Is It Really Grid-Forming?

Findings from a cross-vendor tests of grid-forming converters

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Fraunhofer ISE
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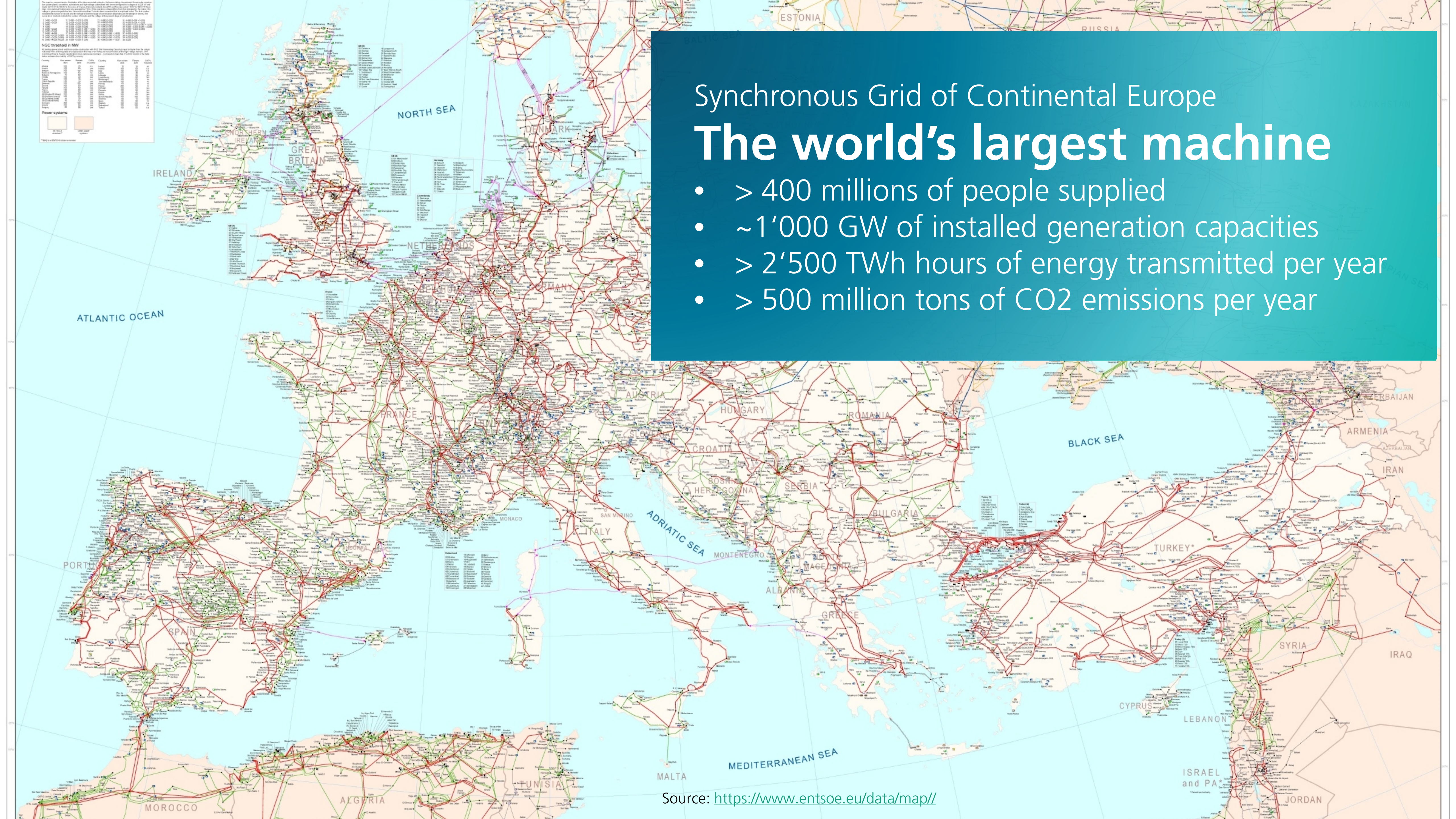
Synchronous Grid of Continental Europe

The world's largest machine

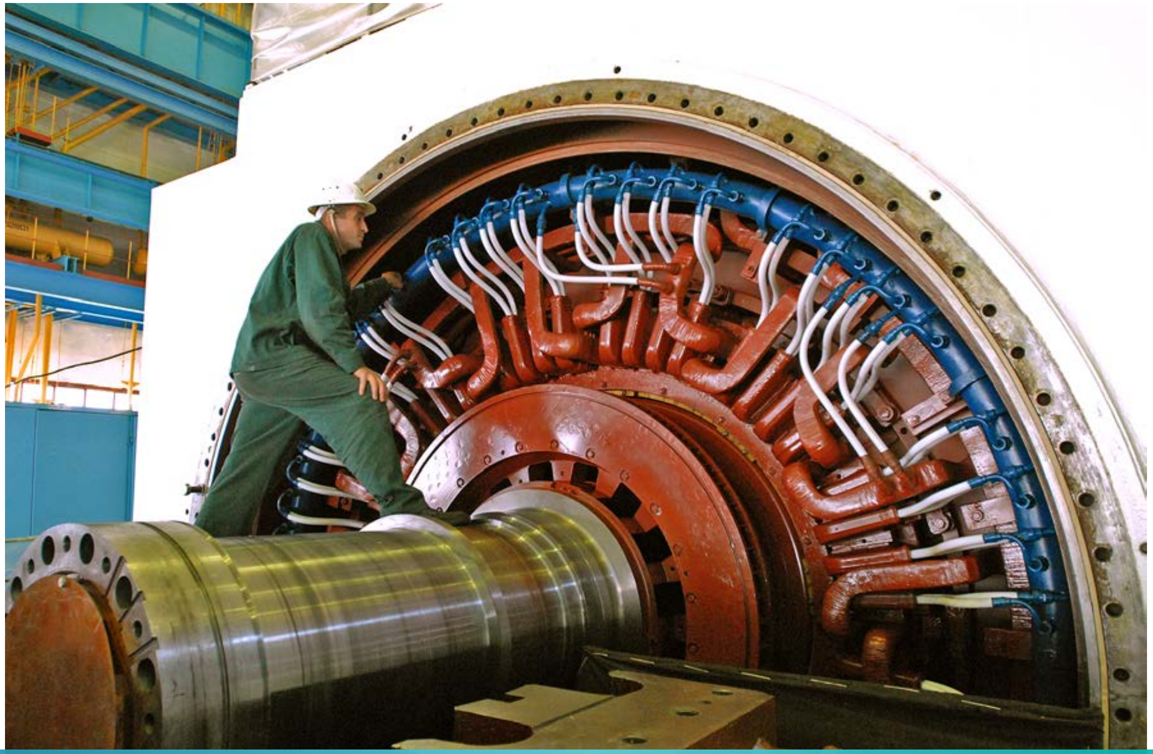
- > 400 millions of people supplied
- ~1'000 GW of installed generation capacities
- > 2'500 TWh hours of energy transmitted per year
- > 500 million tons of CO2 emissions per year



Source: https://www.entsoe.eu/data/map//

Control of Electrical Power Systems
Fundamentals

- An electrical power system connects multiple generators and loads.
- At any moment, generation and load must be balanced.
- Voltage amplitude and frequency must be controlled and kept within defined limits.
- Active and reactive power are the control variables.
- The dynamic behaviour of electrical power systems is mainly defined by the inertia of the system.



Today's control and protection concepts are based on the electrical behaviour of the **synchronous generator**.

Source: https://de.wikipedia.org/wiki/Synchronmaschine

Motivation

Replacement of Synchronous Generators by Converters

Source: Siemens

Source: GE Power Conversion

Synchronous Generators:

Inherent voltage source behaviour

Inertia for rotating masses

High overload capability

Converters:

Freely programmable electrical behaviour

High dynamic controllable

Hardly overloadable

"Electronification" of the Power Grids

Challenges for a Stable Operation of the Energy System

Ranking of the power system stability issues as identified by European TSOs

Ranking	Score	Issue
1	17.35	Decrease of inertia
2	10.16	Resonances due to cables and Power electronics
3	9.84	Reduction of transient stability margins
4	8.91	Missing or wrong participation of PE-connected generators and loads in frequency containment
5	8.19	PE Controller interaction with each other and passive AC components
6	7.50	Loss of devices in the context of fault-ride-through capability
7	7.00	Lack of reactive power
8	6.91	Introduction of new power oscillations and/or reduced damping of existing power oscillations
9	6.09	Excess of reactive power
10	4.27	Voltage Dip-Induced Frequency Dip
11	3.87	Altered static and dynamic voltage dependence of loads

Dynamic Interactions

between IBRs and the grid cause the biggest concerns

Sources:
ENTSO-E report „High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS)", Jan 2020
MIGRATE project: Deliverable 1.1, 'Report on systemic issues. [online]: https://www.h2020-migrate.eu/.'.

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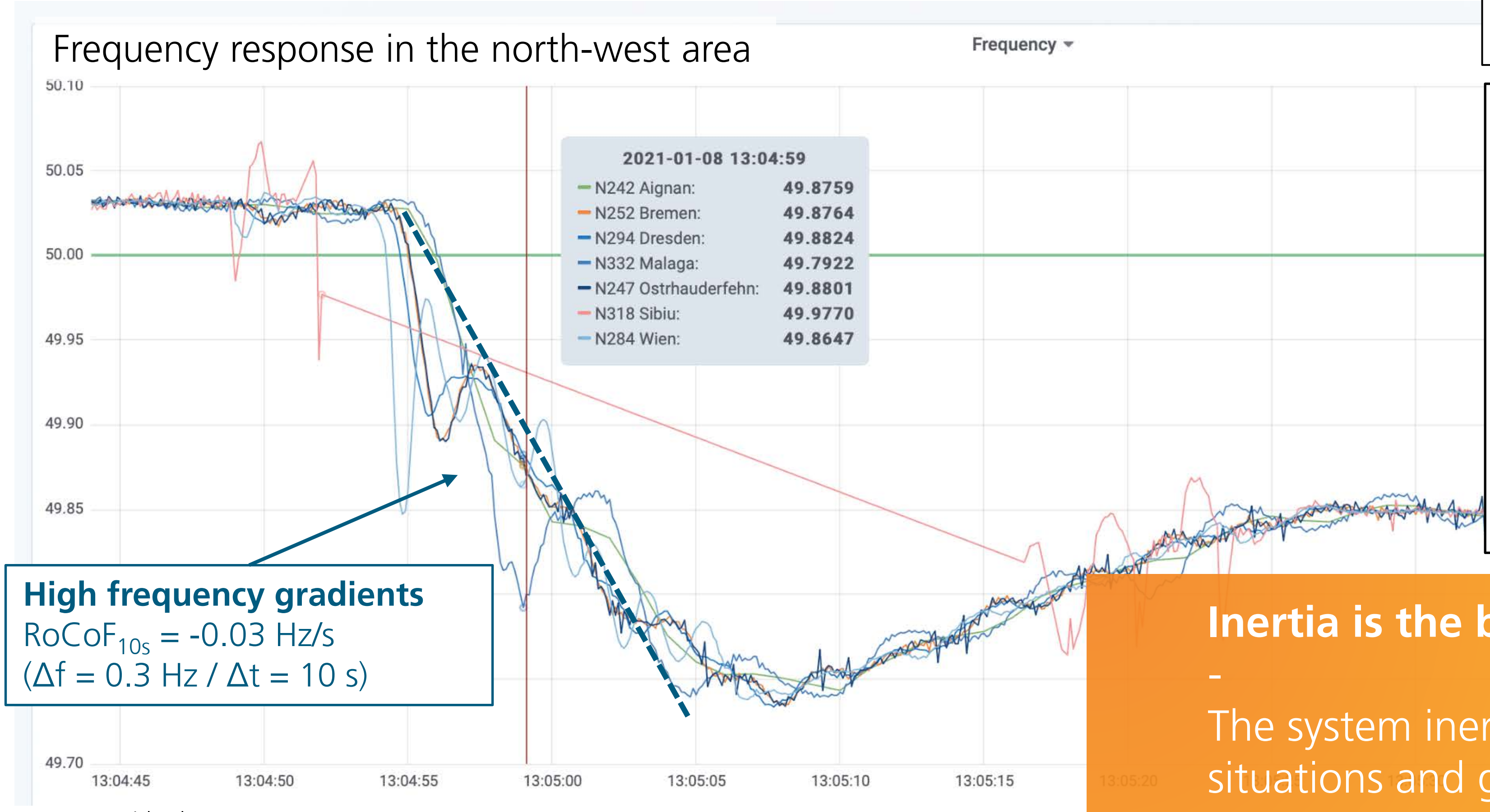
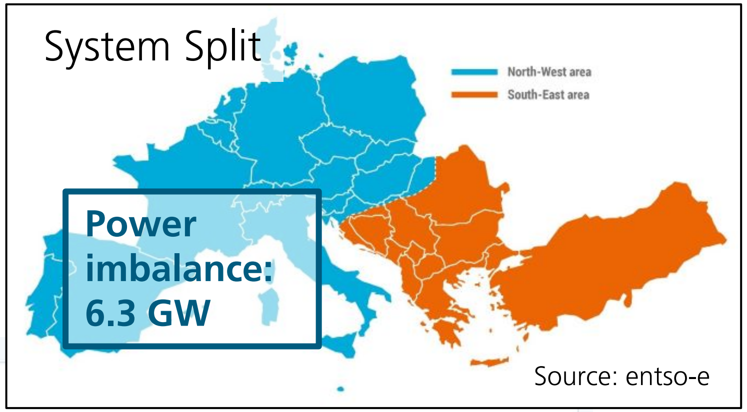
System Split of the ENTSO-E Grid 08.01.2021, 14:05

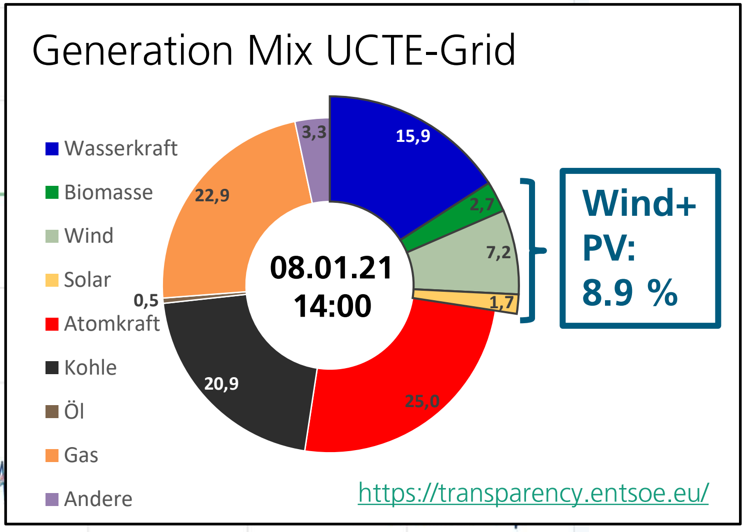
Frequency Reaction



Source: Gridradar

High frequency gradients
$RoCoF_{10s}$ = -0.03 Hz/s
(Δf = 0.3 Hz / Δt = 10 s)





https://transparency.entsoe.eu/

Inertia is the basis for stability
-
The system inertia limits the RoCoF in emergency situations and gives time for counter-measures

Sources: http://gridradar.net/ , www.energy-charts.info, https://www.entsoe.eu/news/2021/01/15/system-separation-in-the-continental-europe-synchronous-area-on-8-january-2021-update)

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What are Grid-Forming Converters?

Grid-Forming Converters

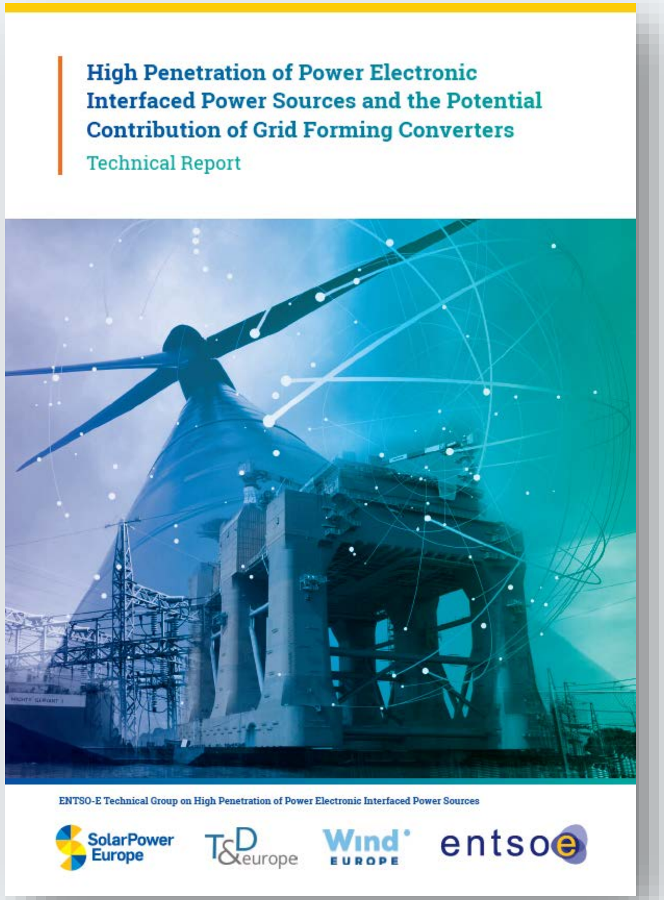
Requirements

GFC should enable stable grid operation without synchronous generators.

"*Grid Forming Converters shall be capable of supporting the operation of the AC power system (from EHV to LV) under normal, disturbed and emergency states without having to rely on capabilities from Synchronous Generators (SGs). This shall include the capabilities for stable operation for the extreme operating case of supplying the complete demand from 100% converter-based power sources.*"
[1] [HPoPEIPS Report.]

Required feature of GFC according to HPoPEIPS report:

- Creating system voltage
- Contributing to fault level
- Sink for harmonics
- Sink for unbalance
- Contribution to inertia
- Preventing adverse control interactions



Source[1]: ENTSO-E, "Technical Report: High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid forming Converters," Jan. 2020.

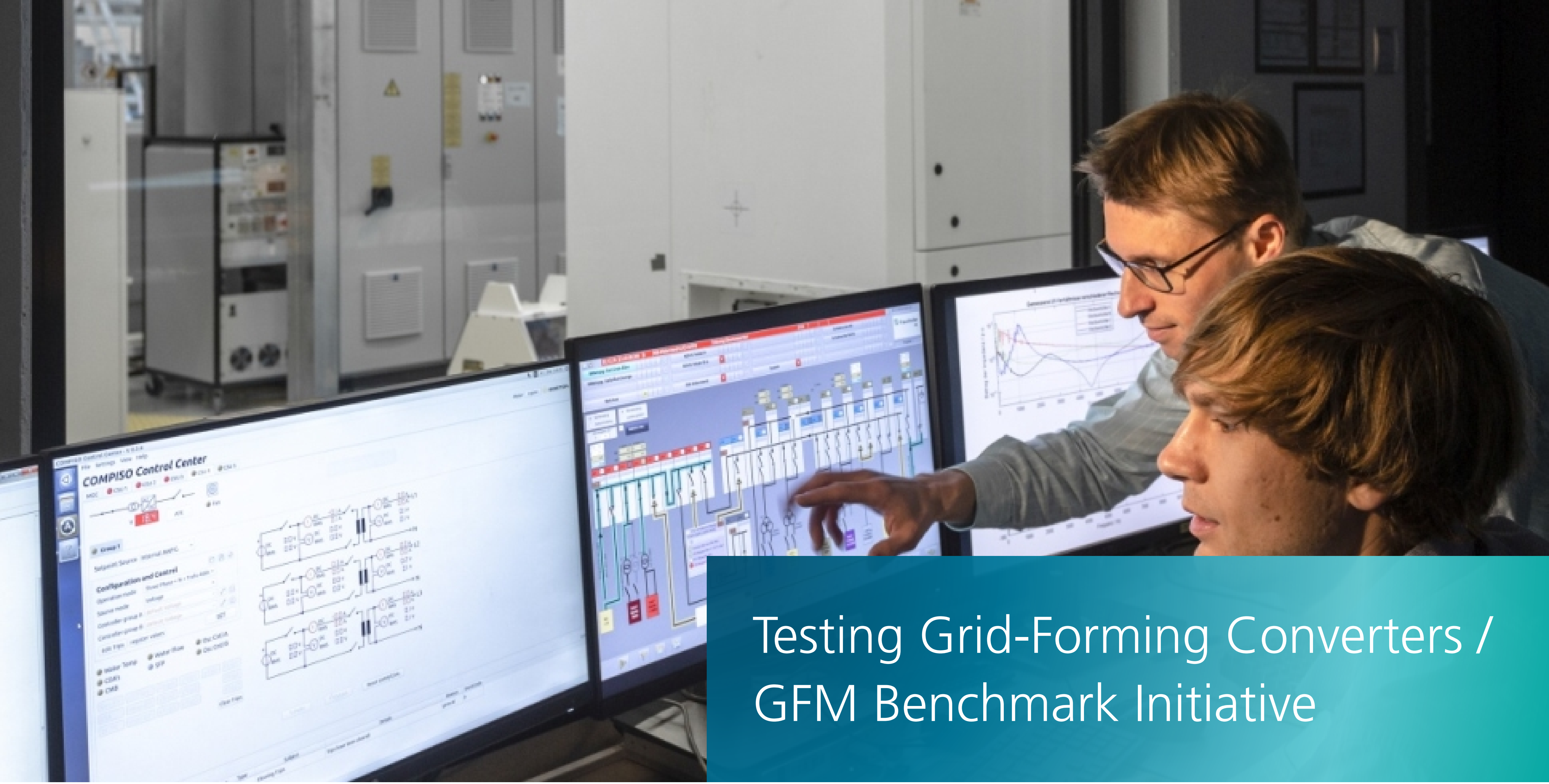
Grid-Coupled Inverters

Control Types

	Current Controlled		Voltage Controlled	
	Grid Following	**Grid Supporting**	**Grid Leading**	**Grid Forming**
Type of Source	Constant current source	Controlled current source	Fixed voltages source	Controlled voltage source behind an impedance
Application	Power feed-in	Power feed-in and provison ancillary grid services	Island grids with single voltage source	Interconnected systems with multiple sources

State of the art

Required for future grids



Testing Grid-Forming Converters / GFM Benchmark Initiative

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GFM Benchmark Initiative

Motivation and Background

- Many research activities on grid forming converters in the recent years
- First manufacturers offer grid forming devices
- First demo-Projects are planned and installed
- Grid forming capabilities will be part of new grid codes
- Numerous grid-forming converters are expected to be installed soon!

But…

- There is **no general specifications of GFM behaviour** yet
- Consequence: different interpretations of GFM behaviour by different manufacturer

GFM Benchmark Initiative

Cross-Vendor Measurements of Grid Forming Converters

Want to join the initiative?
Contact us!

Mission

- Analysis of the current state of available GFM converters.
- Collection of experience with GFM conformity testing.
- Identification of development needs for GFM in the context of system stabilization.

Approach

- Elaboration of a GFM black box testing procedure. ([x] completed)
- Scalable GFM testing campaign open for interested vendors ([…] ongoing)
- Publication of anonymized results ([ ] upcoming)

Partners/Sponsors

- All 4 German TSOs
- 10+ individual inverter manufacturers (10 kW to 4.5 MW)

50hertz | Elia Group
TRANSNET BW
TenneT
amprion

More information:
https://www.ise.fraunhofer.de/en/research-projects/gfm-benchmark.html

GFM Benchmark Initiative

A Win-Win-Win Situation

TSO's benefits

- Learnings about state of the art of GFM converters
- Learnings about different manufacturer interpretations for GFM behaviour
- Base for the definition of future GFM requirements
- Base for the definition of future conformity assessment methods

Manufacturer's benefits

- Preparation for upcoming inertia markets
- Feedback on the performance of their GFM product
- Feedback on possible further development needs
- Learnings about possible future test and conformity assessment methods
- Possibility to discuss requirements, limitations and test methods with system operators and research

Fraunhofer ISE's benefits

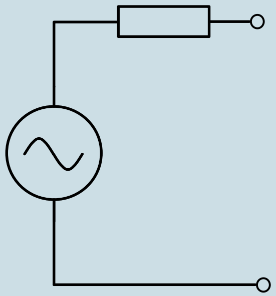
- Practical feedback on the developed test methods
- Practical lab experience in testing GFM converters
- Input for further research topics regarding GFM converter control and their testing

Test methods for grid forming converters

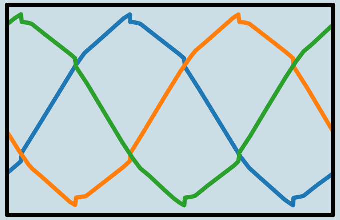
Overview

Behavior of Grid Forming Converter

Voltage source properties

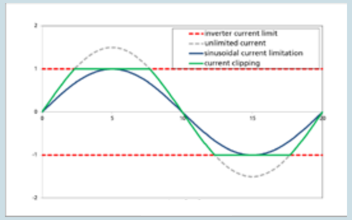


Power quality

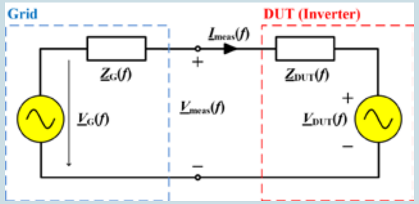


Inertia and Damping

Overload and fault behaviour



Grid interaction

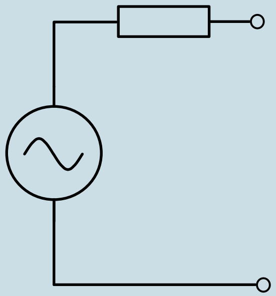


Test methods for grid forming converters

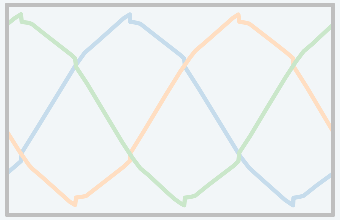
Voltage source properties

Behavior of Grid Forming Converter

Voltage source properties



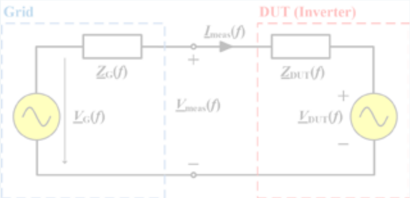
Power quality



Inertia and Damping

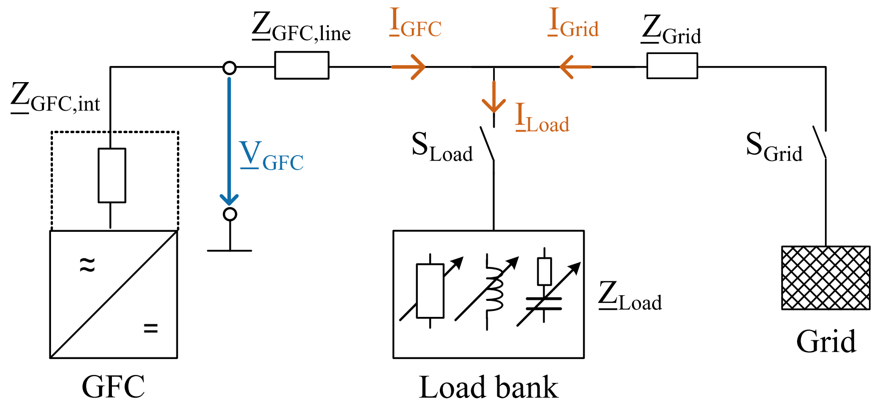
Overload and fault behaviour

Grid interaction



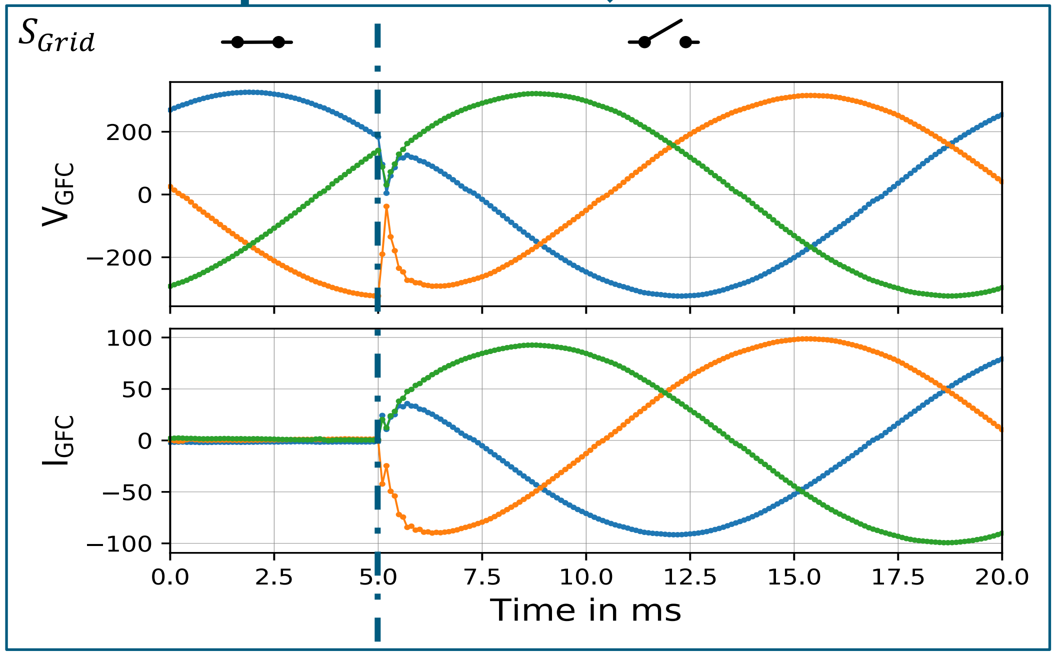
Voltage source behaviour

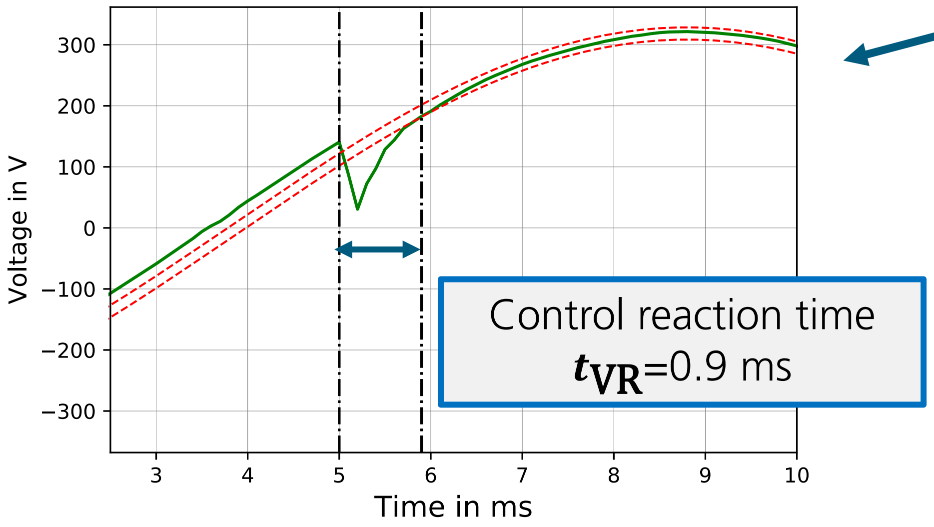
Test setup and procedure



Internal impedance

$$\underline{Z}_{\mathrm{DUT,int}} = \frac{\underline{V}_{\mathrm{GFC,after}} - \underline{V}_{\mathrm{GFC,before}}}{\underline{I}_{\mathrm{GFC,after}} - \underline{I}_{\mathrm{GFC,before}}}$$





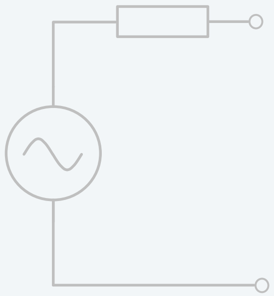
Loads	1	2	3	4	5
P_{set}	0(or P_{min})	0(or P_{min})	0(or P_{min})	0(or P_{min})	0(or P_{min})
P_R	0.2 S_N	0.9 S_N	0	0	0.9 S_N
Q_I	0	0	0.2 S_N	0	0.44 S_N
Q_c	0	0	0	0.1 S_N	0

Test methods for grid forming converters

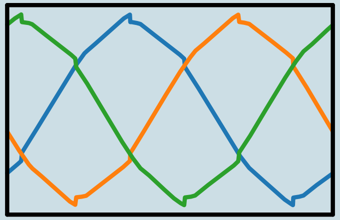
Contribution to power quality

Behavior of Grid Forming Converter

Voltage source properties



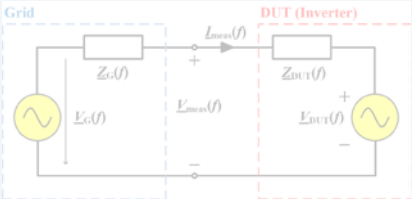
Power quality



Inertia and Damping

Overload and fault behaviour

Grid interaction



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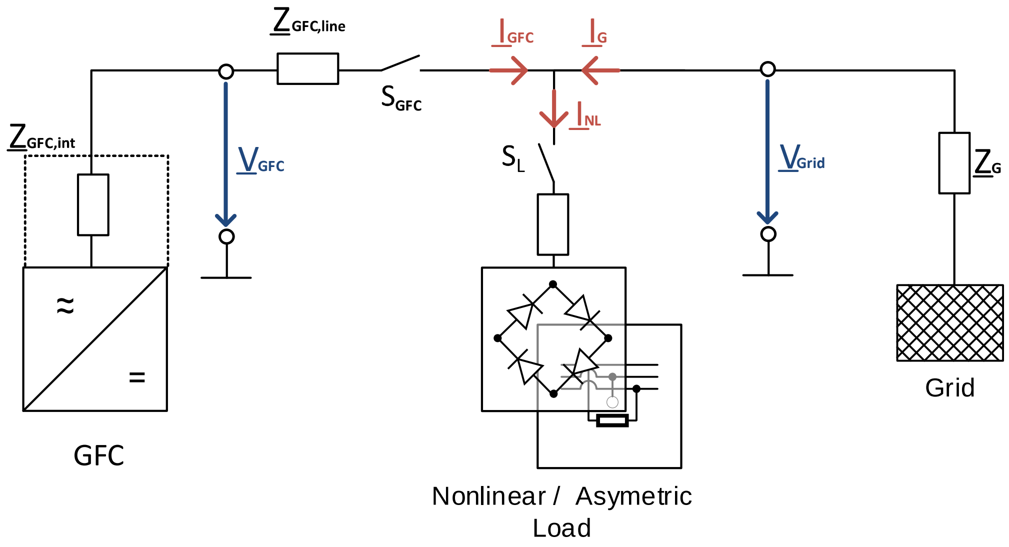
Contribution to power quality



Loading the grid with a nonlinear/asymmetric load

- Comparing the voltage quality with and without the GFC

→ Volage quality must improve with GFC in operation

Asymmetric Loads

- Calculation of the unbalance factor

$$a_{\mathrm{unb}} = \frac{V_-}{V_+} \cdot 100\%$$

- the unbalance factor must improve with GFC in operation

$$\Delta a_{unb} = a_{unb,GFC} - a_{anb,wo\ GFC} < 0$$

Harmonics

- Calculation of the THD of the grid Voltage

$$THD_{u,Grid} = \frac{\sqrt{\sum_{h=2}^{50} \hat{U}_h^{\,2}}}{\hat{U}_1}$$

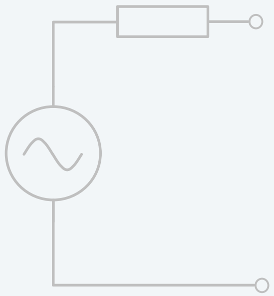
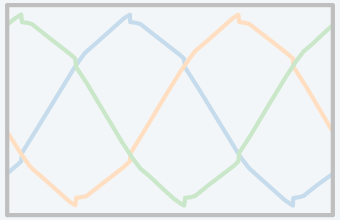
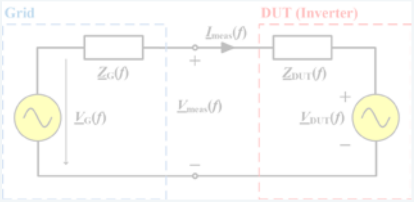
- The THD with GFC must improve

$$\Delta THD_u = THD_{u,GFC} - THD_{u,wo\ GFC} < 0$$

Test methods for grid forming converters

Contribution to system inertia and damping

Behavior of Grid Forming Converter

Voltage source properties	Power quality	**Inertia and Damping**	Overload and fault behaviour	Grid interaction
				

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Contribution to System Inertia

Test Methods

Goal: Determine the effective inertia constant black-box testing

$$T_A = \frac{\Delta P \cdot f_0}{P_N \cdot |RoCoF|}$$

$T_A = 2 \cdot \mathrm{H}$

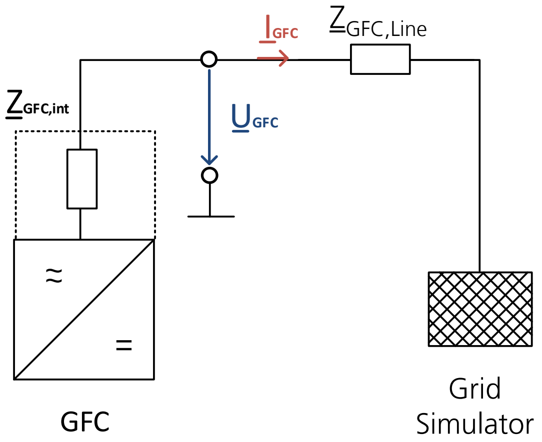
Parametrization recommendation for the DUT

$T_A = 25\ \mathrm{s}$ $(H = 12.5\ \mathrm{s})$

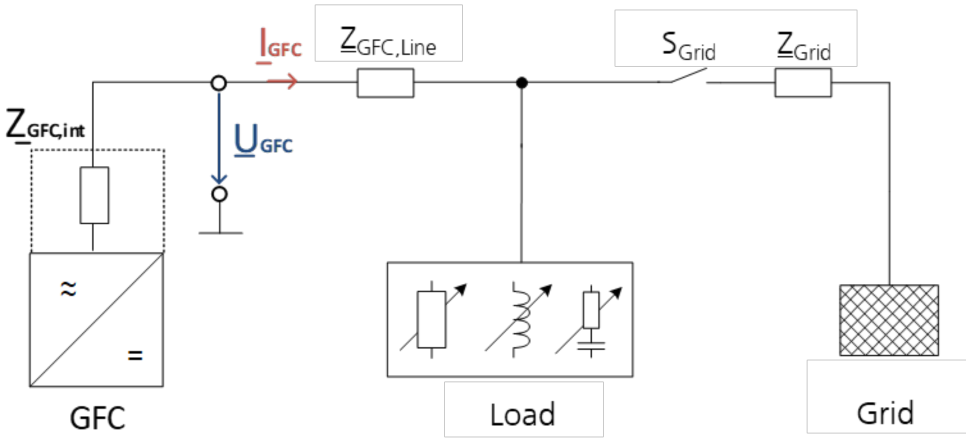
Test runs

Test	$P_{GFC,Set}$[pu]	RoCoF[Hz/s]	Expected ΔP
1	0.3	-0.5	0.2
2	0.5	-1.0	0.5
3	0.5	0.5	-0.2
4	1	1.0	-0.5

Method 1 (RoCoF-based inertia measurement)



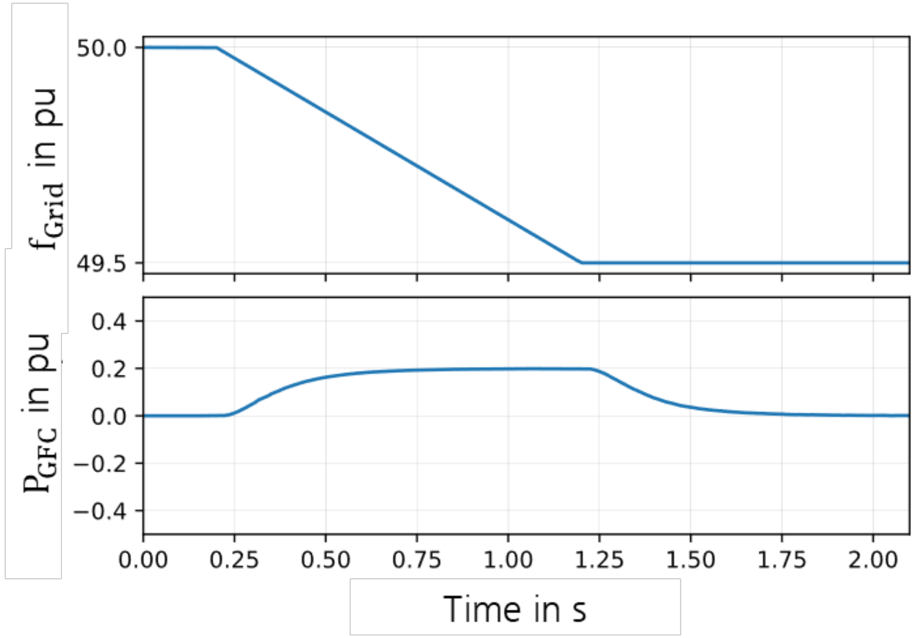
Method 2 (load-based inertia measurement)



Contribution to System Inertia

Measurements and analysis

Method 1 (RoCoF-based inertia measurement)

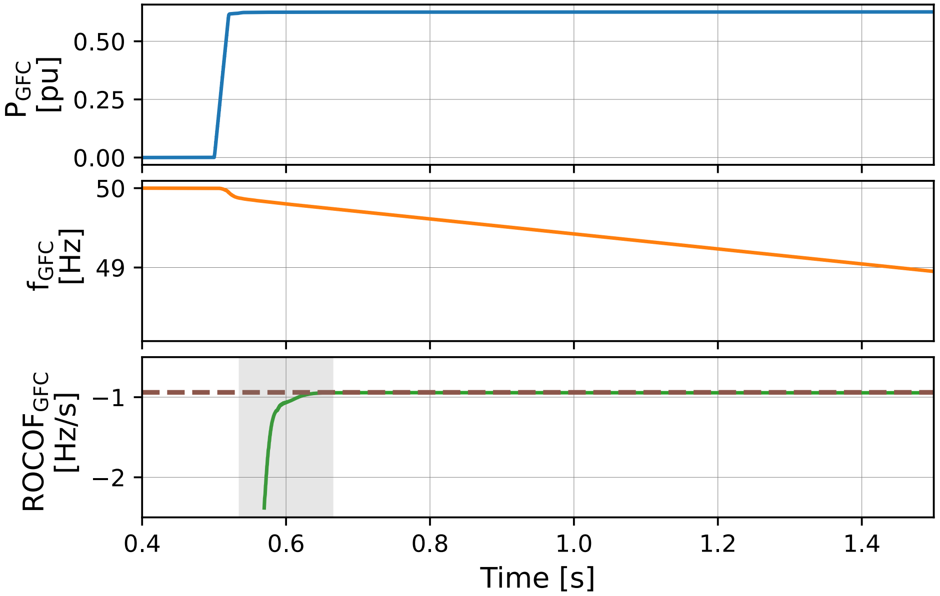


$$T_A = \frac{\Delta P \cdot f_0}{P_N \cdot |RoCoF|}$$

Method 2 (load-based inertia measurement)

Given

Measured

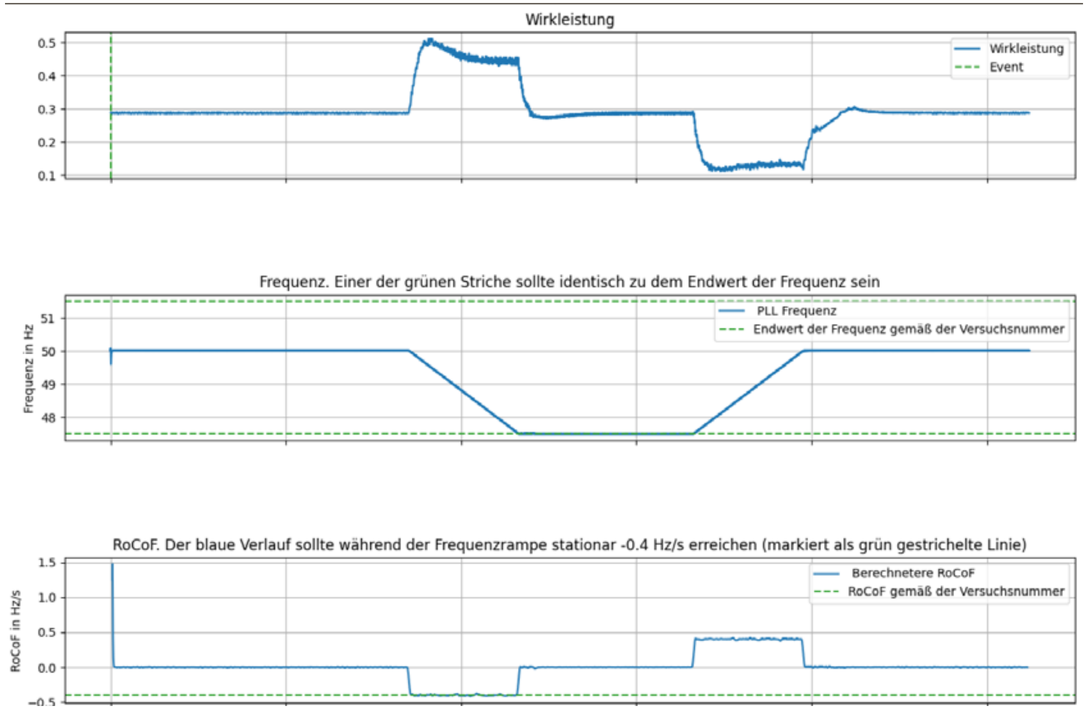


$$T_A = \frac{\Delta P \cdot f_0}{P_N \cdot |RoCoF|}$$

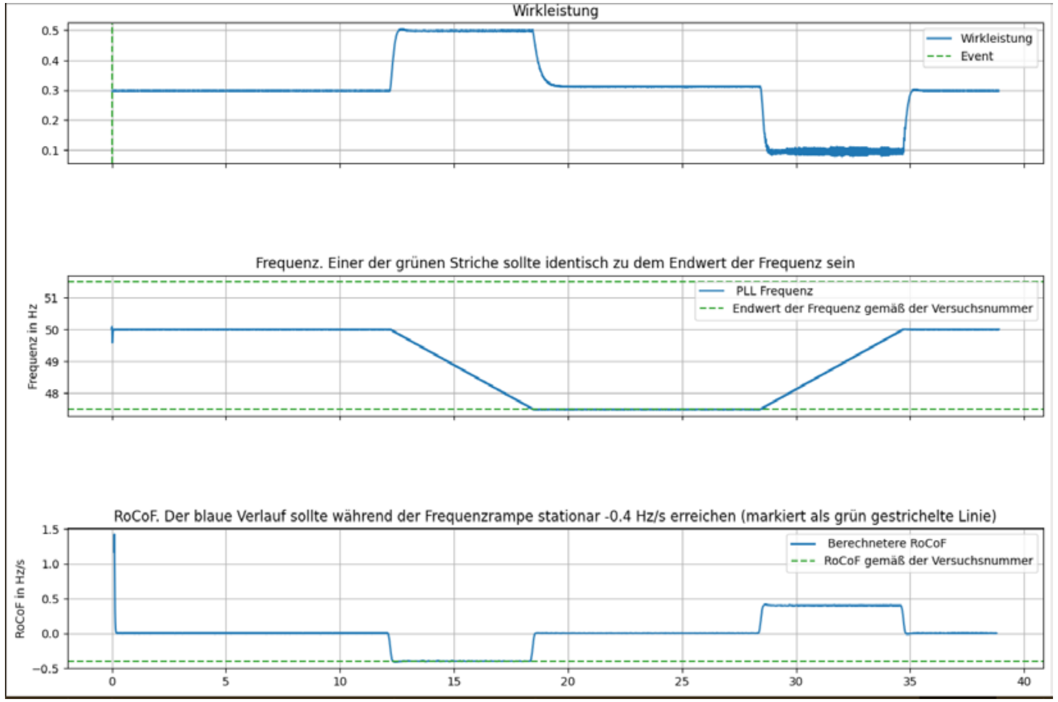
Contribution to System Inertia

Load-based method 2: Exemplary measurement results ($P_{\text{set}} = 0.3\ \text{pu}\,,\ \text{RoCoF} = \pm 0.4\ \text{Hz/s}$)

DUT 1



DUT 2



- Measured $T_A = 19.67\text{s}$ (parametrized 20 s)
- Slow settling (> 3 s)
- Unsymmetrical settling behaviour for pos./neg. RoCoFs

- Measured $T_A = 25.09$ s (parametrized 25 s)
- Fast settling (< 0.25 s)
- Active powerringing for pos. RoCoFs

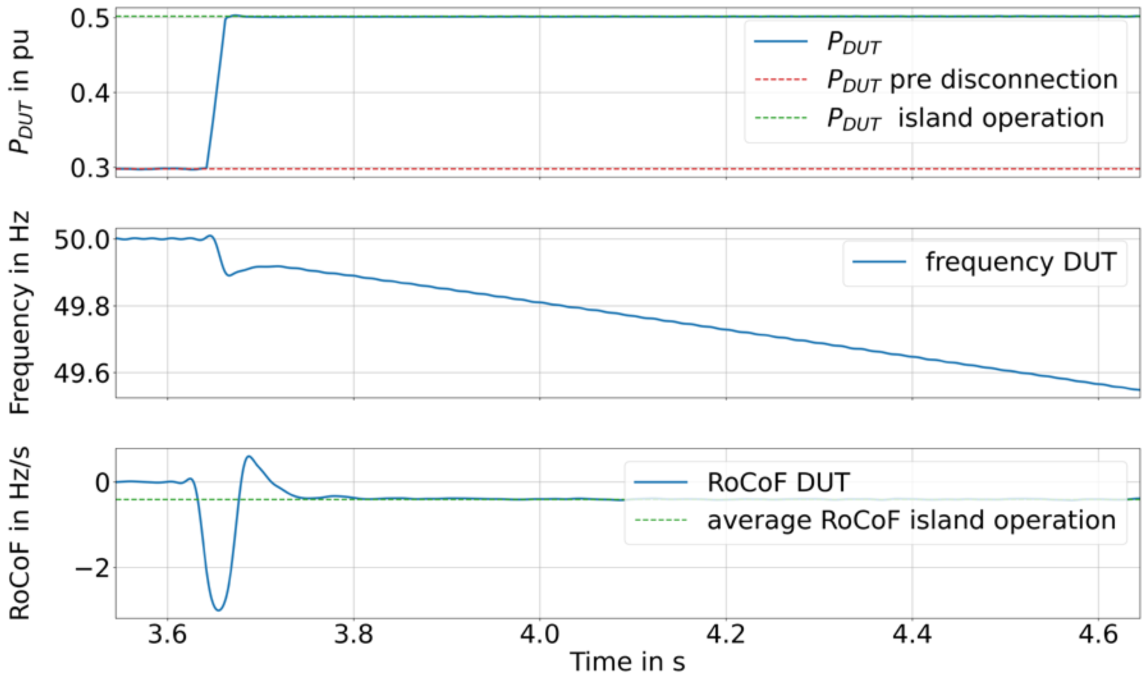
Contribution to System Inertia

RoCoF-based method 1: Exemplary measurement results ($P_{\text{set}} = 0.3$ pu , $P_{\text{Load}} = 0.5$ pu)

Findings

- Methods 1 & 2 show comparable accuracy for the analysed T_A
- Method 2 has transient measurement artefacts due to the dynamics of the frequency measurement.

DUT 2



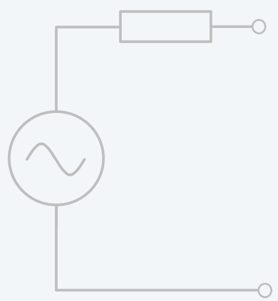
- Measured $T_A = 25.02$ s (parametrized 25 s)

Test methods for grid forming converters

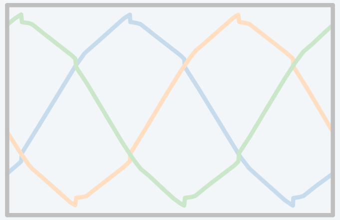
Behaviour during critical grid events

Behavior of Grid Forming Converter

Voltage source properties

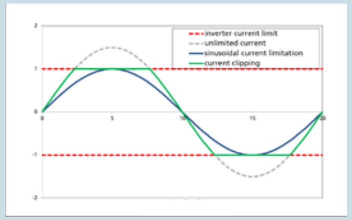


Power quality

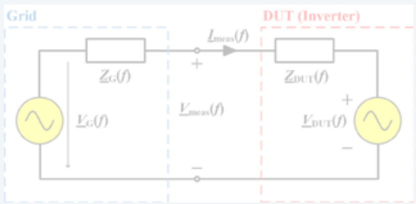


Inertia and Damping

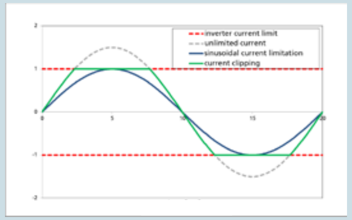
Overload and fault behaviour



Grid interaction

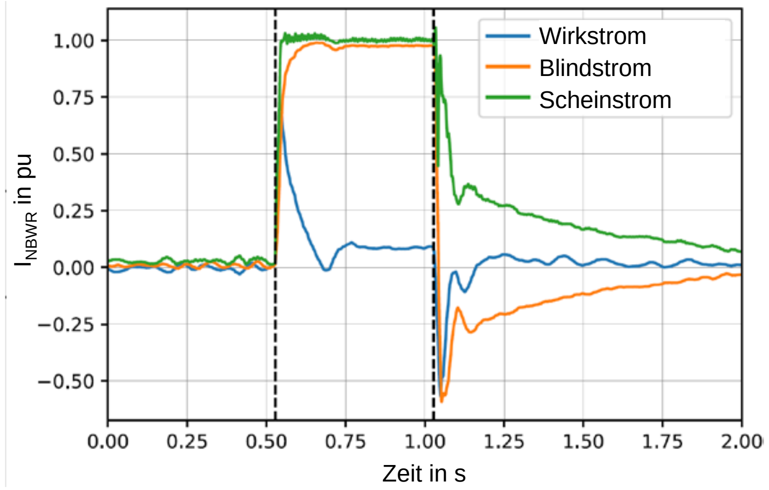


Overload and fault behaviour (I)



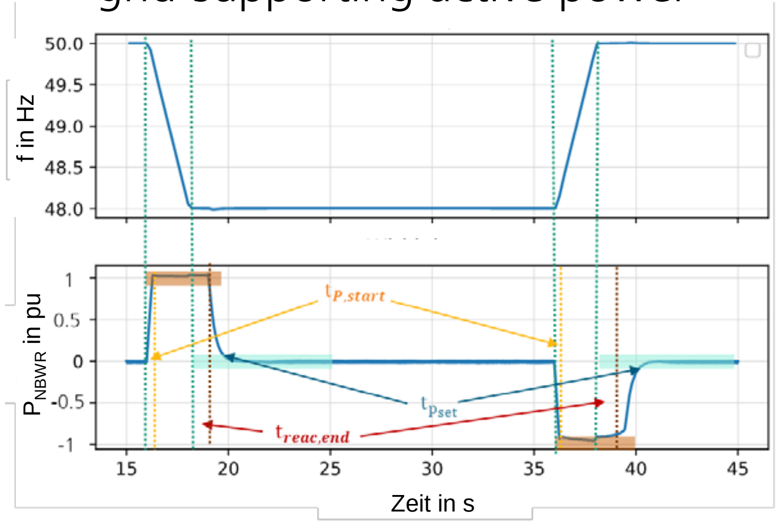
Over and under voltage

- Classical OVRT/UVRT testing
- DUT must show:
  - stable operation
  - instantaneous voltage support



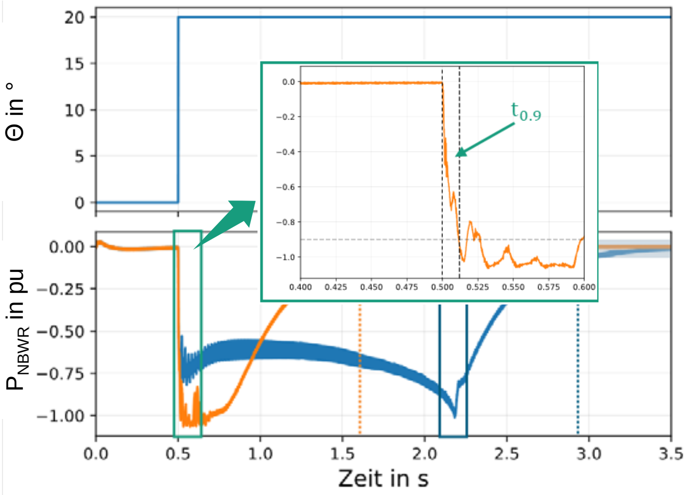
Fast RoCoF

- Exposure to high RoCoF values up to ±4 Hz/s for 0.25 s.
- DUT must show:
  - stable operation
  - grid-supporting active power



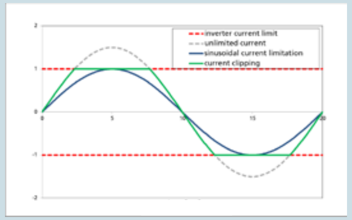
Phase jump

- Exposure to high phase jumps of up to ±90°.
- DUT must show:
  - stable operation
  - instantaneous grid-support



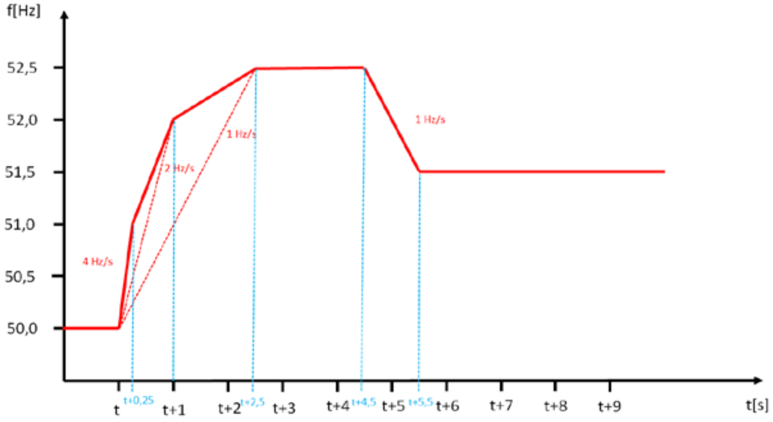
Overload and fault behaviour (II)

Overload and fault behaviour



System split simulation

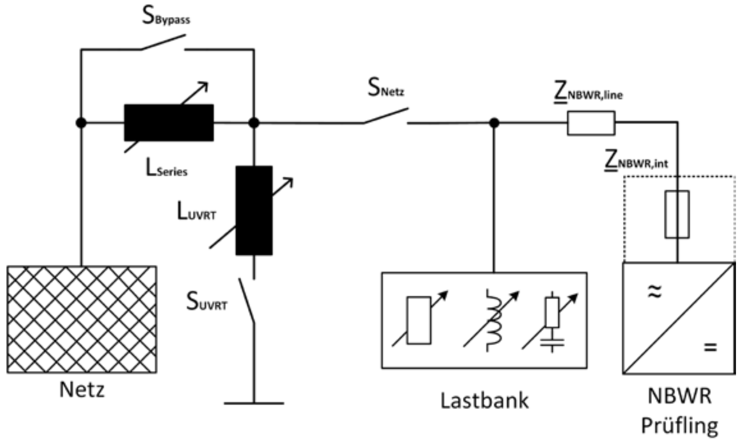
- Combined fault: Phase jump (20°) + RoCoF profile (according to ACER-proposal for RfG 2.0)
- DUT must show:
  - no tripping.
  - Ideally grid-supporting active power



Source: European Union Agency for the Cooperation of Energy Regulators ACER, "NC RfG DC Recommendation: Annex 1 – Amended RfG Regulation, Dec 2023

Grid-forming during overload

- 1) Grid-connected operation with parallel load (P_{GFM} = 50 % P_N, P_{Lord} = 40 % P_N)
- 2) Voltage dip applied
- 3) fault clearance by falling to island mode.
- DUT must restore voltage in island mode.



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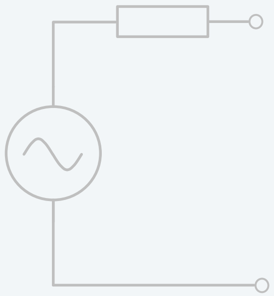
Test methods for grid forming converters

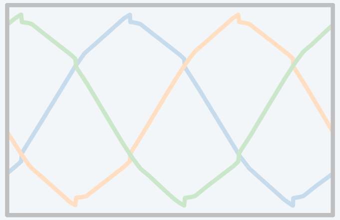
Grid interactions

Behavior of Grid Forming Converter

Voltage source properties



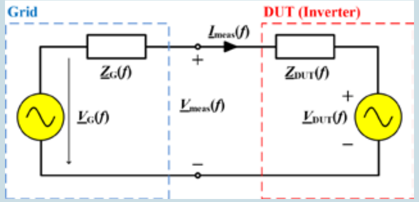
Power quality



Inertia and Damping

Overload and fault behaviour

Grid interactions



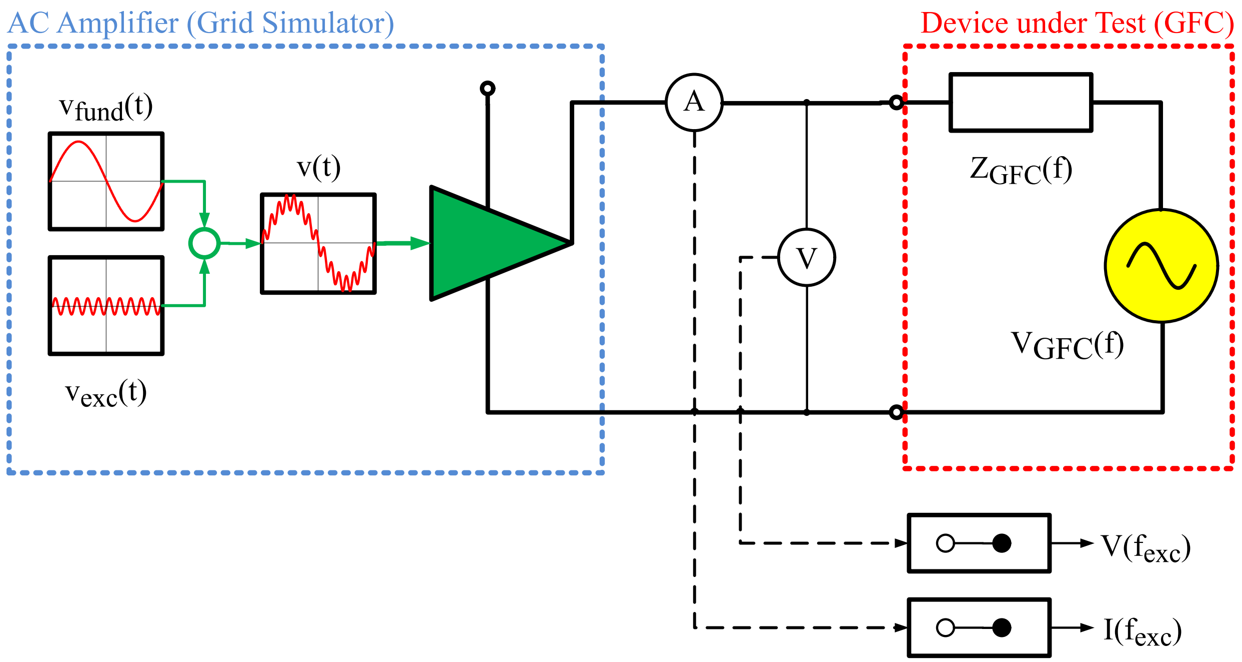
Grid interaction

Impedance spectroscopy – Test setup and procedure

Procedure

$$v_{exc} = 0.01 \cdot |v_{fund}| \cdot \sin(2\pi f_{exc} t + \varphi_{exc})$$

- **At different power setpoints**
  - 0.25, 0.5, 0.75, and 1 of nominal power
- **Use of 3 measurements per f_{exc}**
  - $\varphi_{exc} = 0°, 120°, 240°$
- **Measurement of the current response at f_{exc}**
  - Calculation of $\underline{Z}_{GFC}(f)$ and $\underline{V}_{GFC,i}(f)$ $(j \in [0°, 120°, 240°], i \neq j)$
    - $\underline{Z}_{ij}(f) = \frac{\underline{V}_i(f) - \underline{V}_j(f)}{\underline{I}_i(f) - \underline{I}_j(f)}$
    - $\underline{V}_{ij}(f) = \frac{\underline{V}_i(f) * \underline{I}_j(f) - \underline{V}_j(f) * \underline{I}_i(f)}{\underline{I}_j(f) - \underline{I}_i(f)}$



Grid interaction

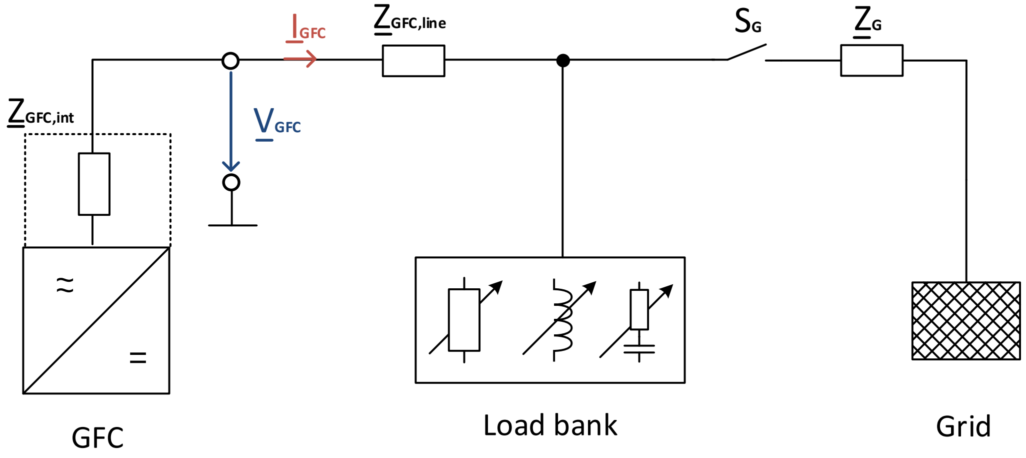
Closed loop stability test

Requirements

- GFM converter must stabilize the island grid (Voltage and Frequency) after disconnection
- Must react on a load step
- All functions are active (LFSM, Q(U), …)

Procedure

1. The converter operates on the grid simulator with a connected load
2. By using the grid switch S_{Grid} the grid is disconnected, and the converter falls with the load into the island
3. After a stabilizing time, the load is increased by 10%
4. A second load step of 10 % is done



Phase	Duration [s]	$P_{GFC,Set}[pu]$	$P_{Load}[pu]$	State S_G
Initial Phase	10	0.9	0.45	closed
1	0	0.9	0.45	open
2	30	0.9	0.45	open
3	0	0.9	0.55	open
4	30	0.9	0.55	open
5	0	0.9	0.65	open
6	30	0.9	0.65	open

Resulting ΔP at disconnection from grid is -0.45 pu

Requirements

Summary

Behavior of Grid Forming Converter

Voltage source properties

- Voltage reaction
  - ➜ $t_{VR} < 5\ ms$
- Impedance (50Hz):
  - ➜ Within 10% of the given values

Power quality

- Sink for harmonics
  - ➜ Improve the voltage THD $\Delta THD_u < 0$
- Sink for asymmetries
  - ➜ Improve unbalance factor $\Delta a_{unb} > 0$

Inertia and Damping

- Contribtion to Inertia
  - ➜ $T_{an} = 25\ s$
- Damping
  - ➜ $D > 0.6$

Overload and fault behaviour

- General
  - ➜ No desynchronisation
  - ➜ Current reaction within 5 ms
- Phase Jump
  - ➜ $t_{0.9}$ as small as possible (< 0.02s)
- RoCoF
  - ➜ $t_{reac,tend}$ as small as possible

Grid interaction

- Impedance spectroscopy
  - ➜ No requirements
- Closed-Loop test
  - ➜ React to load steps and stabilize the island grid

Fraunhofer
ISE

Thank You for Your Attention!

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Want to get involved?
Contact us!

GFM Benchmark Initiative

Energy-Storage Enhanced STATCOMs for Wind Power Plants

Fangzhou Zhao
Aalborg University

eGRID ELECTRONIC POWER GRID AAU ENERGY

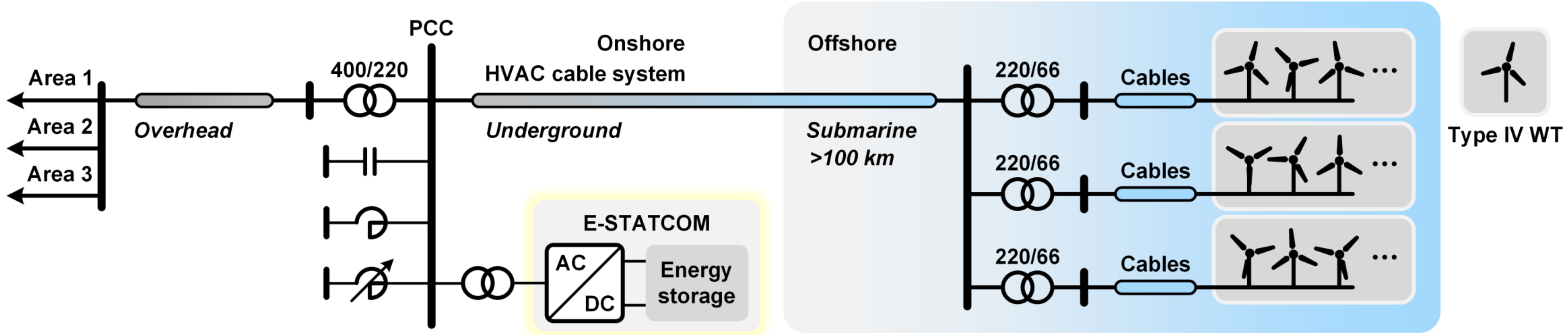
AAU ENERGY

Enhanced STATCOM

Energy storage + power electronics technology

Enhanced STATCOM (E-STATCOM) = Energy Storage + STATCOM, enabling grid-forming (GFM) control

- E-STATCOM can 1) enhance operation performance of wind power plant, 2) handle grid codes and 3) provide grid services



WHY E-STATCOM?

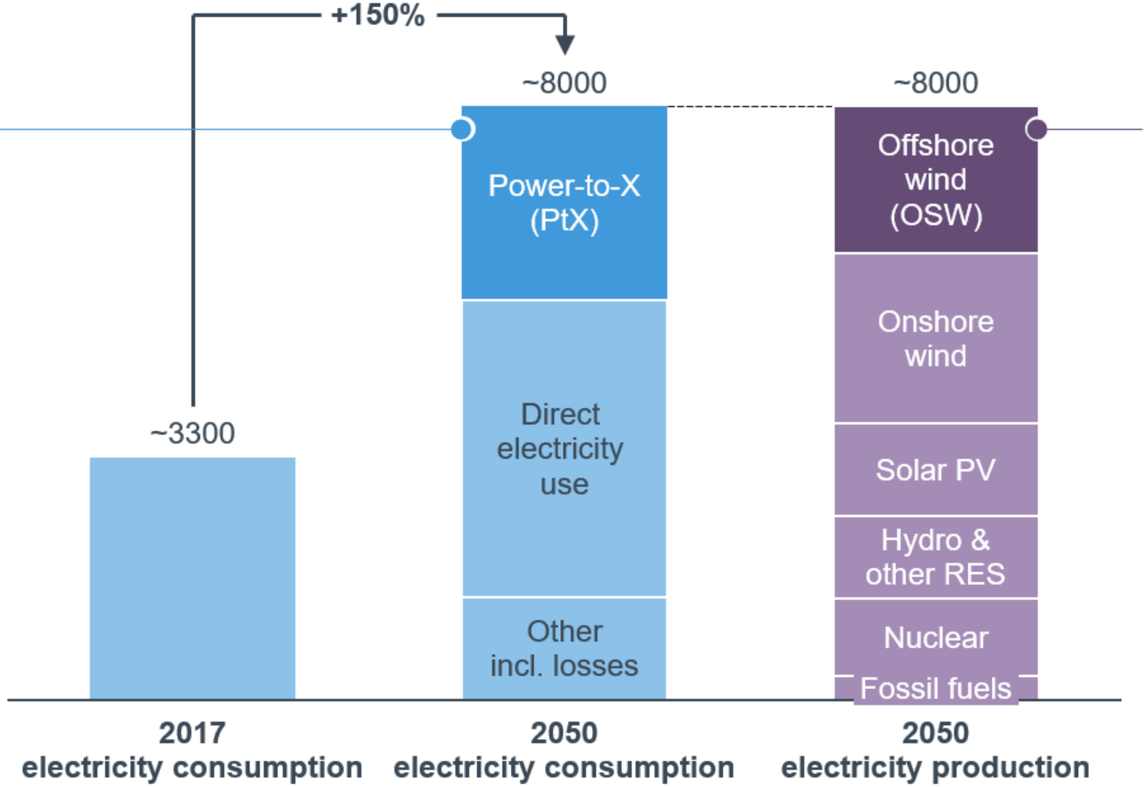
Demand of Offshore Wind Power

Full decarbonisation requires electrification which will increase electricity demand by 150%

EU electricity production and consumption by source[1], TWh

Hydrogen is the bridge between renewable electricity and hard-to-decarbonise sectors

EU has set target of 40 GW of electrolyser capacity by 2030, equal to around 200 TWh of electricity consumption



EU needs 450 GW of offshore wind by 2050 to meet increased demand for electricity

Denmark has some of the best offshore wind sites in Europe, with potential for at least 40 GW[2]

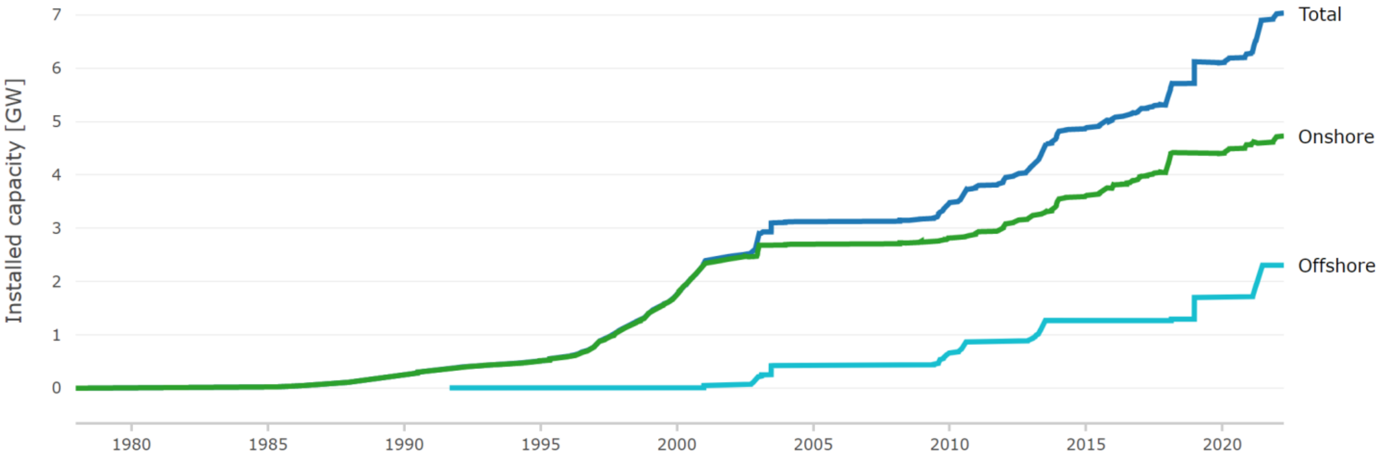
Source 1: EU Commission long term strategy (1.5 tech scenario).
Source 2: Offshore wind and infrastructure, EA Energianalyse for Ørsted, February 2020

AAU ENERGY

WHY E-STATCOM?

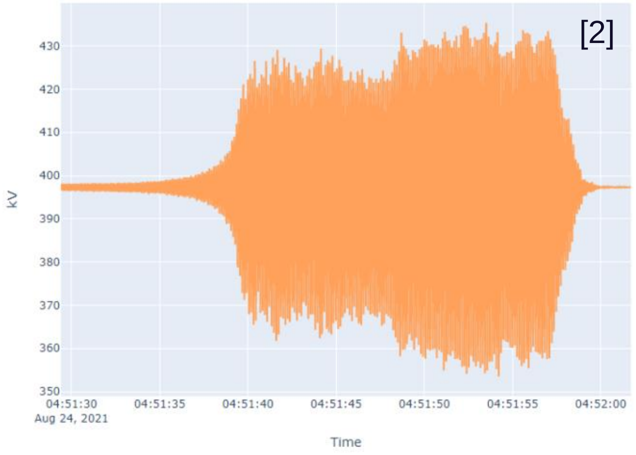
Challenges of more and more WPPs

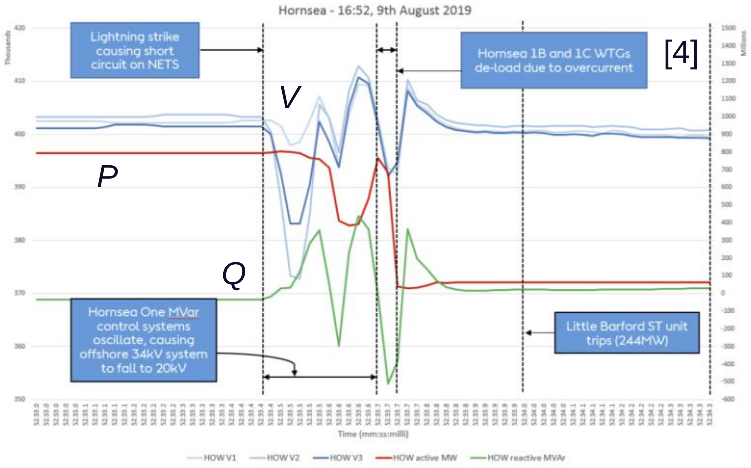
Installed capacity of wind power in Denmark versus time [1]



Tendency in DK

- Capacity grows significantly (now over 7 GW)
- Average capacity per turbine of offshore is over 4 times than onshore now
- Grid becomes weaker for offshore wind power plant (WPP)





Instability challenge

- 8 Hz SSO in Scotland (24 Aug. 2021) [2] related to ***decreased system strength*** characterized by high voltage sensitivity [3]
- Hornsea One offshore WPP (9 Aug. 2019) – system (voltage) collapse and de-loading after a grid disturbance due to insufficient damping [4]

[1] B. Tranberg, K. Tranberg and D. Michalco, "Statistics on wind turbines in Denmark." [Online]. Available: https://turbines.dk/statistics/
[2] National Grid ESO, "ESO Operational Transparency Forum (3rd November 2021)." [Online]. Available: https://www.nationalgrideso.com/document/266861/download
[3] S. Gordon, Q. Hong, and K. Bell, "Implications of reduced fault level and its relationship to system strength: a Scotland case study," CIGRE Session 2022.
[4] National Grid, "Appendices to the Technical Report on the events of 9 August 2019." UK, Sep. 2019, [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/docs/2019/09/eso_technical_report_-_appendices_-_final.pdf

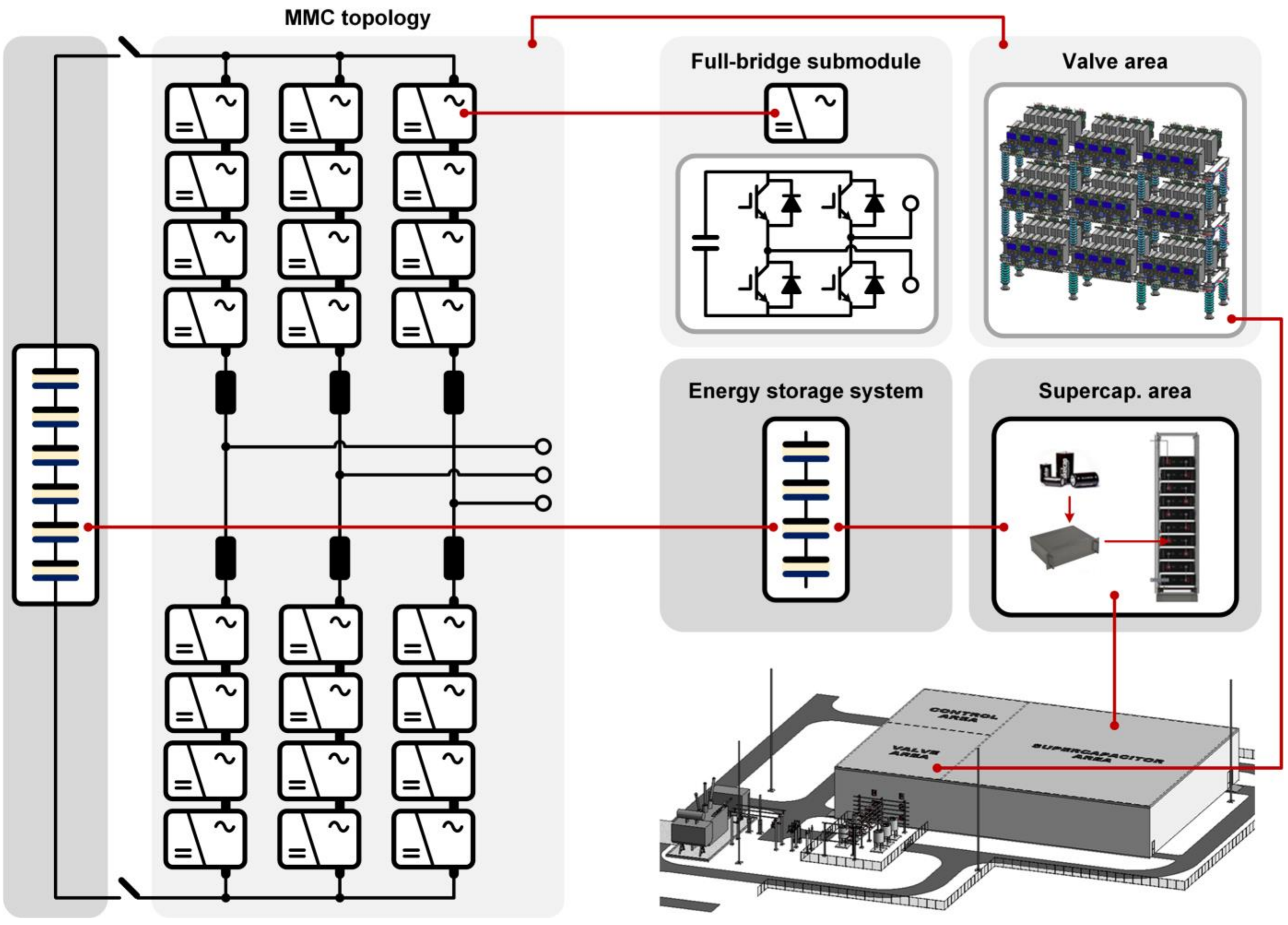
AAU ENERGY

Concept of E-STATCOM

MMC + energy storage system

System layout

- Modular multilevel converter (MMC)
  - Scalability, reduced harmonic distortion and low switching loss
- Integrated energy storage system at DC-link with supercapacitors
  - ***High power density*** and scalability for *fast* active power response of GFM
- ***Separation*** of MMC and energy storage
  - Customized specification of valve room and energy storage room for *reliability, **safety** and flexibility of maintenance*
  - Able to switch to STATCOM with only MMC
- Besides voltage regulation, more services can be enabled by energy storage with GFM



[1] F. Zhao, X. Wang, Z. Zhou, L. Meng, J. P. Hasler, J. R. Svensson, L. Kocewiak, H. Bai, H. Zhang, “Energy-Storage Enhanced STATCOMs for Wind Power Plants,” *IEEE Power Electron. Mag.*, vol. 10, no. 2, pp. 34–39, Jun. 2023.

POTENTIAL SERVICES/CAPABILITIES

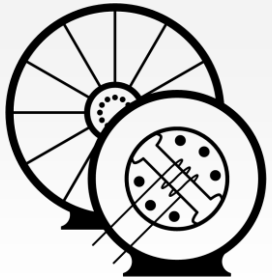
Enabled by energy storage to support WPP

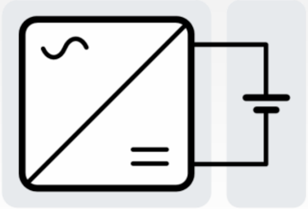
Battery	Super-capacitor	Service (E-STATCOM)	Capability (E-STATCOM)	Operation Mode (WPP)
		Active sub-synchronous resonance damping	Actively stabilize WPPs under varying grid strengths and enhance the voltage stiffness to prevent adverse interactions or oscillations	Grid-connected mode
		Selective harmonic damping	Selectively dampen harmonic voltages at the POI of WPP with enhanced passivity-based design of harmonic resistances	
		Inertial response	Use the energy storage system to provide inertial response for slow down the rate of change of frequency (RoCoF)	
		System strength support	Provide grid strength support by limiting the consequences of power system events	
		Imbalance arbitrage	Provide additional capacity to compensate/balance wind forecast error and to address ramping issues	
		Frequency response	High- and low-frequency response to support the grid and the islanded WPP without the need for partial de-loading of WTs	Islanded mode
		Black start	Charge the local transmission system and enable the WPP to operate in the islanded mode with block loads	
		Soft-charging	Energize the cable network within WPP and provide the auxiliary power supply in the event of grid outage	

[1] F. Zhao, X. Wang, Z. Zhou, L. Meng, J. P. Hasler, J. R. Svensson, L. Kocewiak, H. Bai, H. Zhang, "Energy-Storage Enhanced STATCOMs for Wind Power Plants," *IEEE Power Electron. Mag.*, vol. 10, no. 2, pp. 34–39, Jun. 2023.

Inertial Response

Comparison with synchronous condenser with flywheel (SC-FW)

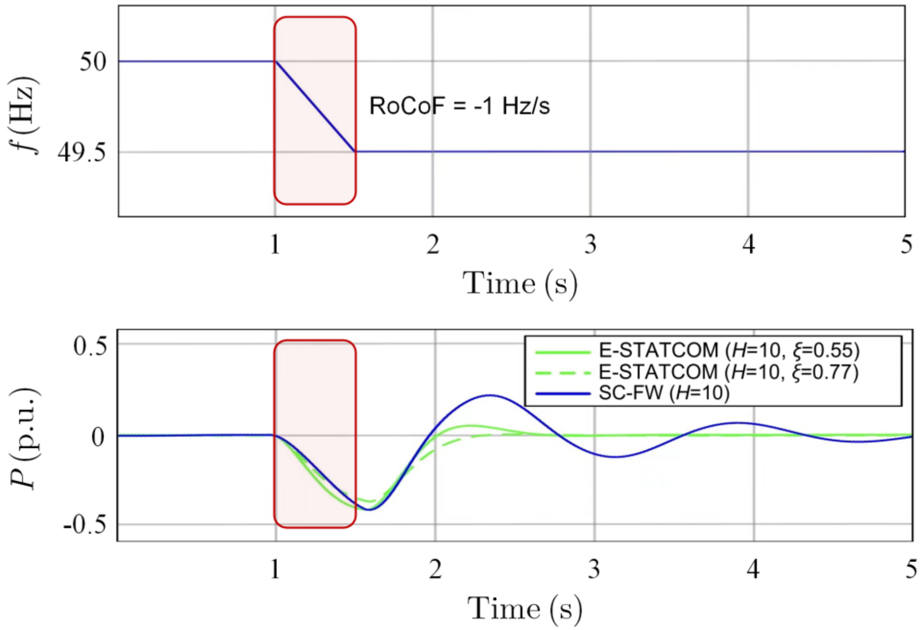




Transmission grid level (100 MVA or above) and inertia 1~10 s [1]	**SC-FW**	**E-STATCOM**
Inertial response	●●●	●●●
Short circuit contribution	●●●	●●
Functionality	●	●●
Power loss	●	●●●
Lifetime	●●●	●●
Maintenance	●●	●●●

Inertial response to frequency change

- Similar response to SC-FW
- Control flexibility of inertia constant and damping



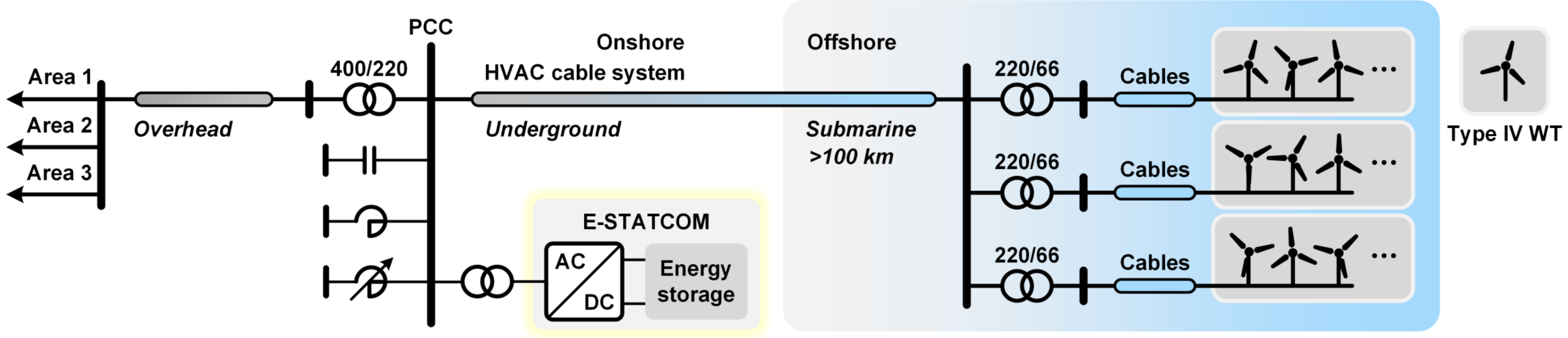
[1] L. Meng, R. Heydari, H. Bai, J. P. Hasler, G. Ingestrom, J. Kheir, A. Owens, and J.R. Svensson, “Energy Storage Enhanced STATCOM for Secure and Stable Power Grids,” in *Proc. CIGRE*, Sep. 2022, pp. 1–12.

ACTIVE DAMPING

Enhance stability of WPP

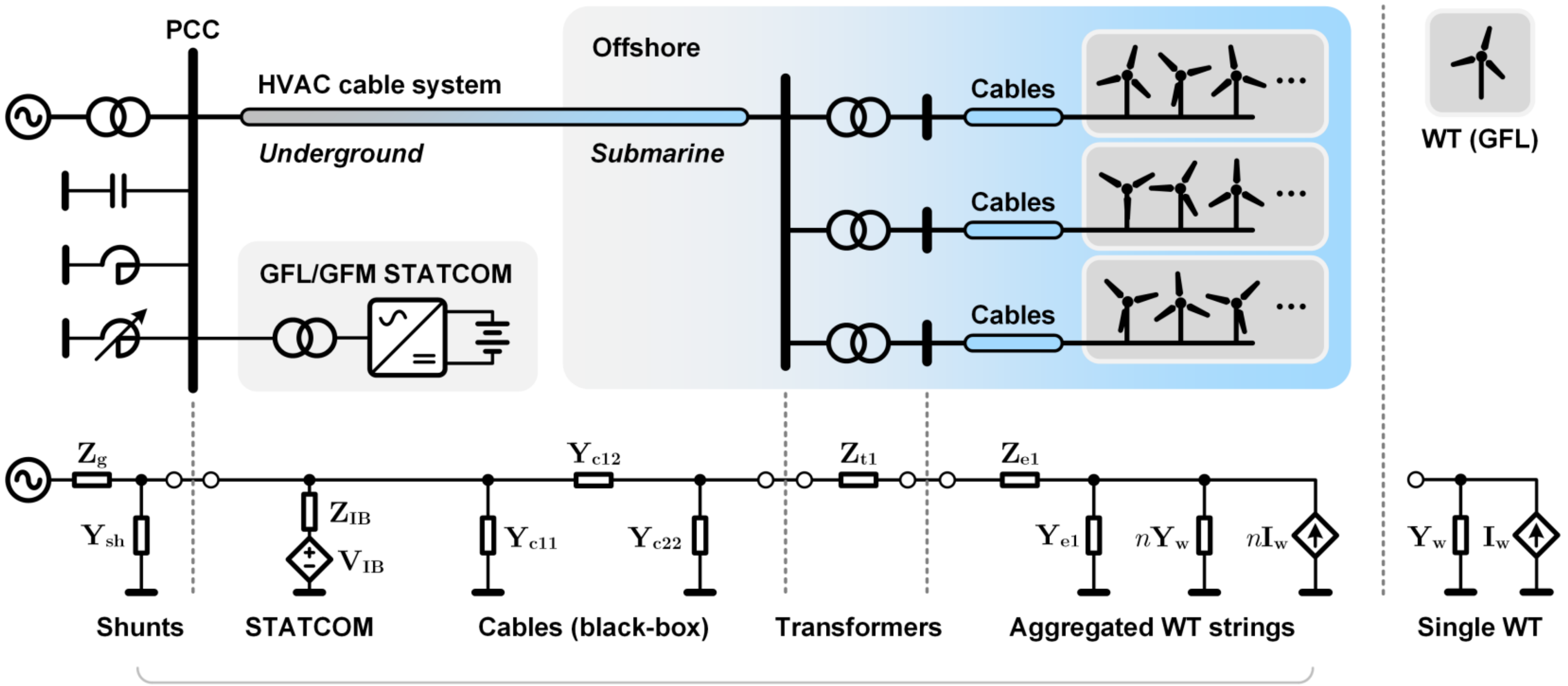
To demonstrate the enhanced stability with E-STATCOM, 3 cases are compared

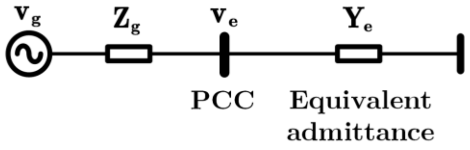
- Case I – only offshore WPP (E-STATCOM disconnected)
- Case II – offshore WPP + a grid-following STATCOM (without energy storage)
- Case III – offshore WPP + E-STATCOM
- Which case is the most stable?



[1] F. Zhao, X. Wang, Z. Zhou, Ł. Kocewiak, and J. R. Svensson, "Comparative study of battery-based STATCOM in grid-following and grid-forming modes for stabilization of offshore wind power plant," *Electric Power Systems Research*, vol. 212, p. 108449, Nov. 2022.

ACTIVE DAMPING
Small-signal modeling





PCC voltage $\mathbf{v}_e = [\mathbf{I} + \mathbf{Z}_g(s)\mathbf{Y}_e(s)]^{-1}\mathbf{v}_g$

Impedance modeling [1]

- Converter dynamics – admittance models in frequency-domain
- Black-box model of cables – frequency scans and vector fitting
- Wind power plant aggregation based on parameter scaling

Stability analysis

- Impedance ratio $\mathbf{L}(s) = \mathbf{Z}_g(s)\mathbf{Y}_e(s)$
- Stability margin of eigenloci $\mathbf{L}(j\omega)$ – the minimal vertical distance from (-1,0) to the eigenloci [2]
- Pole analysis of $[\mathbf{I} + \mathbf{Z}_g(s)\mathbf{Y}_e(s)]^{-1}$

[1] F. Zhao, X. Wang, Z. Zhou, L. Harnefors, J. R. Svensson, L. Kocewiak, M. Gryning, "Control Interaction Modeling and Analysis of Grid-Forming Battery Energy Storage System for Offshore Wind Power Plant,"
[2] IEEE Trans. Power Syst., vol. 37, no. 1, pp. 497-507, Jan. 2022.
O. N. Gasparyan, Linear and nonlinear multivariable feedback control: a classical approach. John Wiley & Sons, 2008, pp. 100-117.

Active Damping

Stability margin analysis

Case studies

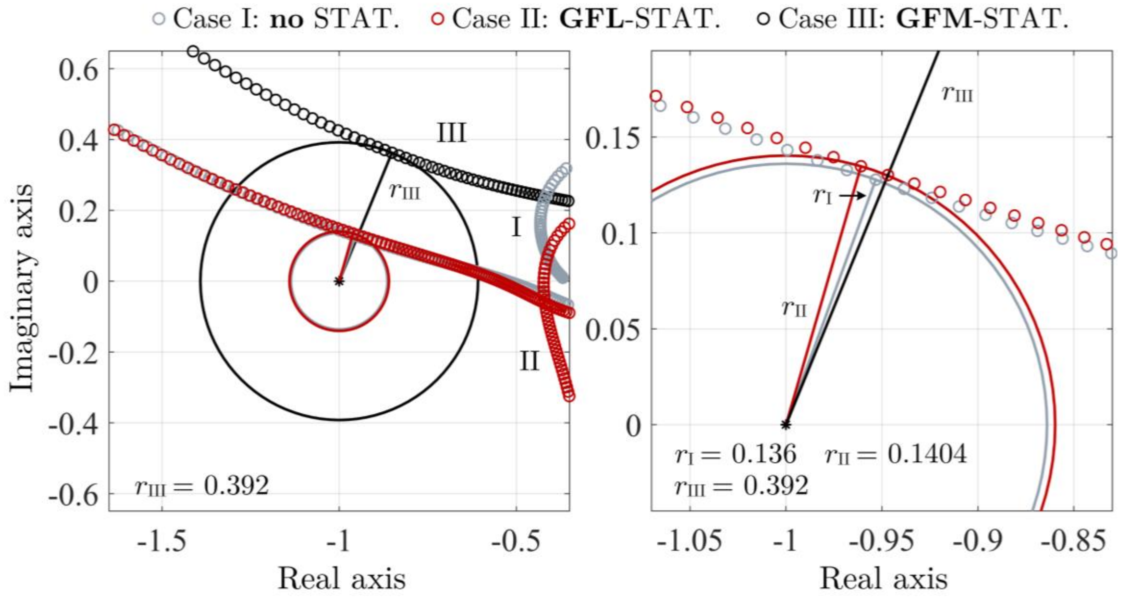
- Case I – GFL-WPP (STATCOM disconnected)
- Case II – GFL-WPP + GFL-STATCOM
- Case III – GFL-WPP + GFM-STATCOM

Stability margin of Nyquist plot

- The vertical distance from (-1,0) to the eigenloci
- Longer distance, wider stability margin

Comparison of 3 cases (SCR=2 for WPP)

- GFL-STAT. slightly enhances stability (case I & II)
- GFM-STAT. offers much more margin than GFL-STAT.

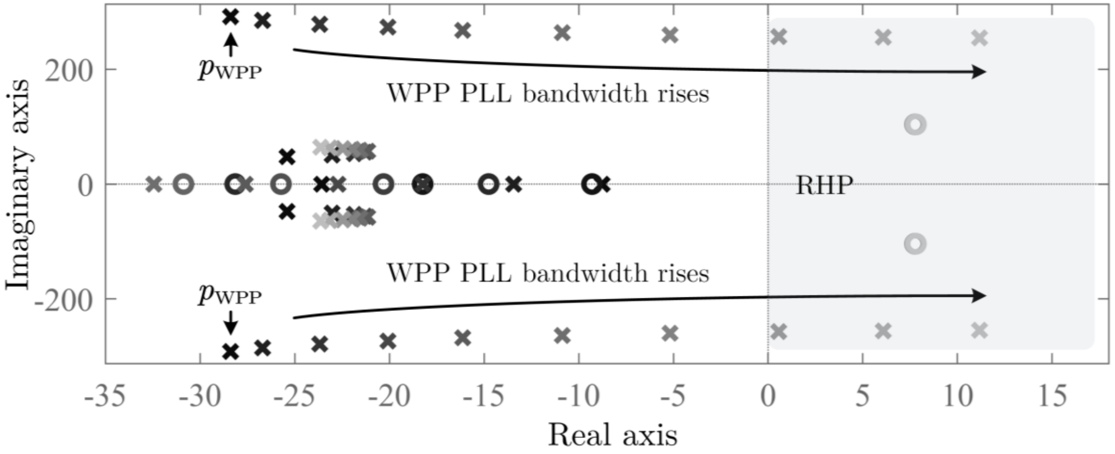


[1] F. Zhao, X. Wang, Z. Zhou, Ł. Kocewiak, and J. R. Svensson, “Comparative study of battery-based STATCOM in grid-following and grid-forming modes for stabilization of offshore wind power plant,” *Electric Power Systems Research*, vol. 212, p. 108449, Nov. 2022.

ACTIVE DAMPING
Closed-loop pole analysis

Case I – E-STATCOM disconnected

- Dominant poles p_{WPP}
- As WPP PLL bandwidth increases, system becomes unstable in a weak grid



Comparison of p_{WPP} in 3 cases

- Case II adds limited damping (< 20%)
- Case III (GFM) offers more damping (> 100%), and the benefit is more obvious in weaker grids
- Improves ***system strength*** for WPP

Grid	Case I – ζ_{WPP}	Case II – ζ_{WPP}	Case III – ζ_{WPP}
SCR=2.00	0.097	0.105 (8.2%)	0.184 (89.7%)
SCR=1.88	0.085	0.097 (14.1%)	0.187 (120%)
SCR=1.79	0.076	0.088 (15.8%)	0.189 (149%)
SCR=1.71	0.066	0.079 (19.7%)	0.192 (191%)
SCR=1.63	0.057	0.067 (17.5%)	0.195 (242%)

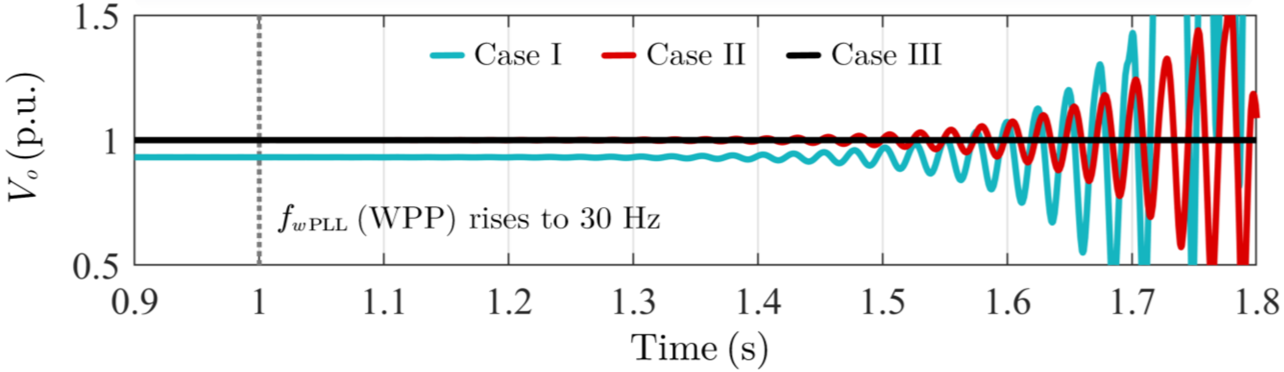
[1] F. Zhao, X. Wang, Z. Zhou, Ł. Kocewiak, and J. R. Svensson, “Comparative study of battery-based STATCOM in grid-following and grid-forming modes for stabilization of offshore wind power plant,” *Electric Power Systems Research*, vol. 212, p. 108449, Nov. 2022.

Active Damping

EMT simulation analysis

- Case I – only offshore WPP; Case II – offshore WPP + a GFL-STATCOM; Case III – offshore WPP + E-STATCOM

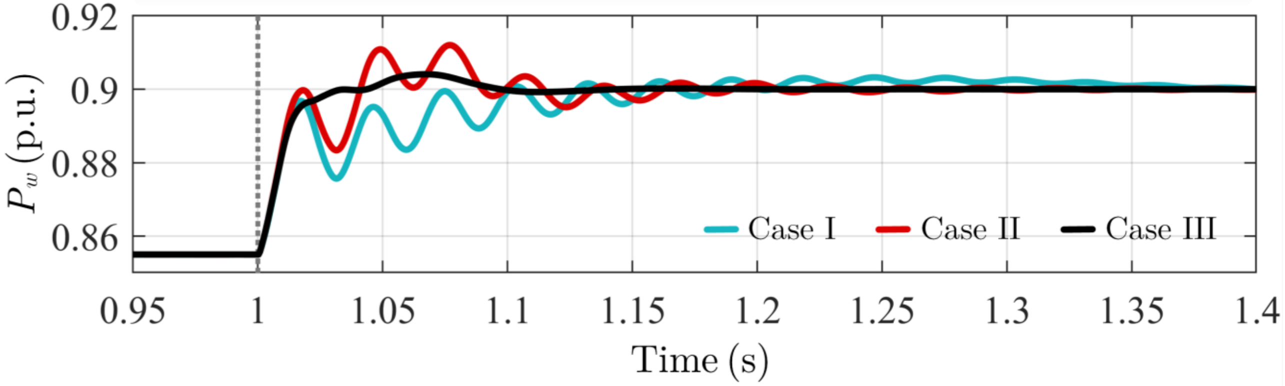
Comparison of PCC voltage magnitude



E-STATCOM enhances stability of WPP

- Control bandwidth tuned at 1 s
- Case I and case II are unstable
- Case III with GFM is more robust

Comparison of active power response



E-STATCOM improves response of WPP

- Control reference of WPP changed at 1 s
- Case I and II show obvious power oscillations
- Case III with GFM enhances power controllability

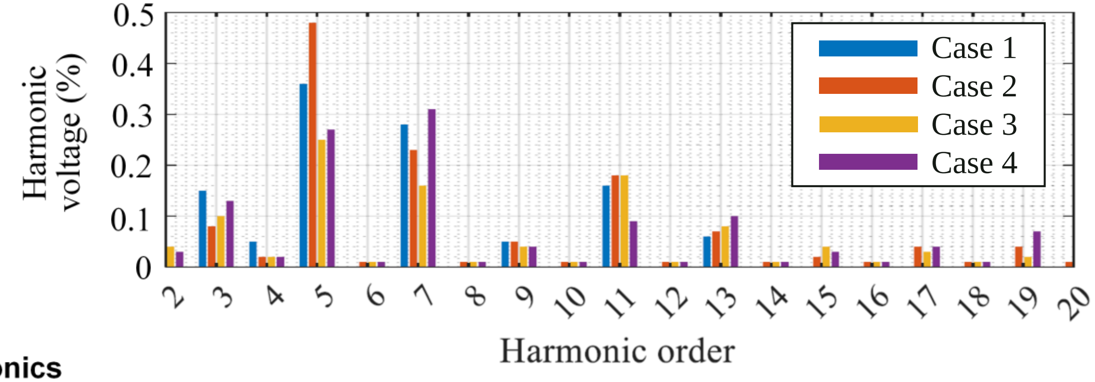
[1] F. Zhao, X. Wang, Z. Zhou, Ł. Kocewiak, and J. R. Svensson, "Comparative study of battery-based STATCOM in grid-following and grid-forming modes for stabilization of offshore wind power plant," *Electric Power Systems Research*, vol. 212, p. 108449, Nov. 2022.

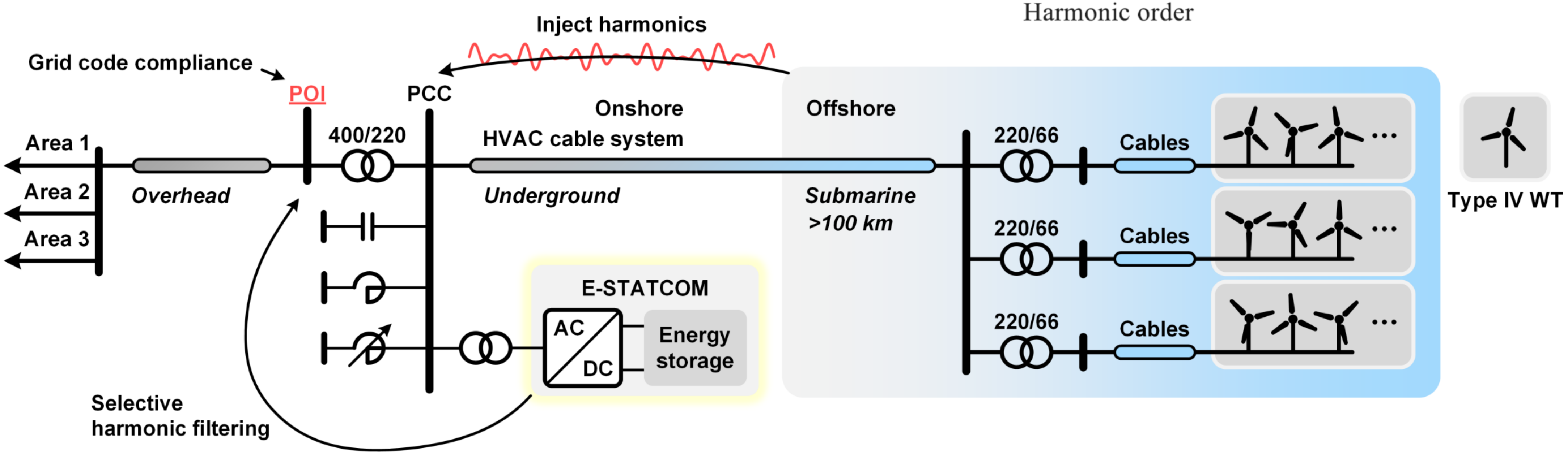
Selective Harmonic Filtering

Harmonic mitigation at POI for grid code compliance

Grid code at point of interconnection (POI)

- Mitigation of harmonic voltages at POI
- Selective harmonic filtering of E-STATCOM
- Better flexibility than passive harmonic filters





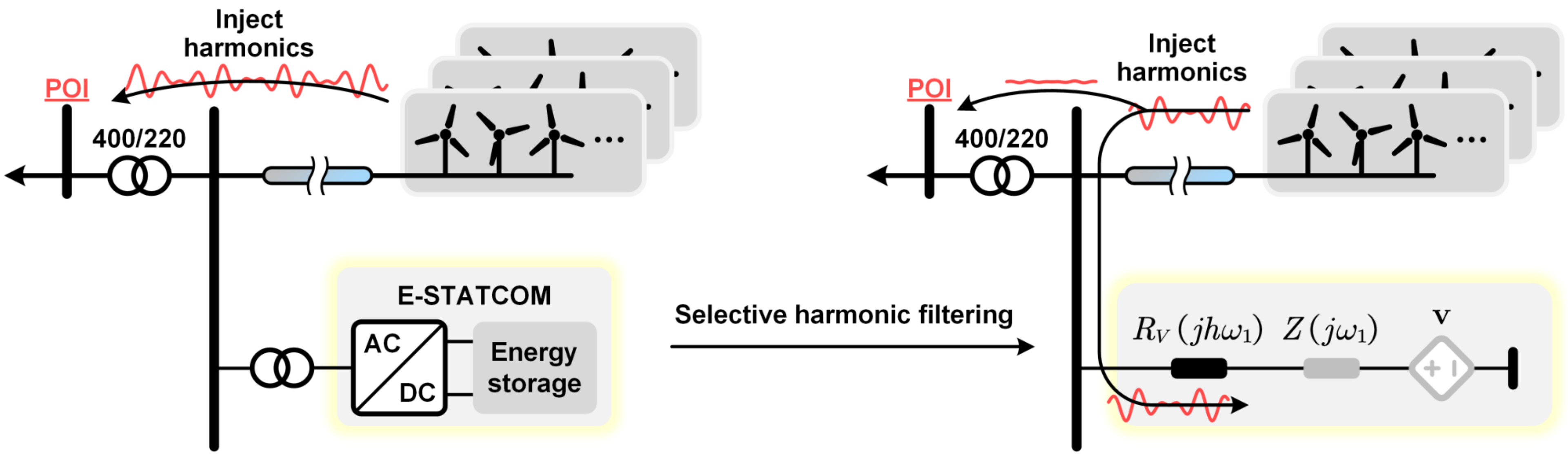
[1] Z. Zhou, X. Wang, F. Zhao, J. R. Svensson, L. Kocewiak, M. Gryning, A. Mohanaveeramani, "Selective Harmonic Voltage Control for STATCOMs in Wind Power Plants," *IEEE Trans. Power Deli.*, vol. 38, no. 3, pp. 2183–2194, Jun. 2023.

Selective Harmonic Filtering

Harmonic mitigation at POI for grid code compliance

Selective harmonic filtering based on impedance shaping

- Shape an equivalent ***low resistance*** of E-STATCOM at harmonic frequency, e.g., 5th, 7th order harmonics
- Shape a negative inductance at harmonic frequency to compensate the inductance of transformer
- Create a ***low-resistance damping branch (harmonic sink [1])*** for WPP

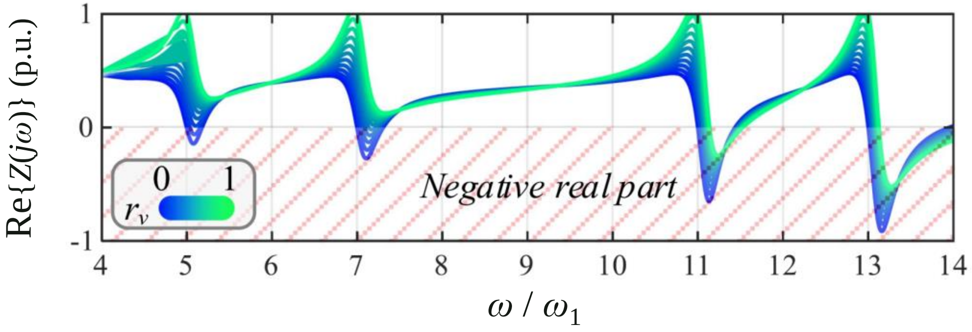


[1] ENTSO-E, "High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters." Jan. 2020. [Online]. Available: https://www.entsoe.eu/

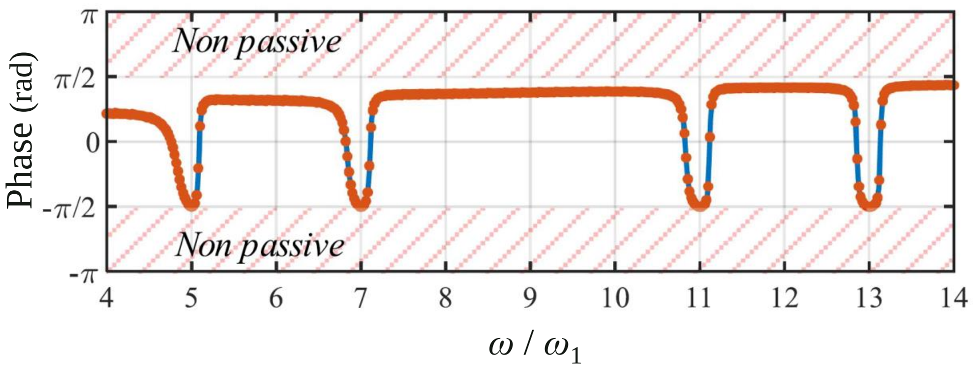
Selective Harmonic Filtering
Passivity-based controller design

Output impedance of E-STATCOM

- Risk of negative resistance around harmonics

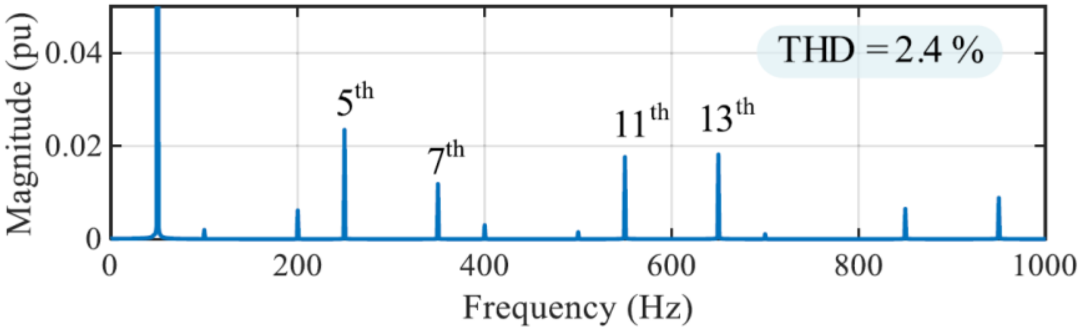


- **Passivity**-based controller design [1]

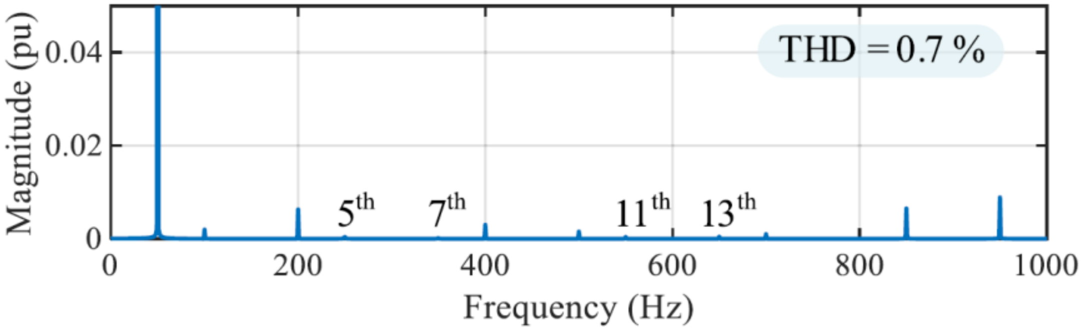


Comparison of FFT results

- Disable selective harmonic filtering control



- Enable selective harmonic filtering control



[1] Z. Zhou, X. Wang, F. Zhao, J. R. Svensson, L. Kocewiak, M. Gryning, A. Mohanaveeramani, “Selective Harmonic Voltage Control for STATCOMs in Wind Power Plants,” *IEEE Trans. Power Deli.*, vol. 38, no. 3, pp. 2183–2194, Jun. 2023.

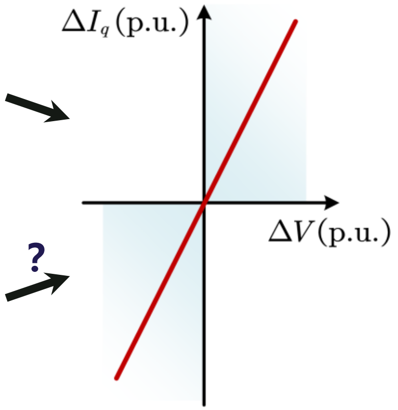
AAU ENERGY

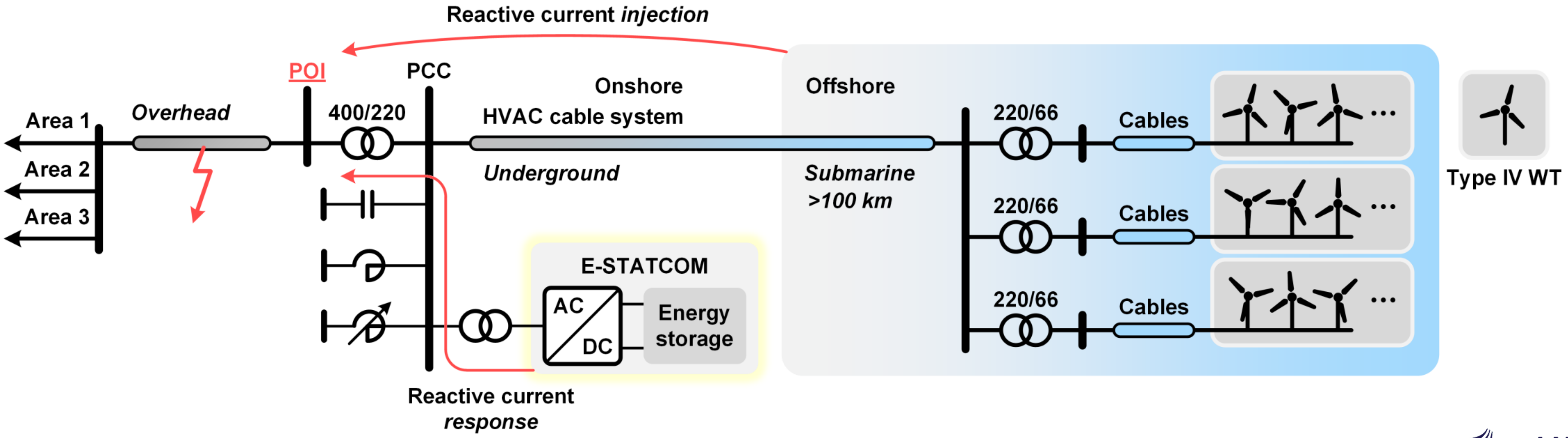
Fast Fault Current Response

Near instantaneous response to voltage disturbance

Voltage event

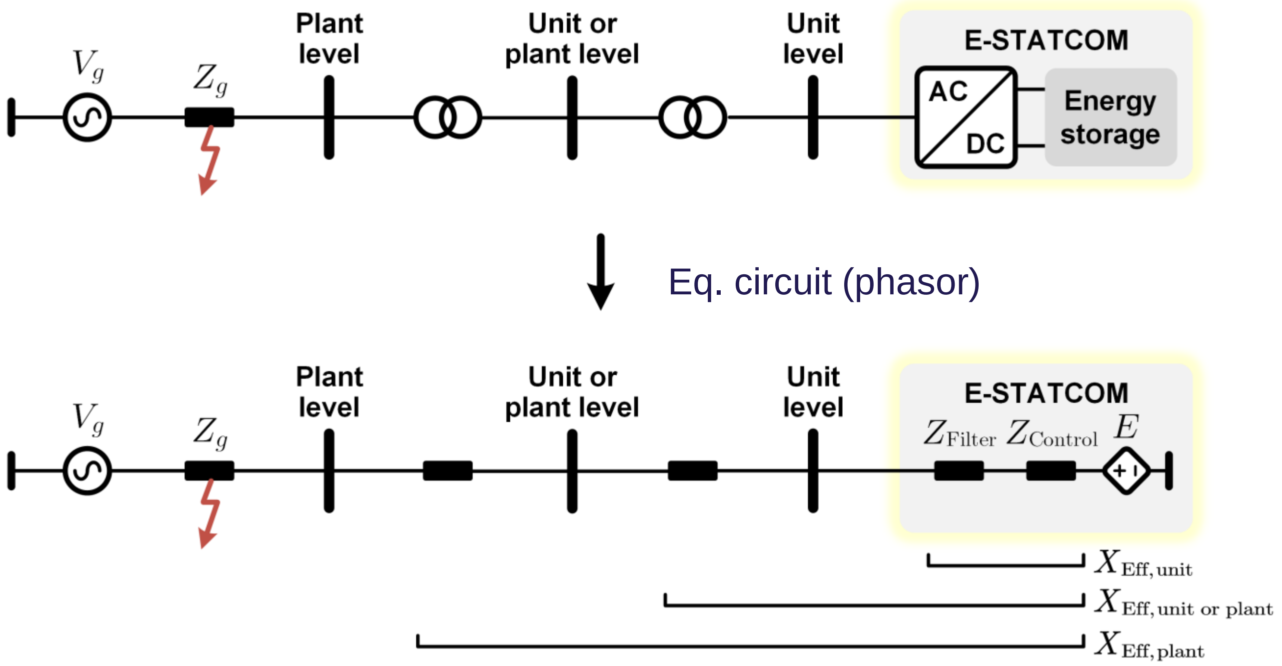
- Grid-following source — Actively **inject** reactive current to support the voltage – **slower** — **Grid code**
- Grid-forming source — Naturally **provide** reactive current in response to the event – **faster** — **Physical law**





Fast Fault Current Response

Near instantaneous response to voltage disturbance



Reactive current response of grid-forming

- Reactive current $I_q \propto$ voltage change ΔV [1]

$$I_q = \frac{V - E\cos\theta}{X} \approx \frac{1}{X}\Delta V$$

Assumptions

- High X/R ratio
- $\cos\theta \approx 1$

Possible ranges of effective reactance [2]

Effective reactance	Min (p.u.)	Default (p.u.)	Max (p.u.)	**Equivalent *k*** factor
$X_{\mathrm{Eff,unit}}$	0.17	0.25	0.27	5.9 .. **4** .. 3.7
$X_{\mathrm{Eff,unit\ or\ plant}}$	0.25	0.33	0.35	4 .. **3** .. 2.8
$X_{\mathrm{Eff,plant}}$	0.4	0.48	0.50	2.5 .. **2.1** .. 2

[1] F. Zhao, X. Wang, H. Wu, Y. Wu, T. Zhu, and Y. Sun, "Reactive Current Profile of Grid-Forming Wind Power Plant Under Symmetrical Faults," in *Proc. WIW*, Copenhagen, Denmark, 2023.
[2] ENTSO-E, "Grid forming capability of power park modules," May 2024. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/SOC/20240503_First_interim_report_in_technical_requirements.pdf

TAKEAWAY
Enhance STATCOM

Grid-forming enabled by energy storage

- MMC + supercapacitors
- Multiple functionalities

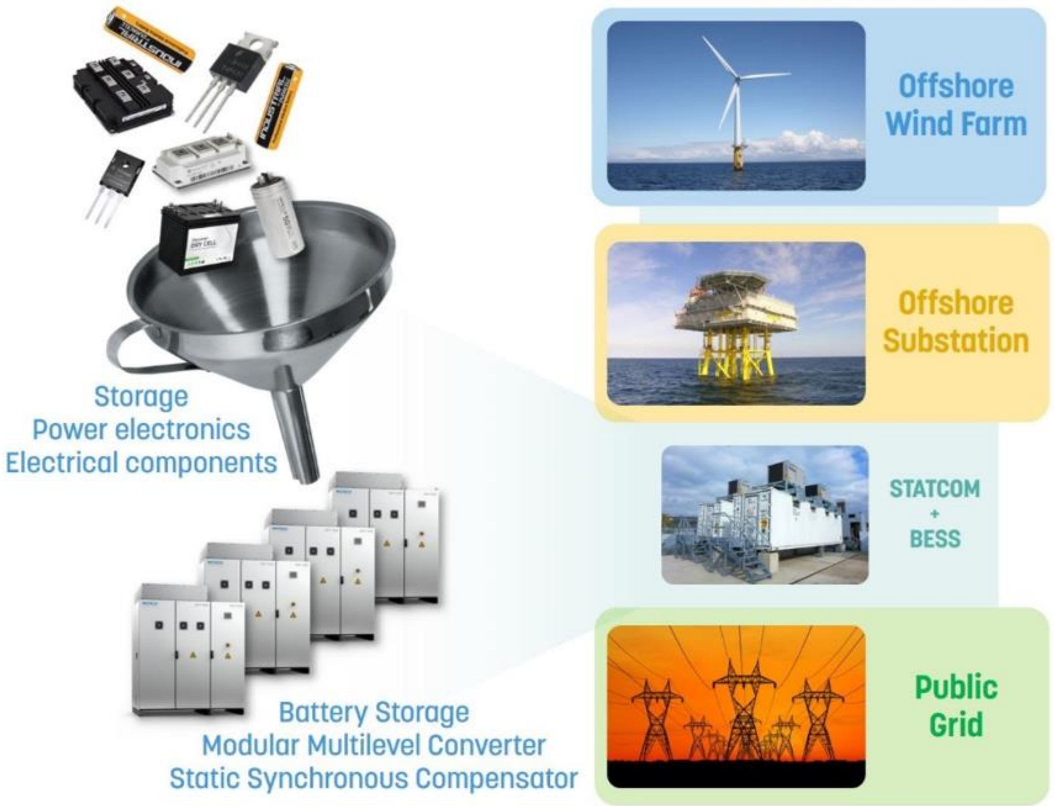
    Flexible inertial response

    Active damping

    System strength support

    Selective harmonic filtering

    Fast fault current response



Thank you and questions

Fangzhou Zhao