PESGM 2020 wind SSO panel session ***Advanced Modelling and Education***

Research and education on wind turbine dynamic modeling

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Denmark

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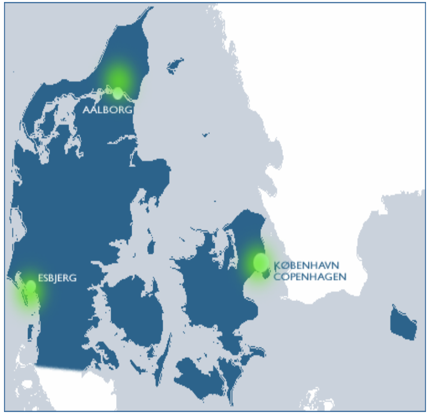
Contents

- Introduction of Aalborg University (AAU) and Department of Energy Technology (ET)
- Wind Power Systems Education at ET AAU
- Wind Power Systems Research Program at ET AAU
- Recent work examples of wind turbine dynamic modeling

Aalborg University

Aalborg

Esbjerg



Copenhagen

AALBORG UNIVERSITY

- Humanities
- Engineering and Science
- Medicine
- Social Sciences
- IT and Design

AALBORG
- approx. 19,800 students and approx. 3,300 employees

KØBENHAVN
- approx. 3,050 students and approx. 340 employees

ESBJERG
- approx. 500 students and approx. 90 employees

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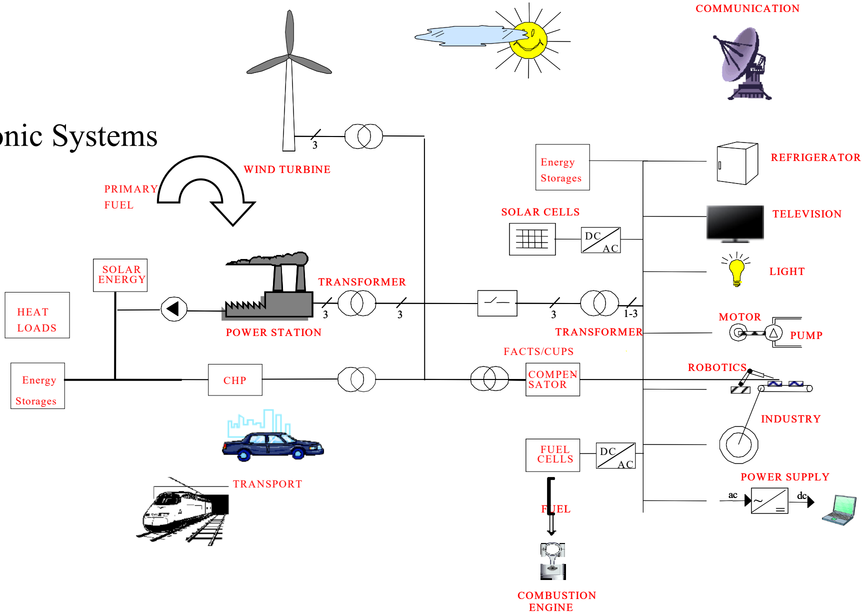
DEPARTMENT OF ENERGY TECHNOLOGY
AALBORG UNIVERSITY

Department of Energy Technology

Sections:

- Electric Power Systems
- Power Electronic Systems
- Electrical Machines,
- Fluid Power and Mechatronic Systems
- Thermofluids
- Thermal Energy Systems

Keywords:
Energy Production,
Energy Distribution,
Energy Consumption,
Energy Control



Research Programs

- Wind Power Systems
- Efficient, Intelligent and Reliable Fluid Power Technology
- Offshore Energy Systems
- Advanced Biofuels
- Biogas and Biorefinering
- Electro-fuels
- Photovoltaic Systems
- Modern Power Transmission Systems
- Intelligent Energy Systems & Active Networks
- Microgrids
- E-mobility and Industrial Drives
- Fuel Cell Systems
- Battery Storage Systems
- Efficient and Reliable Power Electronics
- Low Power Energy Harvesting and I-solutions
- Multiphase Flows and Heat Transfer
- Electronic Power Grid (Egrid)
- Heating and Cooling

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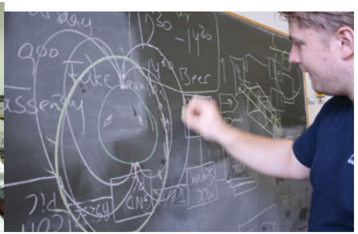
The Unique Study at Aalborg University

"The Aalborg Model for Problem Based Learning (PBL)"

https://www.en.aau.dk/education/problem-based-learning/

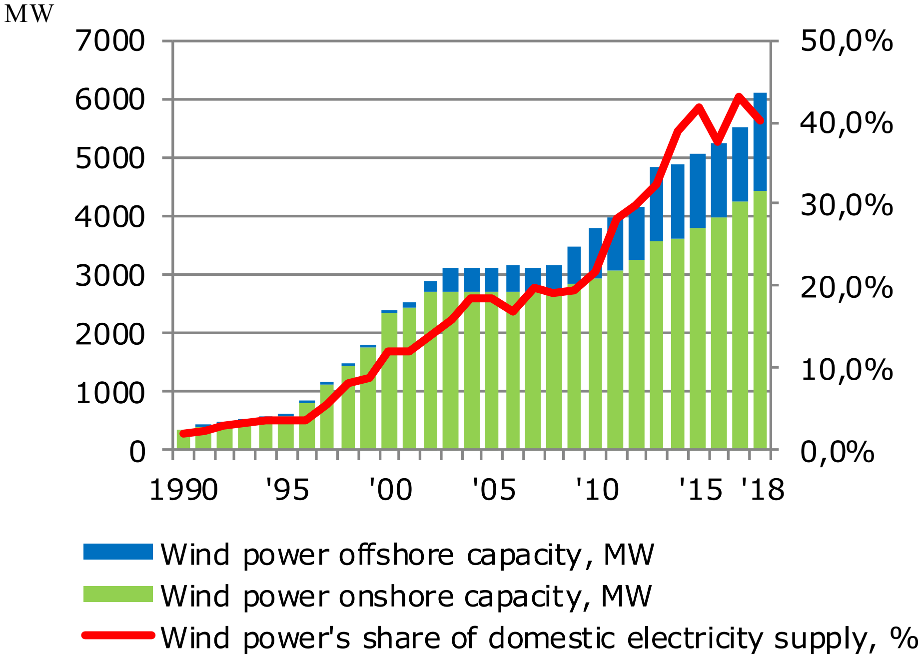
- Acquire knowledge and skills independently at a high academic level
- Work analytically with interdisciplinary and problem and result oriented methods
- Cooperate with the business community for the solution of professional problems
- Develop the abilities within teamwork
- Be well prepared for the labour market





Wind power capacity and wind power's share of domestic electricity supply

In 2019, 46.9% of the Danish electricity consumption was covered by wind energy, up from 40.7% in the previous year, which had seen lower wind, and 43.4% in 2017.



Source: Danish Energy Agency

MSc program: Wind Power Systems

The specialisation in ***Wind Power Systems*** focuses on the electrical aspects of wind power systems, covering knowledge of areas such as generators, power electronics, control engineering and power system technology related to wind power applications.

https://www.en.aau.dk/education/master/energy-engineering/specialisations/wind-power-systems

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MSc program **Wind Power System – Case I**

2nd Semester

Courses

•Advanced Course in Electrical Power Systems (5 ECTS)
•Advanced Power Electronics and Applications (5 ECTS)
•Optimisation Theory and Reliability (5 ECTS)

Examples of Project Topics (15 ECTS)

- Grid connection of large off-shore wind power plants
- Operation of wind turbines in isolated power systems
- Power quality of grid connected wind turbines.

MSc program **Wind Power System – Case II**

4th Semester

Master's thesis (30 ECTS)

Examples of Thesis Topics

- Design of power electronic grid interface system for large scale wind turbines
- Optimisation of an energy conversion system in a power system with large scale wind energy
- Performance of the synchronous generator as wind generator
- Assessment of the reliability of wind power systems.

Ph.D Course

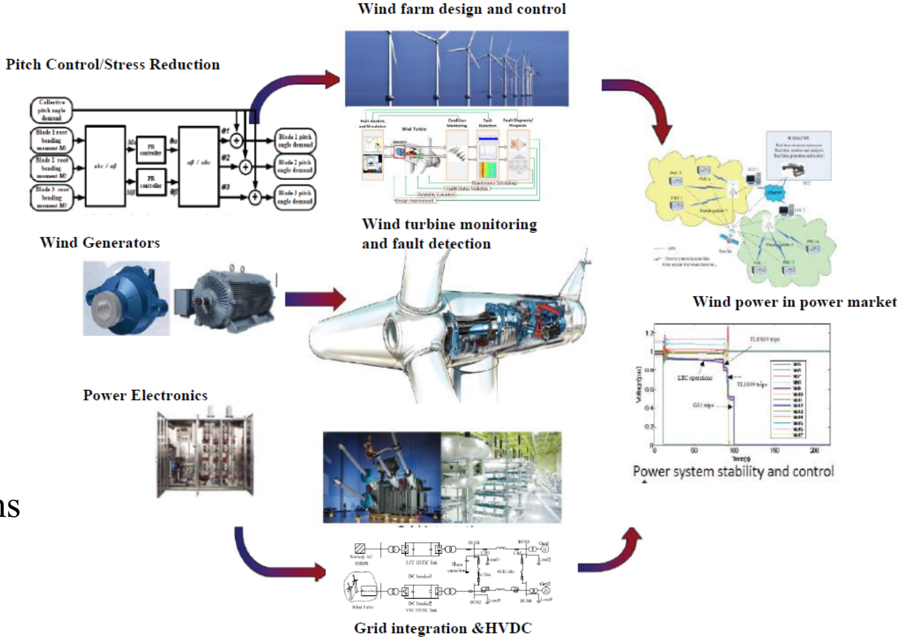
The aim of *Ph.D Courses* is to train the Ph.D students from universities and engineers from companies in the field of wind power system.

Industrial Ph.D Courses in the field of wind power system

- Introduction to Wind Power Systems (Generation and Integration)
- Introduction to Voltage Stability of Electric Power Systems
- Stability of modern power systems with high penetration of renewable energy

Research program: Wind Power Systems

- Pitch Control/Stress Reduction
- Optimal Design of Generators
- Power Electronics Interface
- Wind Turbine Control
- Wind Farm Design and Control
- Wind Turbine Monitoring and Fault Detection
- Wind Power Integration and Interaction with Grid
- Stability of Power System Large Scale Wind Farms
- Economics and Power Market of Wind Power



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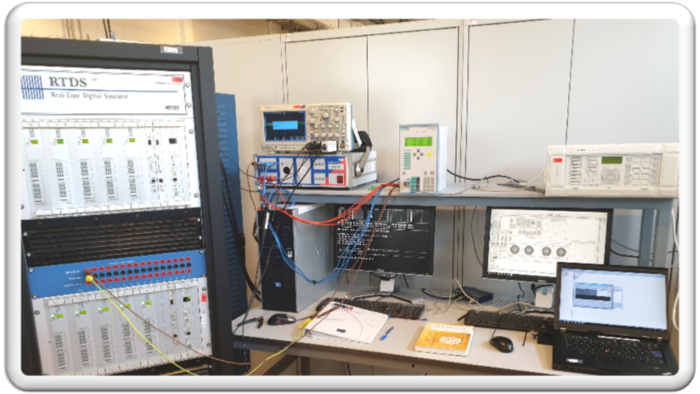
Laborary for research and education

- DFIG-based Wind Turbine test systems
- Real Time Digital Simulator (RTDS)
- dSPACE Real Time Controller
- PLECS RT Box-based Real Time Simulator
- California Instrument (Grid simulator)
- Phasor Measurement Unit (PMU)
- LabVIEW Real Time Operation systems
- DC Wind Power Network Test system
- Modular Multi-level Converters for Wind Power Systems
- Microgrid Test Platform
- Solid-State Transformer Test Platform



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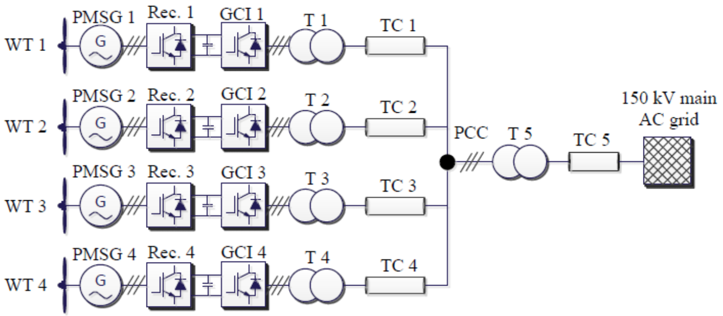
Many research/industrial projects with various focuses and relevant models developed and tools used

- Innovative Wind Conversion Systems (10-20MW) For Offshore Applications (EU-FP7-INNWIND)
- Comparison of Different Generator Configurations (EU-FP6-UPWIND)
- North Sea Region Programme POWER CLUSTER (EU-Project)
- Norwegian Centre for Offshore Wind Energy (International Project)
- Research on DC Network Connection with a Novel Wind Power Generator System (International Project)
- Dynamic wind turbine model - from wind to grid (International Project)
- Development of a Secure, Economic and Environmentally-friendly Modern Power System (National Project)
- Operation of power systems with large scale of wind power and energy storage systems (National Project)
- Modelling and Simulation of Wind Power & VSC-HVDC and Its Application in Offshore Wind Power Integration (International Project)
- Research on Modelling and Simulation Technology for Large-Scale Wind Turbine (International Project)

Effect of reactive power characteristic of offshore wind power plant on low-frequency stability



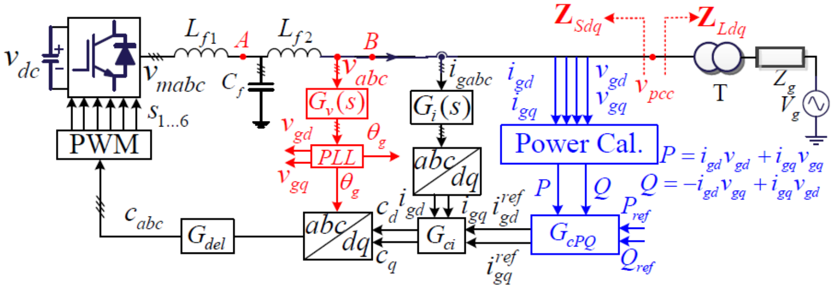
Typical configuration of an HVAC connected offshore wind power plant

Impacts of

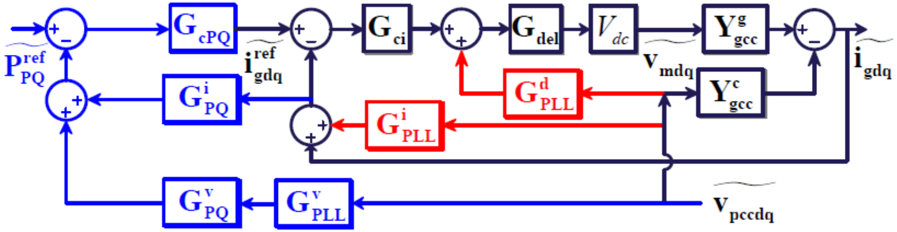
- Active Power Injection
- Reactive Power Injection
- Number of Paralleled Grid-Connected Inverters

W. Zhou, Y. Wang, R. E. Torres-Olguin, and Z. Chen, "Effect of reactive power characteristic of offshore wind power plant on low-frequency stability," IEEE Trans. Energy Convers., vol. 35, no. 2, pp. 837–853, Jun. 2020.

Effect of Active and Reactive Power on q-axis Impedance



Control structure of grid-side converters of PMSGs.



Control block diagram of GCI with power control loop, current control loop and PLL

$$Z_{qq}^{PCL} = -\frac{\Gamma_1 + \Gamma_2 P^{ref} + \Gamma_3 Q^{ref}}{A}$$

where Γ_1, Γ_2 and Γ_3 are shown as follows.

$$\Gamma_1 = L_f s + \frac{G_{del} V_{dc} G_{ci}(1 + G_{cPQ} V_{PCC,d}^s)}{2} = \Gamma_{1\_1} s + \Gamma_{1\_2}$$

$$\Gamma_2 = \frac{G_{ci} G_{cPQ} G_{del} L_f s}{V_{PCC,d}^s} + \cdots$$

$$\frac{G_{ci}^2 G_{cPQ} G_{del}^2 V_{dc}(1 + G_{cPQ} V_{PCC,d}^s)}{2 V_{PCC,d}^s} = \Gamma_{2\_1} s + \Gamma_{2\_2}$$

$$\Gamma_3 = \frac{G_{ci} G_{cPQ} G_{del} \omega_1 L_f}{V_{PCC,d}^s}$$

Then, phase angle of Z_{qq}^{PCL} at specific angular frequency ω_0 can be derived as follows.

$$\angle Z_{qq}^{PCL}\Big|_{s=j\omega_0} = -180^\circ + \arctan \frac{(\Gamma_{1\_1} + \Gamma_{2\_1} P^{ref})\omega_0}{\Gamma_{1\_2} + \Gamma_{2\_2} P^{ref} + \Gamma_3 Q^{ref}}$$

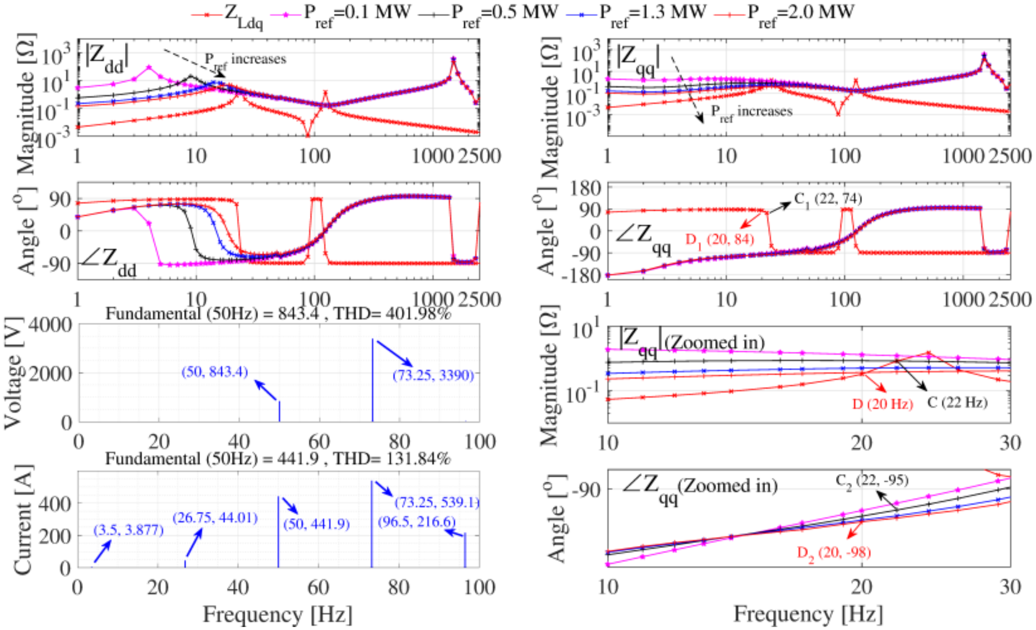
Therefor, to guarantee the passivity of q-axis impedance component, i.e.,

$$\angle Z_{qq}^{PCL} \in (-90^\circ, -0^\circ) \leftrightarrow \Gamma_{1\_2} + \Gamma_{2\_2} P^{ref} - \Gamma_3 \left|Q^{ref}\right| < 0$$

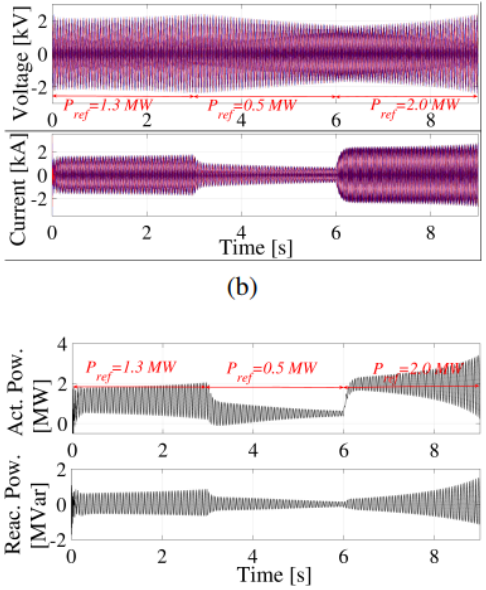
$$\left|Q^{ref}\right| > \left|Q_{\min}^{ref}\right| = \frac{\Gamma_{1\_2} + \Gamma_{2\_2} P_{ref}}{\Gamma_3}$$ or $$P^{ref} < P_{\max}^{ref} = \frac{-\Gamma_{1\_2} + \Gamma_3 \left|Q_{ref}\right|}{\Gamma_{2\_2}}$$

Impact of Active Power Injection

Q_{ref}=0 and different P_{ref}:



Impedance-based stability analysis of GCI 1 connected with 19 km transmission cable with different P_{ref}.

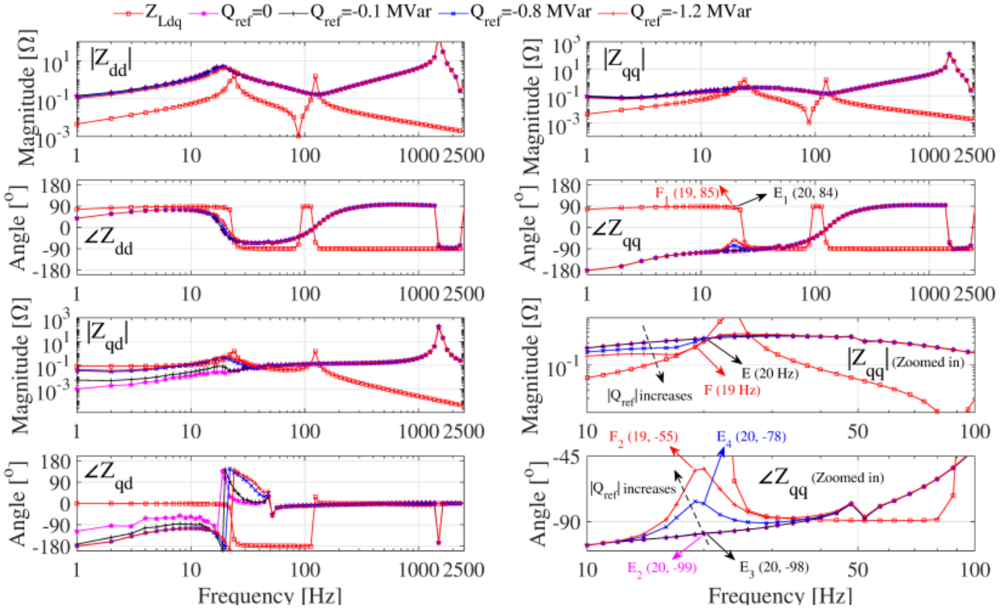


Time-domain simulation results of GCI 1 connected with 19 km transmission cable with different P_{ref}.

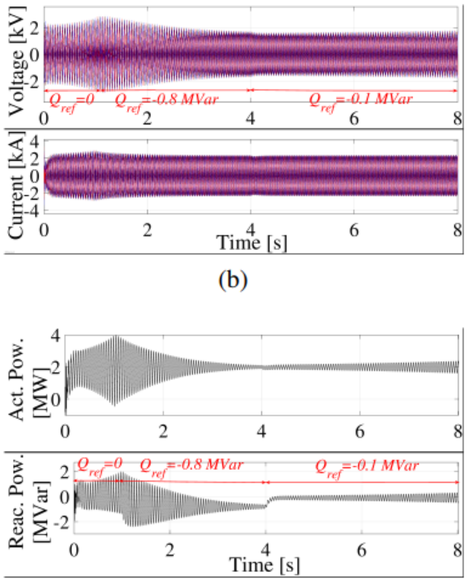
High P_{ref} increases the possibility of SSO.

Impact of Reactive Power Injection

P_{ref}=2 MW and different Q_{ref}:



Impedance-based stability analysis of GCI 1 connected with 19 km transmission cable with P_{ref}= 2 MW and different Q_{ref}.

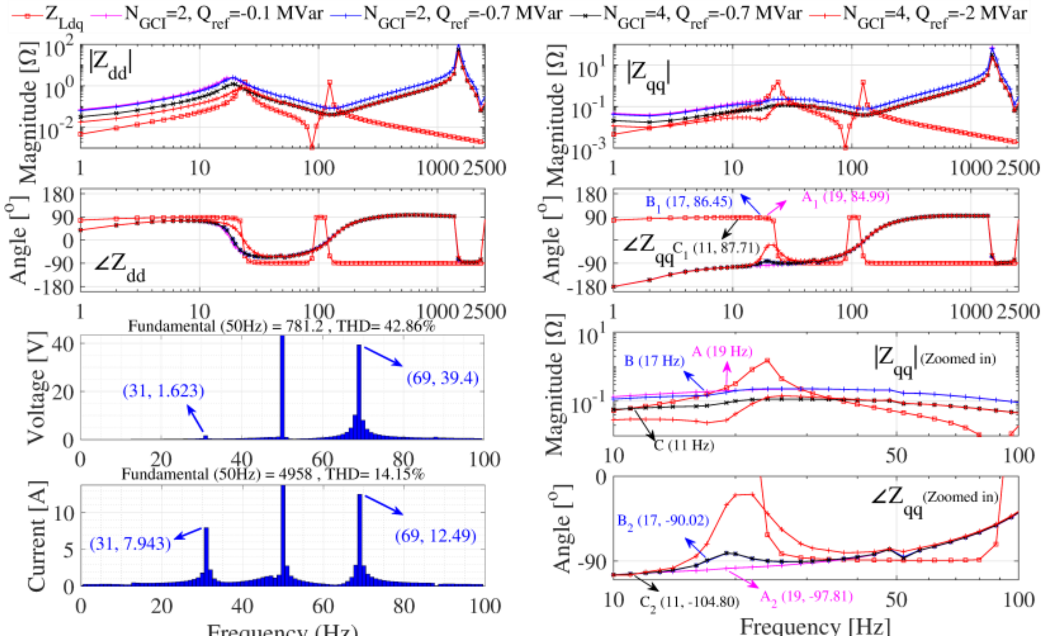


Time-domain simulation results of GCI 1 connected with 19 km transmission cable with P_{ref} = 2 MW and different Q_{ref}.

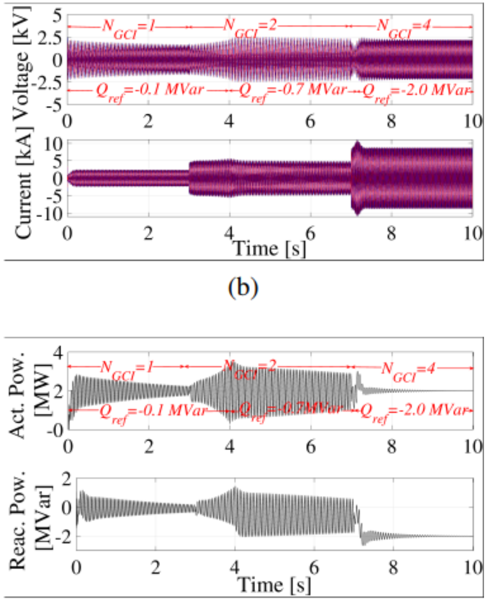
Reactive power may be adjusted to stabilize the low frequency oscillation.

Impact of Number of Paralleled Grid-Connected Inverters

P_{ref}=2 MW and different number of paralleled GCIs:



Impedance-based stability analysis of the whole OWPP.



Time-domain simulation results of the whole OWPP.

More converters tends to make system unstable, and more reactive power may help to stabilize the system

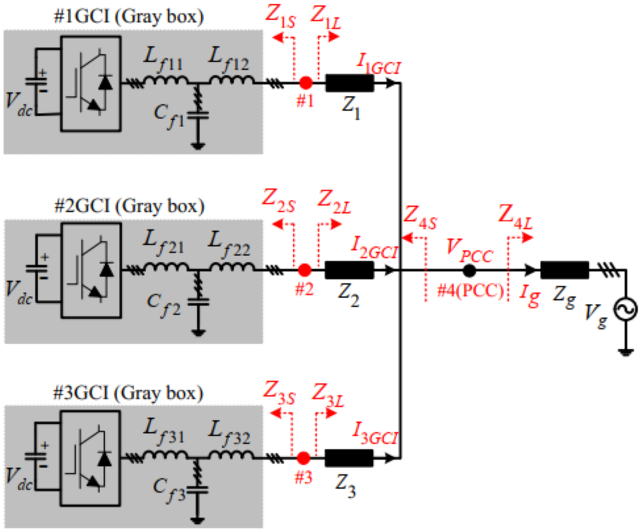
Effect of reactive power characteristic of offshore wind power plant on low-frequency stability

Result Summary

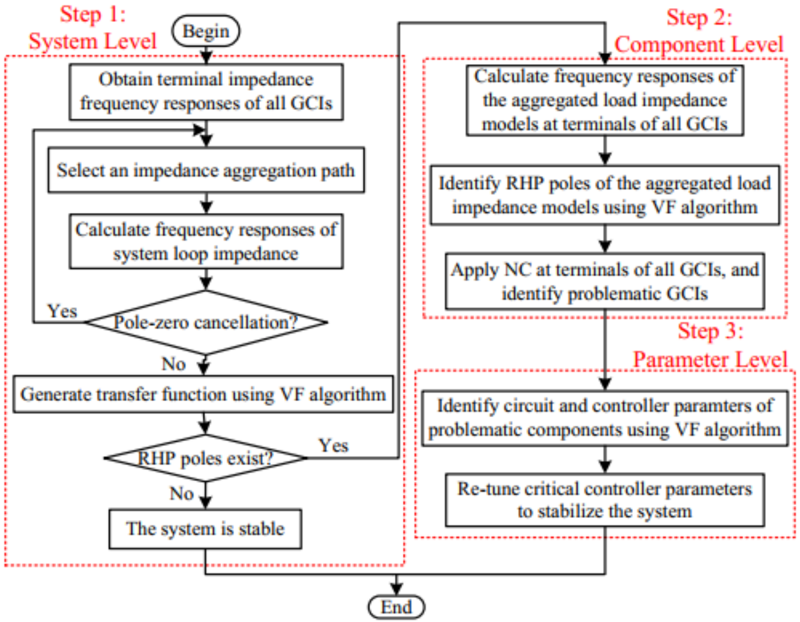
- A power electronic system may become unstable in low-frequency range if active power reference is increased or converter number is increased.
- The reactive power control may help to stabilized the system.

W. Zhou, Y. Wang, R. E. Torres-Olguin, and Z. Chen, "Effect of reactive power characteristic of offshore wind power plant on low-frequency stability," IEEE Trans. Energy Convers., vol. 35, no. 2, pp. 837–853, Jun. 2020.

A Gray-Box Hierarchical Oscillatory Instability Source Identification Method of Multiple-Inverter-Fed Power Systems



Circuit configuration of the multi-paralleled converter system.

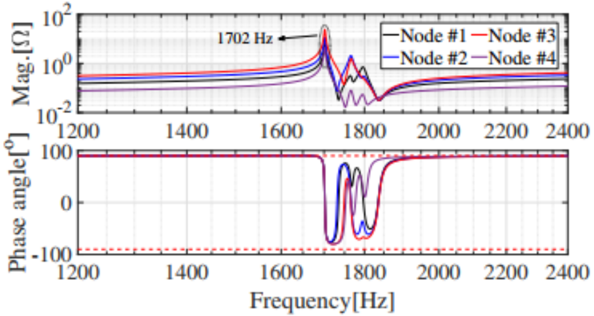


Flowchart of the gray box-based hierarchical three-level harmonic instability source identification method.

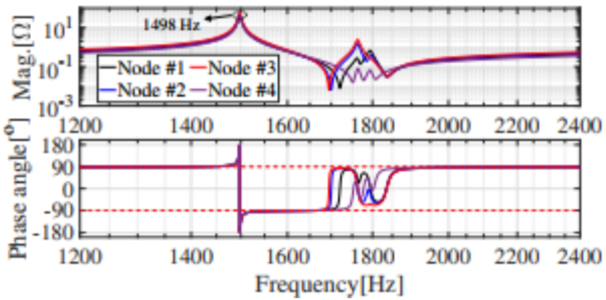
Zhou W, Torres-Olguin R E, Wang Y, Chen Z, “A Gray-Box Hierarchical Oscillatory Instability Source Identification Method of Multiple-Inverter-Fed Power Systems”. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2020.

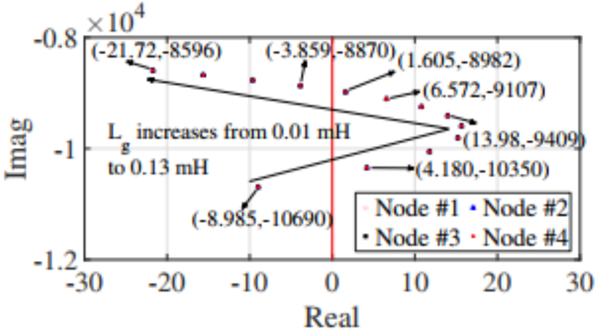
A Gray-Box Hierarchical Oscillatory Instability Source Identification Method

Stable cases (l(Zg) is 1 km): Step 1



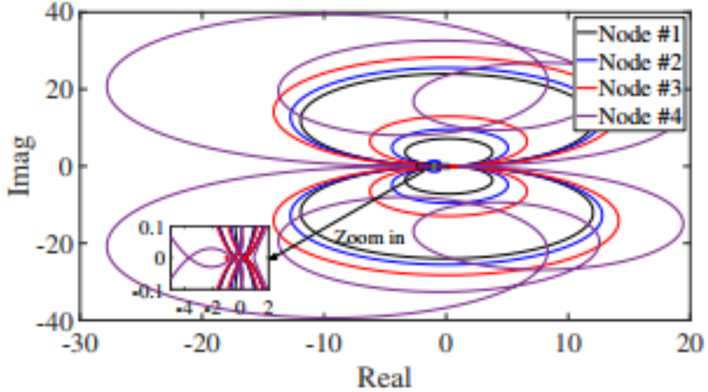
Unstable cases (l(Zg) is 6 km): Step 1





It can be seen that the resonance frequencies 1702 Hz and 1498 Hz are accurately identified using VF algorithm, where 10690=(2π) =1701 Hz and 9409=(2π) =1498 Hz.

Unstable cases (l(Zg) is 6 km): Step 2



Nyquist plots of the impedance ratios $\frac{Z_{iL}}{Z_{iS}}$ $(i \in [1, 4])$ when $l(Z_g) = 6$ km.

It can be seen that node #3 is weakest, because the Nyquist plot at node #3 is closest to (-1, j0) among nodes #1, #2, and #3.

Unstable cases ($l(Zg)$ is 6 km): Step 3

To confirm the situation, different parameters of the three capacitor-current feedback active damping coefficients may be adopted. Kcp1={0.6, 0.6, 0.6}, Kcp2={0.6, 0.6, 0.85}, and Kcp3={0.85, 0.6, 0.6}.

	$l(Z_g) = 6$ km	
K_{cp1}	$13.98 \pm j9409$	-1720
K_{cp2}	$-1.643 \pm j9505$	-1730
K_{cp3}	$1.222 \pm j9486$	-1728

It can be seen that if the capacitor-current-feedback active damping coefficient of the #3 converter is re-tuned, the critical zeros moved from RHP to LHP.

A Gray-Box Hierarchical Oscillatory Instability Source Identification Method of Multiple-Inverter-Fed Power Systems

Result Summary

- The method of stability assessment at system, component and parameter levels is presented.
- The proposed method integrates the conventional eigenvalues based and impedance-based stability analysis methods by extracting eigenvalues from the impedance frequency responses.

Zhou W, Torres-Olguin R E, Wang Y, Chen Z, "A Gray-Box Hierarchical Oscillatory Instability Source Identification Method of Multiple-Inverter-Fed Power Systems". IEEE Journal of Emerging and Selected Topics in Power Electronics, 2020.

Summary

- Aalborg University (AAU), Department of Energy Technology (ET) and Aalborg Model PBL
- Wind Power Systems Education at ET AAU
- Wind Power Systems Research Program at ET AAU
- Some work examples of wind turbine dynamic modeling

Thank You !

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