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Swiss National Science Foundation

International Workshop on

Dynamic Stability Challenges of the Future Power Grids

Stability-Oriented Modeling, Grid Support, and Oscillation Assessment of Offshore Wind-Hydrogen Energy Systems

Chunjun Huang, Maria Camila Castrillón Franco

Delft University of Technology (TU Delft)

Netherlands

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Agenda

- **Part I: Stability-Oriented Modeling and Grid Support of OWHES**
  - Introduction & Background
  - Stability-Oriented Modeling for Electrolyzer and OWHES
  - Grid Support Control
  - Takeaways

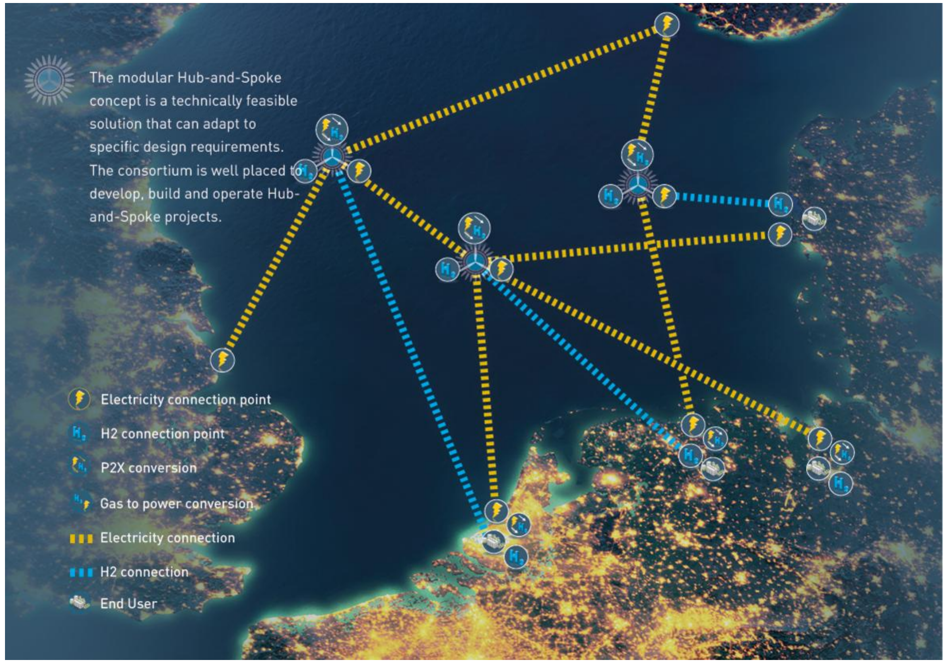
- **Part II: Oscillation Assessment of OWHES**
  - Motivation & Background
  - DMD Introduction
  - Measurement-Based Stability Analysis
  - Takeaways

Part I: Stability-Oriented Modeling and Grid Support of OWHES

OWHES: Stability Challenge and Modeling Focus

Background

- Offshore Hub Plan in North Sea
- GW-level Wind-hydrogen Energy System

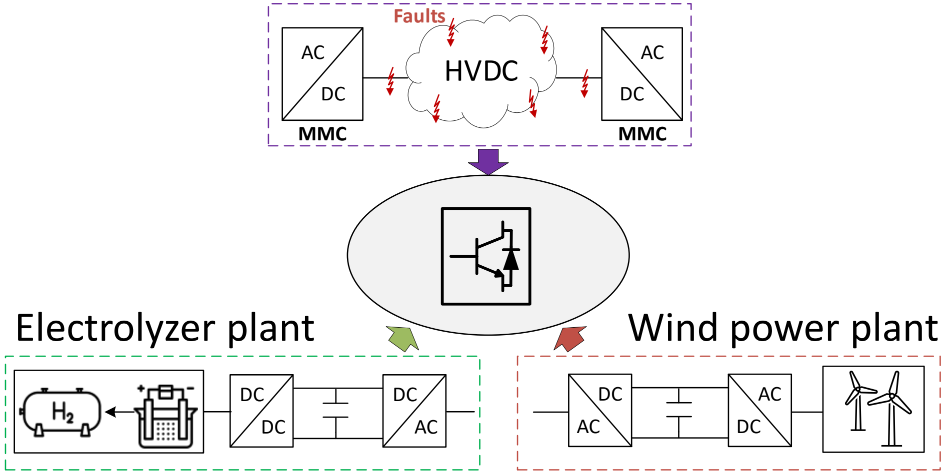


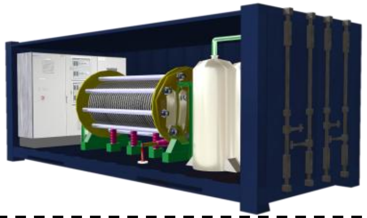
www.offshore-energy.biz/nswph-consortium-seeks-support-in-discussions-with-policymakers/

Hub-and-Spoke Network

Challenge

- Complex dynamic interaction and instability risk
- Demand for efficient modeling and control methods

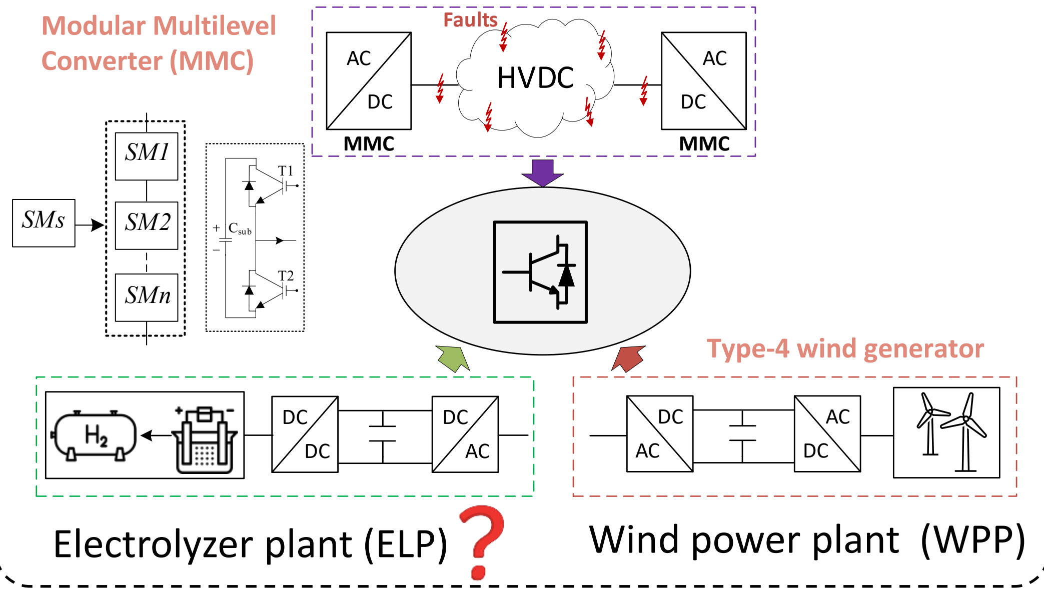




Converter-Dominated AC/DC Hybrid System

OWHES: Stability Challenge and Modeling Focus

Key Components Modeling

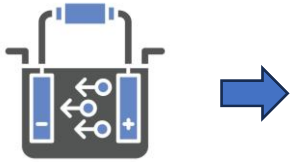


Existing Research Groundwork

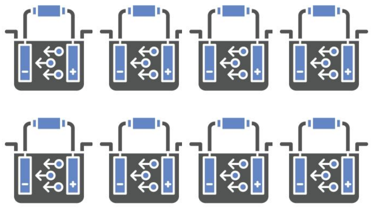
- MMC-HVDC models
- Type-4 WPP models

Remaining Modeling Gap

Gap： Modeling of large-scale electrolyzer plants



How to properly represent an electrolyzer to capture critical multi-physics in EMT-scale?

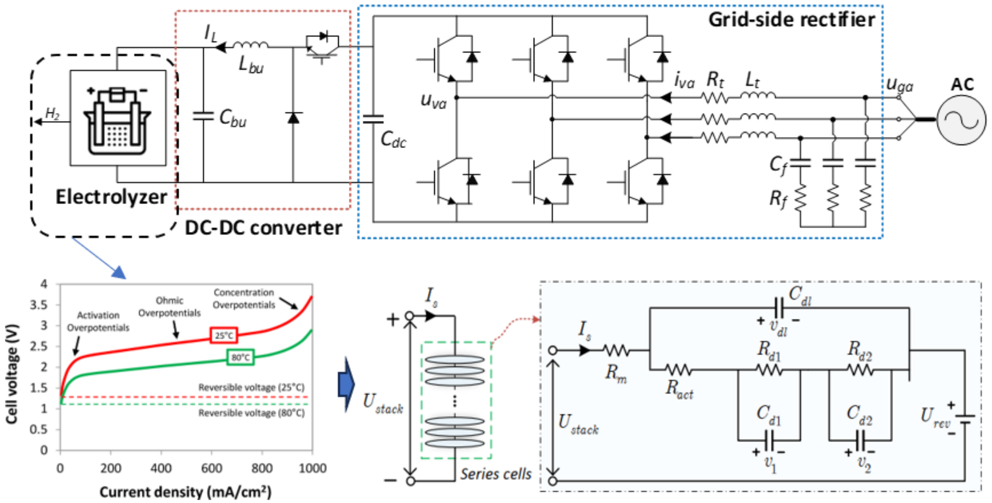


How to aggregate units into large-scale ELPs for capturing system-level dynamics for grid-interaction analysis

Electrolyzer Module: Stability-Oriented Analytical Modeling

- **From the physical module topology to a unified analytical model for small-signal stability assessment.**

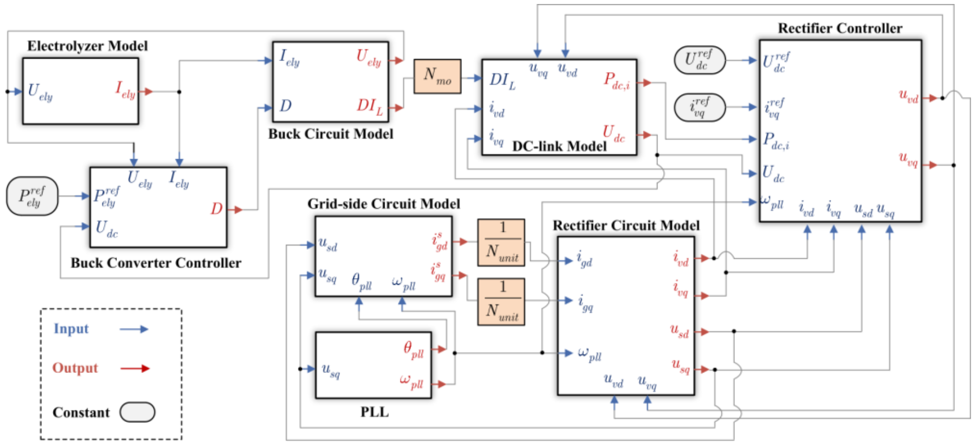
Electrolyzer Module-Level Model



- Two-stage power interface: rectifier + DC-DC buck converter.
- PEM stack represented by an equivalent electrochemical circuit.

derive & linearize

Holistic Analytical Model



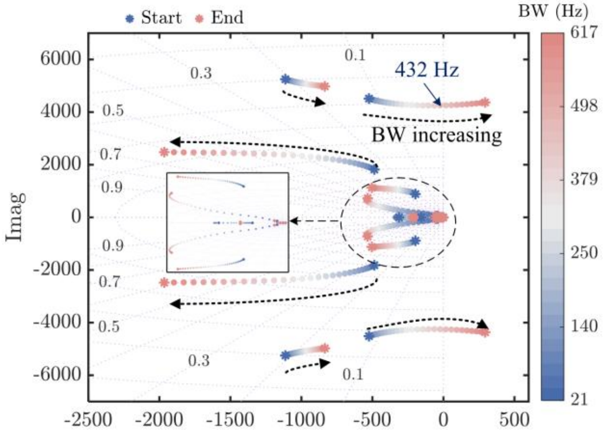
- Unified model captures stack, buck, DC link, rectifier, PLL, and control loops.
- Eigenvalue + participation-factor analysis reveals dominant interaction modes.

Outcome: EMT-scale module model + quantified stability relationships for controller design.

Module-Level Stability Analysis and Design Insights

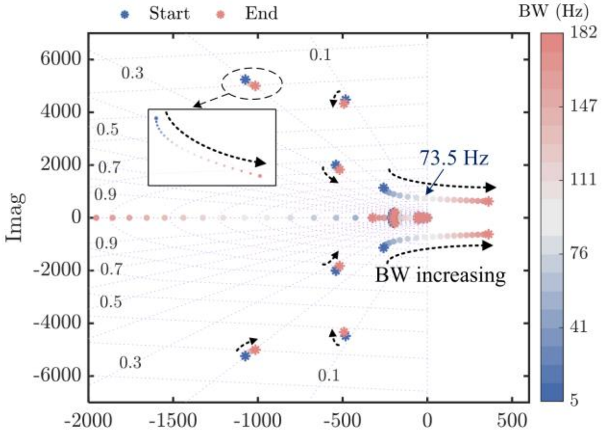
- **The module-level analytical study reveals stability limits of key control loops.**

PLL bandwidth



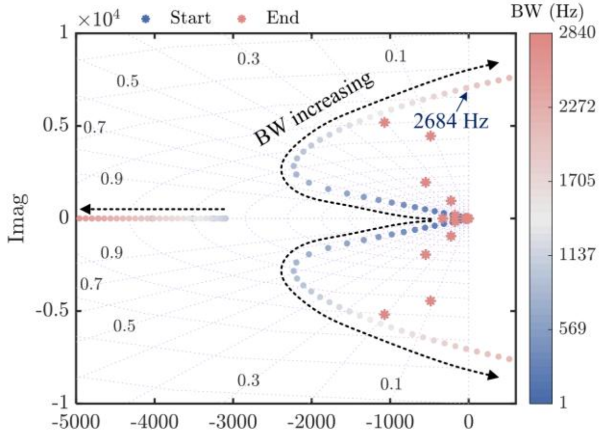
Critical BW ≈ 432 Hz

DC-link voltage-control bandwidth



Critical BW ≈ 73.5 Hz

Buck power-control bandwidth



Critical BW ≈ 2684 Hz

Implication for Module Design

Electrolyzer flexibility is constrained by converter-control interactions. Controller tuning must therefore respect explicit stability limits.

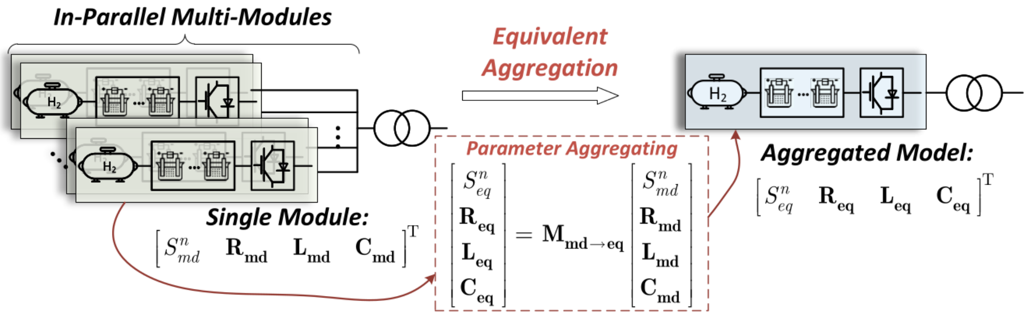
Guideline for Control Design

These insights guide the single-module controller design and indicate which module dynamics should be retained.

Scalable ELP Modeling: From Many Modules to an Equivalent Plant

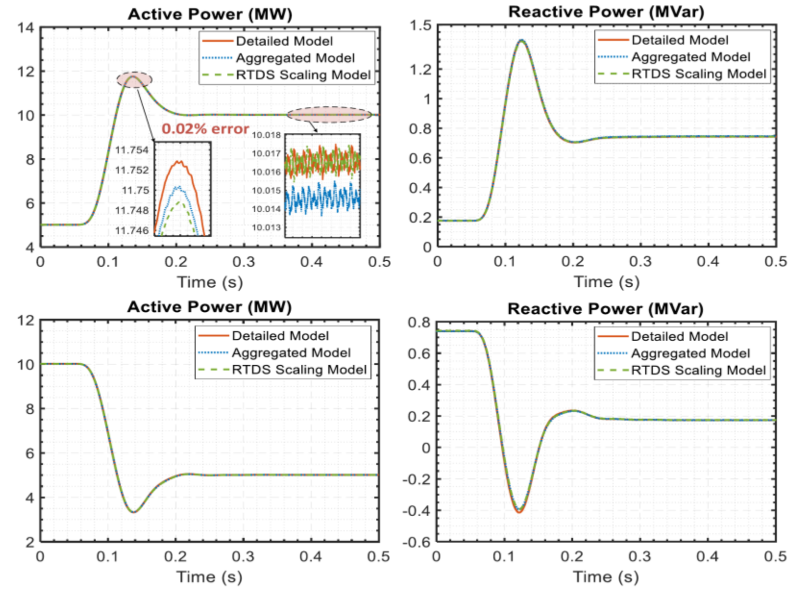
- **Next challenge: plant scalability. Explicitly simulating hundreds of 1 MW modules is impractical for real-time EMT studies.**

Module-to-Plant Aggregation



- **Parameter-aggregation matrix** maps N parallel modules into one equivalent plant.
- The equivalent retains the module-level dynamic structure; per-unit controller gains can be reused.

Aggregation Verification In 10 MW Plant



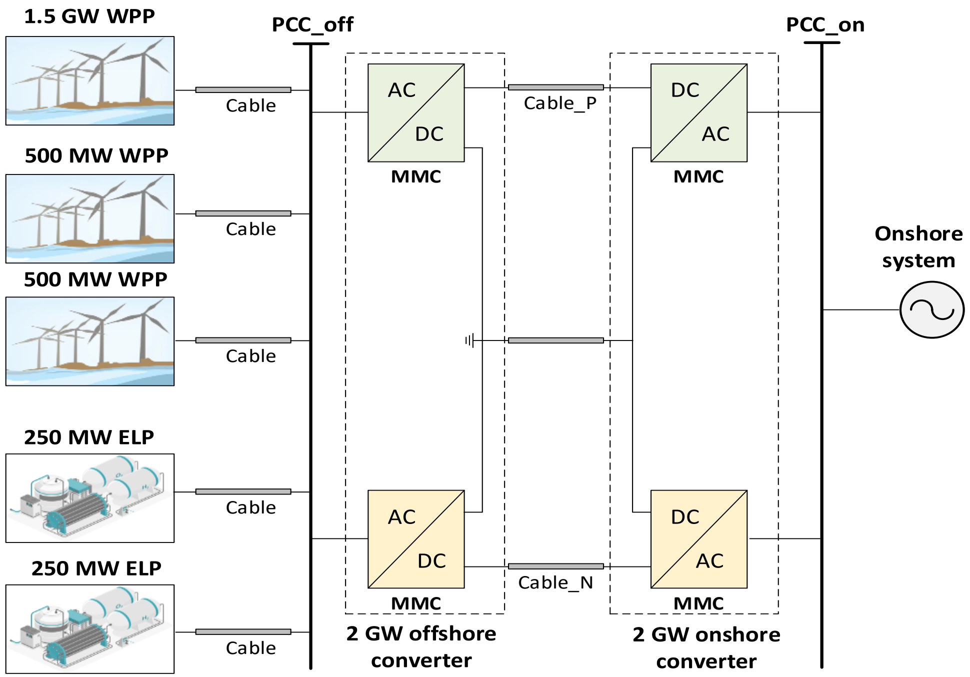
Detailed model vs. proposed aggregated model vs. RTDS scaling model

0.02%	**4642 → 481**	**30 μs real time**
maximum active-power response error	Number of control components	detailed model overflow; aggregated model stable

Dynamic Digital Model Implementation in RTDS

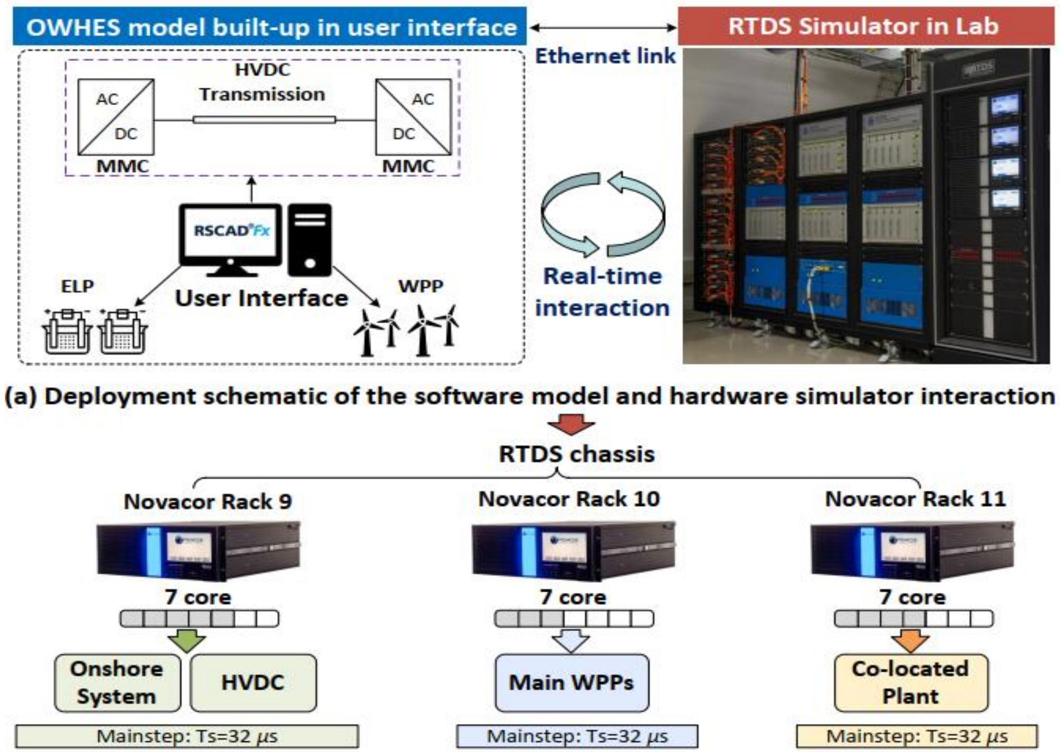
- **Development of Real-Time EMT-scale Simulation Model for OWHES**

Offshore Wind-Hydrogen Energy System (OWHES)



2 GW Synthetic System Model for OWHES

Digital Model Development in RTDS

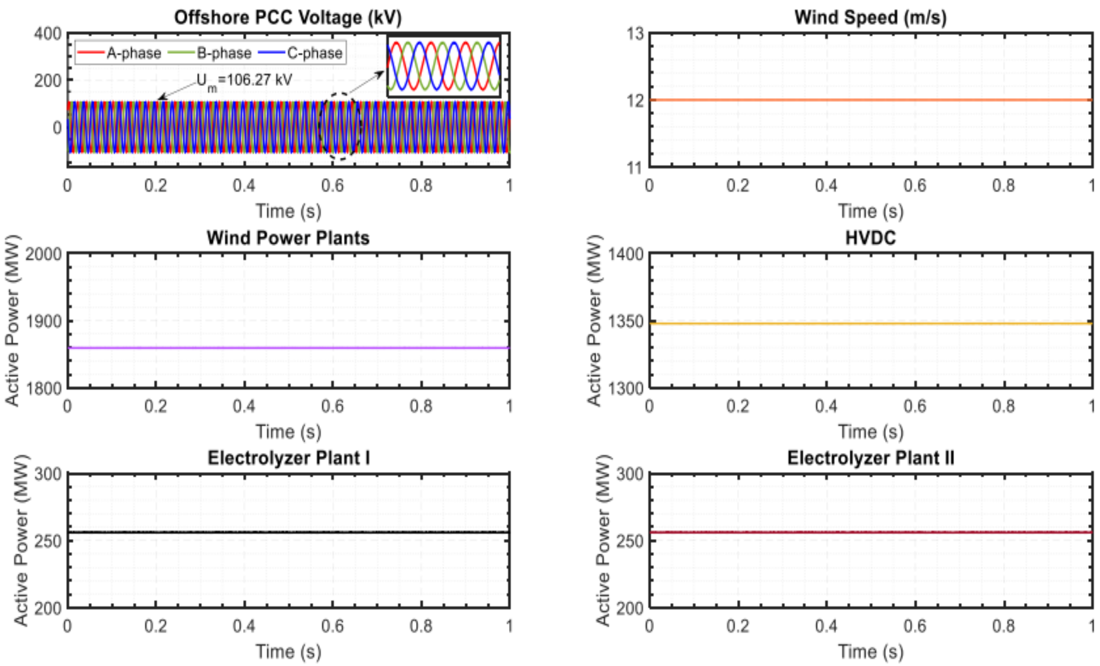


(a) Deployment schematic of the software model and hardware simulator interaction

(b) Model decomposition and rack allocation for highly-efficient parallel processing

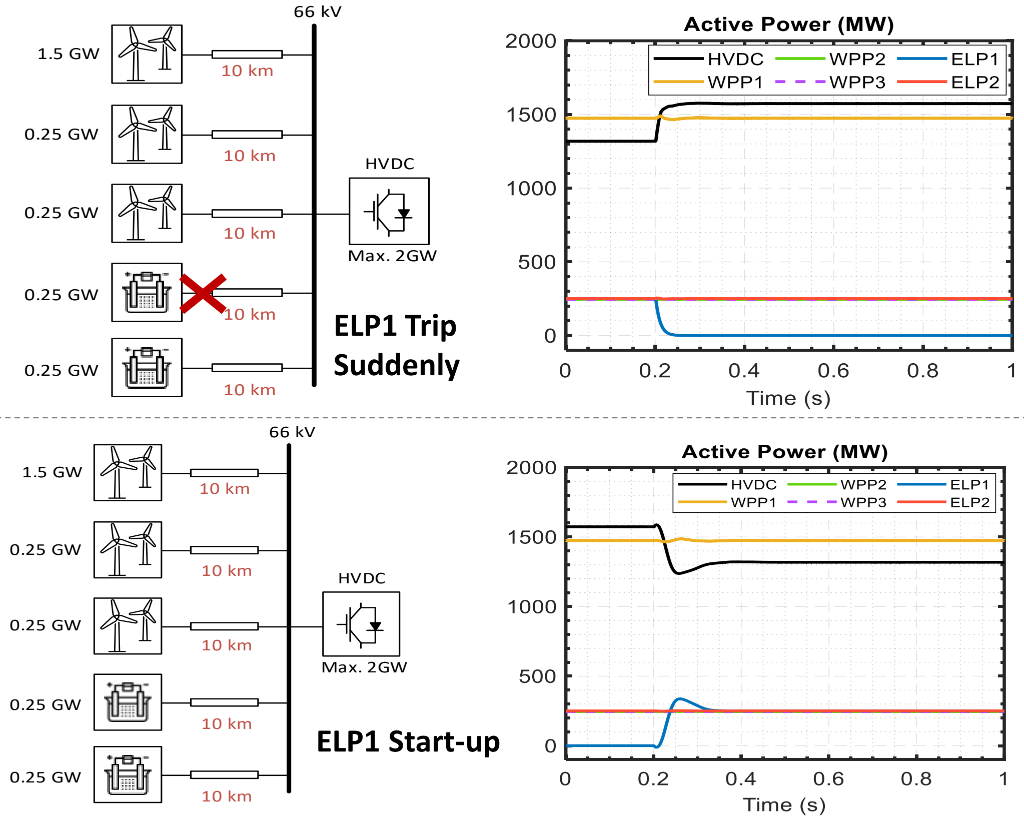
- ## Multi-Scenario Performance Evaluation

Normal Operation Scenario



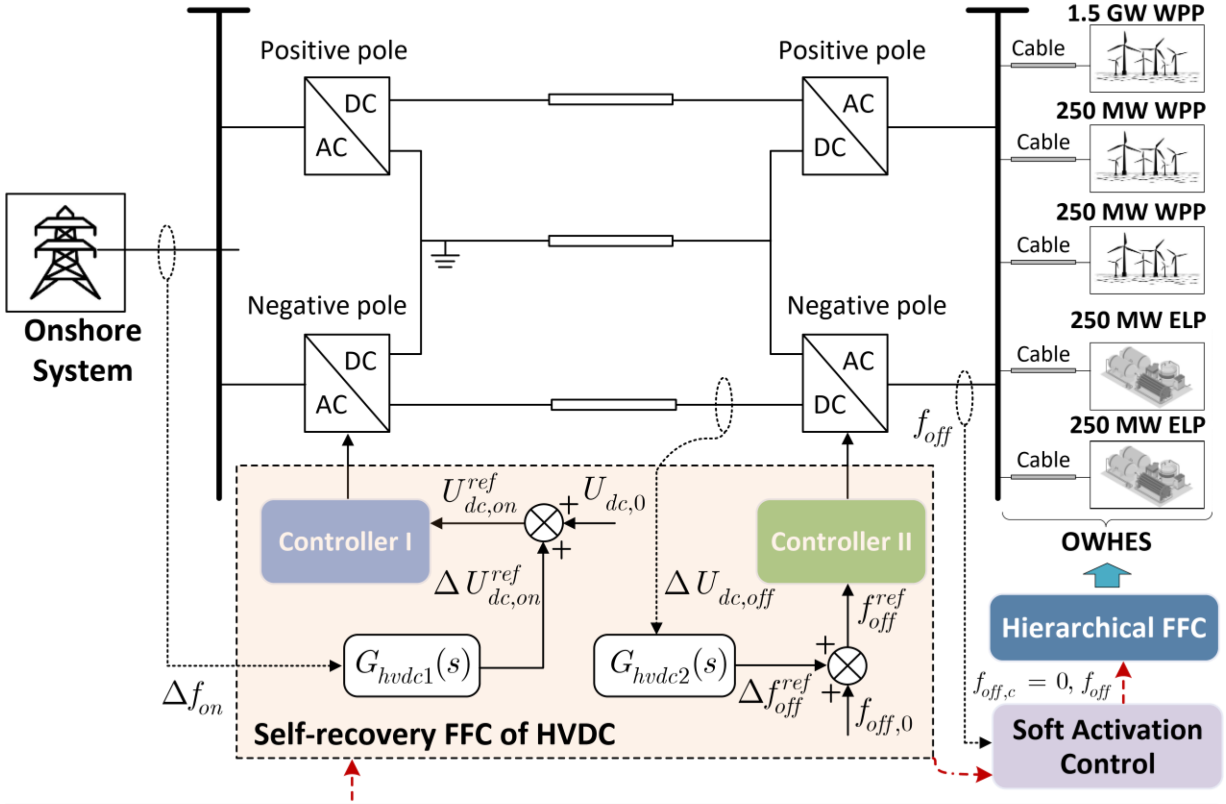
- System states (e.g., PCC voltage, components' power) are **effectively controlled at their setpoints**

Disturbance Scenario Example : ELP trip and recovery



Coordinated Fast Frequency Control Framework

Coordinated Fast Frequency Control (FFC) Framework

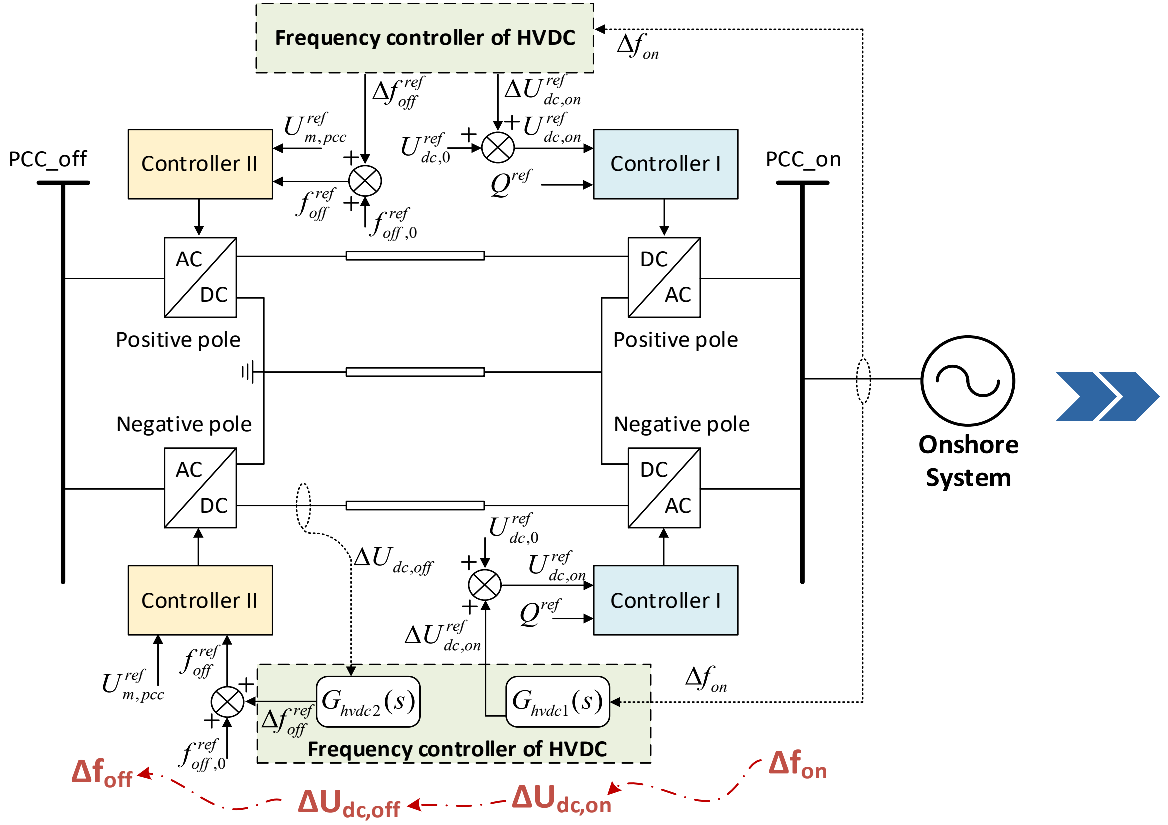


Proposed Coordinated Fast Frequency Control Framework for OWHES

Three Key Modules

- Self-recovery Fast Frequency Control of HVDC
- Soft Activation Control (SAC)
- Hierarchical Fast Frequency Control

Self-recovery FFC of HVDC: U_{dc}-f droop characteristic



Control Principle and Design

- Onshore Converter Station:

$$G_{hvdc1}(s) = \frac{\Delta U_{dc,on}^{ref}(s)}{\Delta f_{on}(s)} = K_1 \frac{sT_h}{1+sT_h}$$

Washout filter

- Offshore Converter Station:

$$G_{hvdc2}(s) = \frac{\Delta f_{off}^{ref}(s)}{\Delta U_{dc,off}(s)} = \frac{K_2(U_{dc,off}(s) - U_{dc,0} - \Delta U_{dc,l})}{\Delta U_{dc,off}(s)}$$

- Frequency Signal Transfer via DC voltage:

Offshore — Onshore

$$\Delta f_{off}(s) = K_2 K_1 \frac{sT_h}{1+sT_h} \Delta f_{on}(s)$$

Washout filter (static gain 0) → Control action vanishes at steady state

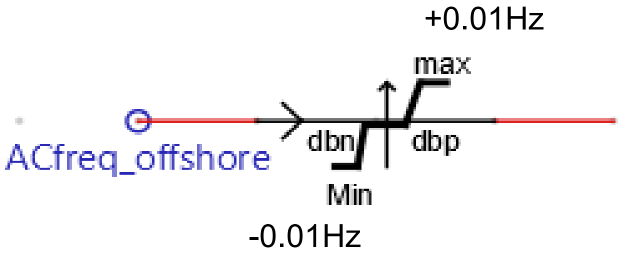
Soft Activation Control (SAC)

- **Traditional frequency control deadband:**

To prevent false trigger of control due to noise and small-signal disturbances

- **Conventional Method:**

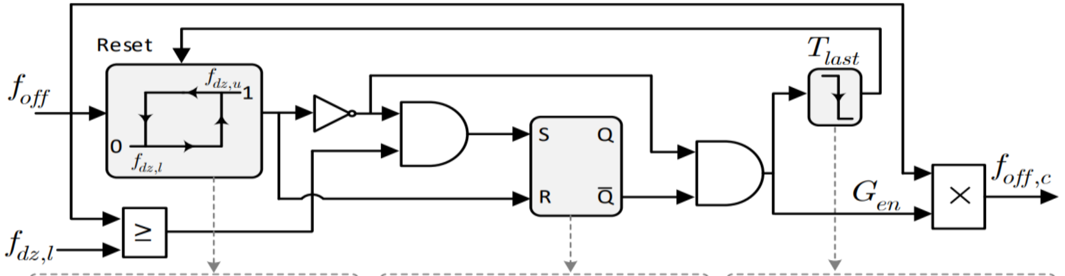
Utilizing a deadzone function with upper and lower limits



Output f $f_{off,c} = \begin{cases} f_{off} \\ 0 \end{cases}$ Input f ← frequency deviation exceeds the deadzone

Control Principle and Design

- Smart Integration of Basic Control Logic blocks:



Reset	Output
0	1
1	$y = \begin{cases} 1 & \text{if } f_{off} \geq f_{dz,u} \\ 0 & \text{if } f_{off} \leq f_{dz,l} \end{cases}$

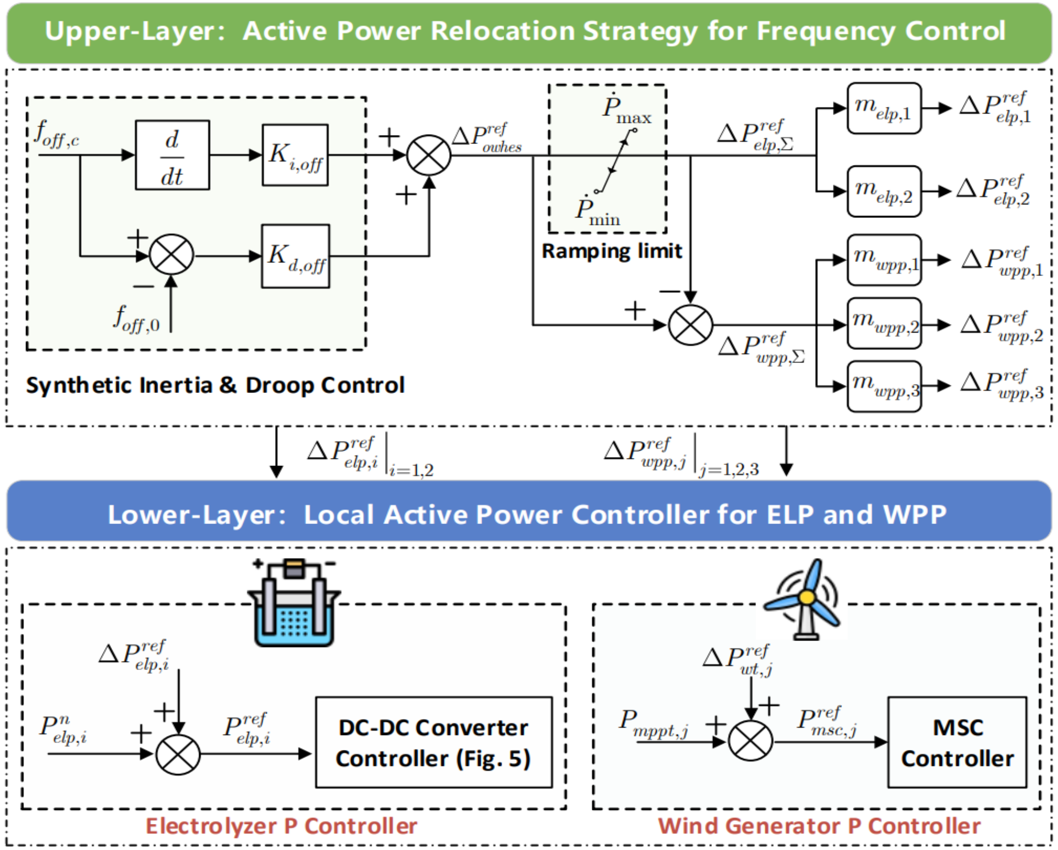
S	R	Q	Q̄
0	0	Hold	Hold
0	1	0	1
1	0	1	0
1	1	0	0

Input	Output
Falling	1 with T_{last} duration
Otherwise	0

- Output Signal:

Output f $f_{off,c} = \begin{cases} f_{off} \\ 0 \end{cases}$ Input f ➡ Maintaining the same deadband function while enabling smoother frequency recovery

- **Hierarchical Fast Frequency Control (FFC)**



Control Principle and Design

- **Active Power Relocation Strategy:**

Total power: $$\Delta P_{owhes}^{ref} = K_{p,off}(f_{off,c} - f_{off,0}) + K_{d,off}\frac{df_{off,c}}{dt}$$

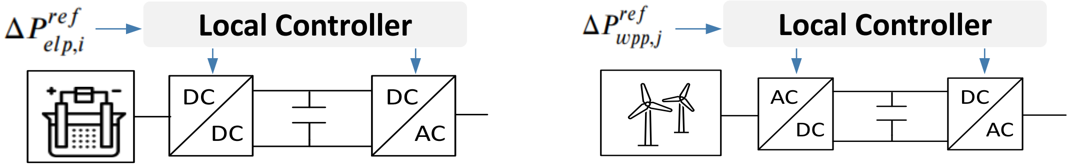
Fast-response power for WPPs:

$$\Delta P_{wpp,j}^{ref} = m_{wpp,j}\Delta P_{wpp,\Sigma}^{ref},\ j = \{1,2,3\}$$

Slow-response power for ELPs:

$$\Delta P_{elp,i}^{ref} = m_{elp,i}\Delta P_{elp,\Sigma}^{ref},\ i = \{1,2\}$$

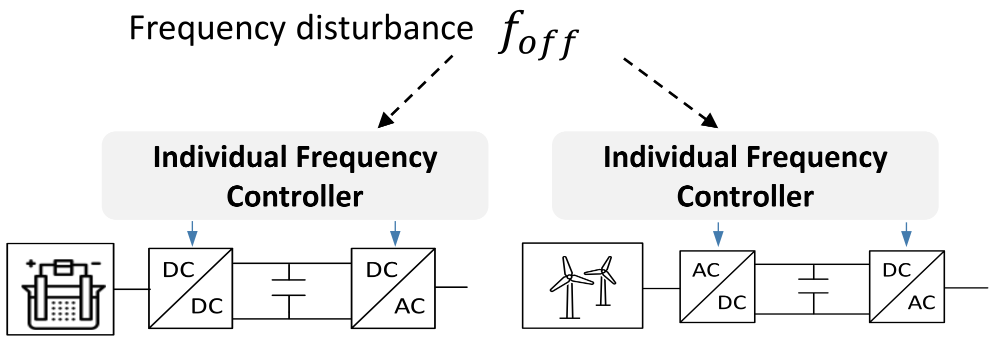
- **Active Power Regulation:**



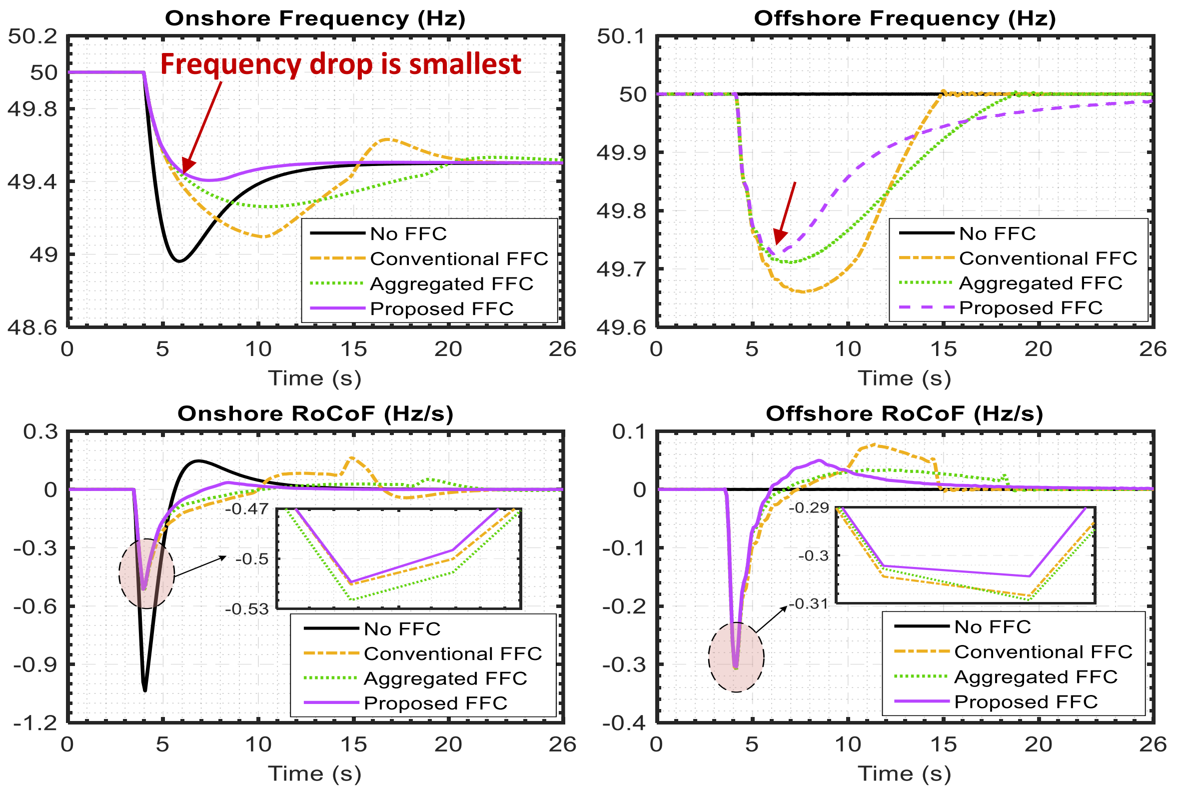
Performance Examination: Under-Frequency Event

Case Setup

- **Proposed coordinated fast frequency control (FFC)**
- **No FFC:** no fast frequency control
- **Conventional FFC:** conventional control
- **Aggregated FFC:** Non-coordinated control

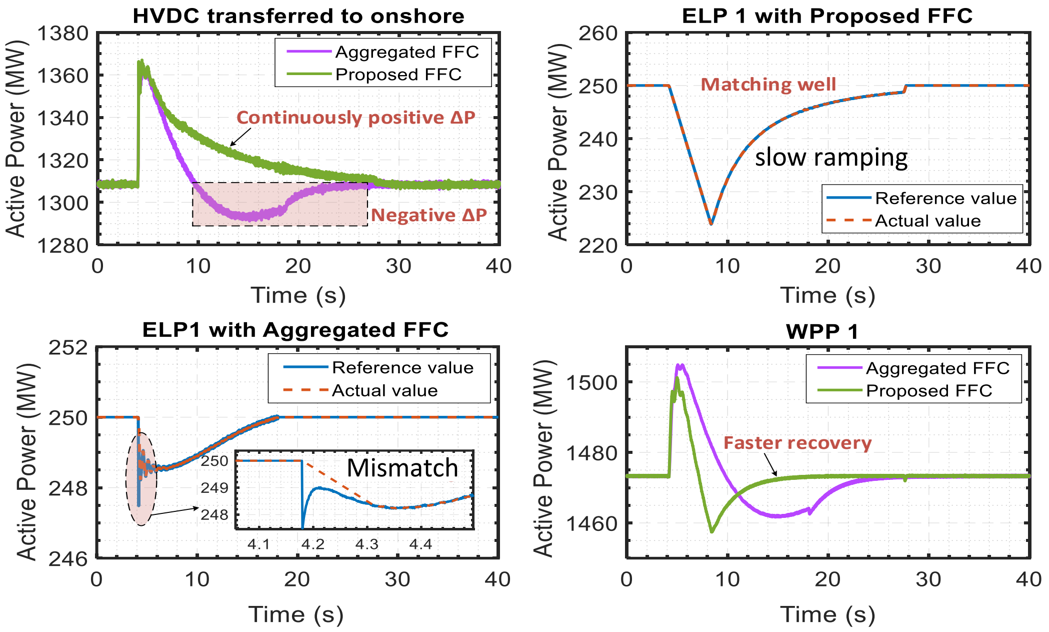


Comparative Results



Why Coordination and Soft Activation Matter

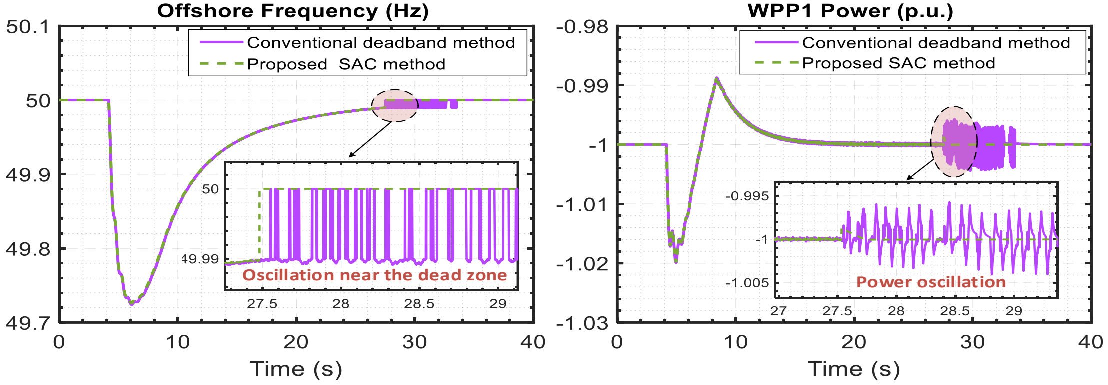
Aggregated control VS. Coordinated FFC



Disadvantage of aggregated FFC: less positive power support; electrolyzer cannot track the reference due to ramping limitation

Traditional Deadzone Method vs. Proposed SAC FFC

Frequency oscillation during recovery using the deadzone method



Proposed soft activation control (SAC) method: smooth frequency recovery completely eliminating these oscillations

Disadvantage of deadzone method: sharp oscillations in frequency and WPP power during frequency recovery

Takeaways

- A **stability-oriented modeling chain** is established from grid-integrated electrolyzer dynamics to scalable multi-GW OWHES real-time EMT simulation, enabling dynamic-interaction and stability assessment.
- A **coordinated fast frequency control framework** exploits the complementary dynamics of HVDC, WPPs, and ELPs, delivering stronger onshore frequency support with smooth self-recovery.

	Research Problem	Innovation
Model	Lack of a **stability-oriented modeling framework** linking electrolyzer dynamics with scalable multi-GW OWHES EMT analysis.	❖ **Real-time EMT dynamic model for OWHES**
Control	Limited exploitation of **heterogeneous OWHES resource flexibility** for grid support.	❖ **Coordinated Fast Frequency Control**

[1] **C. Huang**, J. L. Rueda, et al., "Aggregated electrolyzer modeling and coordinated frequency support of multi-GW offshore wind-hydrogen energy systems," *Energy Conversion and Management*, vol. 366, 121862, 2026.

[2] **C. Huang**, J. L. Rueda, et al., "Grid-integrated hydrogen production systems: A holistic analytical modeling framework for stability assessment and dynamic interaction," *International Journal of Hydrogen Energy*, vol. 240, 155391, 2026.

Part II: Oscillation Assessment of OWHES

Oscillation identification challenges in OWHES

- Increase in the reported oscillation events in power systems with a high presence of IBR.
- The incidents show that the mechanism behind the oscillations is complex, and the RMS model can not capture it.
- Lack of availability of a detailed model of IBR due to intellectual property.
- Some signal-processing techniques like Prony don't easily separate spatial mode shapes from multi-channel measurement data.

Bart Meijer. (2023). *Netherlands to Build 500MW Offshore Green Hydrogen Facility*. https://www.oedigital.com/news/503755-netherlands-to-build-500mw-offshore-green-hydrogen-facility

Koopman Operators

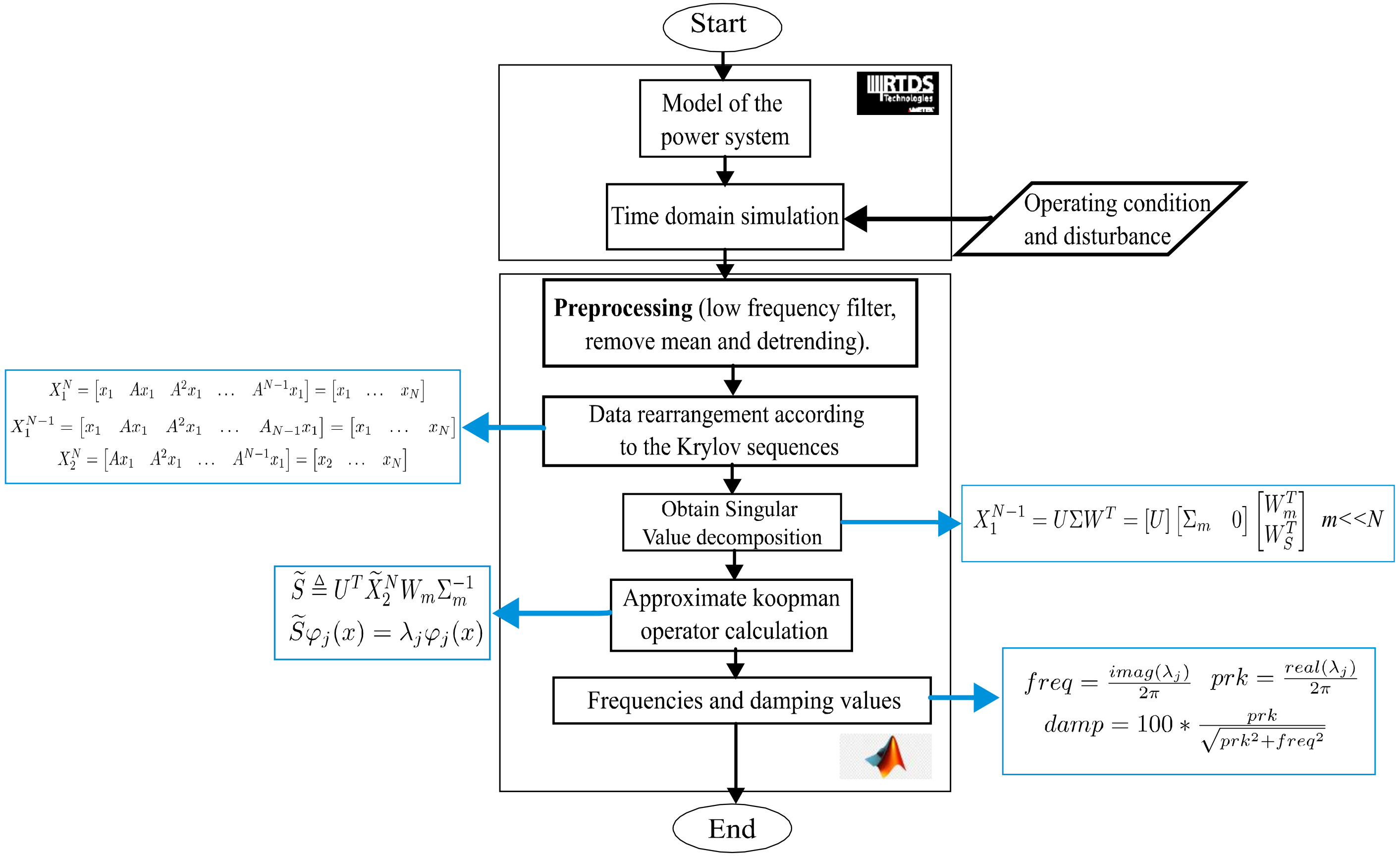
The Koopman operator K is a linear (but infinite-dimensional) operator acting on observable functions: $g\colon \mathbb{R}^n \to \mathbb{C}$.

$$(Kg)(x) = g(\phi^{\Delta t}(x))$$

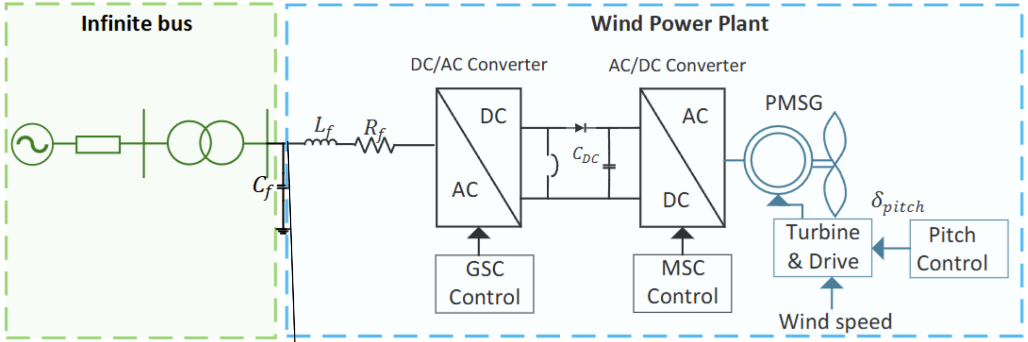
Observable at current state $g(x_k)$ | K (linear) | Observable at next state $g(x_{k+1})$

- Linear evolution of observables:
  $$g(x_{k+1}) = (Kg)(x_k) = Kg(x_k)$$
- Eigenfunctions φ_i and eigenvalues λ_i satisfy:
  $$K\varphi_i = \lambda_i \varphi_i \Rightarrow \varphi_i(x_{k+1}) = \lambda_i \varphi_i(x_k)$$

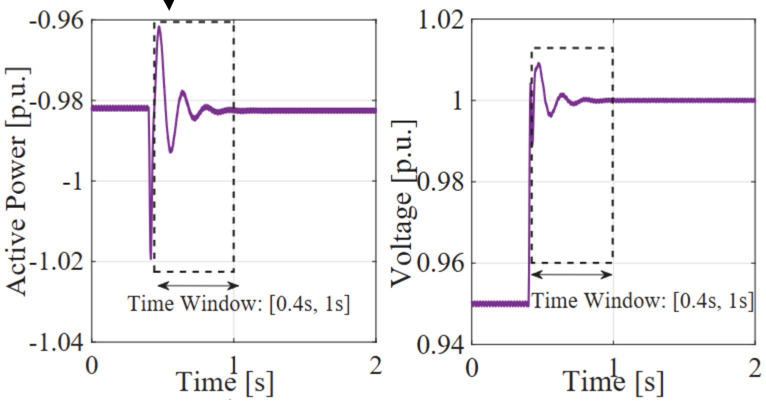
DMD implementation



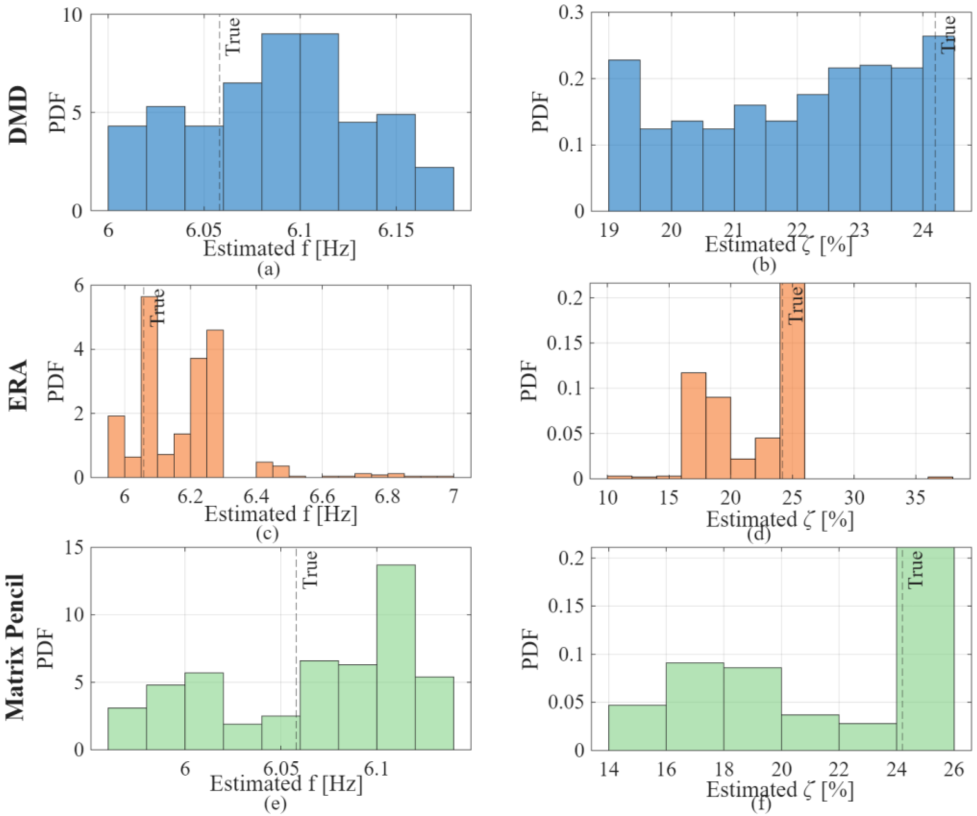
Noise-sensitivity was assessed using a **Monte Carlo** simulation, varying the signal-to-noise ratio (SNR) from 30 dB to 50 dB.



Time step response

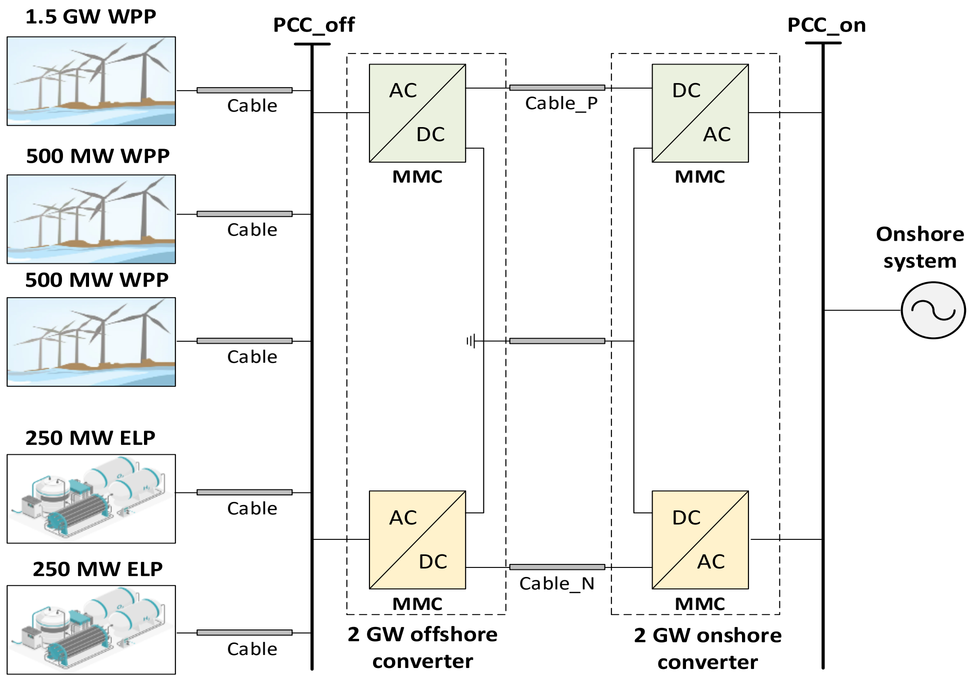


Noise-sensitivity Histogram



At t = 0.4 s, change in Vac ref from 1 p.u. to 0.95 p.u.

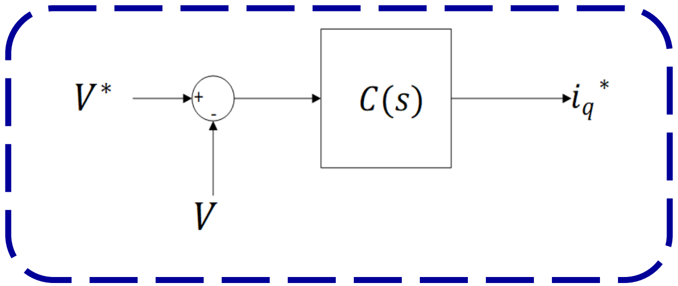
Simplified synthetic model of a 2-GW Offshore Wind-Hydrogen Energy System.



At t = 0.4 s, change in Vac ref from 1 p.u. to 0.9 p.u.

Initial Operating Conditions

- WPP injecting 1 p.u. of P and 0 p.u. of Q to PCC
- Ely absorbing 1 p.u. of P and 0 p.u. of Q from PCC



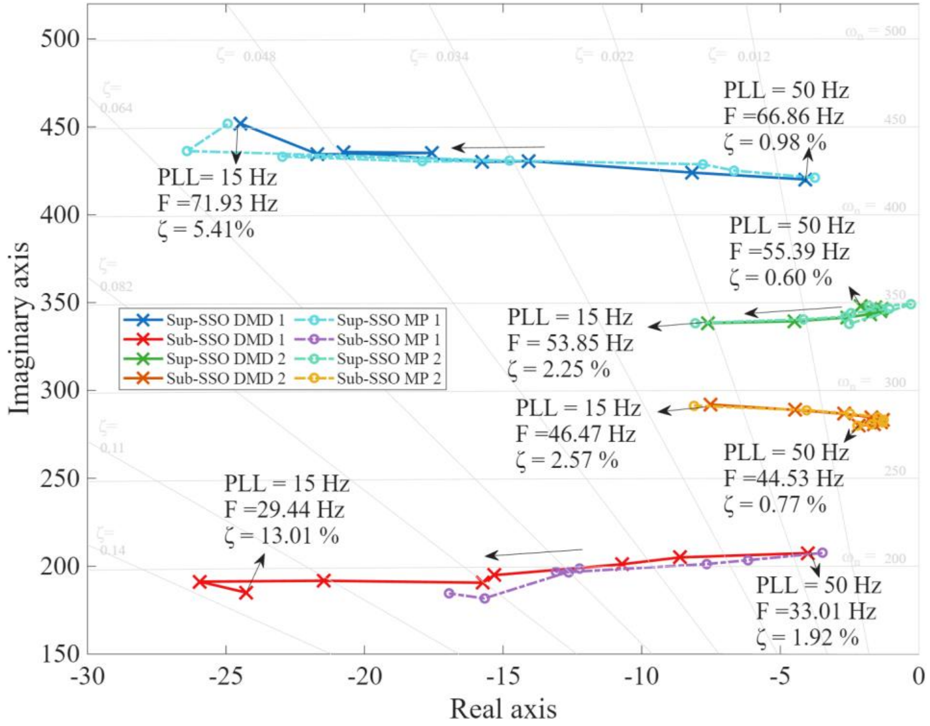
$$C(s) = K_p\left(\frac{s + \frac{k_i}{k_p}}{s}\right)$$

Identified frequency [Hz]	Identified damping [%]
28,01	13,44

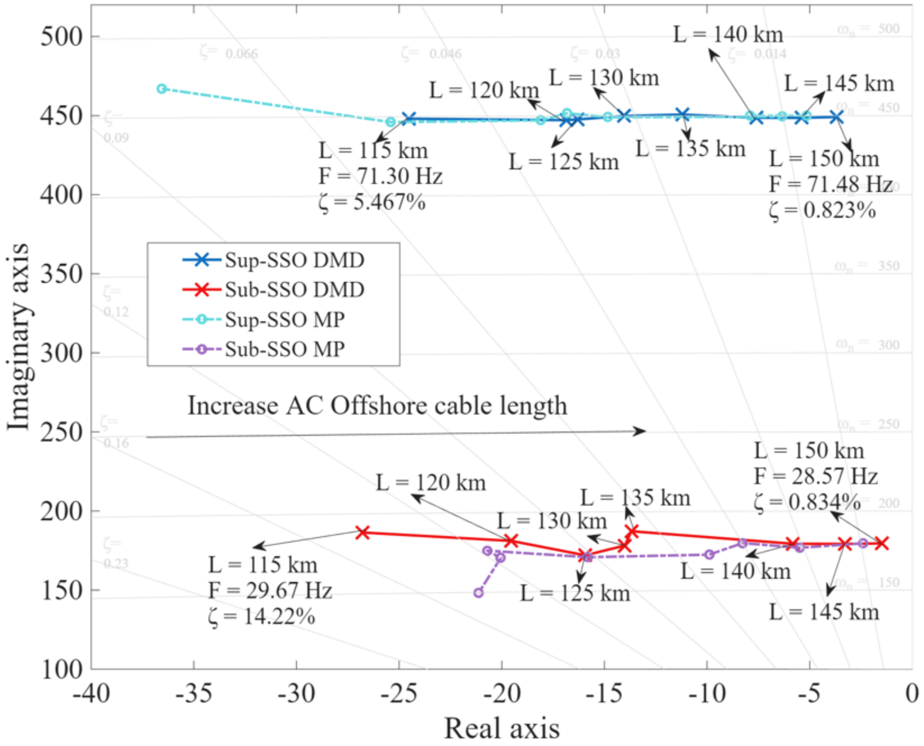
Root-locus considering system parameters

Measurement-based root-locus using the DMD and Matrix Pencil method, evaluating control interaction with equivalent impedance.

Root-locus changing PLL bandwidth



Root-locus changing AC Offshore cable length

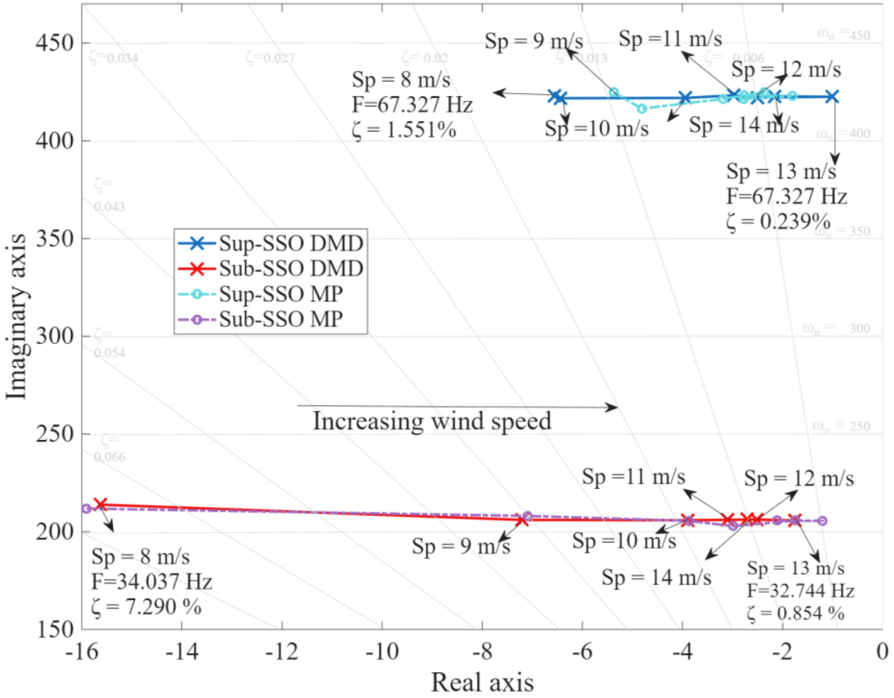


Increasing the system's equivalent impedance reduces oscillation damping.

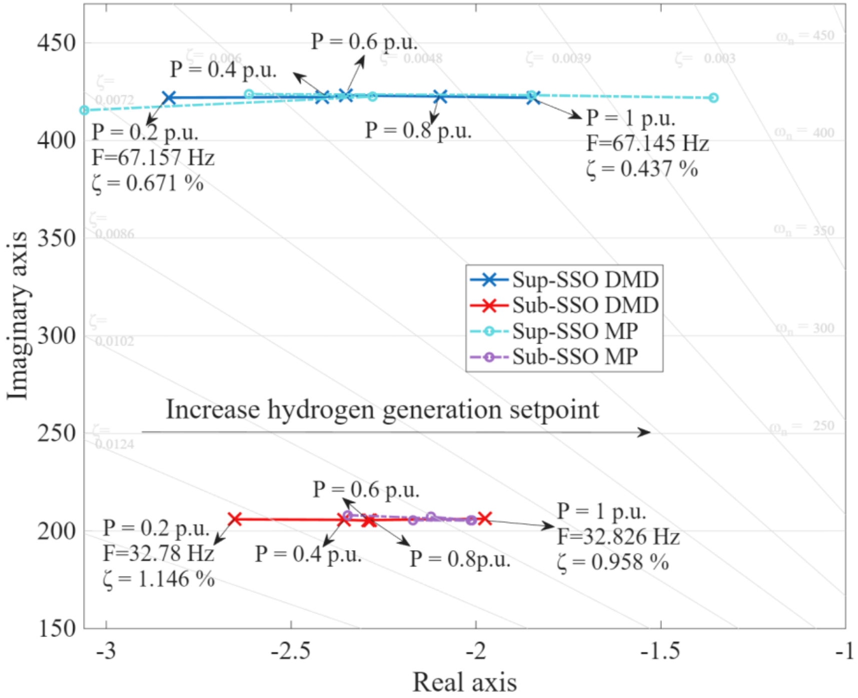
Root-locus considering different operating scenarios

Measurement-based root-locus using the DMD and Matrix Pencil method, evaluating the effect of wind generation and electrolyser generation setpoint.

Root-locus changing wind speed

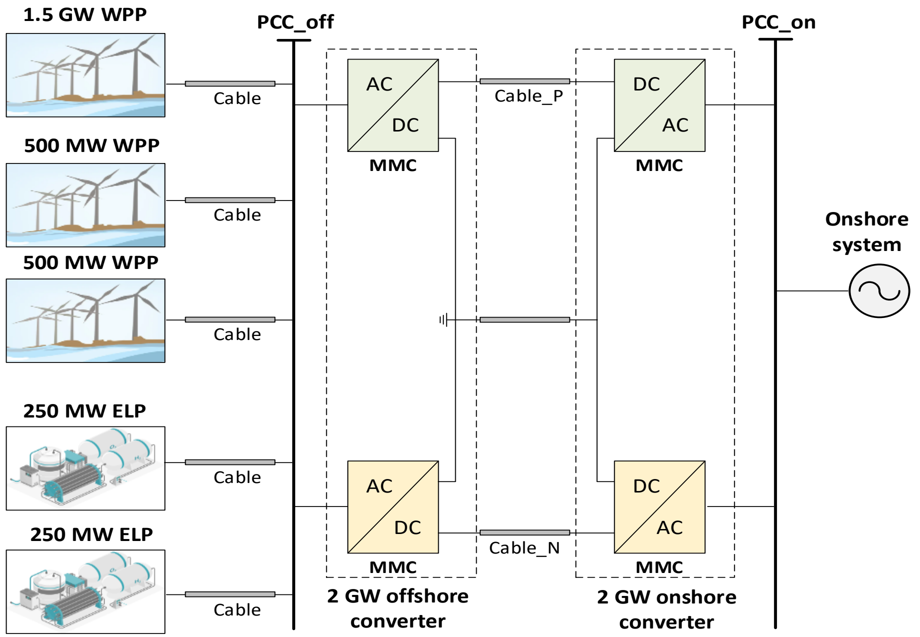


Root-locus changing hydrogen generation setpoint

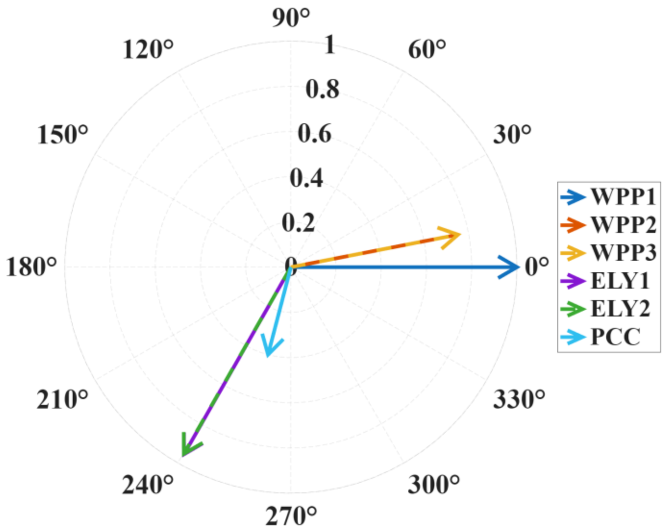


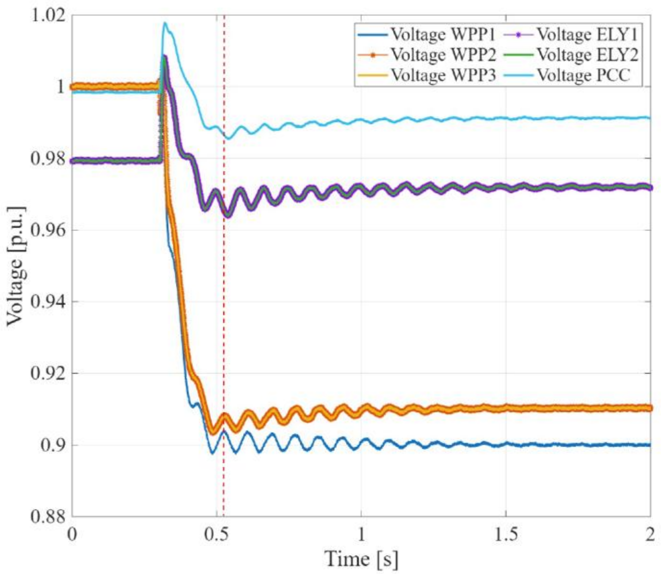
Increasing the power flow through AC cables decreases the damping of the oscillations

In this scenario, the **PLL bandwidth** is set to 50 Hz for the GSC of the IBR in the offshore energy system.



At t = 0.4 s, change in Vac ref from 1 p.u. to 0.9 p.u.





The mode shape results indicate that the oscillation is caused by interactions between the different control loops associated with the IBR.

Other available DMD versions

Randomised DMD

- Use randomised linear algebra to cut the cost of the SVD step.

Multiresolution DMD:

- Filtered decomposition across scales.

Extended DMD:

- Augments the state with nonlinear observables rather than raw measurements

Physics-informed DMD:

- Restrict the least-squares optimisation to lie on a matrix manifold that reflects known physics of the system.

DMD with control:

- Generalised regression for a globally linear control framework.

Colbrook, M.J. (2023). The Multiverse of Dynamic Mode Decomposition Algorithms. *ArXiv, abs/2312.00137*.

- **DMD** reconstructs the OWHES signal by fitting a linear approximation to the **system's nonlinear behaviour.**
- DMD can assess **sensitivity** to **parameter** and **scenario changes**, though the estimated damping deviates from that obtained with Matrix-Pencil as **damping increases**.
- Fast operating-condition changes fall outside DMD's **quasi-stationary assumption** and cannot be reliably tracked.
- PMU sampling **rates violate the Nyquist criterion for SSOs**, so waveform measurement units remain necessary.
- The switching behaviour of IBR introduces **strong harmonic content** into the extracted modes, making it difficult to distinguish genuine oscillatory modes from harmonic artefacts.

C. Castrillón-Franco, J. L. Rueda-Torres, N. Narayanan and A. R. Messina, "Oscillation Mode Identification in Converter-based Offshore System using Dynamic Mode Decomposition," *IECON 2025 – 51st Annual Conference of the IEEE Industrial Electronics Society*, Madrid, Spain, 2025, pp. 1-6, doi: 10.1109/IECON58223.2025.11221794.

C. Castrillón-Franco, J. L. Rueda-Torres and A. R. Messina, "Performance assessment of DMD for SSO identification in Multi-Converter Power Systems”, International Transactions on Electrical Energy Systems, Under revision.

Thank you!

Dr. Chunjun Huang
C.J.Huang@tudelft.nl

Maria Camila Castrillón Franco
M.C.CastrillonFranco@tudelft.nl

Delft University of Technology