

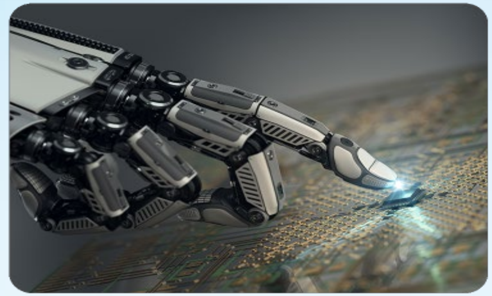

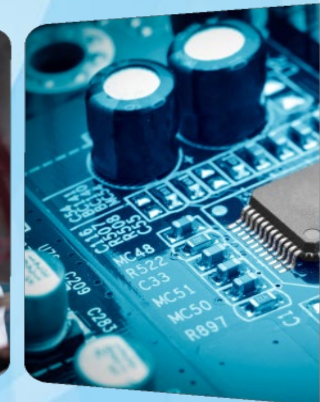

Small-signal Stability Studies in Offshore Wind Power Plants

Łukasz Hubert Kocewiak, Ørsted Wind Power

5 December 2018, Aalborg University

Small-signal Stability Studies

in Offshore Wind Power Plants

1. **Wind power plant electrical infrastructure**
   - main wind power plant components
   - basic electrical single-line diagram
   - grid converter integration

2. **Grid converter stability aspects**
   - #1 classical stability approach
   - #2 impedance-based stability analysis
   - #3 eigenvalue-based stability analysis
   - converter stability vs. power quality
   - reliable damping modeling and stability analysis

3. **What next?**

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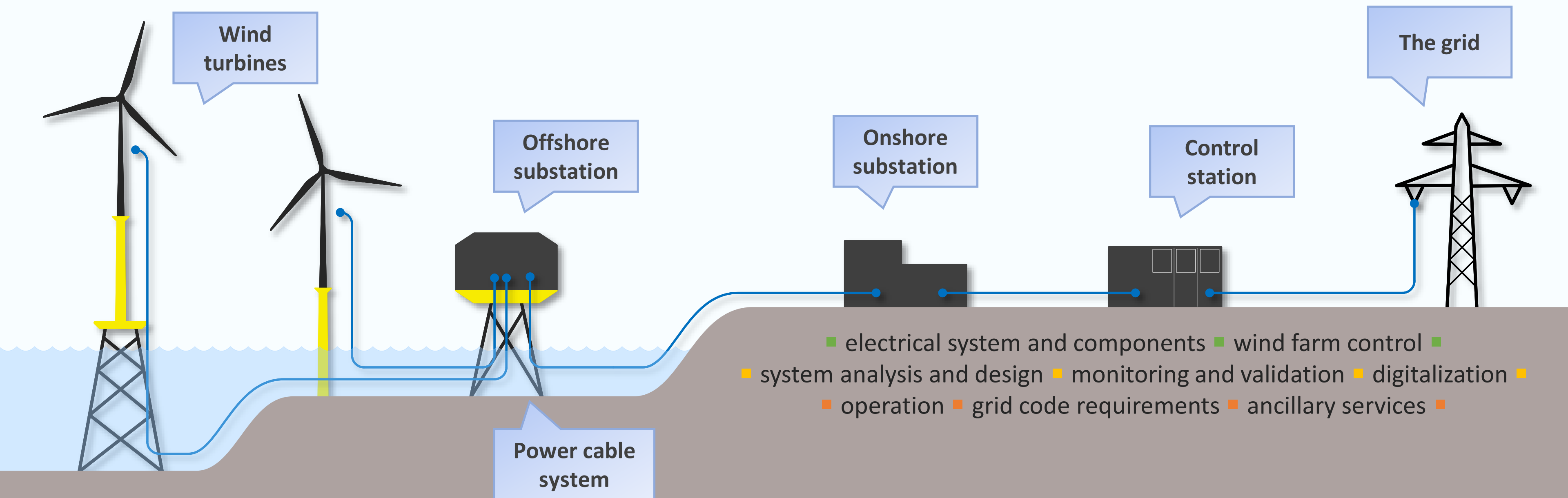
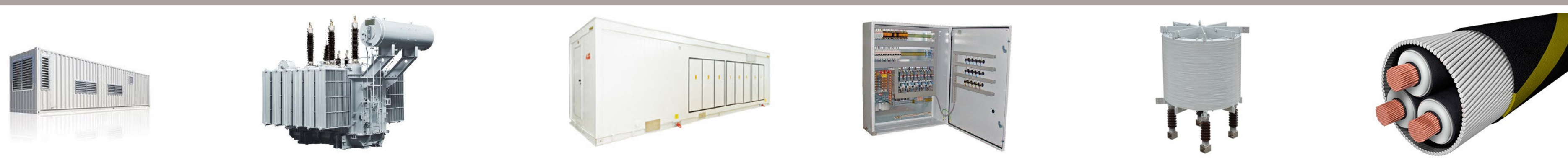
Wind power plant electrical infrastructure



Energy Storage | Power Transformers | Reactive Power Balancing | Active Harmonic Filter | Air Core Reactor | Power Cable

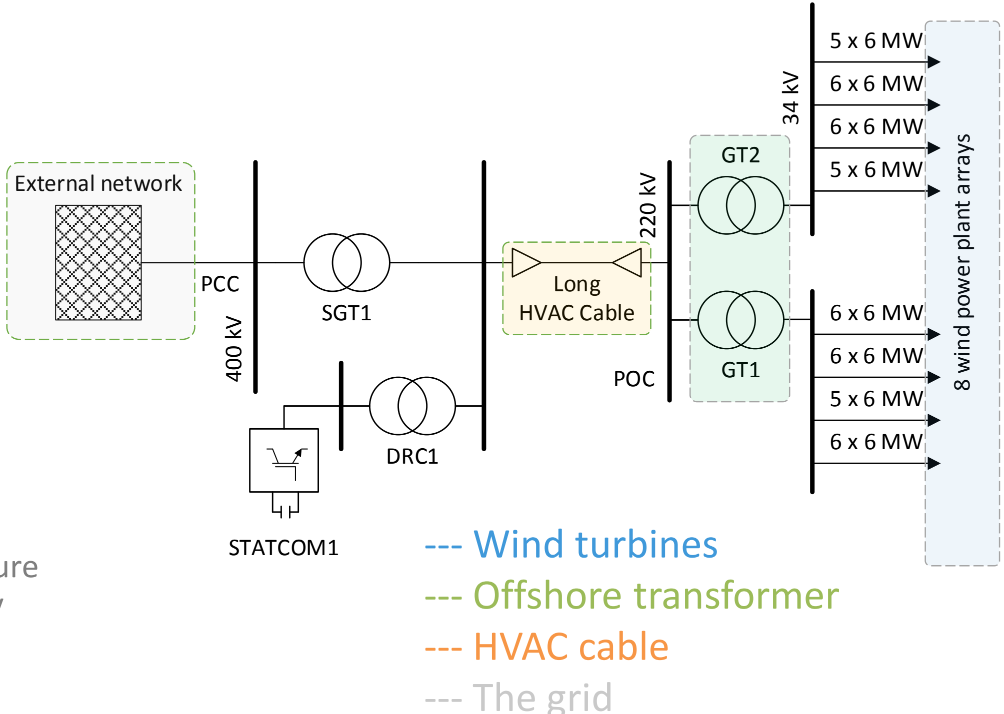


Wind power plant electrical infrastructure

grid converter stability challenges

Electrical infrastructure

- Point of common coupling (PCC) at the HV onshore substation
- Cable export system longer than 100km
- Widespread array cable network of more than 100km
- Wind power plant consists of even more than 100 wind turbines
- Total installed capacity even above 1GW



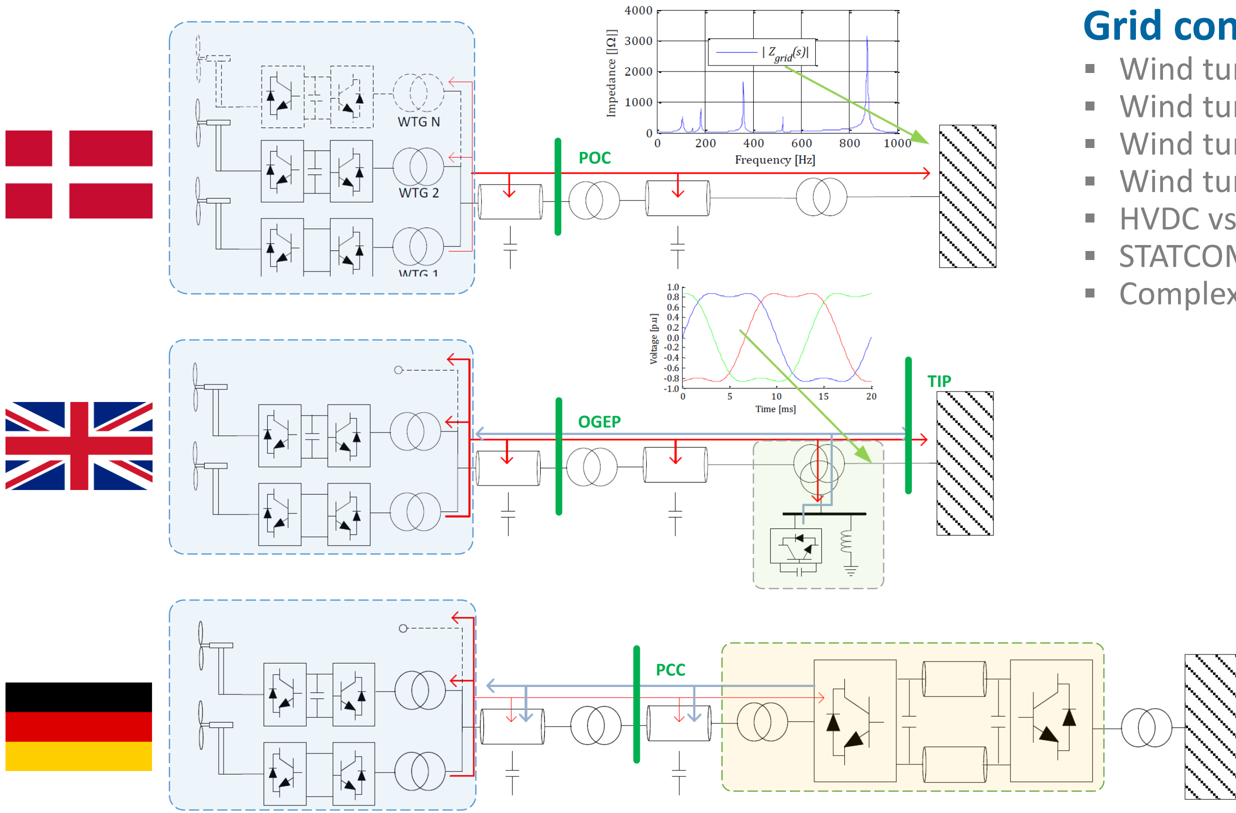
Stability challenges

- Different converter types in the network
- Multiple resonances within the infrastructure
- Far distance from shore and low-frequency resonances
- Connection to the weak power system
- Voltage, frequency and harmonic control coordination

Ł. H. Kocewiak, B. Gustavsen, A. Hołdyk, "*Wind Power Plant Transmission System Modelling for Harmonic Propagation and Small-signal Stability Analysis*," in in Proc. The 16th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 25-26 October 2017, Berlin, Germany

Wind power plant electrical infrastructure

grid converter integration



Grid converter interactions

- Wind turbine vs. resonant network
- Wind turbine vs. wind turbine
- Wind turbine vs. STATCOM
- Wind turbine vs. HVDC
- HVDC vs. resonant network
- STATCOM vs. resonant network
- Complex interactions

--- Wind Turbines
--- STATCOMs
--- HVDC

Source: Jakob Bærholm Glasdam, *"Harmonics in Offshore Wind Power Plants: Application of Power Electronic Devices in Transmission Systems,"* Springer, October 2015.

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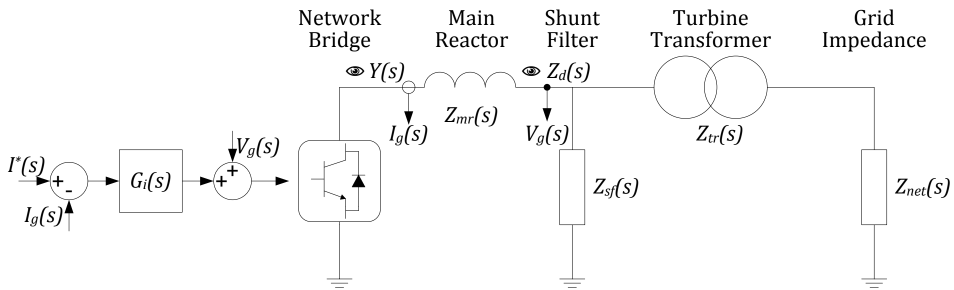
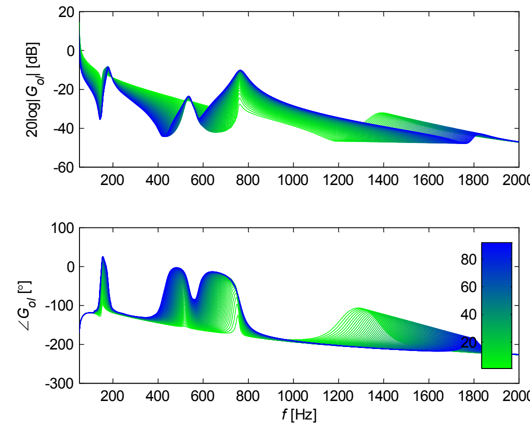
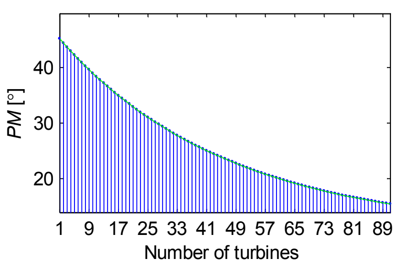
Grid-converter stability aspects

#1 classical stability analysis approach

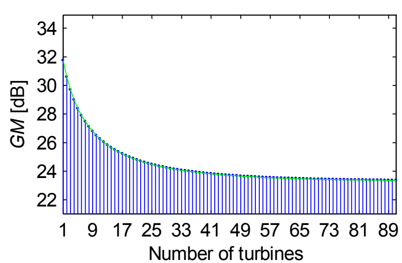




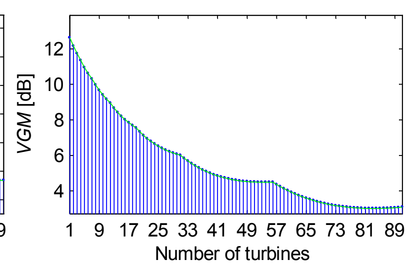
PM ≥ 30°

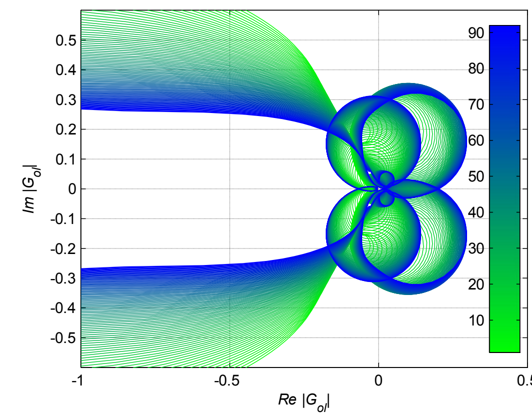


GM ≥ 3dB



VGM ≥ 3dB



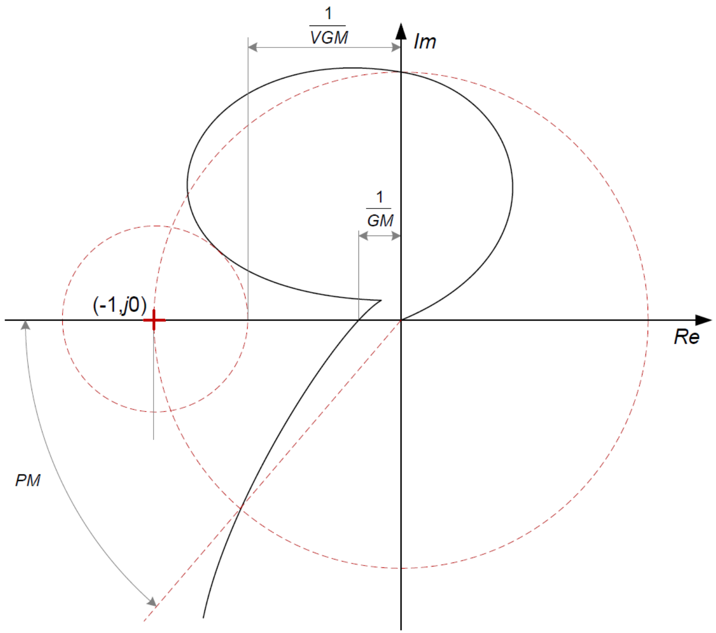


Source: Ł. H. Kocewiak, J. Hjerrild, and C. L. Bak, "*Wind Turbine Converter Control Interaction with Complex Wind Farm Systems*," IET Renewable Power Generation, pp. 1-10, 2013

Classical stability analysis

Stability margins

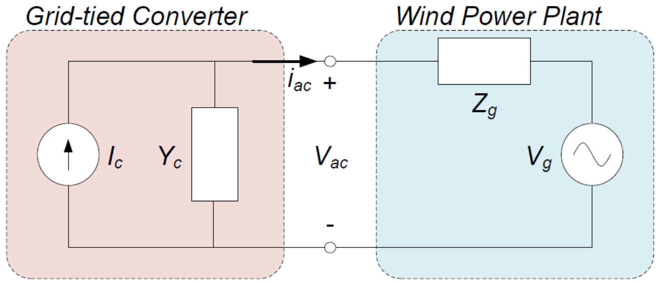
- Various stability indices such as gain margin (GM), vector gain margin (VGM) and phase margin (PM) are used in order to indicate the sensitivity to the source and load impedance changes.
- The stability margins measure the robustness of the controller and system design.
- GM and PM are defined to provide a two-point measure of how close the Nyquist plot is to encircling the -1 point.
- The GM is the factor by which the gain can be increased before causing the system to be unstable, and is the inverse of the magnitude of G_{OL} when its phase is 180°.
- The PM is the difference between -180° and the phase of G_{OL} when its amplitude is 1.
- The maximum value of $|S|=|1/(1+G_{OL})|$ is often a more accurate measure of stability margin than either GM and PM alone.

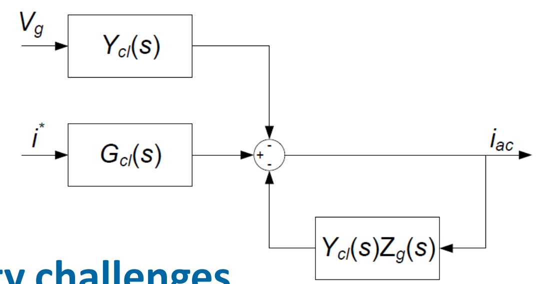


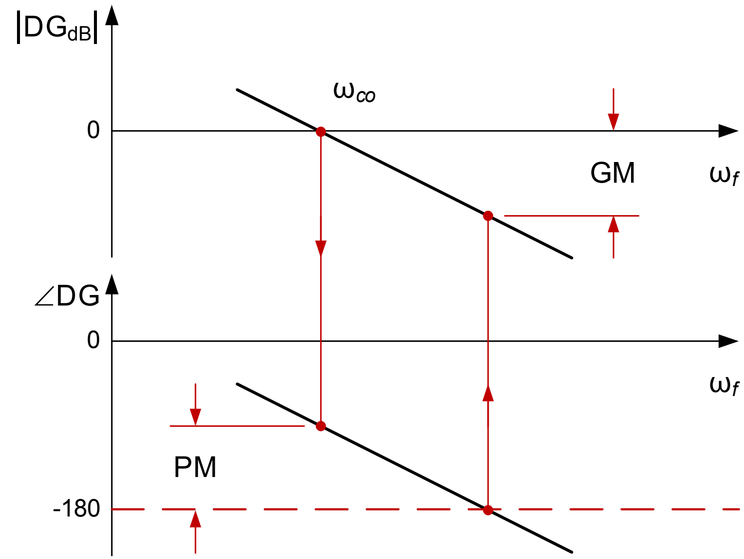
PM	≥	30°
GM	≥	3dB
VGM	≥	3dB

Grid-converter stability aspects

#2 impedance-based stability analysis







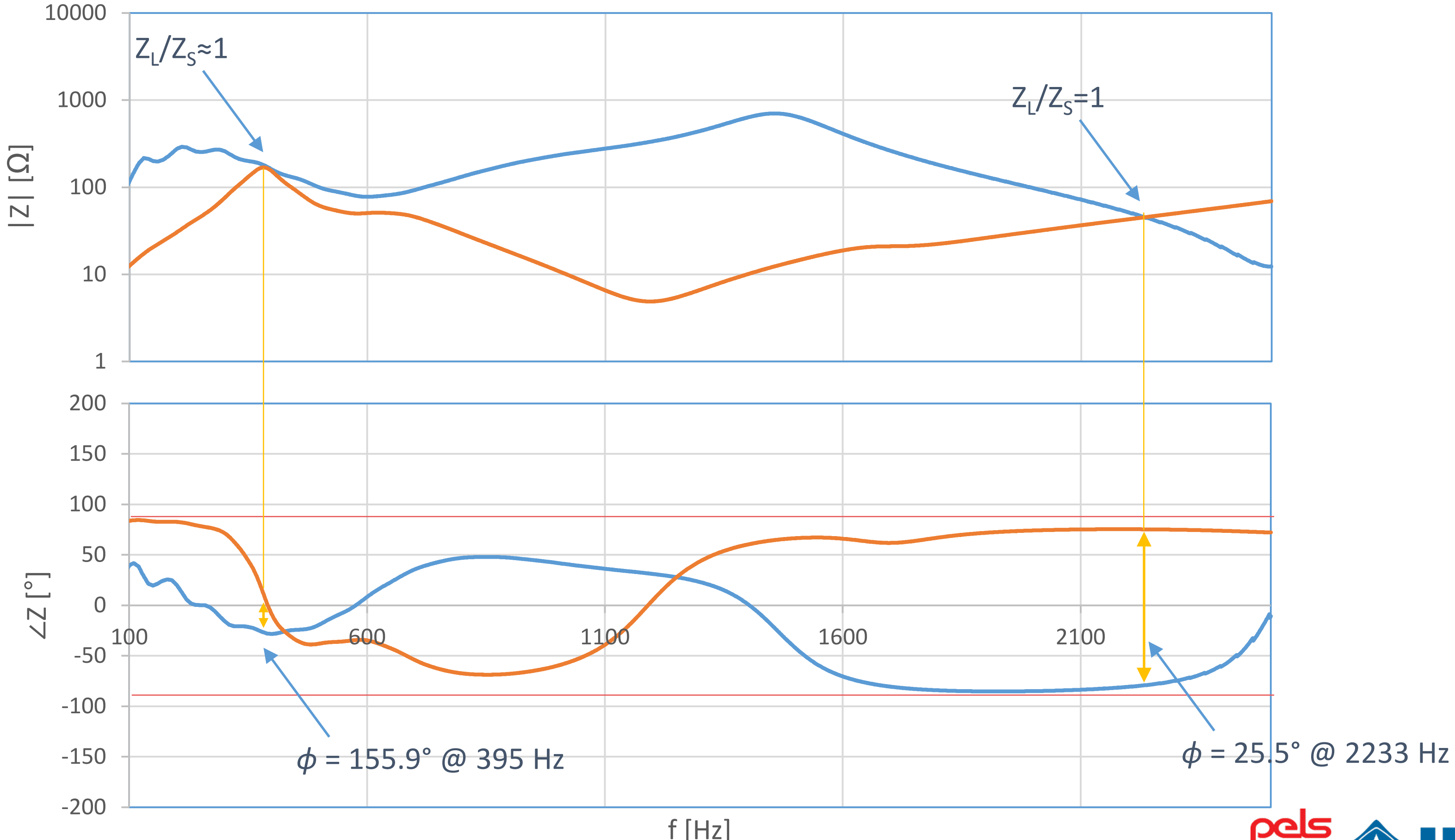
Stability challenges

- Equivalent to classical control theory stability investigation of SISO systems.
- Nyquist stability criterion as well as stability margins can be used to evaluate the stability.
- Evaluates the ratio of the plant/grid/load impedance to the converter/source impedance, i.e. Z_L/Z_S.

$$i_{ac} = \frac{I_c}{1 + Y_c(s)Z_g(s)} - \frac{Y_c(s)V_g}{1 + Y_c(s)Z_g(s)} =$$

$$= \frac{G_{cl}(s)i^*}{1 + Y_{cl}(s)Z_g(s)} - \frac{Y_{cl}(s)V_g}{1 + Y_{cl}(s)Z_g(s)}$$

Impedance-based stability analysis



State space to transfer function

State Space

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

$$x(s) = (sI - A)^{-1}Bu(s)$$
$$y(s) = [C(sI - A)^{-1}B + D]u(s)$$
$$y(s) = G(s)u(s)$$

Transfer Function

$$Y(s) = G(s)U(s)$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & \dots & 0 \\ 0 & 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 1 \\ -\frac{a_n}{a_0} & -\frac{a_{n-1}}{a_0} & -\frac{a_{n-2}}{a_0} & -\frac{a_{n-3}}{a_0} & \dots & -\frac{a_1}{a_0} \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{b_n}{a_0} - \frac{a_n}{a_0^2}b_0 & \frac{b_{n-1}}{a_0} - \frac{a_{n-1}}{a_0^2}b_0 & \frac{b_{n-2}}{a_0} - \frac{a_{n-2}}{a_0^2}b_0 & \dots & \frac{b_1}{a_0} - \frac{a_1}{a_0^2}b_0 \end{bmatrix}, D = \frac{b_0}{a_0}$$

IBSA vs. EBSA

IBSA	EBSA
— Simple method with linear assumptions and easy to apply as only impedance characteristic is needed.	— Everything must be linearized and modelled in state space.
— Not clear evaluation criteria as stability margins can vary depending on a busbar.	— Eigenvalue analysis allows to determine the damping and frequency.
— If unstable, not straight forward to find the root cause and propose the mitigation method.	— Participation factor analysis allows to define the instability root cause.
— Not clear how to define the source and the load as well as the impedance ratio.	— Can help in finding the most optimal mitigation measure.
	— More complex more powerful analysis method.

A. Rygg, M. Amin, M. Molinas, and B. Gustavsen, "Apparent impedance analysis: A new method for power system stability analysis," in 2016 IEEE 17th Workshop on Control and Modeling for Power Electronics (COMPEL), pp. 1–7, 2016.

Eigenvalue-based stability analysis

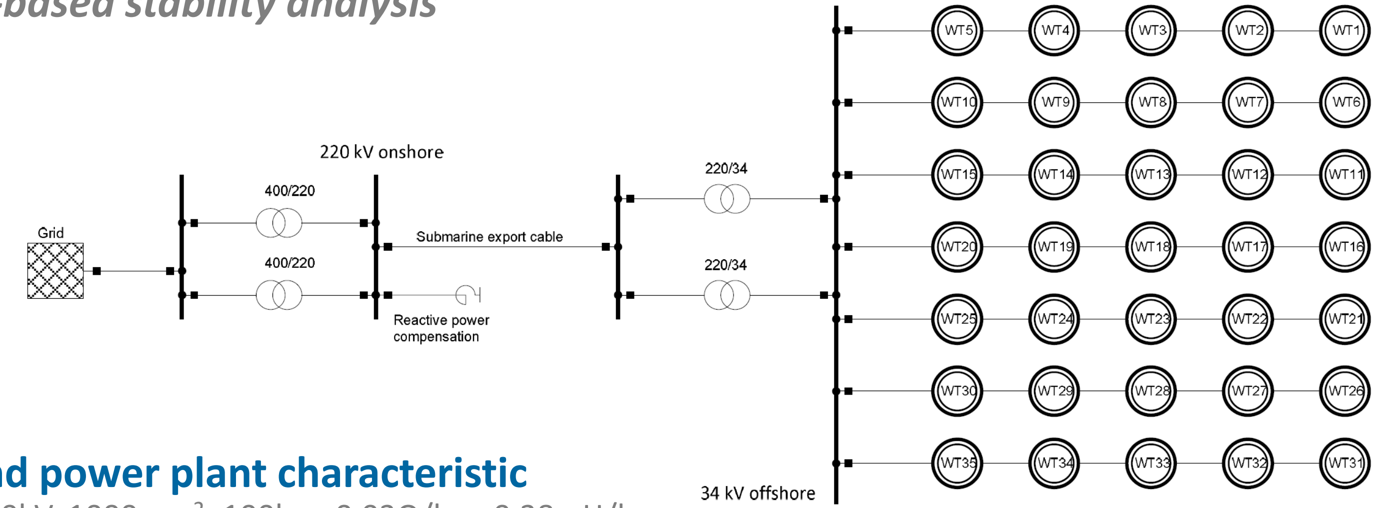
pros and cons

Pros	Cons
— The models of different components (SM, AVR, INV, …) are available in the state space form. — We can clearly see the effects of each parameter (sensitivity analysis). — Eigenvalue analysis for stability (damping and frequency). — Controller tuning and root cause investigation based on the participation factor analysis.	— Everything must be modelled in state space. Non-linear state space modelling is also possible. — Identification techniques (e.g. vector fitting) are required when only numerical data is available (e.g. look-up table). — The system should be linearized for each operating point to apply linear analysis; critical especially for low frequency range.

M. K. Bakhshizadeh Dowlatabadi, "*Harmonic Modelling, Propagation and Mitigation for Large Wind Power Plants Connected via Extra Long HVAC Cables: With special focus on harmonic stability*," Ph.D. thesis, Aalborg Universitetsforlag, 2018.

Grid-converter stability aspects

#3 eigenvalue-based stability analysis



Reference wind power plant characteristic

- Export cable: 220kV, 1000mm^2, 100km, 0.03Ω/km, 0.38mH/km, 0.19µF/km.
- Array cable: 34kV, 630mm^2, 3km (each section), 0.042Ω/km, 0.31mH/km, 0.32µF/km.
- Wind turbine transformer: 9MVA, 35kW, 0.09pu.
- Offshore transformer: 200MVA, 300kW, 0.14pu.
- Onshore transformer: 200MVA, 375kW, 0.12pu.

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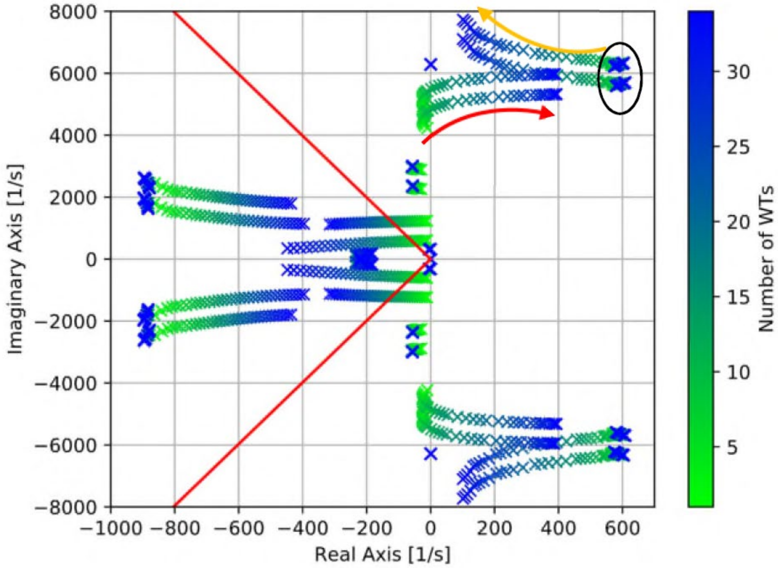
Grid-converter stability aspects

#3 eigenvalue-based stability analysis

Component name	Contribution on [%]		
	Black group	Yellow group	Red group
Export cable	0	0.5	0.3
400/220 kV Tr. (Onshore)	0	0	0
220/34 kV Tr. (Offshore)	0	12	3.7
34/1 kV Tr. (WT)	4.3	30.6	1.2
Array cables	0	38.4	7.3
WT Filter cap.	16.8	8.5	7.5
WT's reactor	35	4.6	34
PLL	0	0	0
Controller delay	43.1	5.3	45
Current controller	0.8	0.1	1



Analysis approach

- Eigenvalues show the oscillatory modes and their damping.
- Participation factor analysis can show which components contribute the most to the instability.
- Sensitivity analysis can cover various topology changes and operating points.

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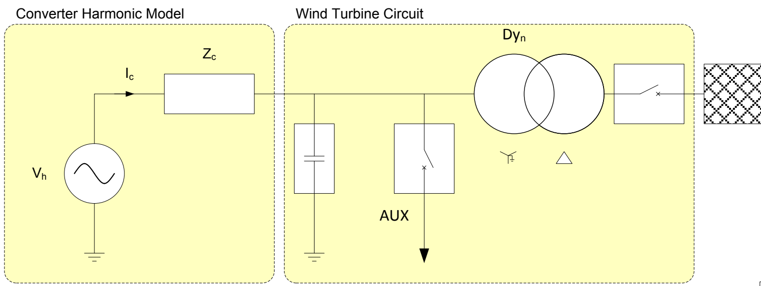
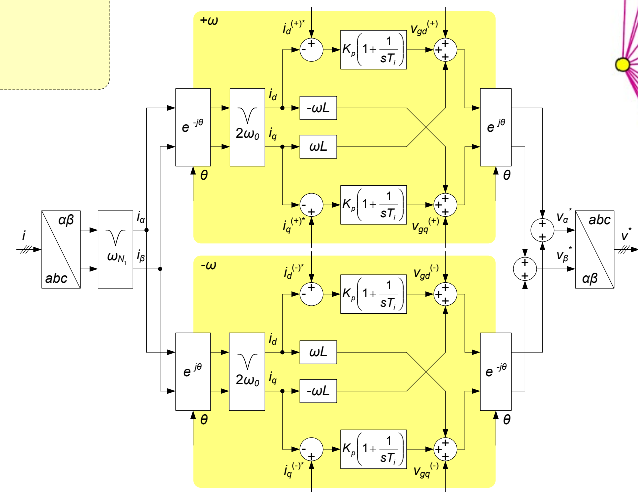
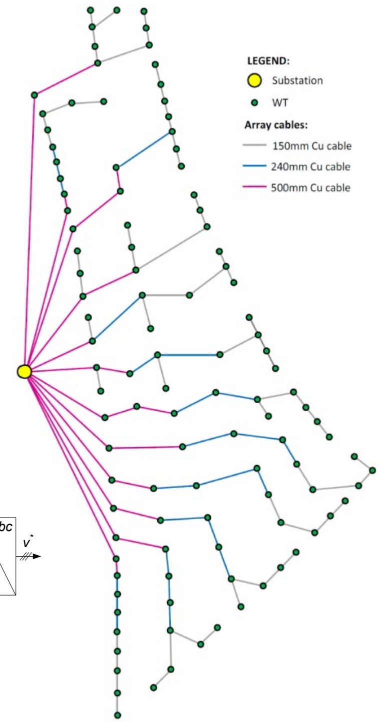
Grid-converter stability aspects

converter stability vs. power quality







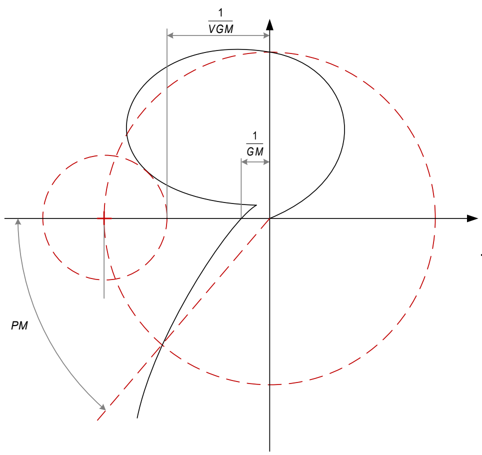
Stability challenges

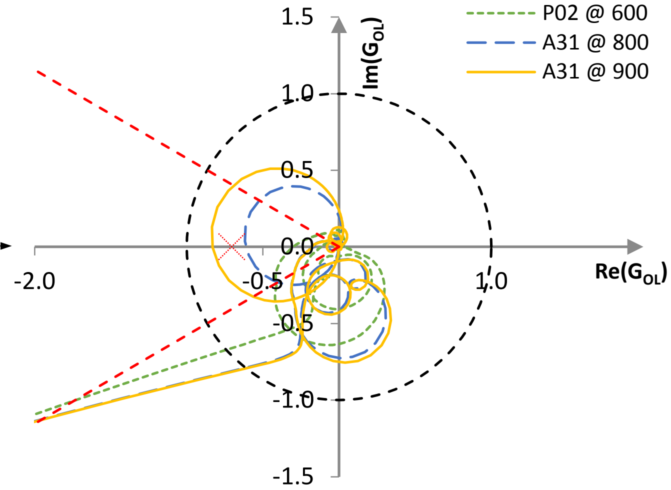
- Grid converter control strategy affects its frequency response
- Converter frequency characteristic can affect both the harmonic performance as well as stability
- Better power quality is not always aligned with better robustness

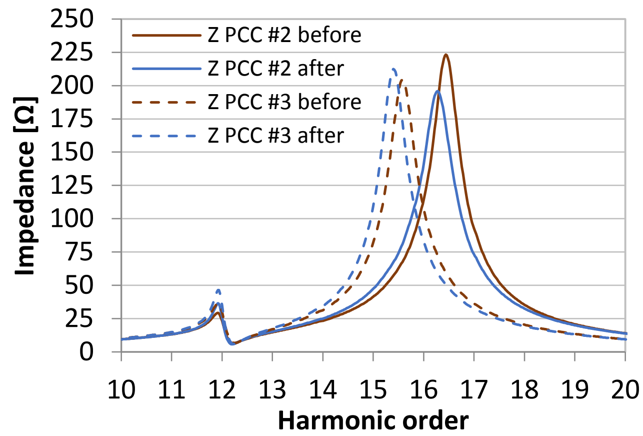
Ł. H. Kocewiak, B. Laudal Øhlenschlæger Kramer, O. Holmstrøm, K. Høj Jensen, L. Shuai, "*Resonance Damping in Array Cable Systems by Wind Turbine Active Filtering in Large Offshore Wind Power Plants*," IET Renewable Power Generation, Institution of Engineering and Technology, 6 July 2017, Volume 11, Issue 7, Page(s) 1069-1077.

Grid-converter stability aspects

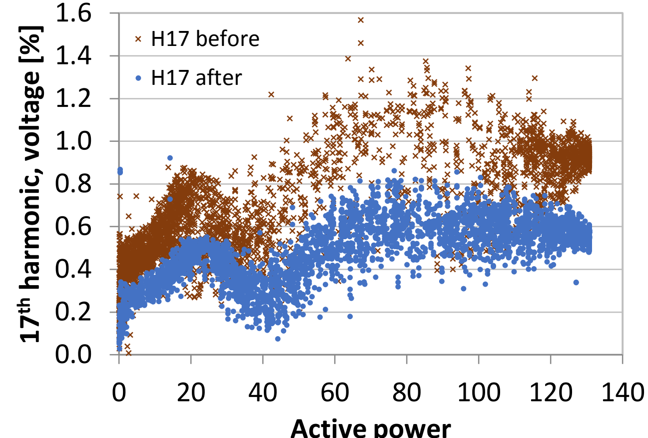
converter stability vs. power quality







	Notch filter tuning frequency		
	600 Hz	800 Hz	900 Hz
GM, dB	10.44	4.32	1.61
PM, deg.	33.61	36.48	36.58
VGM, dB	5.22	4.21	1.61



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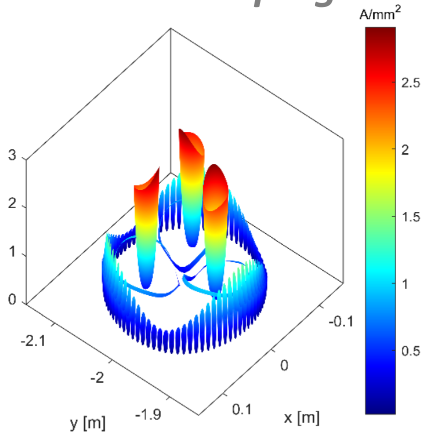
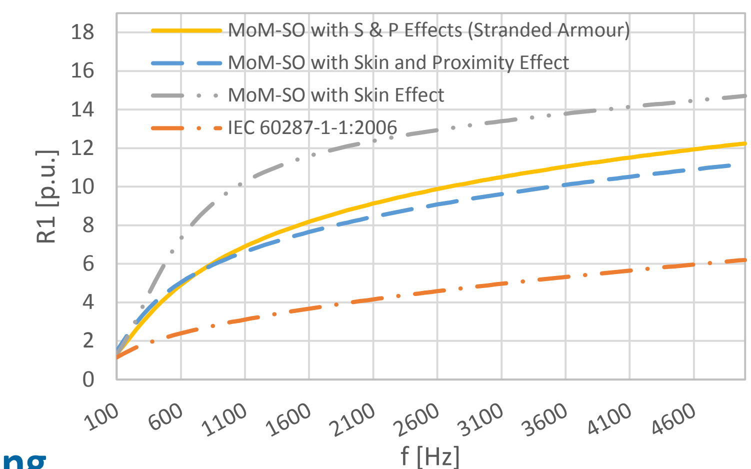
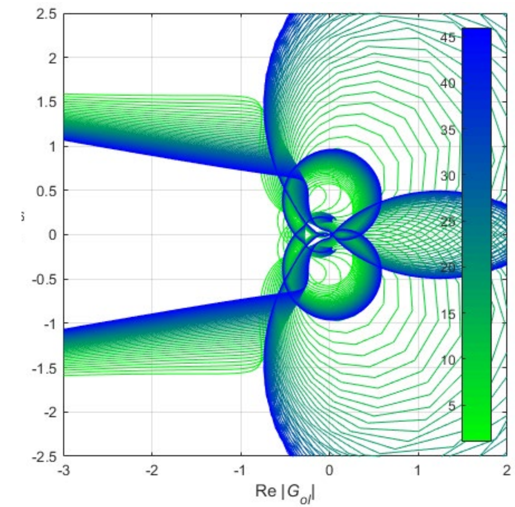
Grid-converter stability aspects

reliable damping modeling and stability analysis







System damping modelling

- More detailed damping modelling can significantly improve system robustness (GM and VGM), especially for higher frequencies.
- Low frequency resonances and related to them PM are not affected much by harmonic losses modelling.
- The system damping is lowering as more WTs are connected.

Stability margin	No damping	IEC 60287-1-1	MoM-SO (S+P)	MoM-SO (S+P) & sFRA
GM in [dB]	4.62dB @ 1400 Hz	4.93dB @ 1402 Hz	5.34dB @ 1405 Hz	5.28dB @ 1404 Hz
PM in [°]	40.6° @ 117 Hz	40.9° @ 117 Hz	40.15° @ 117 Hz	40.15° @ 117 Hz
VGM in [dB]	4.13dB @ 1384 Hz	4.5dB @ 1386 Hz	4.99dB @ 1388 Hz	4.92dB @ 1387 Hz

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3. **What next?**

What next?

- Which method is the best to be used by the industry to design and integrate wind power plants into power systems?
- Are there any challenges for the industry and academia to provide suitable and accurate converter models?
- Is it possible to specify generic rules regarding the grid converter coordination / interoperability which can be standardized?
- How the converter instability can be linked to the standard power quality definition?
- Do the industry and academia need an international standard regarding grid converter stability?

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