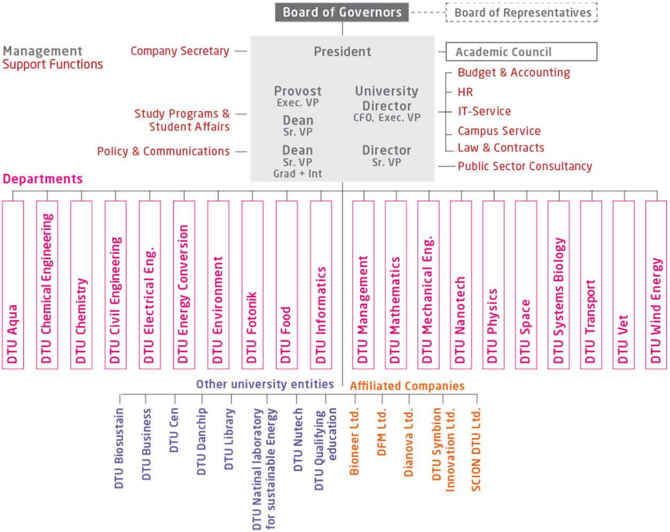
Key Figures

Total Students	~8.900
- Including PhDs	1.300
- And Int. M.Sc.	700
Total DTU staff	~5.000
- Professors	150
- Assoc. Prof. & senior researchers	722
- Assist. Prof, researchers & postdocs	592

DTU main Campus - Lyngby

Center for Electric Power and Energy
Department of Electrical Engineering

DTU Organization

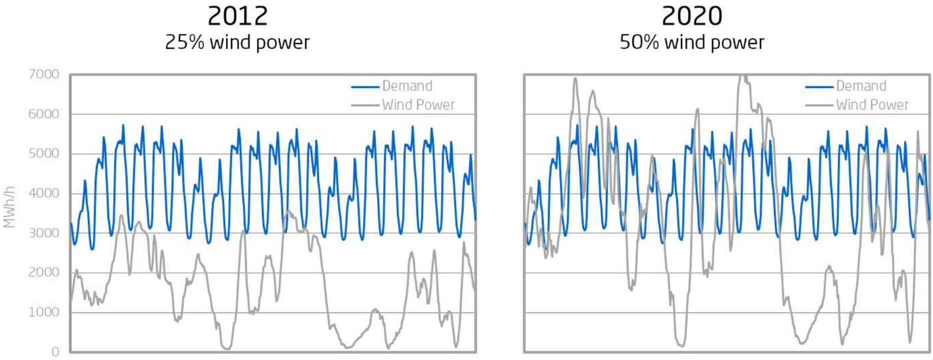


Center for Electric Power and Energy (CEE)

Department of Electrical Engineering

- CEE established 15 August 2012 as a merger of existing units:
  - Center for Electric Technology, DTU Electrical Engineering
  - Intelligent Energy Systems, Risø National Laboratory for Sustainable Energy
- Main competences
  - Electric Power Engineering
  - Automation and control
  - Information and Communication Technology
- A strong university center within its field
  - Staff: 85 persons incl. PhD-students
  - Covers discipline oriented research as well as national lab type application-driven research and proof-of-concept
- Strategic partnerships

Research Challenges



Center for Electric Power and Energy
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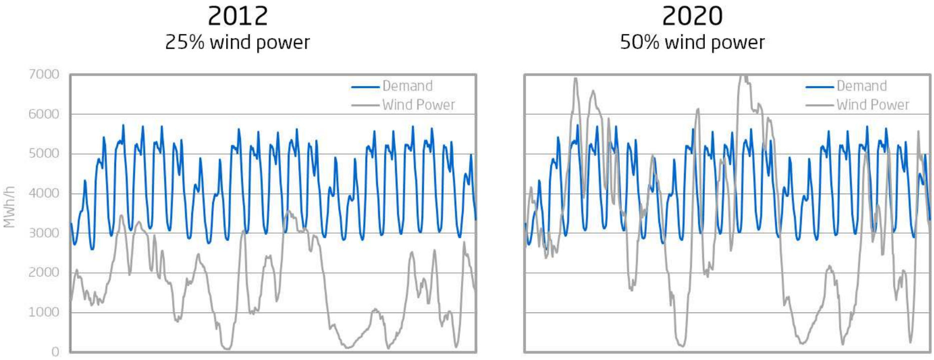
Research Challenges

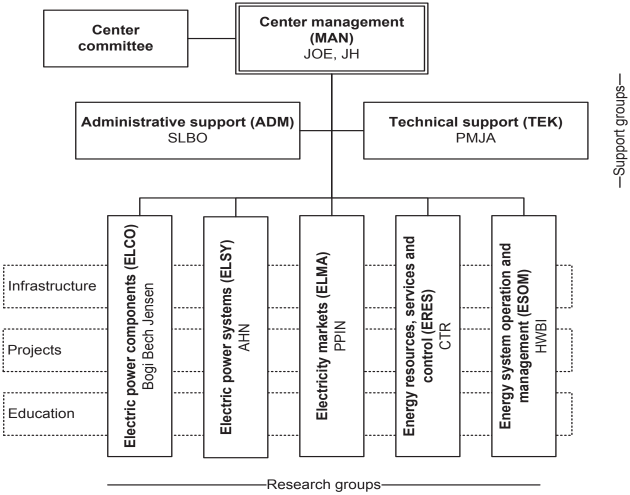


The Main Research Challenge of CEE

Development of a reliable, cost effective and environmentally friendly electric power and energy system based on renewable energy sources.

Center for Electric Power and Energy

Organisation



Head of Center

Jacob Østergaard

Deputy Head of Center

Joachim Holbøll

ADM
Solveig Lind Bouquin

TEK
Per Munch Jakobsen

ELCO
Bogi Bech Jensen

ELSY
Arne Hejde Nielsen

ELMA
Pierre Pinson

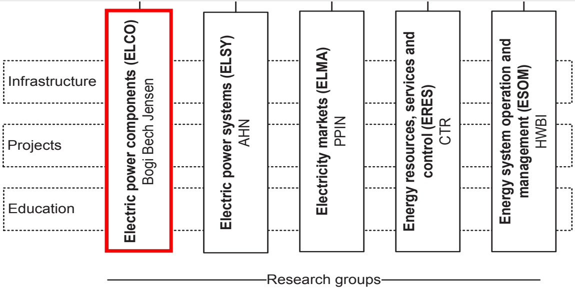
ERES
Chresten Træholt

ESOM
Henrik Bindner

Electric Power Components (ELCO)

Examples of research activities:

- Superconducting generators and superconducting drive train
- Lightning protection of wind turbine blades
- Transient conditions and protection in HVDC offshore grids



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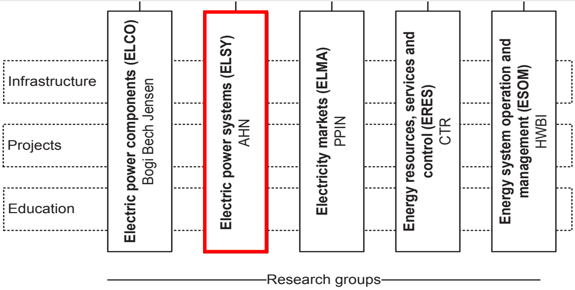
Electric Power Systems (ELSY)

Examples of research activities:

- Secure operation of sustainable power systems
- Operation of distribution networks after electrification of transport and heating
- Application of smart grid in photovoltaic power systems



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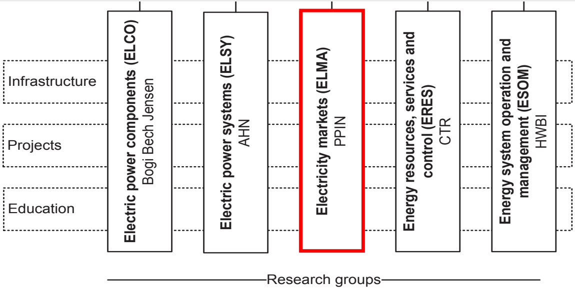
Electricity Markets (ELMA)

Examples of research activities:

- Electricity market design for distributed energy resources and flexible demand
- Impact of Stochastic Generation on Electricity Market Dynamics
- Electric vehicle integration in a real-time market



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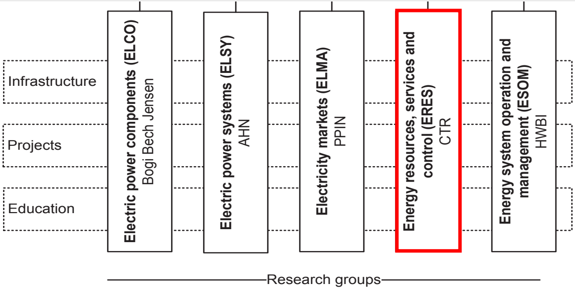
Energy Resources, Services and Control (ERES)

Examples of research activities:

- Energy storage and energy system integration
- Intelligent electric vehicle integration
- Local area coordination, fleet management, home automation and individual RES controllers
- Energy conversion, storages and flexible demand technologies and their efficiency



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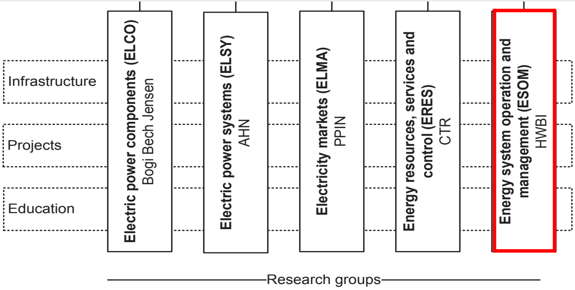
Energy Systems, Operation and Management (ESOM)

Examples of research activities:

- Communication architecture for service based control of distributed power systems
- Smart modelling of optimal integration of large amount of PV
- Integrated communication and electric power distribution system design



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For further information:

http://www.cee.dtu.dk

Outline

Danish Government Energy Target towards 2050

Regeringens energipolitiske milepæle frem mod 2050

For at sikre, at vi opnår 100 pct. vedvarende energi i 2050, har regeringen en række energipolitiske milepæle i årene 2020, 2030 og 2035. Disse målsætninger er hver især skridt i den rigtige retning, der sikrer fremdrift mod 2050.

2020	2030	2035	2050
Halvdelen af det traditionelle elforbrug er dækket af vind	Kul udfases fra danske kraftværker Oliefyr udfases	El- og varmeforsyningen dækkes af vedvarende energi	Hele energiforsyningen – el, varme, industri og transport – dækkes af vedvarende energi
50% wind in the electricity system	No coal	100% RE in electricity and heating systems	100% RE (incl. transport and industry)

Initiativerne frem til 2020 resulterer i en reduktion af drivhusgasudledningerne på 35 pct. i forhold til 1990

Future Challenges:

Secure Operation of Sustainable Electric Power Systems

- ***Future visions:*** a society with minimal dependency of fossil fuels
  - Requires power production to be mainly based on renewable energy sources (RES)
  - Production becomes subject to prevailing weather conditions

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- The challenge of maintaining balance between production and consumption has received significant research focus
  - Demand as a frequency controlled reserve
  - Utilize controllable loads (EVs, heat pumps, etc.)

Future Challenges:

Secure Operation of Sustainable Electric Power Systems

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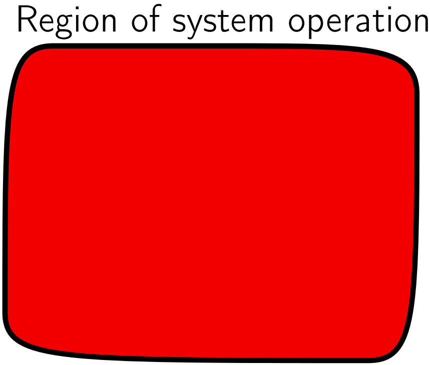
  - Production becomes subject to prevailing weather conditions
- The challenge of maintaining balance between production and consumption has received significant research focus
  - Demand as a frequency controlled reserve
  - Utilize controllable loads (EVs, heat pumps, etc.)
- The effect that large amount of RES has on the overall system stability or security has not received same attention
  - Highly loaded grid during high wind situations
  - Conditions for other types of stability problems

Need for Real-Time Stability/Security Assessment



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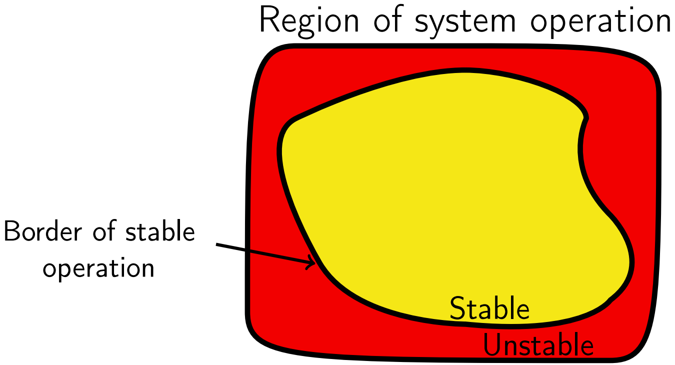

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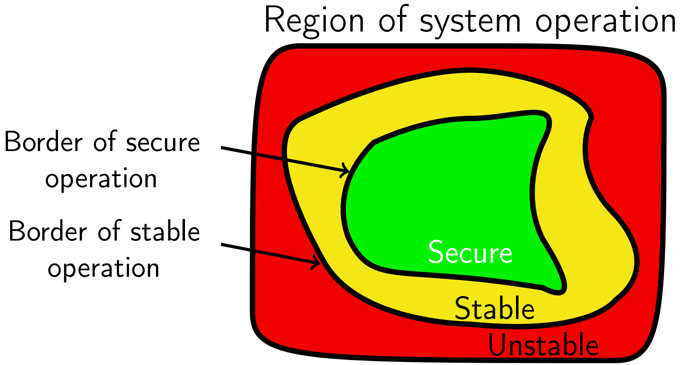

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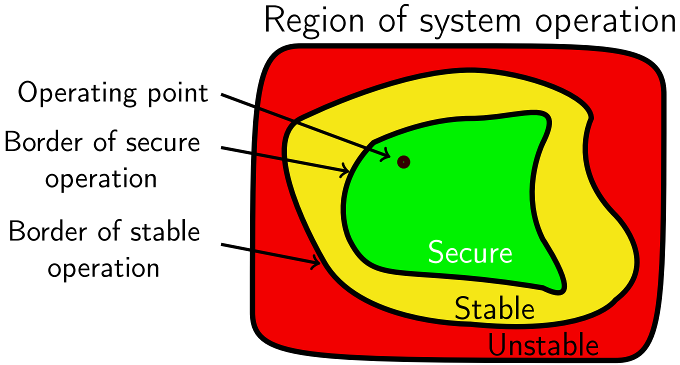

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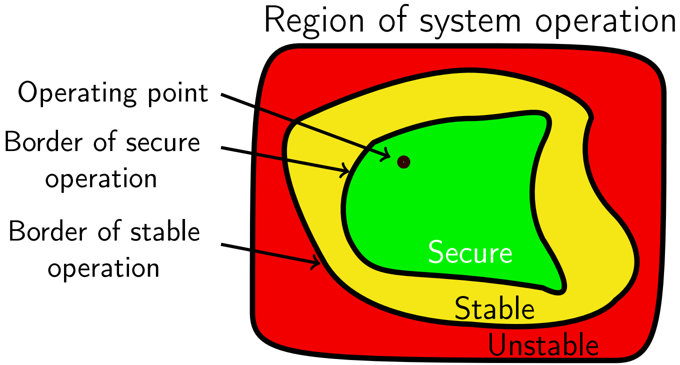
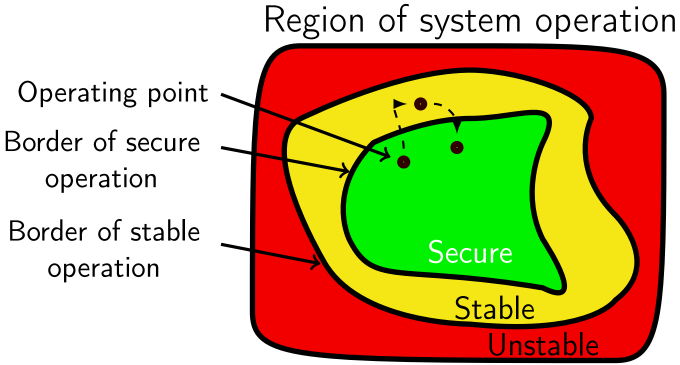


Historically, security assessment is based on off-line analysis

$\Rightarrow$ Time consuming

Need for Real-Time Stability/Security Assessment



Historically, security assessment is based on off-line analysis

⇒ Time consuming

System with high share of production based on non-controllable energy sources

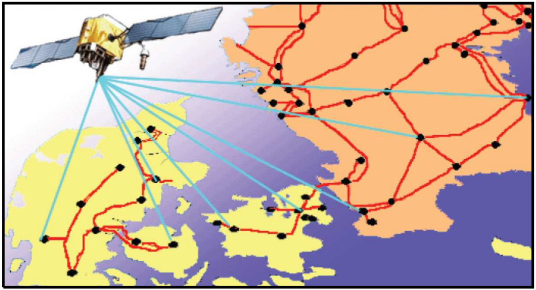
⇒ Fluctuating operating point

⇒ Need for real-time security/stability assessment

⇒ PMUs as enabling technology

Phasor Measurment Unit (PMU)

Introduction



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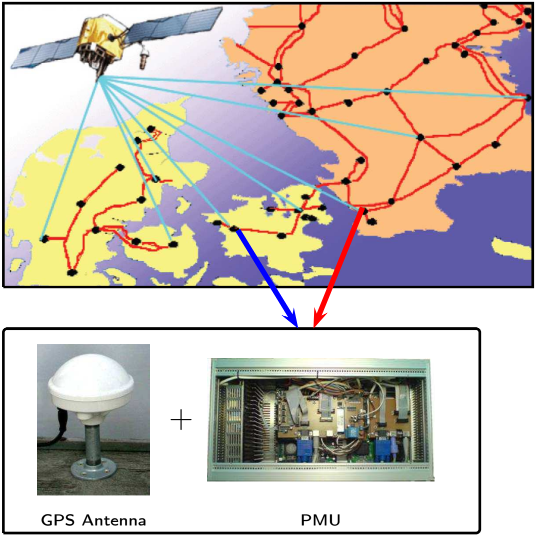

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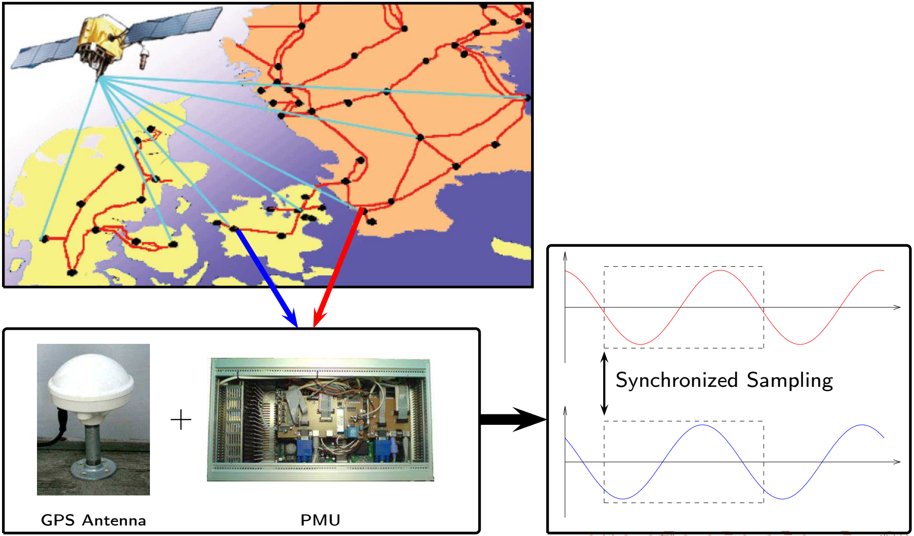

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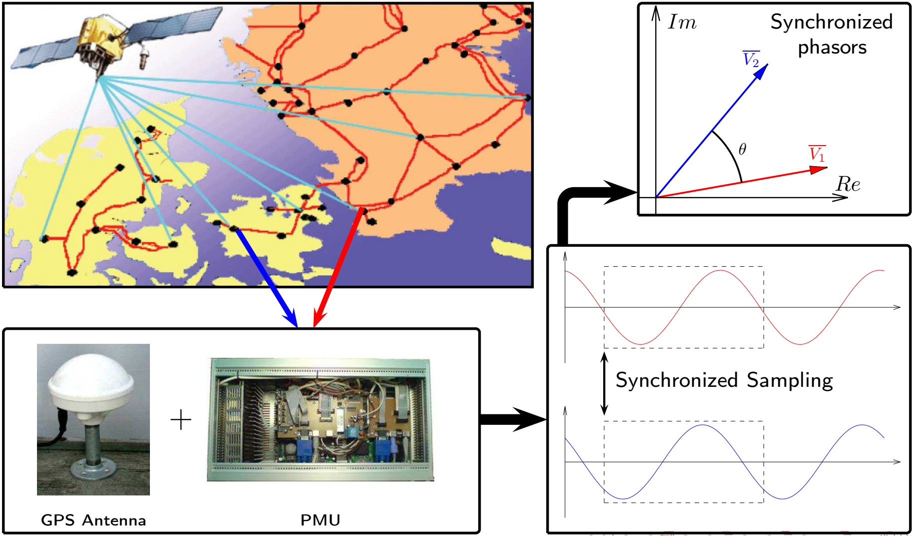
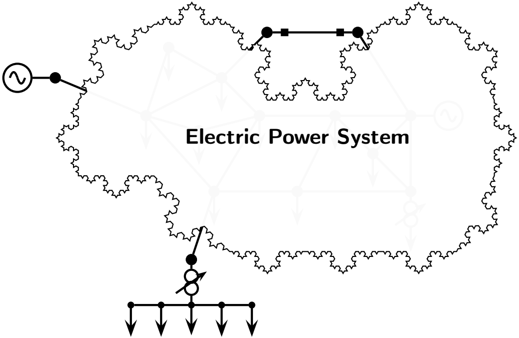


Advancing Power System Protection and Control

- Traditionally, power system protection and control has been based on local measurements



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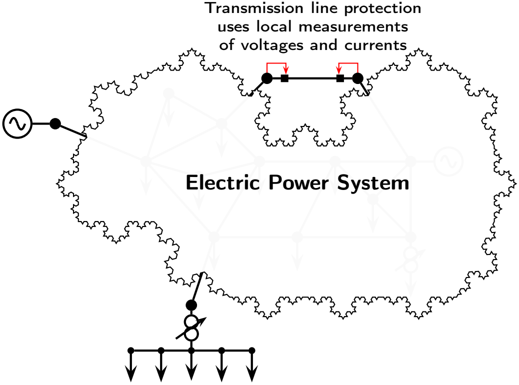

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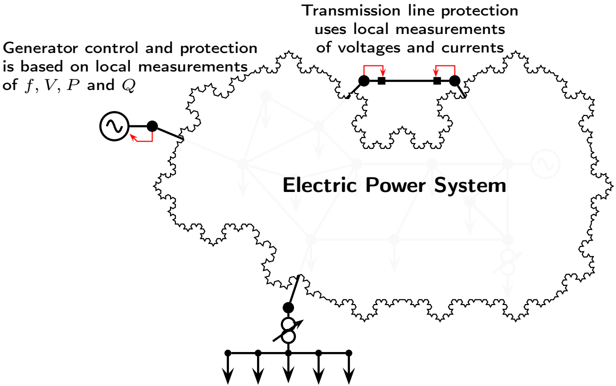

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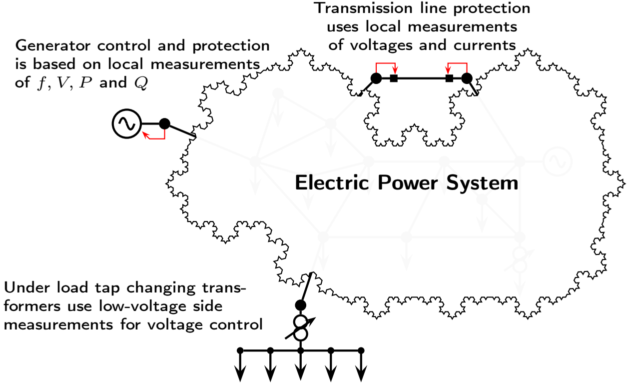

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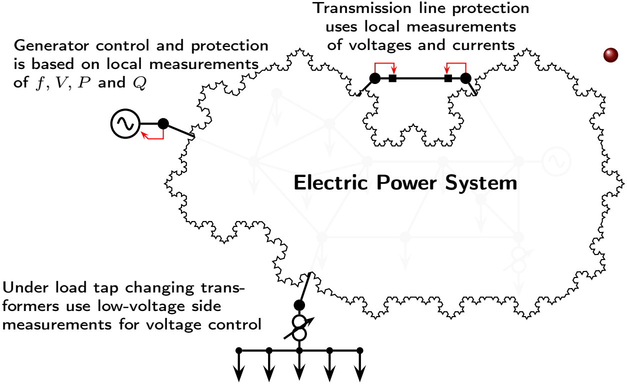

- During critical operating conditions, the control and protection equipment can have negative effect on the system stability and directly contribute to the process leading to a system blackout.

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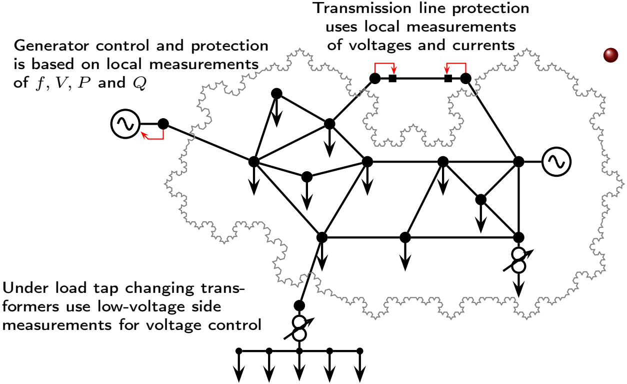


- During critical operating conditions, the control and protection equipment can have negative effect on the system stability and directly contribute to the process leading to a system blackout.

- Wide area measurement can be used to identify critical operating conditions and use that information to change control and protection parameters to avoid large scale blackout

Outline

Center for Electric Power and Energy
Department of Electrical Engineering

The SOSPO Project - Objective

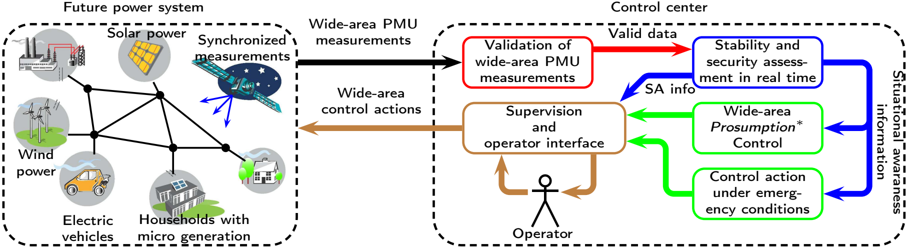
Secure Operation of Sustainable Power Systems

- The SOSPO project aims to solve critical, difficult and not yet treated problems in relation to the operation of future power systems:

  How to ensure a secure operation of the future power system where the operating point heavily is fluctuating?

The SOSPO Project

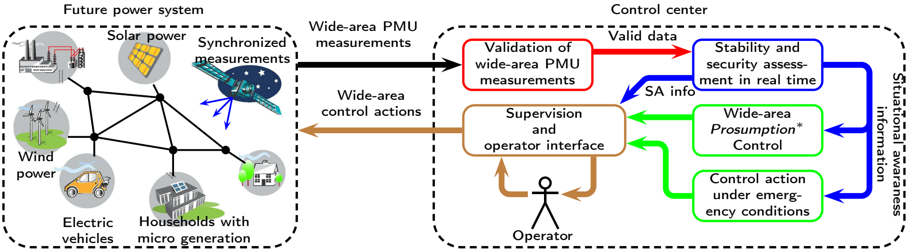
Secure Operation of Sustainable Power Systems



Prosumption involves both distributed production and consumption

The SOSPO Project

Secure Operation of Sustainable Power Systems



**Prosumption* involves both distributed production and consumption

Resources	***Persons***	***Man Months***
Senior Researches	14	105
Research Training	8	240
TAP	3	63
TOTAL	**25**	**408**

Total budget: DDK 32.2 mio. (EUR 4.3 mio.)
DSF grant: DDK 20.2 mio. (EUR 2.7 mio.)

Funded by:

The Danish Council for Strategic Research

The SOSPO Project - Partners

Partners from academia:

DTU

Center for Electric Power and Energy (CEE)
Automation & Control (AUT)

LUND UNIVERSITY

Att. Olof Samuelsson

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Att. Göran Anderson

CHALMERS

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Swiss Federal Institute of Technology Zurich

Att. Göran Anderson

CHALMERS

Att. Bo Egardt

Partners from industry and consultants:

ENERGINET DK

The Danish TSO

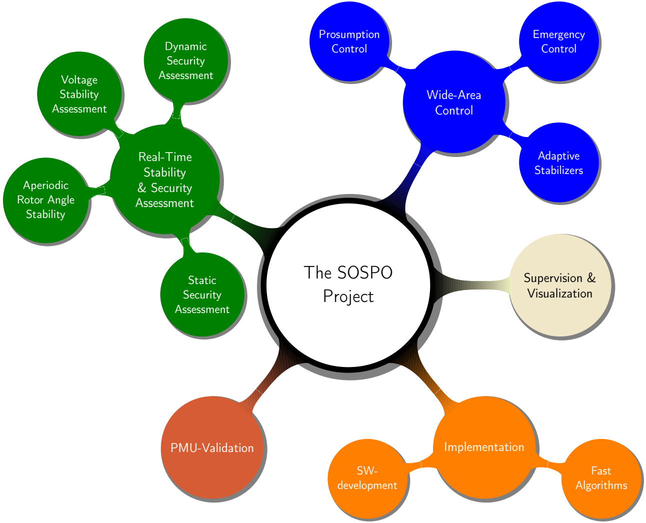
SIEMENS

Siemens AG, Germany

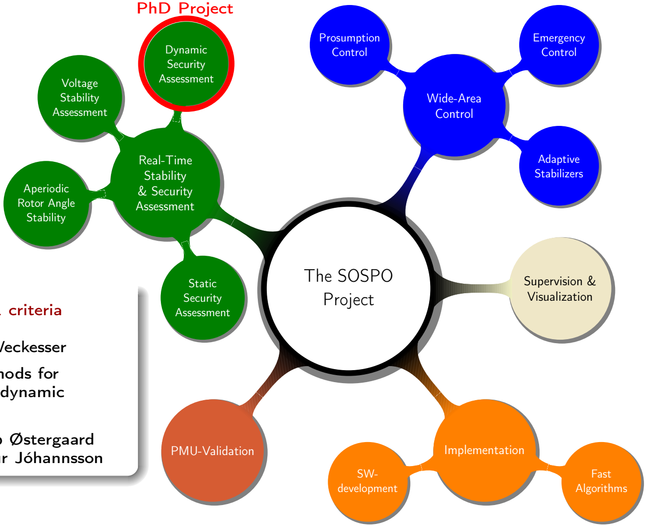
KenM Consulting

Att. Ken Martin

Major R&D Tasks in SOSPO



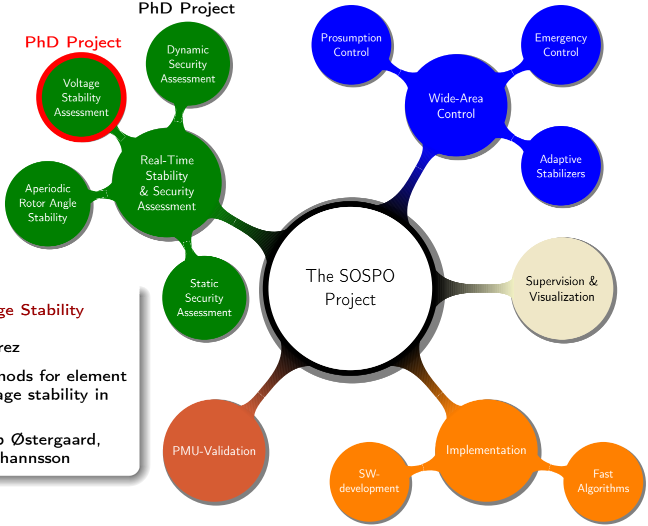
Major R&D Tasks in SOSPO



PhD Project:
Fast Dynamic Evaluation of N-1 criteria

- **PhD Student:** Tilman Weckesser
- **Objective:** Develop methods for real-time assessment of dynamic security.
- **Supervisors:** Prof. Jacob Østergaard and Assist. Prof. Hjörtur Jóhannsson

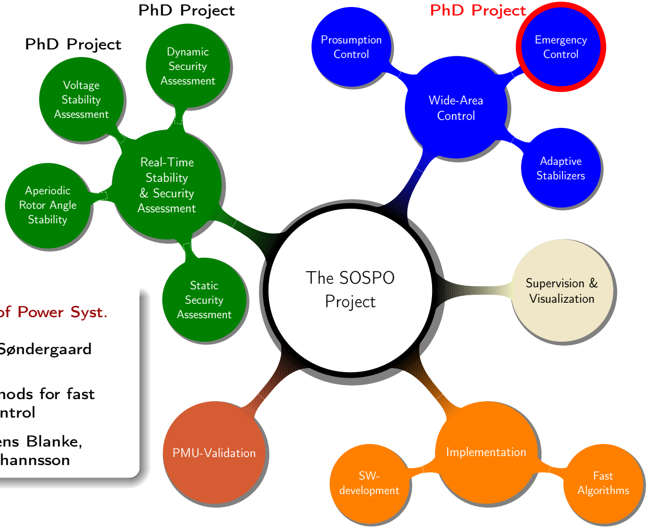
Major R&D Tasks in SOSPO



PhD Project:
Real-Time Assessment of Voltage Stability

- **PhD Student:** Angel Perez
- **Objective:** Develop methods for element wise assessment of voltage stability in real-time
- **Supervisors:** Prof. Jacob Østergaard, Assist. Prof. Hjörtur Jóhannsson

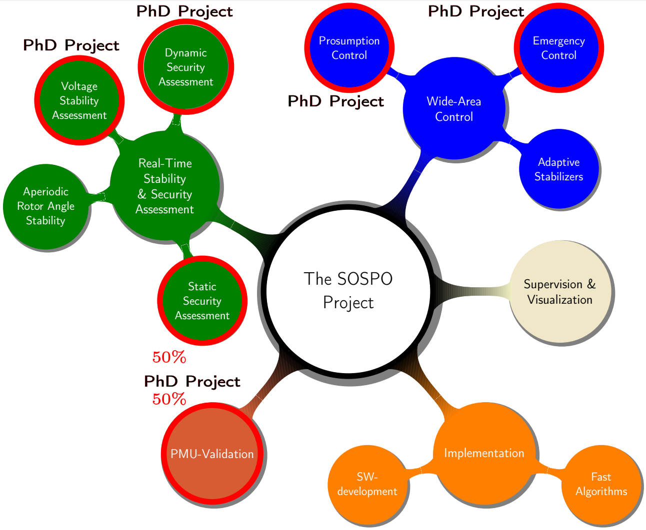
Major R&D Tasks in SOSPO



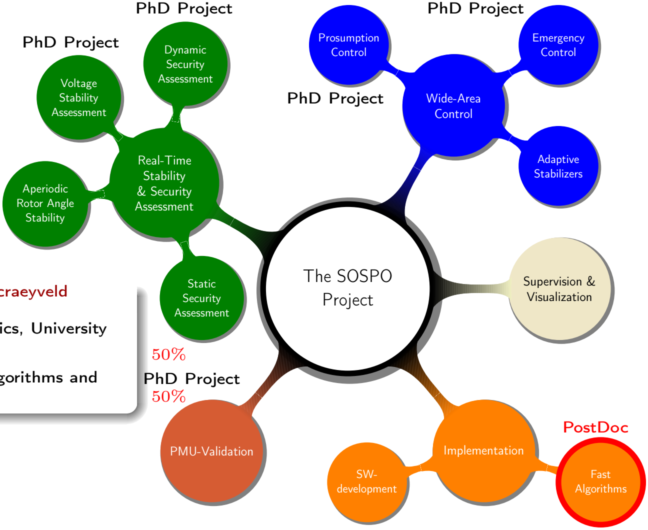
PhD Project:
Wide-Area Emergency Control of Power Syst.

- **PhD Student:** Andreas Søndergaard Pedersen
- **Objective:** Develop methods for fast wide area emergency control
- **Supervisors:** Prof. Mogens Blanke, Assist. Prof. Hjörtur Jóhannsson

Major R&D Tasks in SOSPO



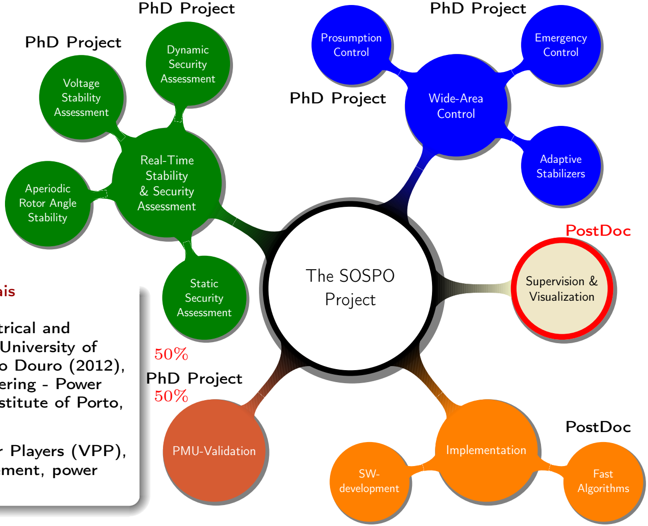
Major R&D Tasks in SOSPO



PostDoc Candidate: Pieter Vancraeyveld

- **Education:** PhD in Physics, University of Gent (2011)
- **Expertise:** Numerical Algorithms and implementation

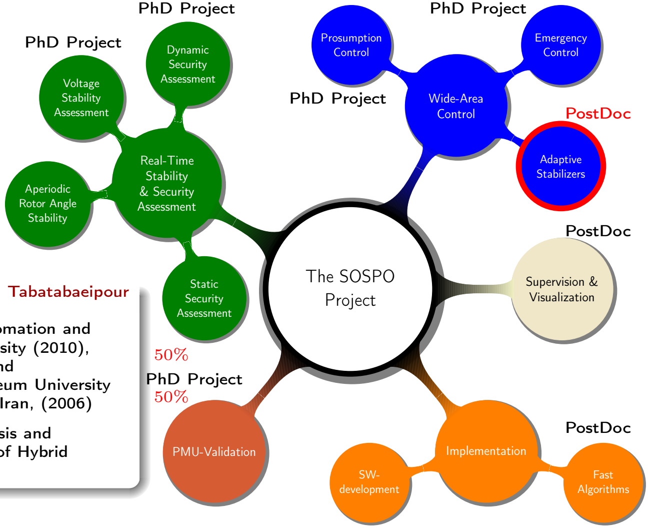
Major R&D Tasks in SOSPO



PostDoc Candidate: Hugo Morais

- **Education:** PhD in Electrical and Computer Engineering, University of Trás-os-Montes and Alto Douro (2012), M.Sc. Electrical Engineering - Power Systems, Polytechnic Institute of Porto, Portugal, (2010)
- **Expertise:** Virtual Power Players (VPP), energy resource management, power systems

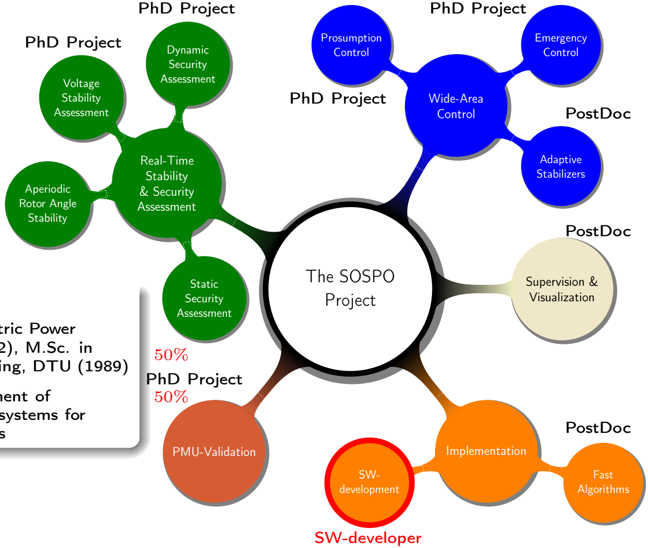
Major R&D Tasks in SOSPO



PostDoc Candidate: S. Mojtaba Tabatabaeipour

- **Education:** PhD in Automation and Control, Aalborg University (2010), M.Sc. in Automation and Instrumentation, Petroleum University of Technology, Tehran, Iran, (2006)
- **Expertise:** Fault Diagnosis and Fault-Tolerant Control of Hybrid Systems

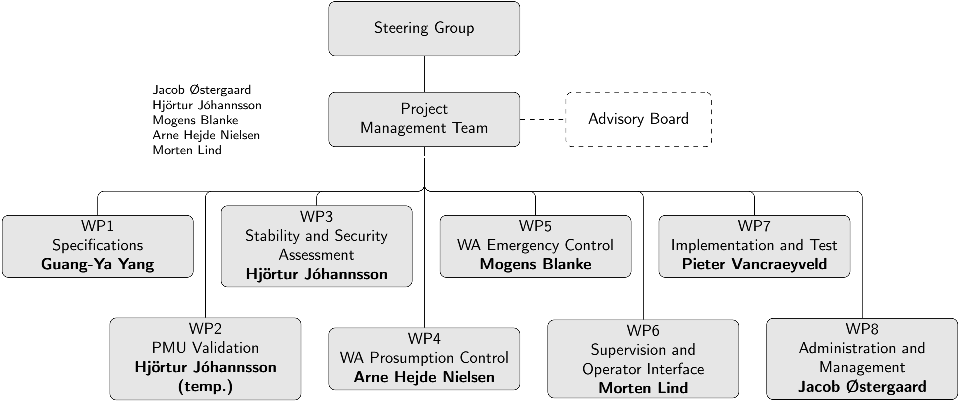
Major R&D Tasks in SOSPO



SW-developer: Allan Pedersen

- **Education:** PhD in Electric Power Engineering, DTU (1992), M.Sc. in Electric Power Engineering, DTU (1989)
- **Expertise:** SW-development of monitoring and control systems for communication networks

The SOSPO Project - Project Structure



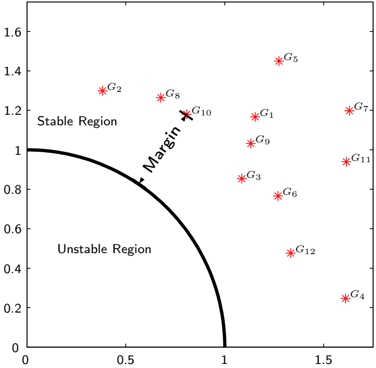
Outline

Center for Electric Power and Energy
Department of Electrical Engineering

Early Warning Against Emerging Blackouts

Element-wise assessment of stability

- Element-wise assessment of a particular mechanism of instability
  - Individual assessment of each relevant system element (a generator or a node)
  - Focussing on an assessment of one particular stability mechanism
  - The system model is reduced such that only factors that have a significant influence on the stability mechanism are included
  - Possibility for assessment times suitable for real-time operation



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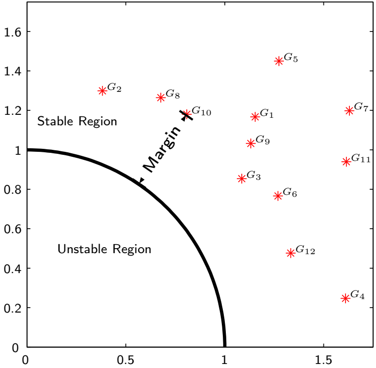

- Provides both a proximity-to-instability information and the mechanism of instability (where and what)

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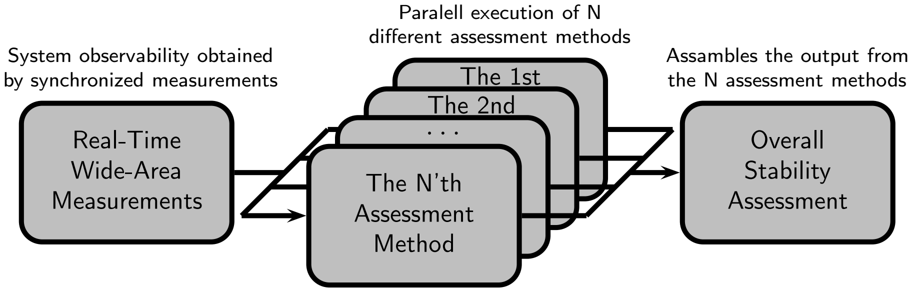
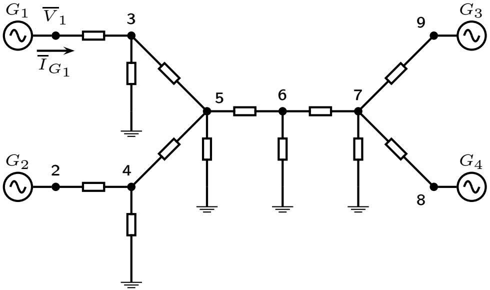
Early Warning Against Emerging Blackouts

Overall assessment in real-time



Early Warning Against Emerging Blackouts

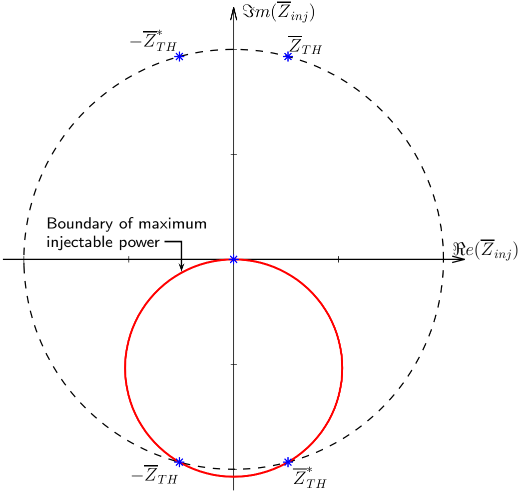
Element-Wise Assessment of Stability



- Category: Aperiodic small-signal rotor angle stability
- Mechanism: Steady state torque balance in each generator G_i
- Boundaries: Maximum steady-state injectable power from G_i
- The stability can be assessed if $\overline{Z}_{inj}$ and $\overline{Z}_{th}$ are known

Early Warning Against Emerging Blackouts

Assessment of Aperiodic Small Signal Stability - Stability Boundary



Boundary:

$$Z_{inj} = -\frac{Z_{th}\sin\theta}{\sin\phi_{th}}$$

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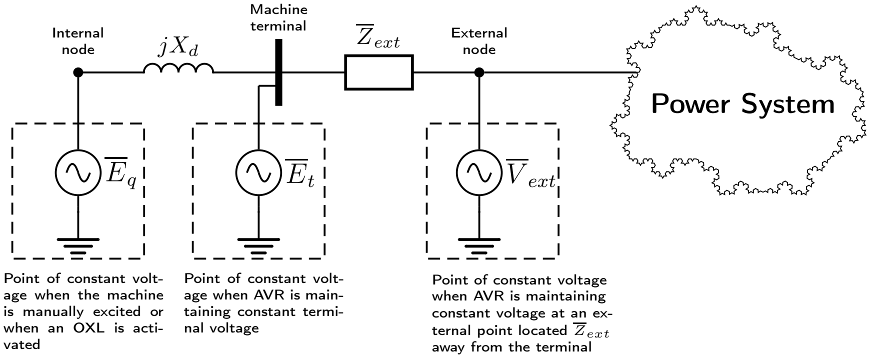
Early Warning Method

Assessment of Aperiodic Small Signal Stability: Generator Representation

- The synchronous machines have to be appropriately represented when the assessment is carried out
- This includes that excitation control and protection (AVR and OXL) have to be considered



Visualizing System Operating Conditions

Normalizing Multiple Operating Points

- The method performs an element-wise assessment of the generators stability by utilizing their operating points $\{\overline{Z}_{inj,i}, \overline{Z}_{th,i}\}$

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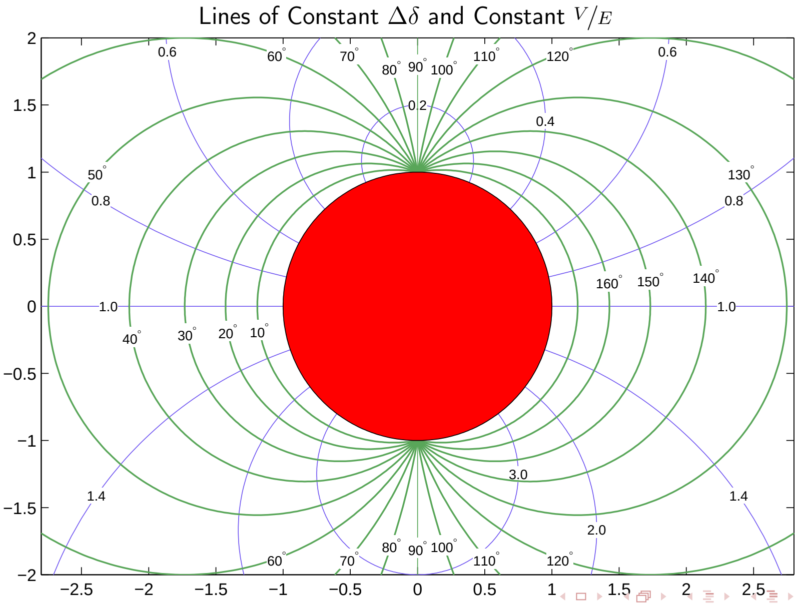
- The mapping of $\{\overline{Z}_{inj,i}, \overline{Z}_{th,i}\}$ into a normalized injection impedance plane was derived such that the voltage phase angle margin $\Delta\delta$ to the critical stability boundary and the lines of constant $V/E_{th,i}$ ratio were preserved

Visualizing System Operating Conditions

Multiple Operating Points in Normalized Injection Impedance Plane



Outline

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Department of Electrical Engineering

Test I: 2003 Blackout in E-DK and S-SW

Introduction

- Simulation of the 2003 blackout in E-DK and S-SW was carried out for the purpose of testing the method on a realistic case
  - Output used to generate synthetic PMU measurements
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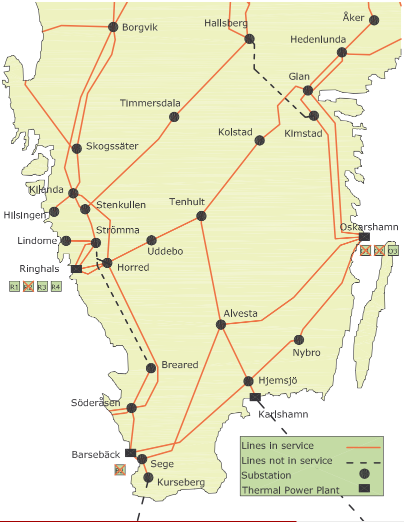
- Assessment of 144 generator states in $7.86ms$

Test I: 2003 Blackout in E-DK and S-SW

The Development of the Blackout



Initial Conditions

$\Rightarrow$ Stable and Secure

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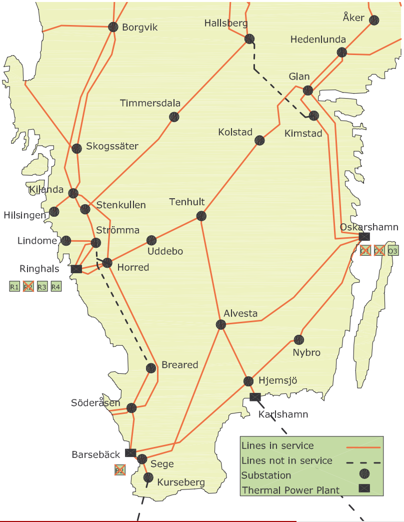

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Fault in Oskarshamn

$\Rightarrow$ Loss of $1200MW$ unit

$\Rightarrow$ Actions initiated to raise the frequency

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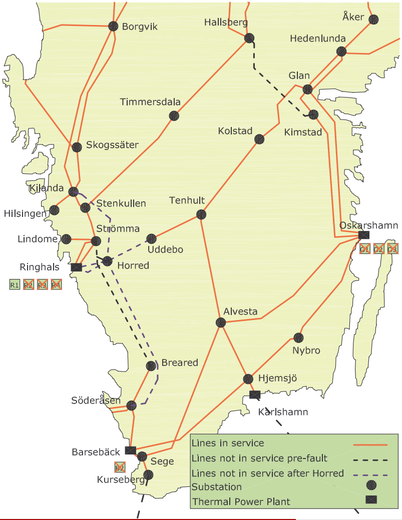

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⇒ Double busbar fault five minutes after Oskarshamn
⇒ $4 \times 400kV$ lines and $2 \times 900MW$ units lost
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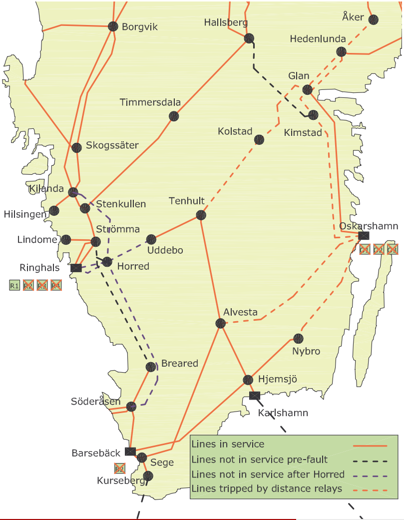

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⇒ Distance relays activated → system separation

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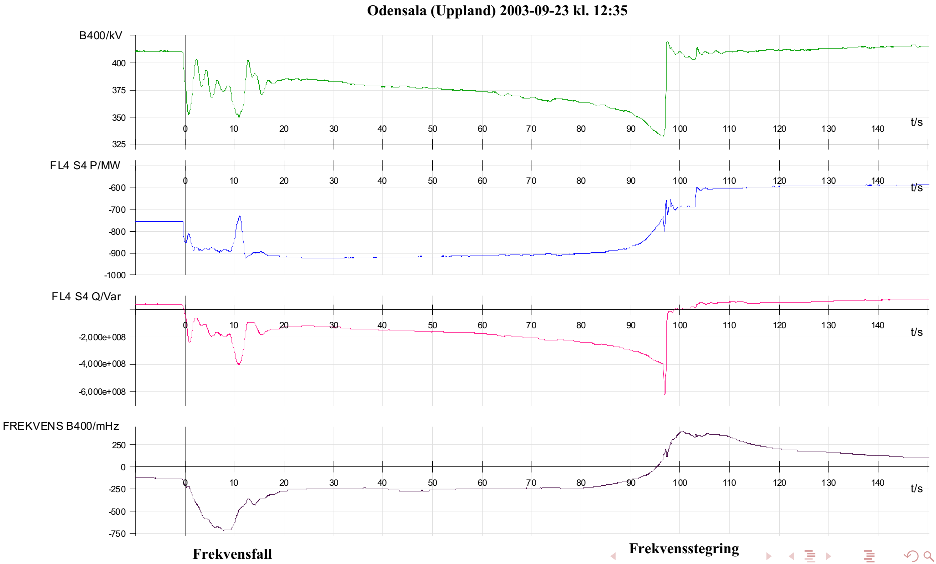
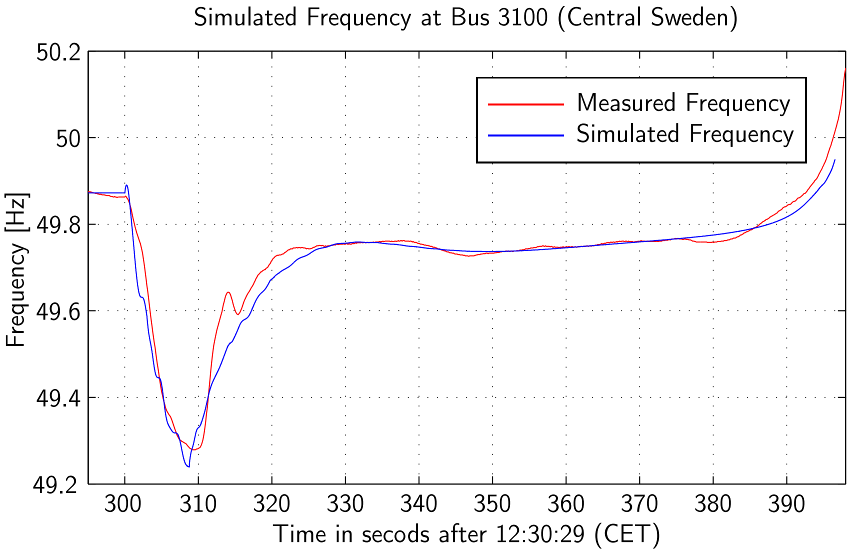
Actual Measurements from the Blackout



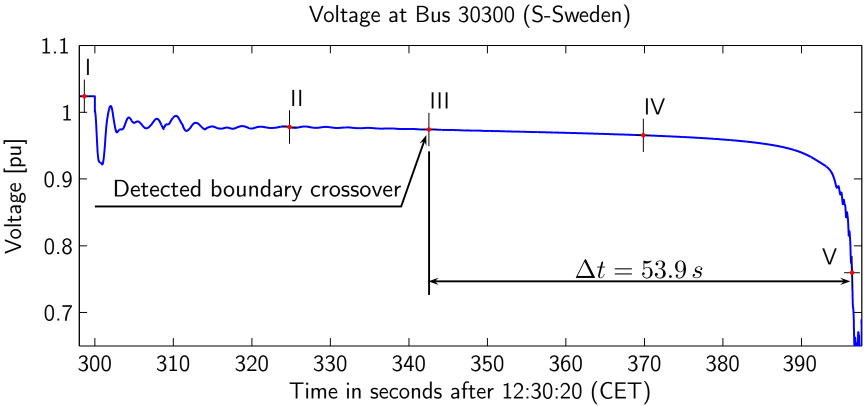
Test I: 2003 Blackout in E-DK and S-SW

Test - Simulated vs Measured Frequency

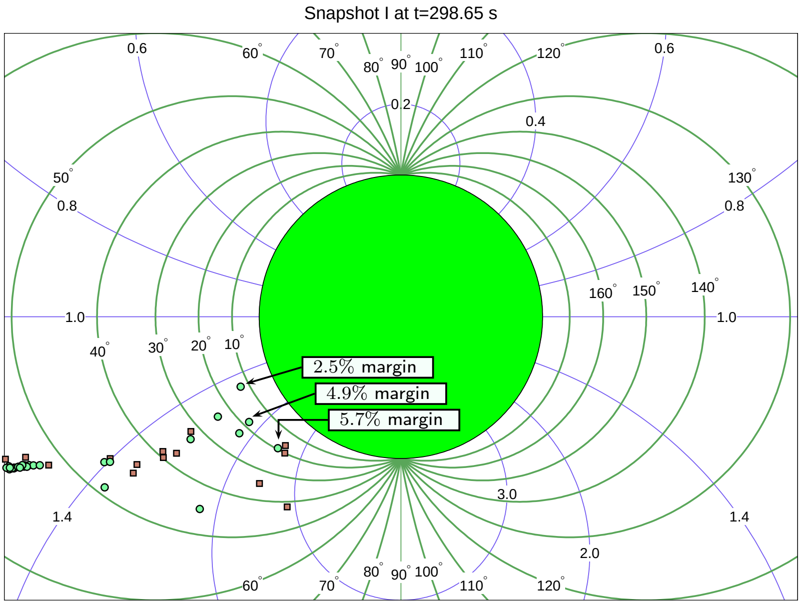


Demonstration of a Large-Scale Test

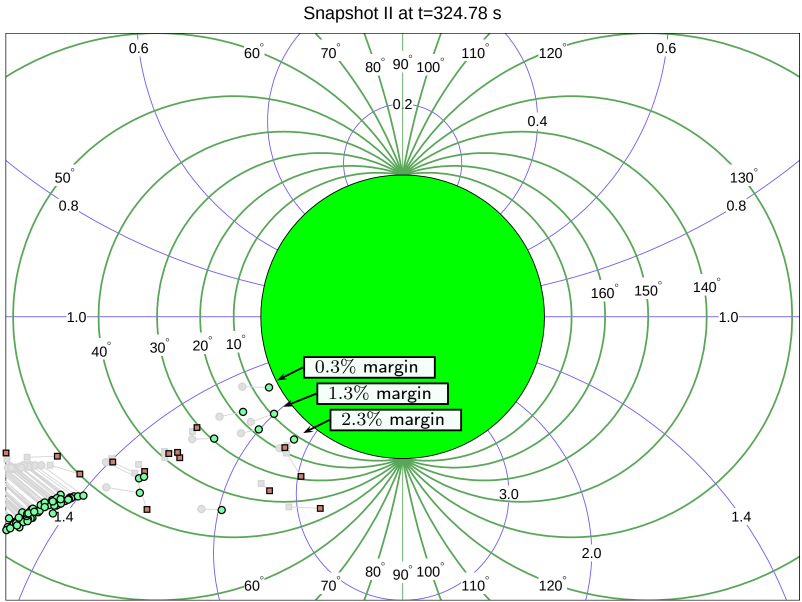
Test I: Results



Test Results

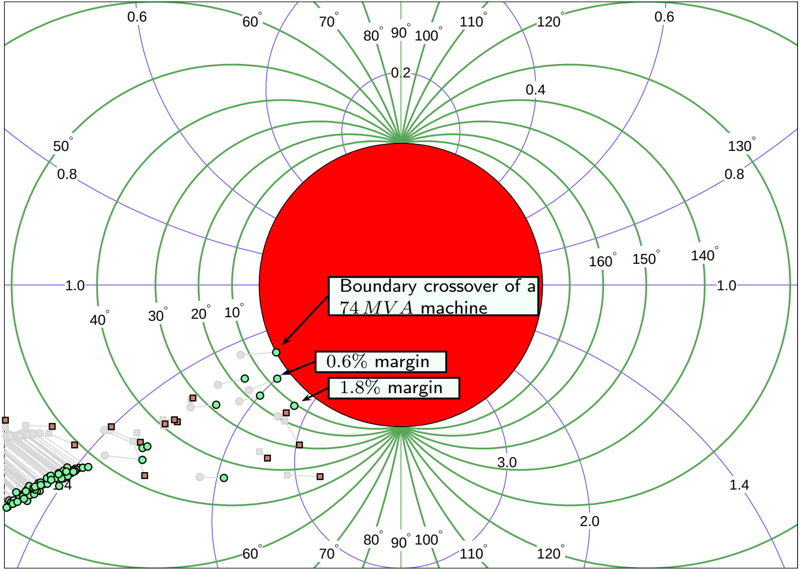


Test Results



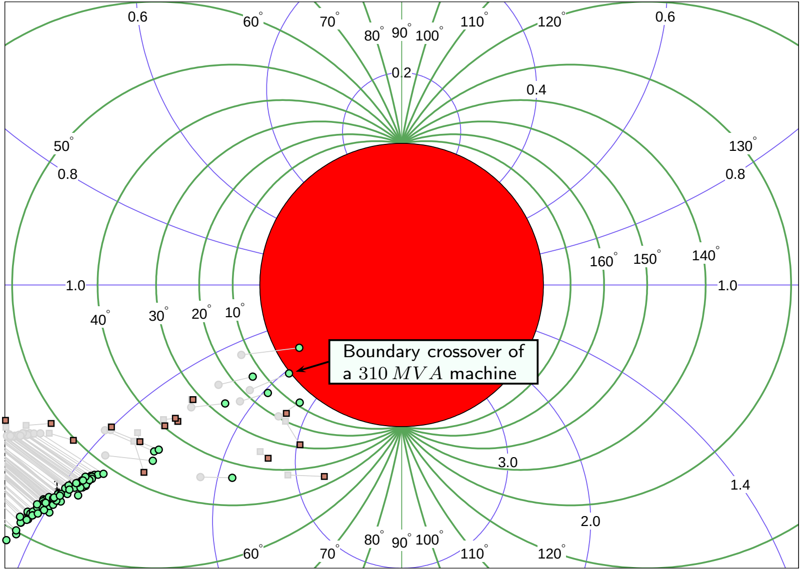
Test Results

Snapshot III at t=342.54 s



Test Results

Snapshot IV at t=369.85 s



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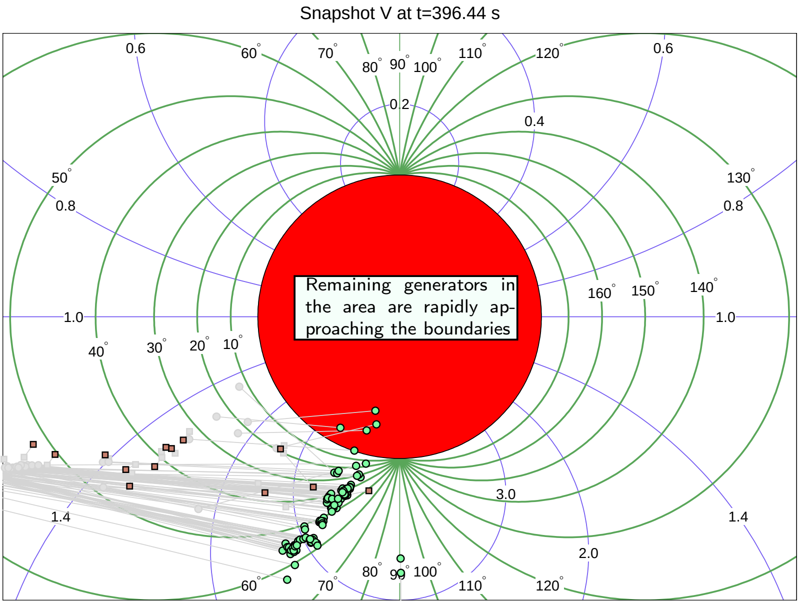

thank you