Blake Clough
CONSULTING

Sub-Synchronous Oscillations

Theory, Risks & NESO Study Requirements

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01.

ABOUT US

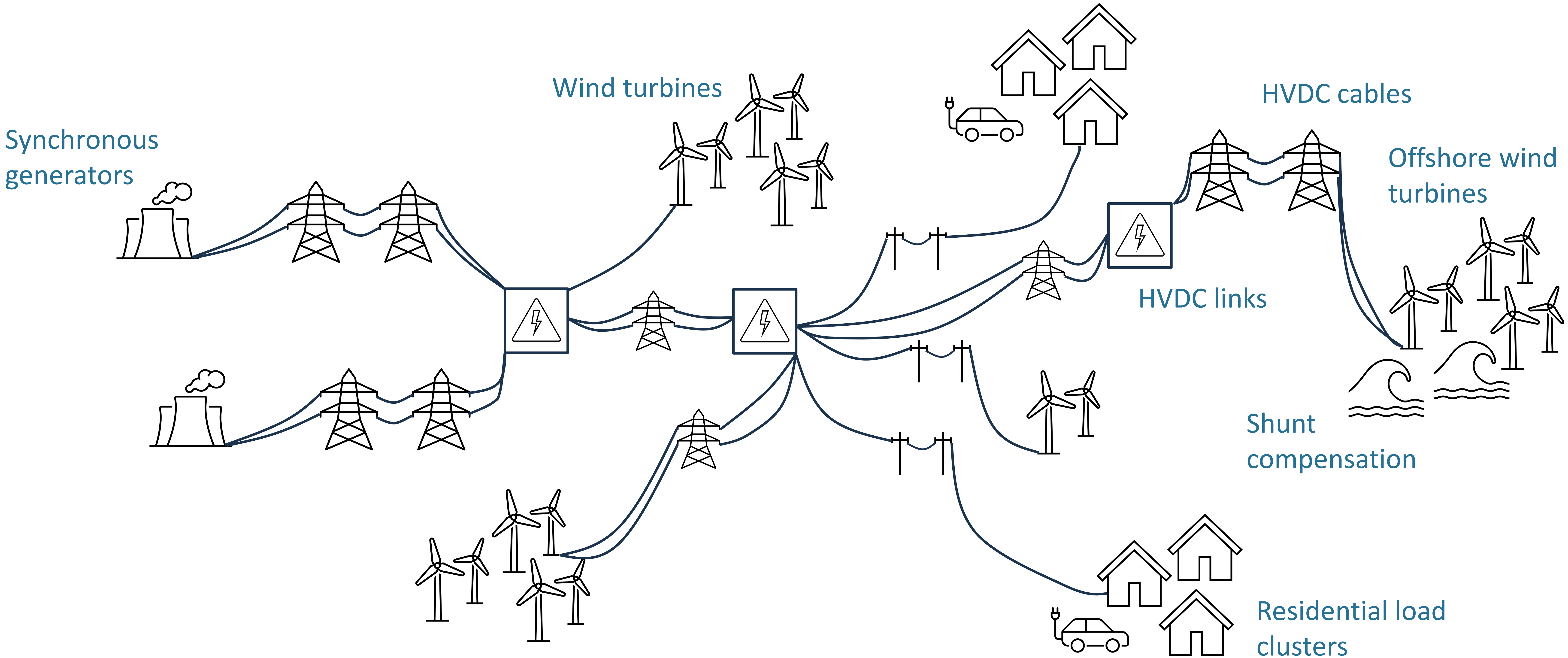
WHO ARE WE?

- Specialist energy consultancy, focused on Electricity Networks
- Our mission: To accelerate the decarbonisation of the energy networks to help slow climate change, whilst optimising the costs and benefits to the end user
- Strong track record & experience in the industry, + access to a range of associates with deep technical skills
- Blake Clough has grown from just 3 people in 2021 to a team of 60 in 2026, now spread across four locations

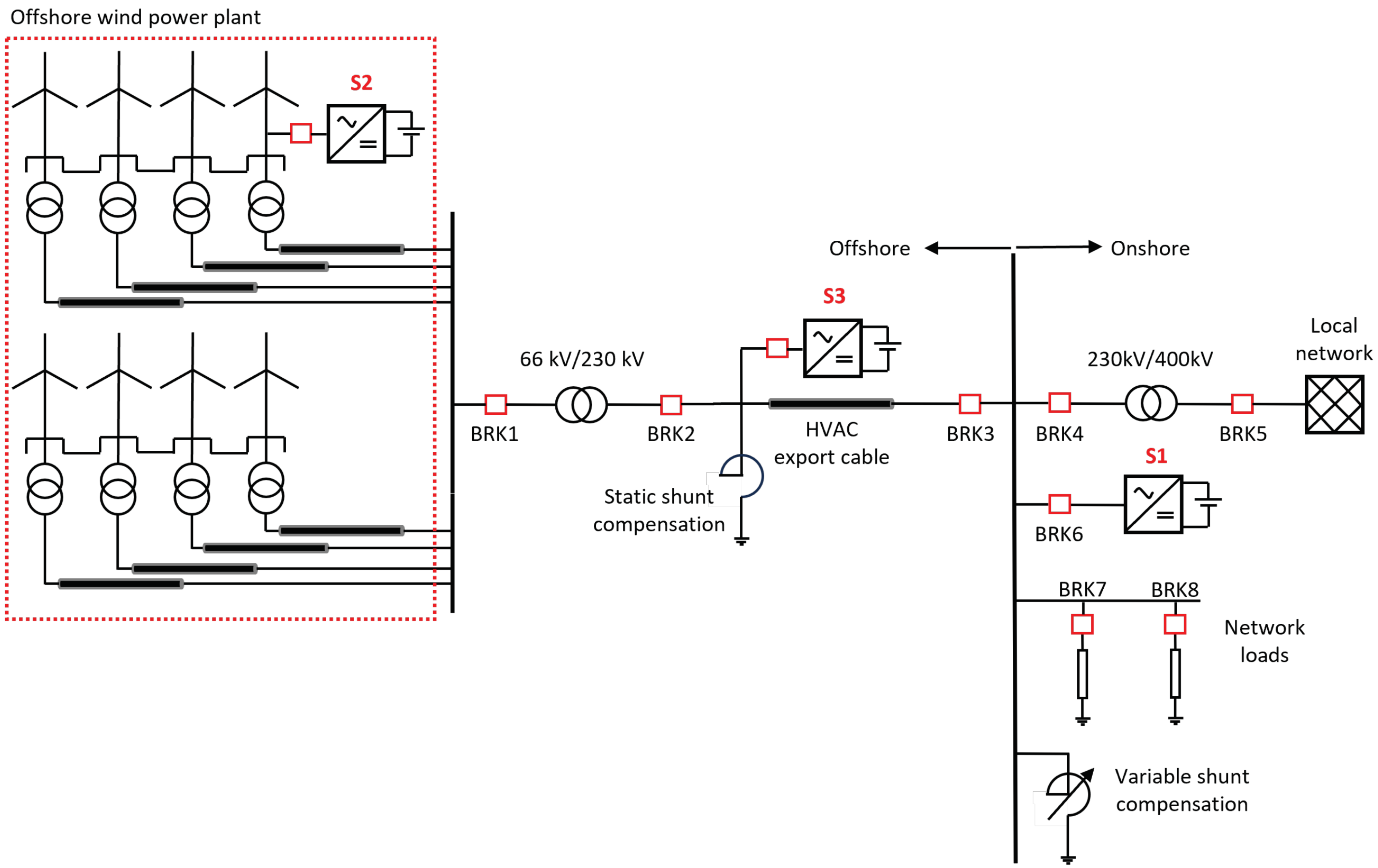
02.

WHAT ARE SSOs?

POWER SYSTEMS COMPLEXITY

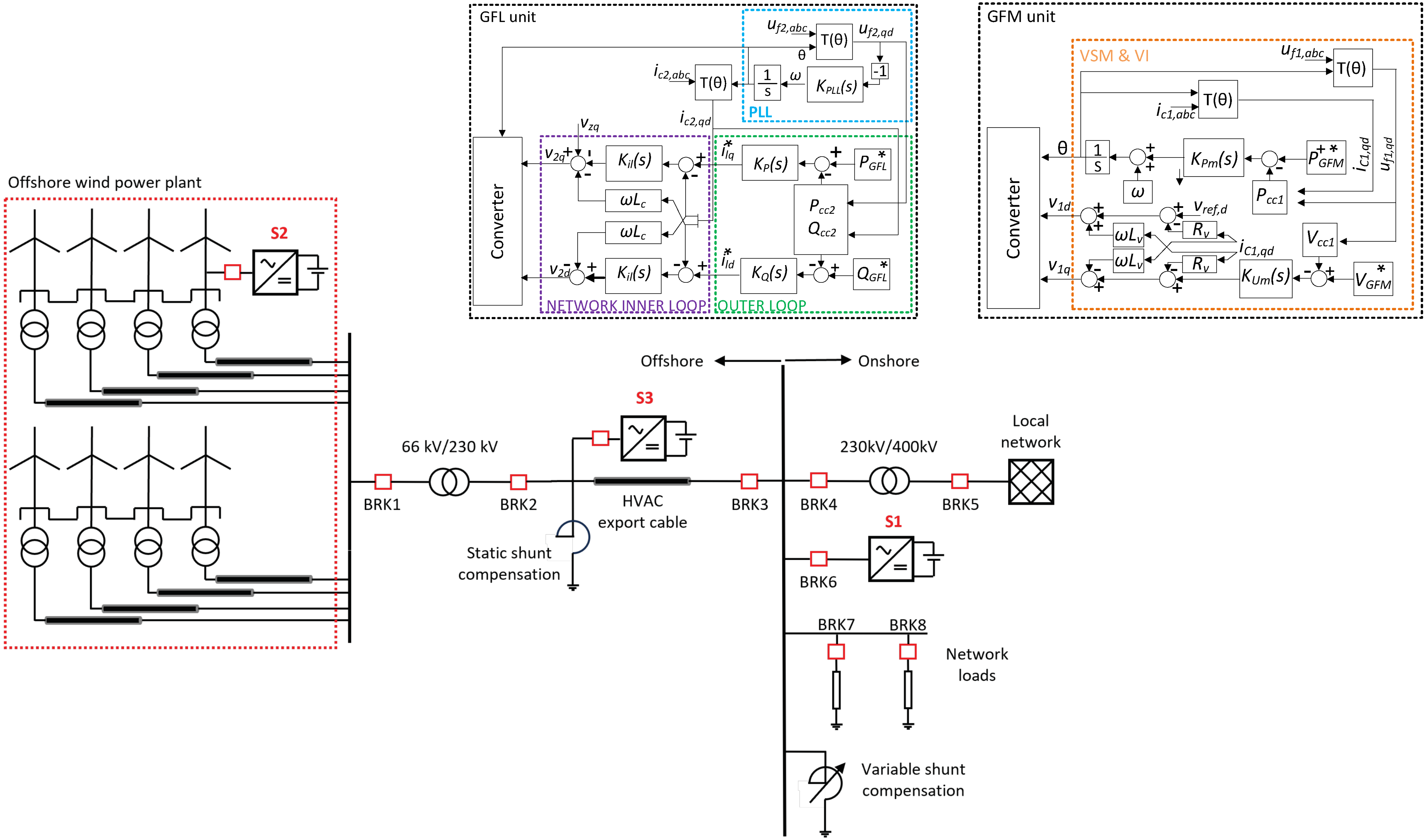


POWER SYSTEMS COMPLEXITY



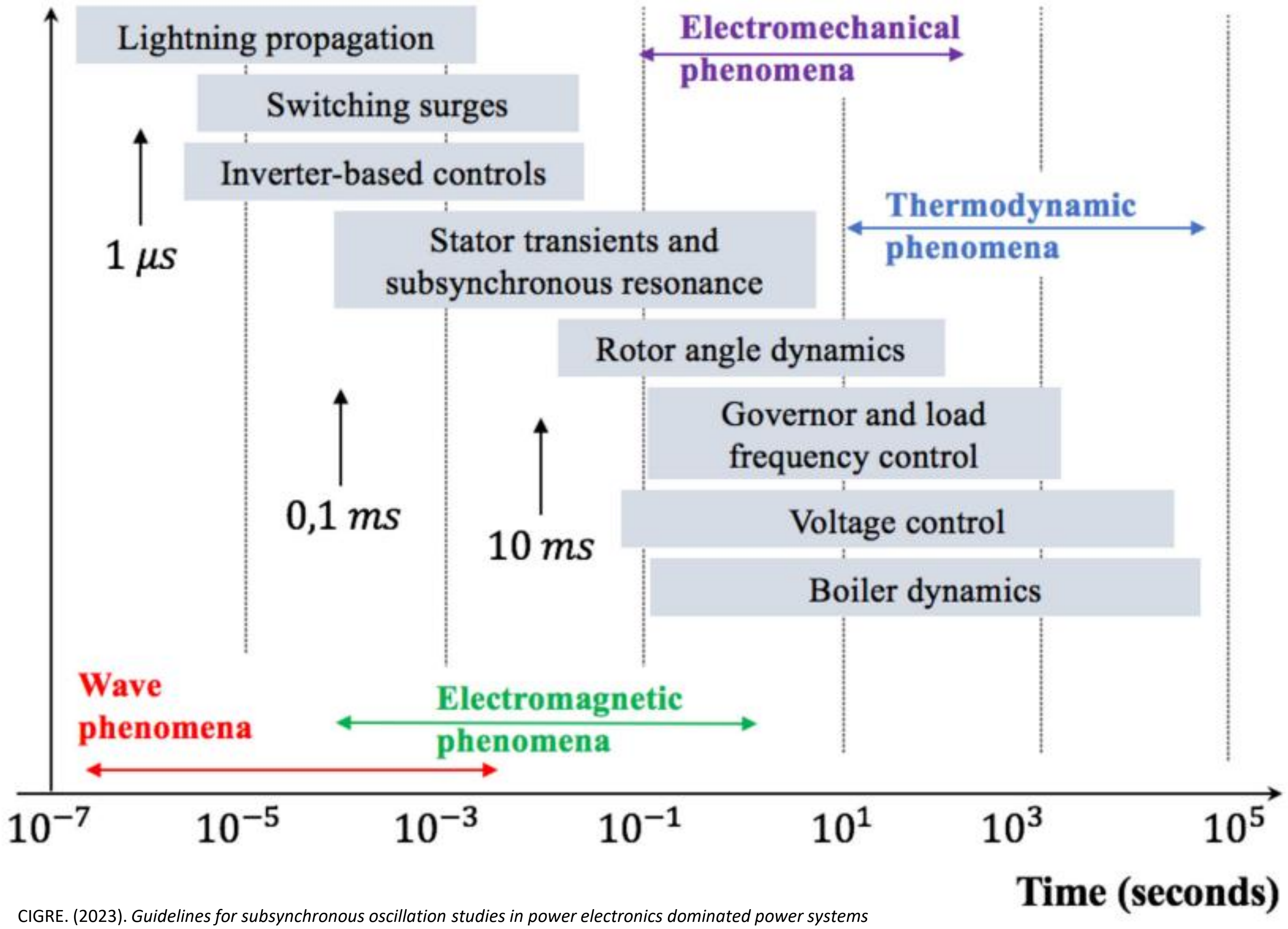
- Wind turbines and converters
- Offshore substations
- Export cables
- Shunt compensation
- Transformer
- Onshore substation
- Grid-side and loads

POWER SYSTEMS COMPLEXITY



DYNAMIC PHENOMENA IN POWER SYSTEMS

- Interactions between equipments and components in a power system leads to undesiderd phenomena
- Sub-synchronous range
- Electromechanical oscillations
- Mid-frequency oscillations
- Harmionics & resonances
- Slow dynamics



CIGRE. (2023). *Guidelines for subsynchronous oscillation studies in power electronics dominated power systems* (Technical Brochure No. 909). Joint Working Group C4/B4.52

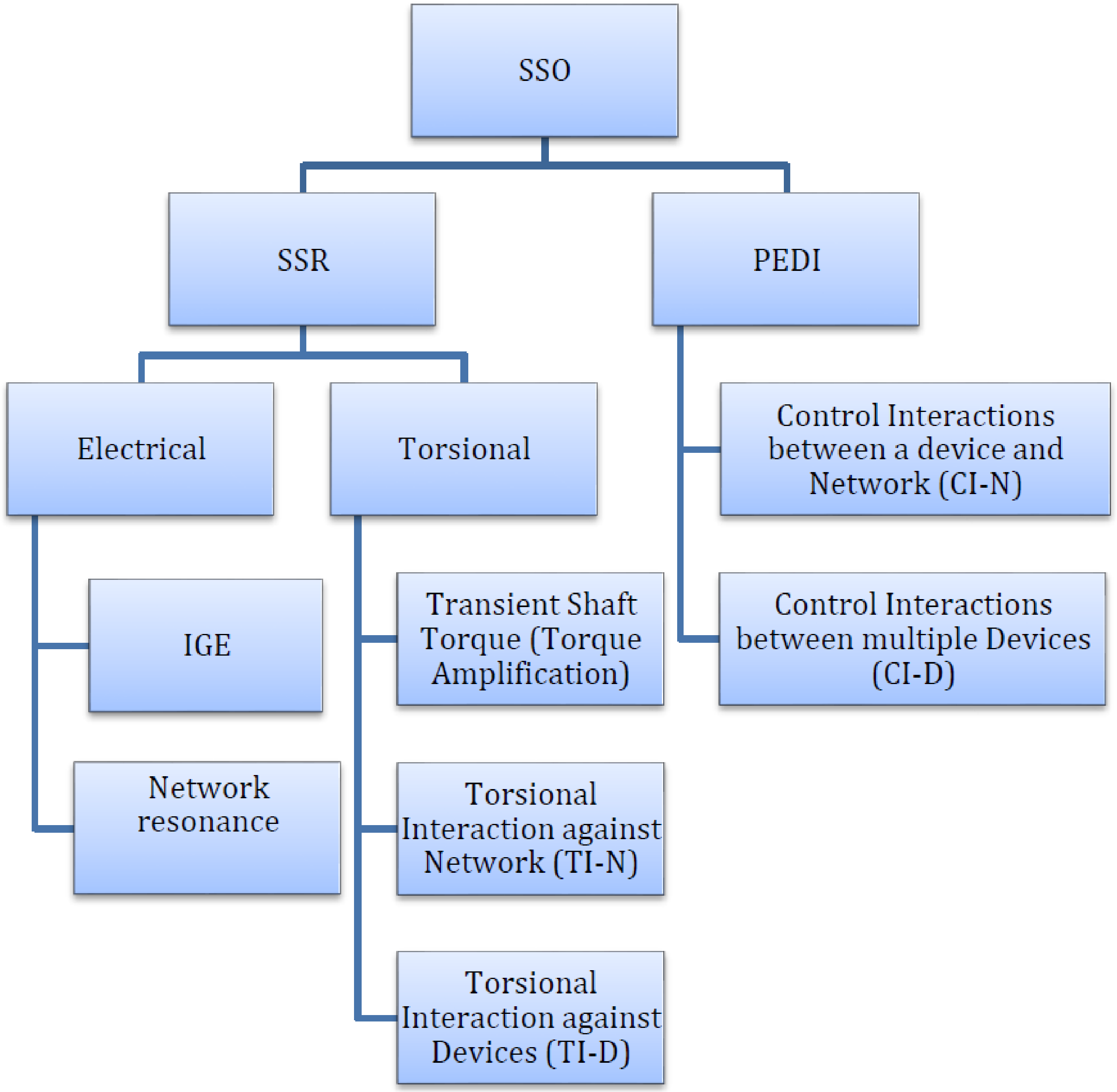
WHAT ARE SSOs?

- Oscillatory phenomena occurring at frequencies below the system fundamental (50 Hz in GB)
- Arise from dynamic interactions between network elements, machines, and control systems
- Known since the 1970s through sub-synchronous resonance and torsional interactions
- Early incidents in the United States, notably in Arizona, led to severe turbogenerator shaft failures

Wall, Peter & Dattaray, Papiya & Osborne, Mark & Ashton, Phil. (2015). VISOR project: Opportunities for Enhanced Real Time Monitoring and Visualisation of System Dynamics in GB.

WHAT ARE SSOs?

- Historically, SSOs were associated with classical sub-synchronous resonance (SSR) involving synchronous generators
- Today, SSOs are treated as a family of phenomena, including classical SSR and power electronic device interactions (PEDI)
- PEDI covers control-driven interactions between converters and the network, or between multiple converters



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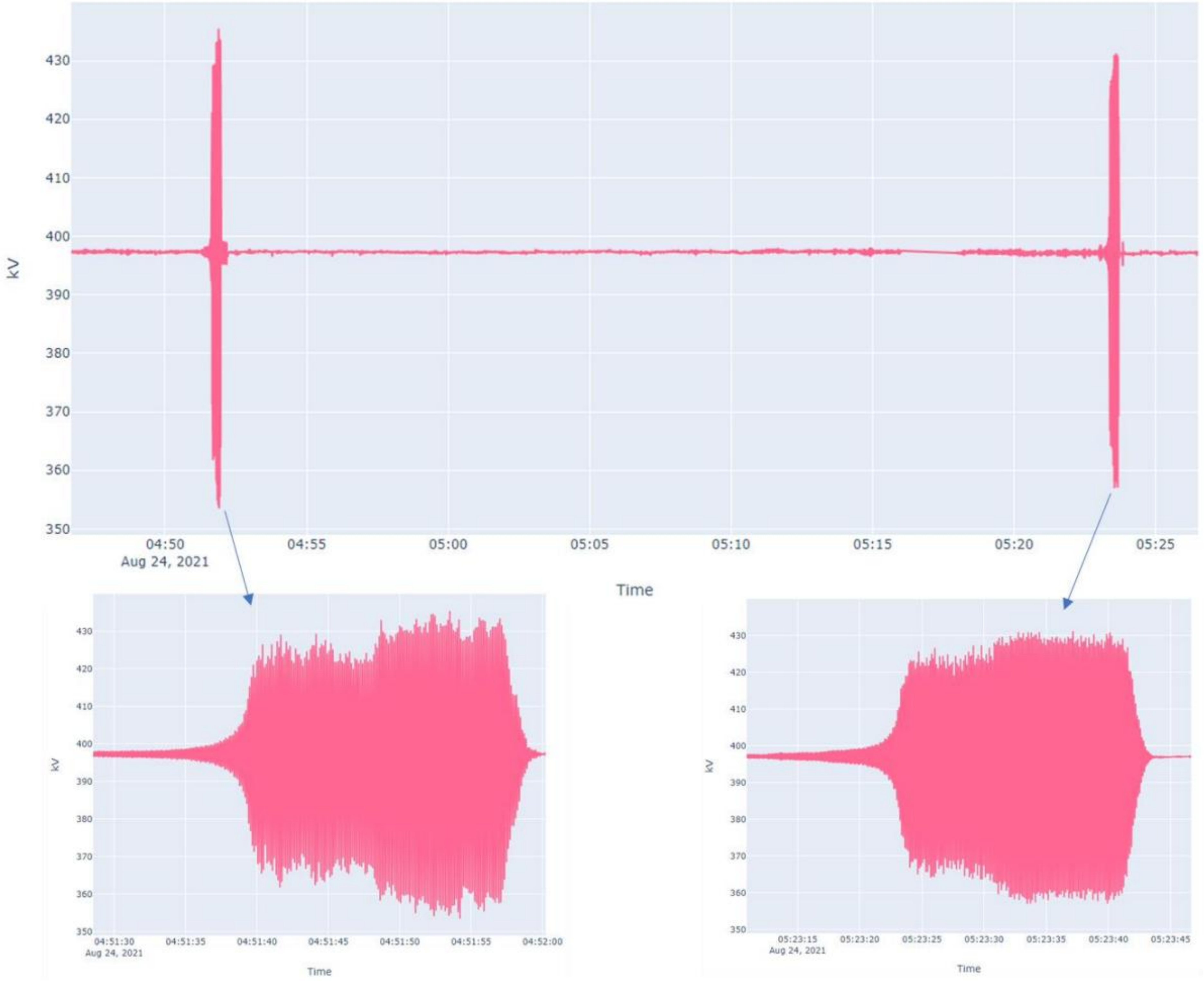
WHY IT MATTERS NOW

- Increasing penetration of inverter-based resources introduces new SSO mechanisms, particularly control-driven interactions
- SSOs are no longer limited to series-compensated networks and can occur under weak-grid conditions
- Recent events demonstrate the need for robust EMT modelling, validation, and updated compliance practices
  - GB, 2019 – ~9 Hz oscillations under weak system conditions
  - Australia, 2019 – multiple oscillations in a 720 MW renewable-dominated area
  - USA, 2021 – sustained oscillations at a large PV plant
  - GB, 2021 – sub-synchronous events in North Scotland

EXAMPLE OF AN SSO IN GB



https://www.neso.energy/document/319056/download

03.

HOW ARE SSOs STUDIED?

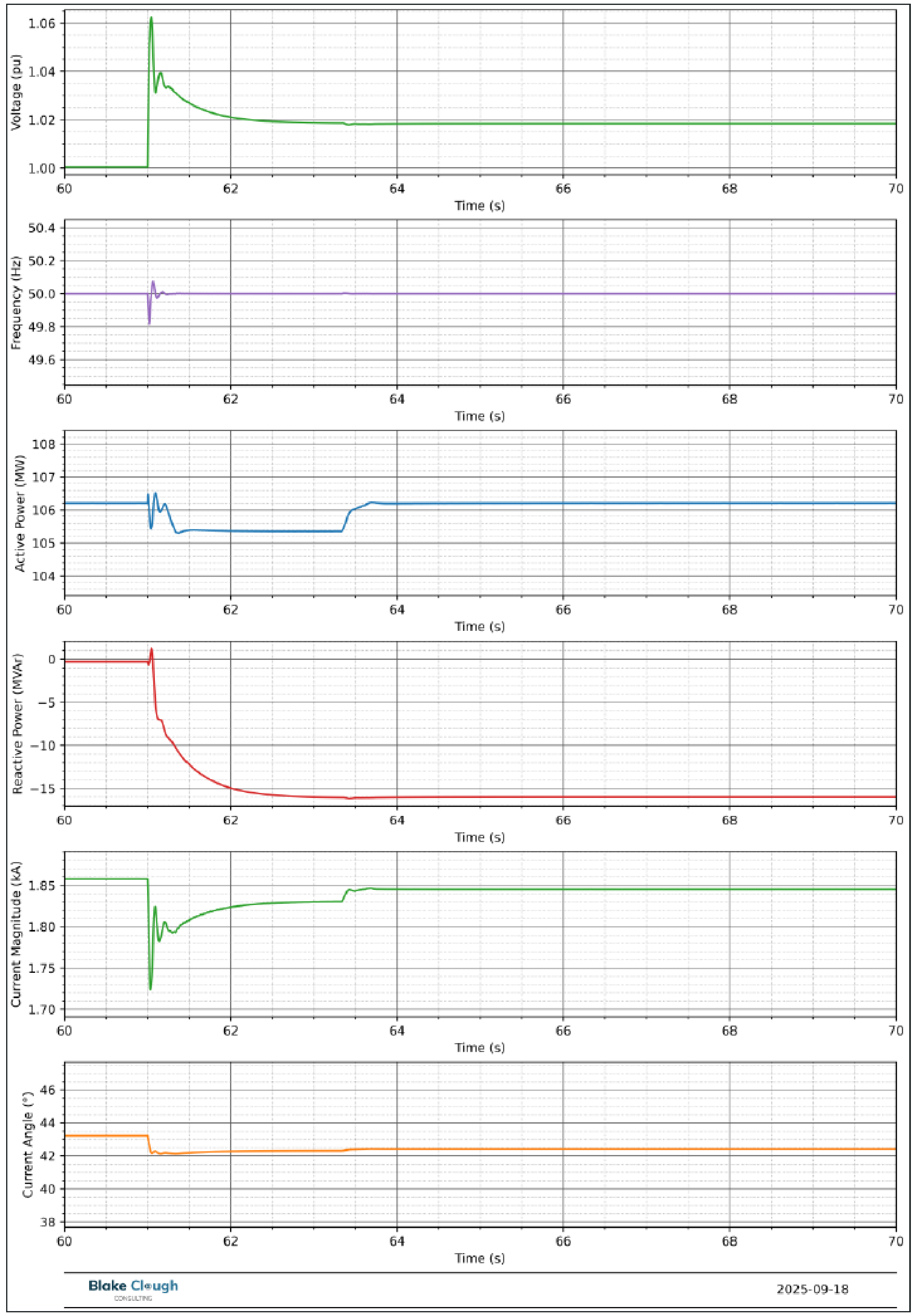
SSO ANALYSIS METHODS

- EMT time-domain simulations
- Small-signal and modal analysis
- Frequency-domain and impedance-based methods

SSO ANALYSIS METHODS

EMT time-domain analysis

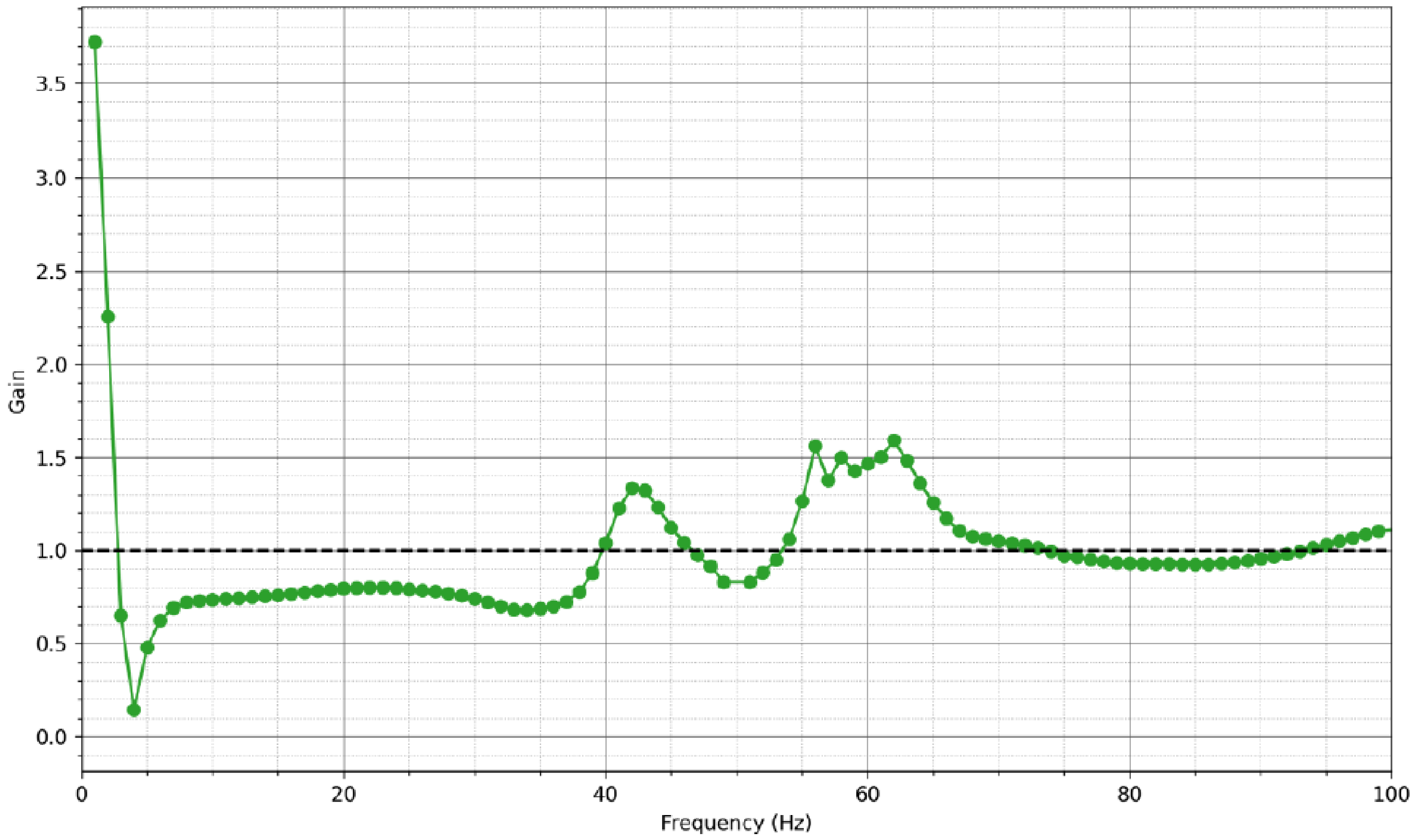
- Non-linear EMT simulations of the full plant and network
- Application of disturbance tests, including
  - Voltage magnitude steps
  - Voltage angle steps
  - Active and reactive power steps
- Used to assess large-signal stability and oscillations growth or decay



SSO ANALYSIS METHODS

Small-signal and modal analysis

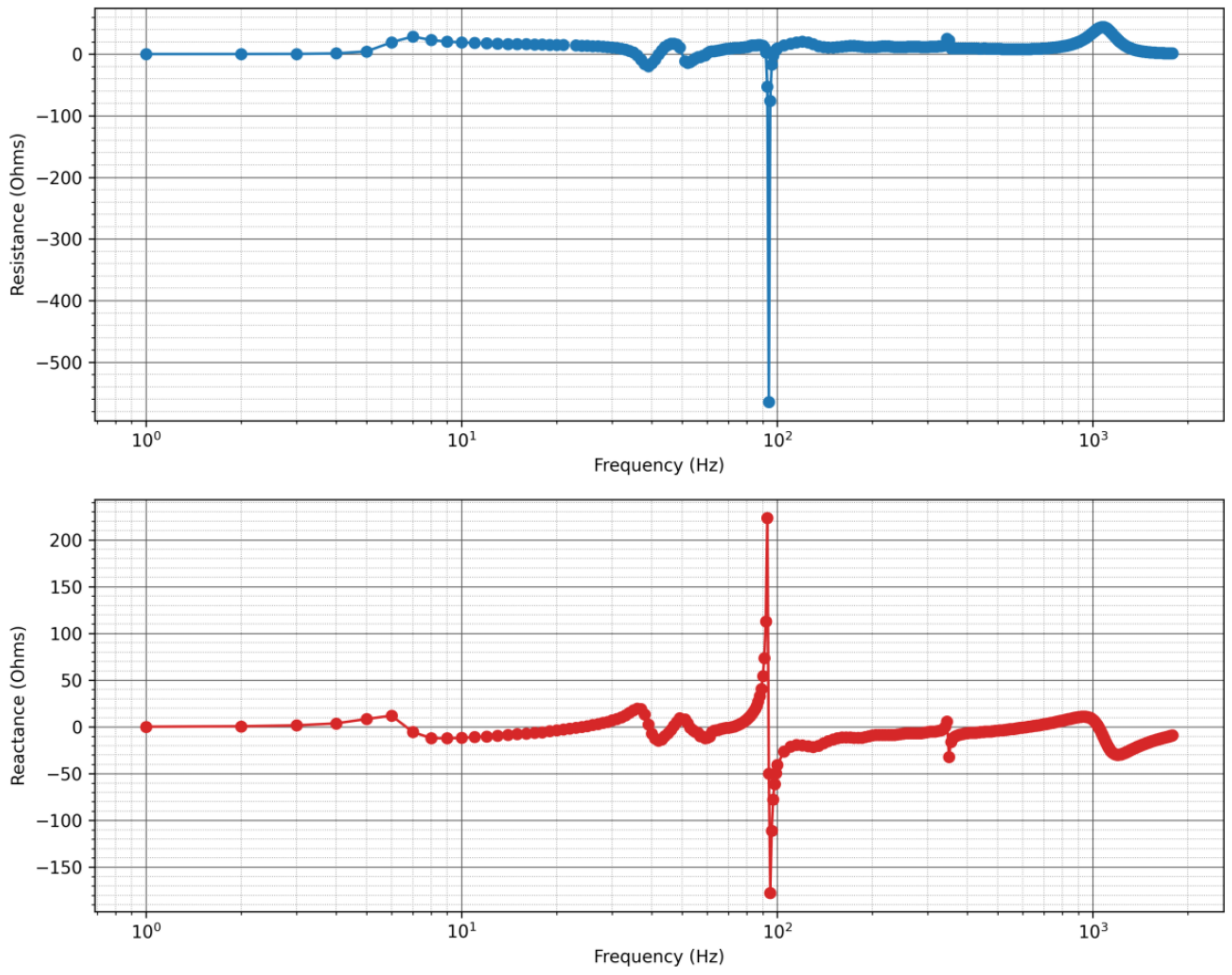
- Linearised system representation
- Small voltage perturbations injected at discrete frequencies
- Plant response compared against a baseline
- Gain used as an indicator of damping
  - Gain < 1 – damping contribution
  - Gain > 1 – amplification of oscillations



SSO ANALYSIS METHODS

Frequency-domain and impedance-based methods

- Active frequency scan performed at the point of connection
- Plant impedance derived as seen from the network
- Resistance and reactance evaluated across frequency
- Negative resistance used as an indicator of potential SSO risk



04.

NESO GUIDELINES

NESO GUIDELINES

Why were they issued?

System risk is changing

- Increasing penetration of IBRs
- Past SSO events
- Converter control interactions

Lessons from recent GB incidents

- NESO public reports
- Assets had to be re-tuned and phased back in to maintain stability
- Short circuit level alone proced insufficient as a risk indicator

Need for consistency and compliance

- Before 2023 no formal GB process for SSO compliance
- Developers faced uncertainty
- NESO guidance now standardises study scope, modelling and acceptance

Overall aim

- Protect network
- Provide developers with clear expectations
- Ensure a level playing field across all ner IBR connections

NESO’S METHODOLOGY

Earlier Approach	Updated Approach
- First formal requirement for SSO compliance in GB - Applied broadly to new IBR and BEGA/BELLA projects - Relied on EMT step tests, small-signal injections, and active frequency scans - Eigenvalue analysis optional - “One-size-fits-all” methodology	- Refines scope by technology and connection type - Grid-following: minimum short-circuit level studies. - Grid-forming: both minimum & maximum SCL - Requires MIMO scanning (multi-input multi-output), not just SISO - PSCAD MHI tool adopted, with transition period - More emphasis on system-wide interactions

NESO'S METHODOLOGY

- Study requirements depend on connection type
- Interaction-based tests prioritised for system-critical connections
- No single test determines compliance in isolation

Connection type	SSO Test Methods				
	Step change	Small signal injection - magnitude	Small signal injection - angle	Frequency scan	Eigenvalue analysis
Type A/B	Required	Optional	Optional	Optional	Optional
Directly Connected (Type C/D)	Optional	Required	Optional	Required	Optional

SSO Guideline Update – General Info, NESO

05.

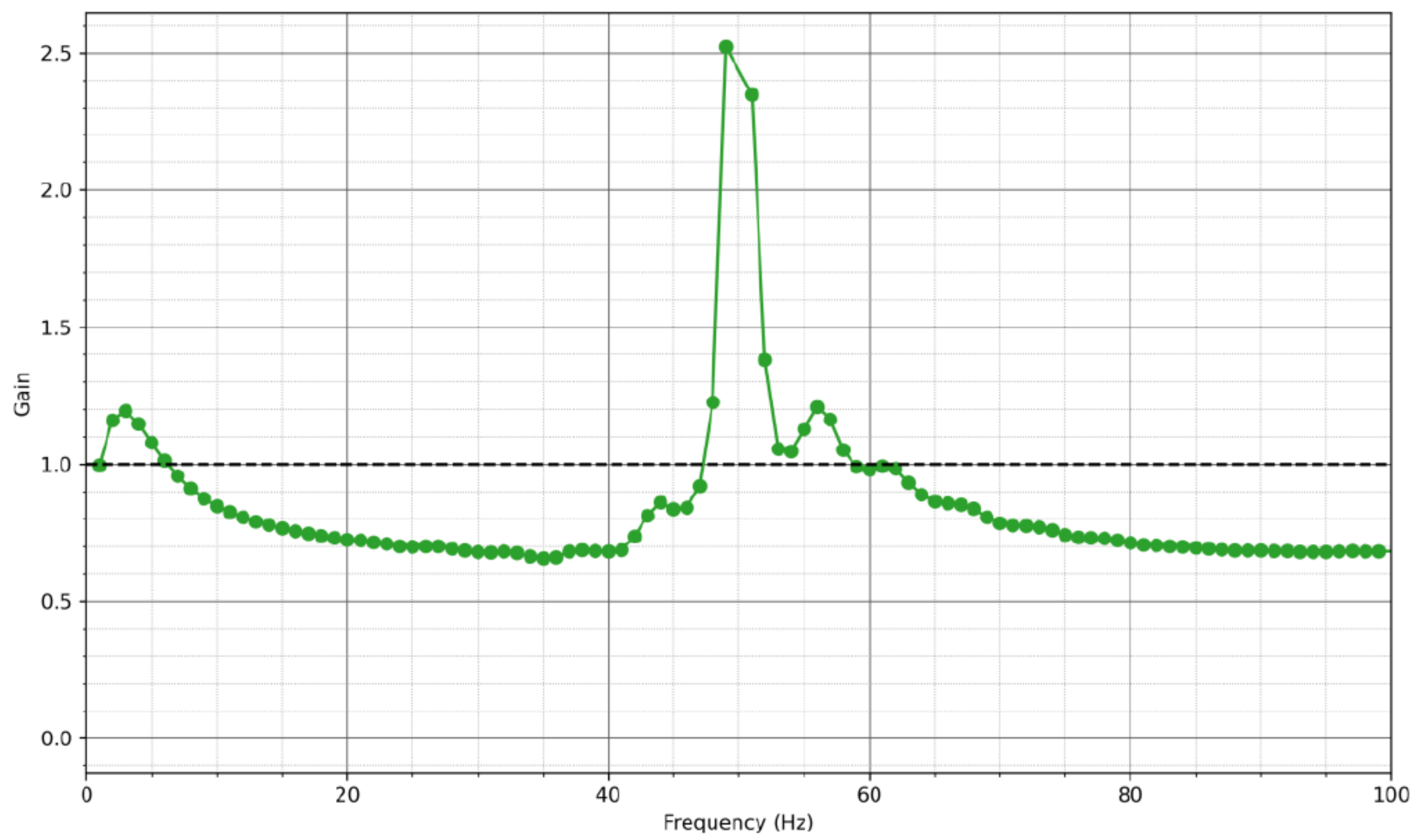
Example SSO Assessment

STUDY OVERVIEW

- Purpose
  - Assess risk of SSO associated with the connection of a large RES plant
  - Demonstrate compliance with NESO
- Scope
  - EMT-based assessment in PSCAD
  - External network represented using a Thevenin equivalent at the PCC
  - Minimum and maximum fault level conditions
  - Studies performed at defined operating points
- Assessment
  - Small-signal voltage injection (time-domain)
  - Active frequency scans (frequency-domain impedance analysis)

SMALL SIGNAL INJECTION

- Voltage perturbations injected across a wide frequency range.
- System response compared against a baseline case with the plant disconnected.
- Gain remained below unity for most frequencies, indicating adequate damping.
- Limited frequency bands showed gain slightly above unity, aligned with known control operating regions.
- Time-domain responses showed oscillations remained bounded and decayed once injections were removed.



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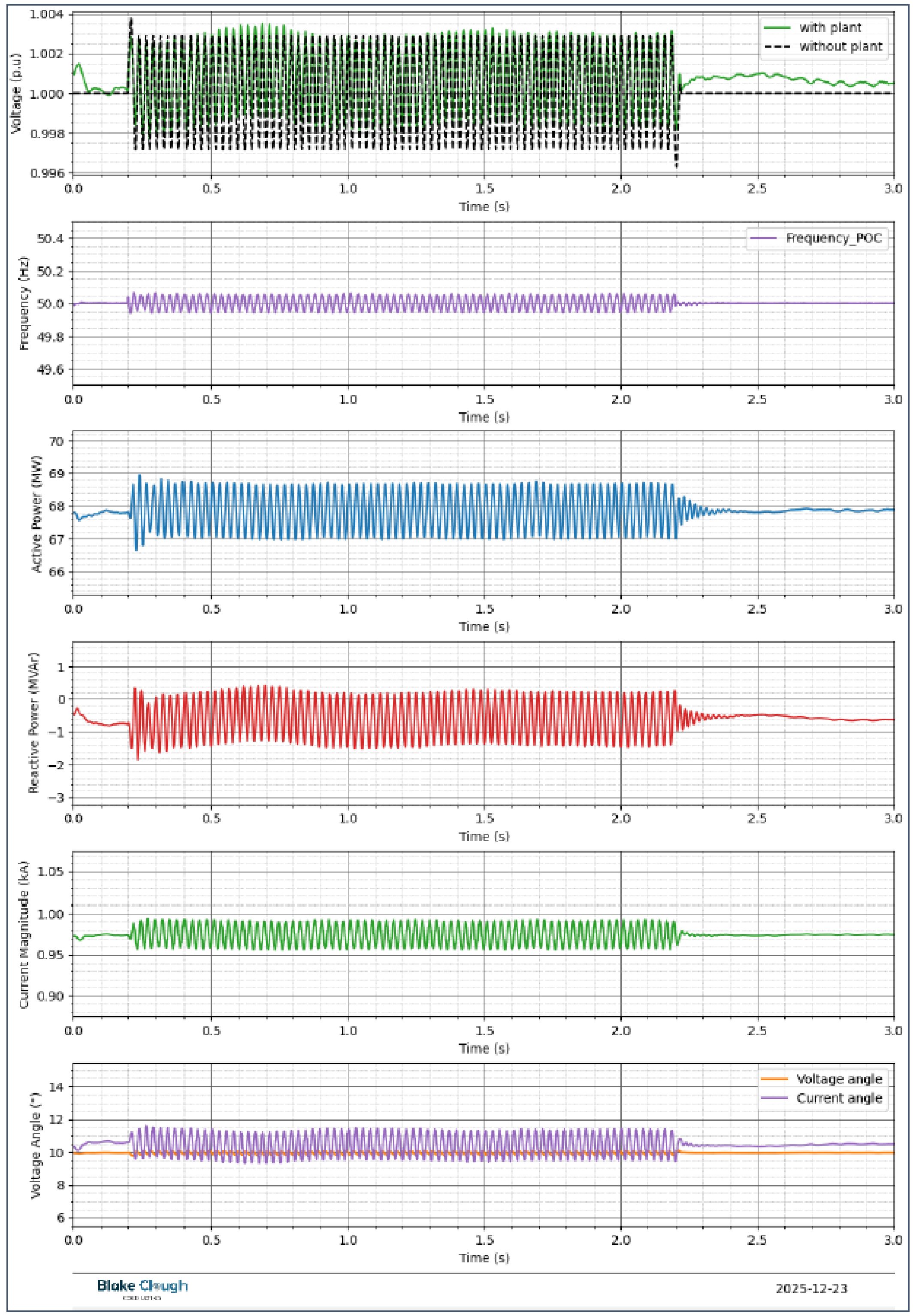
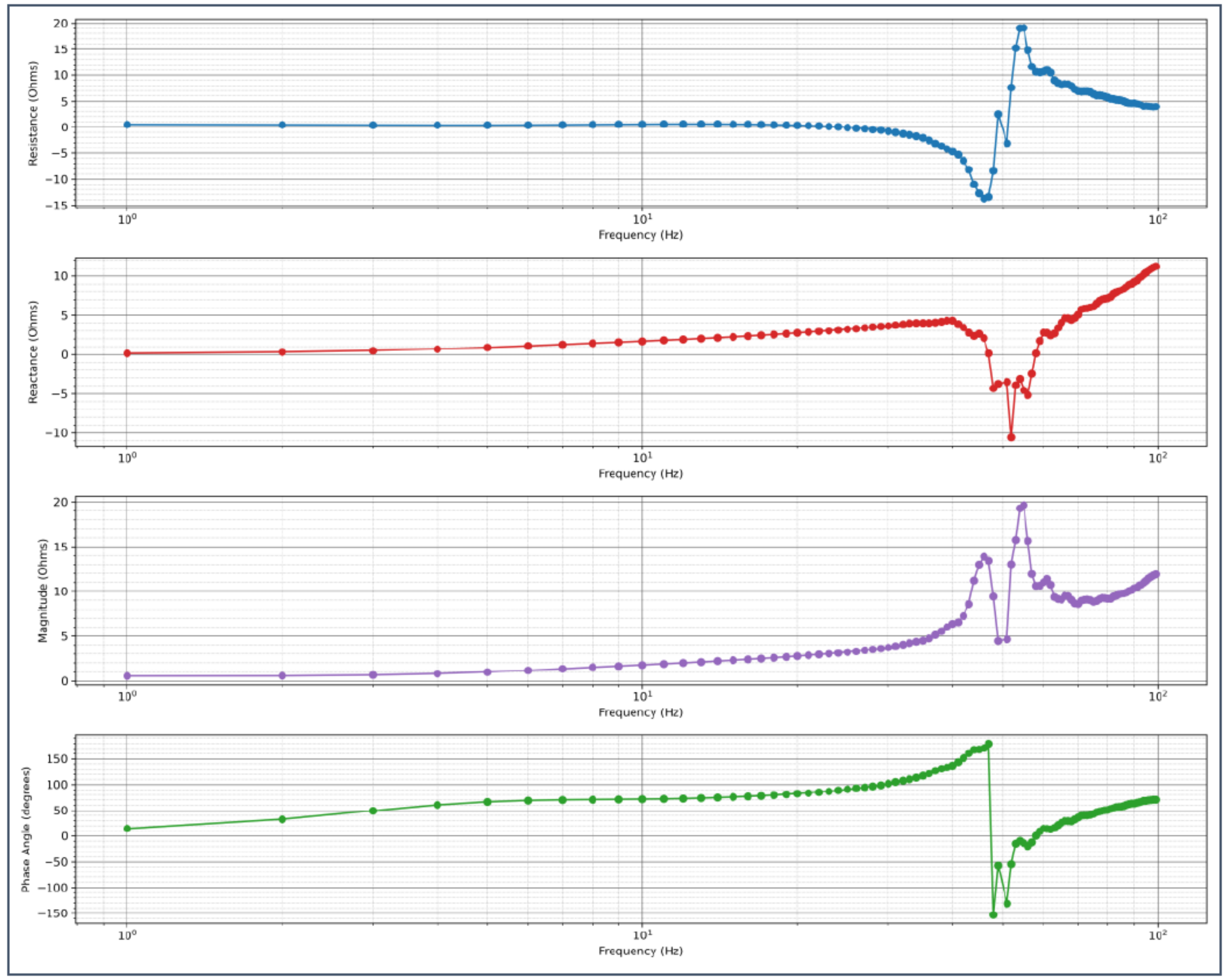


ACTIVE FREQUENCY SCAN

- Plant impedance measured across a broad frequency range.
- Negative resistance observed in specific frequency bands under weak-grid conditions.
- Follow-up time-domain injections confirmed oscillations were limited and non-divergent.
- Combined evidence indicated stable system behaviour, with no sustained SSO risk identified.



06.

MITIGATION STRATEGIES

MITIGATING SSOs

In practice,

- Traditional mitigation
  - Synchronous machines online, series capacitors bypass, torsional damping
- Modern mitigation
  - Converter control tuning, STATCOMs/FACTs with damping, adaptive control strategies

System strength & network measures

Converter Control Tuning

FACTS & compensation devices

Dedicated damping controllers

Operational measures

07.

TAKEAWAYS AND QUESTIONS

TAKEAWAYS AND QUESTIONS

Takeaways

- Converter–network interactions are now a dominant SSO driver
- No single method is sufficient; results must be interpreted together
- Frequency-domain indicators require time-domain confirmation
- NESO guidance improves consistency, but judgement remains essential

Discussion

- Are current SSO screening methods sufficient for future IBR-dominated systems?
- How much conservatism is appropriate when interpreting negative resistance or gain > 1?
- Is a Thevenin-equivalent network an adequate representation of the real system?

THANK YOU

Have any questions?

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