IMPERIAL

Stability as the core of flexibility

How to improve the stability of electrical systems

Balarko Chaudhuri & Mark O’Malley

8th XM Forum, Cartagena, Columbia, August 20th, 2026

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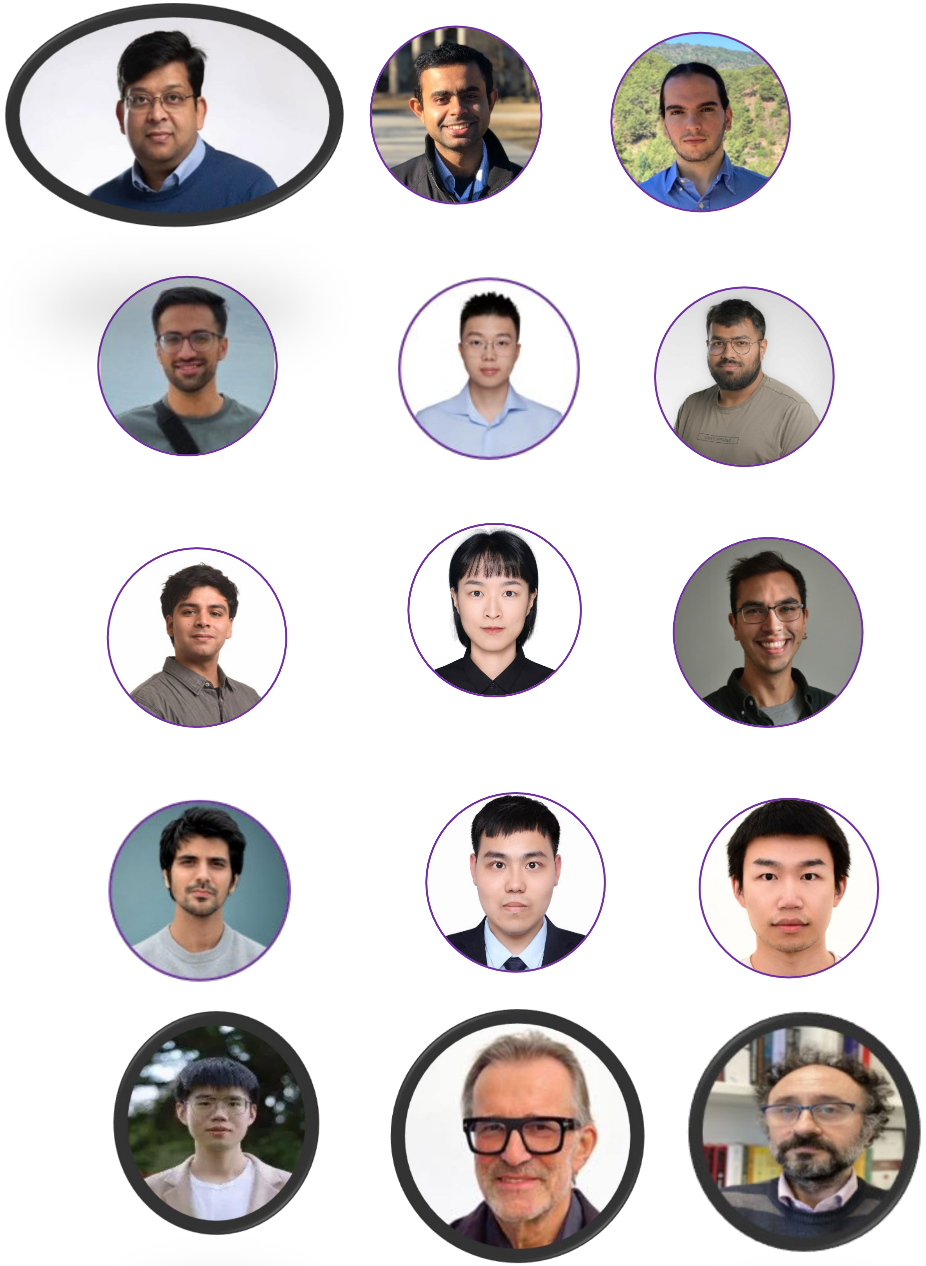
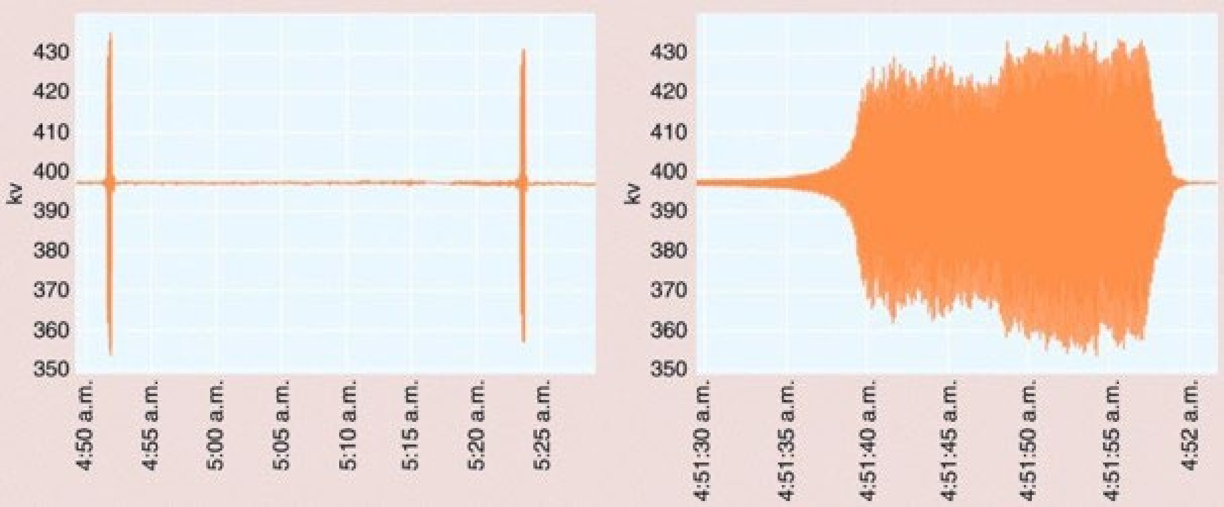


Global Power System Transformation Consortium Research Agenda

https://globalpst.org/wp-content/uploads/G-PST_Research_Agenda_2025_FINAL.pdf

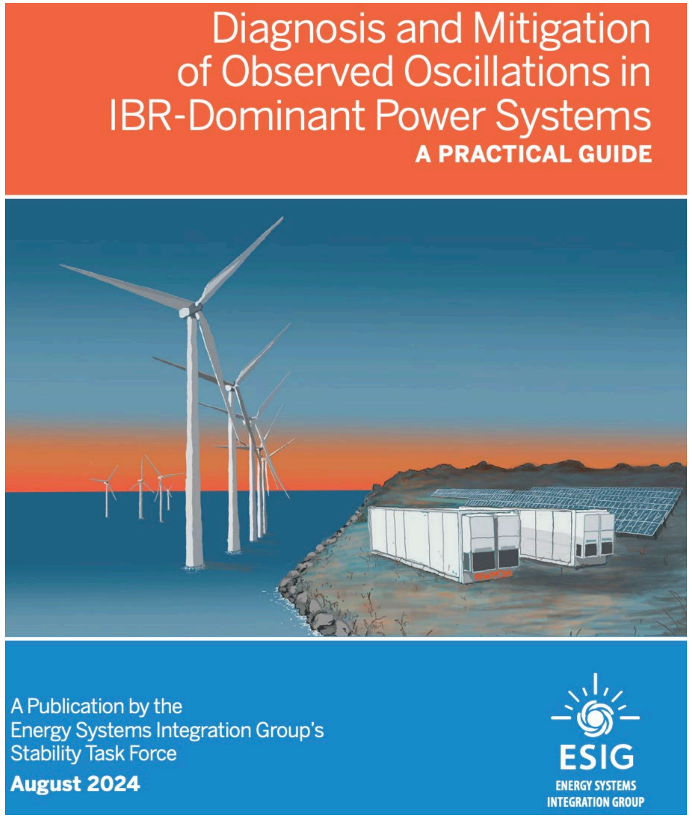
Wide-spread (or wide-area) SSO

Due to adverse interaction between IBRs and network



8 Hz oscillations in Scotland, 2021 (source NESO)

Miller et. al, “Diagnosis and Mitigation of Observed Oscillations in IBR-Dominant Power Systems: A Practical Guide” ESIG Stability TF, 2024



High Inverter-Based Resource Integration

POWER SYSTEM TRANSFORMATION BRINGS A number of challenges, such as interconnecting inverter-based resources (IBRs) and assessing their impact on system security and reliability, ensuring that appropriate

The Experience of Five System Operators

Modi et. al., "High Inverter-Based Resource Integration: The Experience of Five System Operators," *IEEE P&E Mag*, 22(2), Mar-Apr 2024

316 IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 38, NO. 1, JANUARY 2023

Real-World Subsynchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources

Yunzhi Cheng, *Senior Member, IEEE*, Lingling Fan, *Fellow, IEEE*, Jonathan Rose, Shun-Hsien Huang, John Schmall, Xiaoyu Wang, *Senior Member, IEEE*, Xiaorong Xie, *Senior Member, IEEE*, Jan Shair, Jayanth R. Ramamurthy, *Senior Member, IEEE*, Nilesh Modi, Chun Li, *Senior Member, IEEE*, Chen Wang, Shahil Shah, *Senior Member, IEEE*, Bikash Pal, *Fellow, IEEE*, Zhixin Miao, *Senior Member, IEEE*, Andrew Isaacs, Jean Mahseredjian, *Fellow, IEEE*, and Jenny Zhou, *Senior Member, IEEE*

***Abstract*—This paper presents a survey of real-world subsynchronous oscillation events associated with inverter-based resources (IBR) over the past decade. The focus is on those oscillations in the subsynchronous frequency range known to be influenced by power grid characteristics, e.g., series compensation or low system strength. A brief overview of the historical events is presented followed by detailed descriptions of a series of events. This paper also examines causation mechanisms and proposes future research directions to meet grid needs worldwide.**

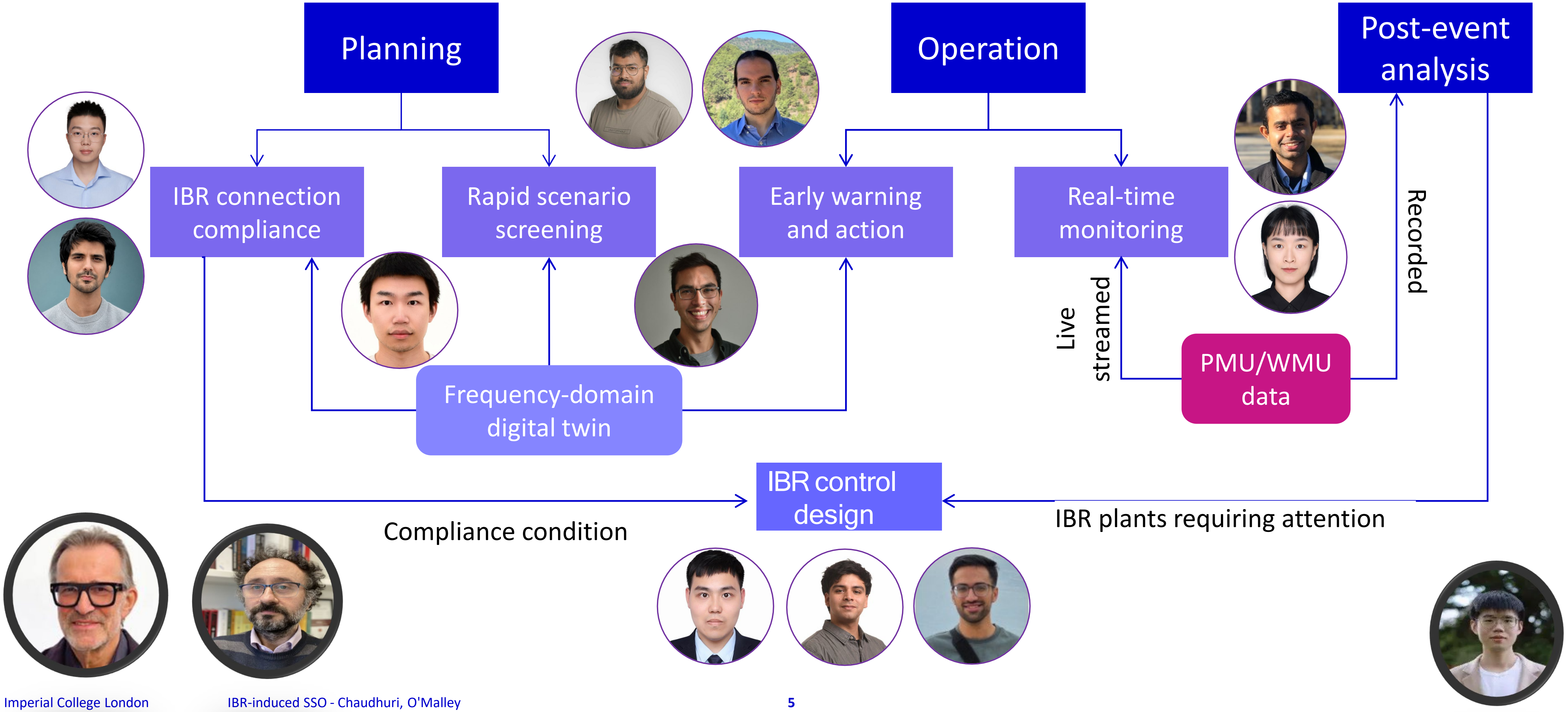
I. Introduction

PENETRATIONS of inverter-based resources (IBRs) are increasing worldwide. The maximum instantaneous penetration levels of IBRs in South Australia, Texas, Ireland, and Tasmania have reached 150%, 66%, 92%, and 95%, respectively [1]. The operation with such high levels of IBRs has introduced undesirable dynamics, including subcycle overvoltage [2], ac

Cheng et al., "Real-World Subsynchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources," *IEEE TPWRS*, 38(1), 2023

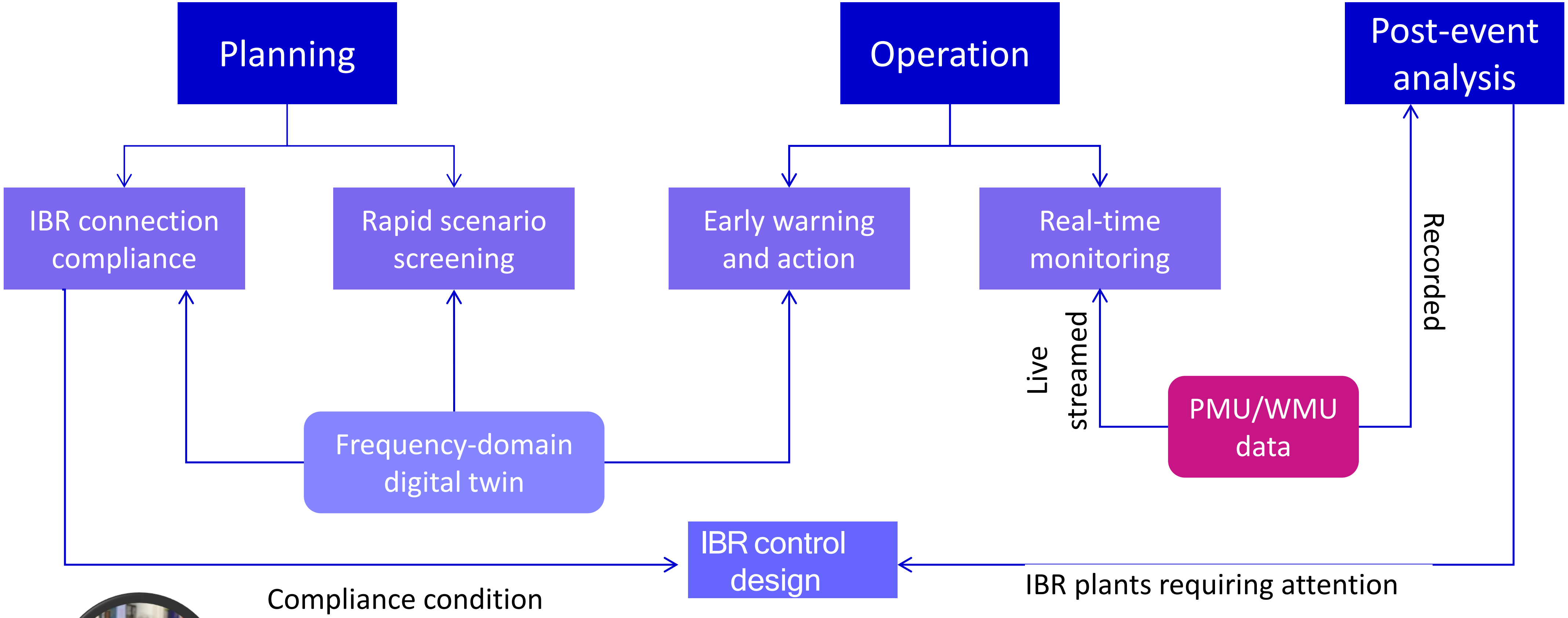
Identify and mitigate SSO risk

Multi-layered defense & attack – team positions and game plan



Identify and mitigate SSO risk

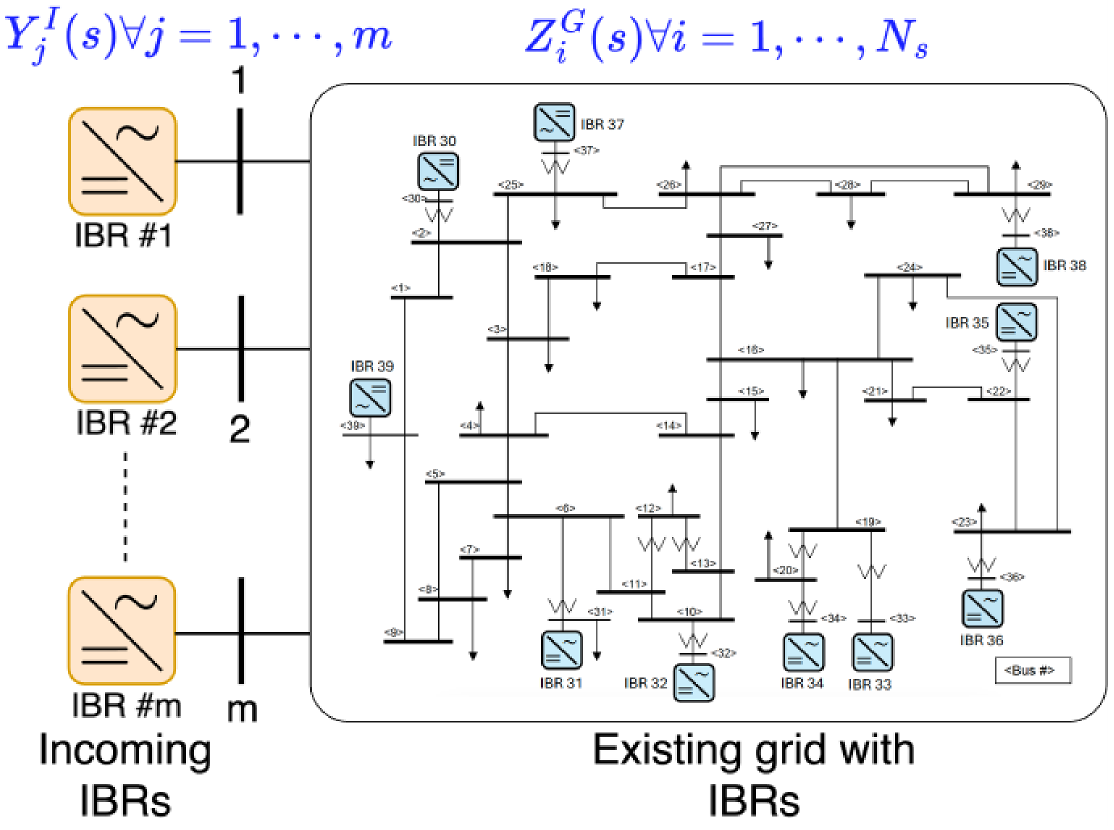
Multi-layered defense & attack


Enhanced connection compliance

Decentralised stability condition for a batch of upcoming IBRs

- State of the art
  - Simplistic representation of the grid
  - Each connecting IBR considered in isolation
- Develop a decentralised stability criterion to be satisfied by each of m upcoming IBRs with admittance transfer function $Y_j^I(s) \forall j = 1,2,\cdots,m$
  - minimum conservativeness
  - cover 'all credible' or 'worst case' operating points $Z_i^G(s) \forall i = 1,2,\cdots,N_s$
- Locally verifiable criterion but provides stability (and damping) guarantee for the batch of IBRs
- Block diagonal dominance (BDD) to reduce conservativeness

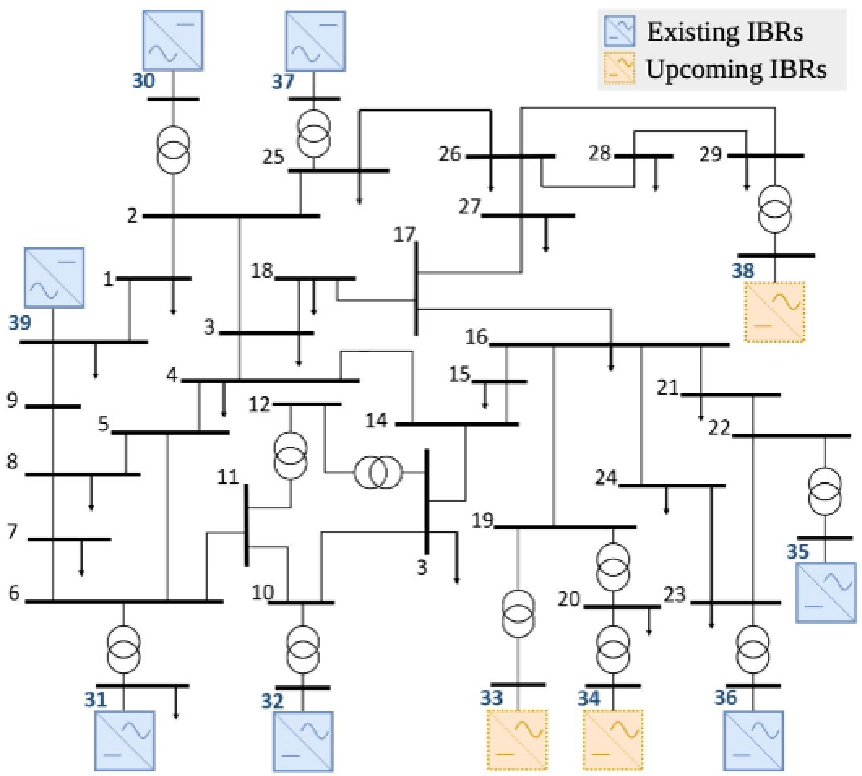


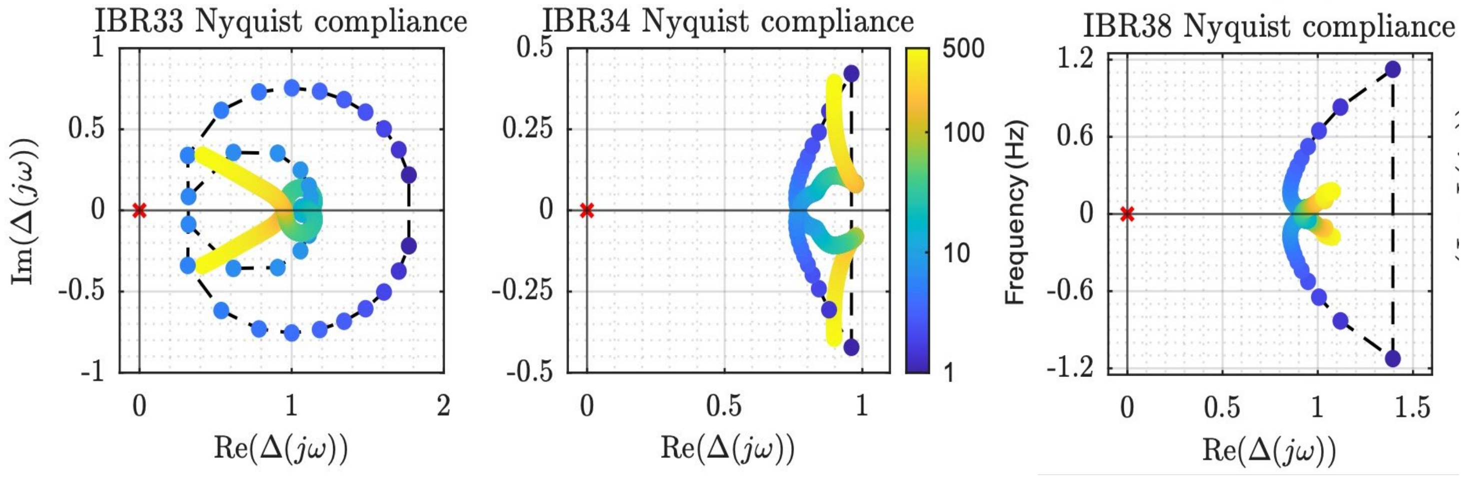
Researchers: Steven Tan, Sharjeel Javaid, Youhong Chen

Chen, Tan, Javaid, Angeli, and Chaudhuri, "Decentralized Stability of IBR-dominated Power Grids Using Block Diagonal Dominance," https://arxiv.org/abs/2606.28023

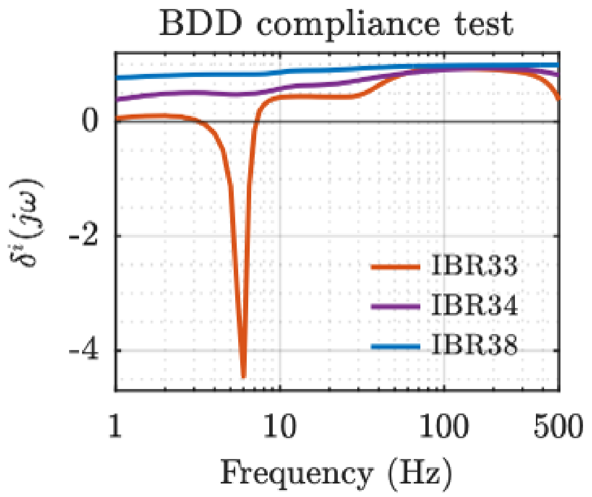
Validation of BDD for connection compliance

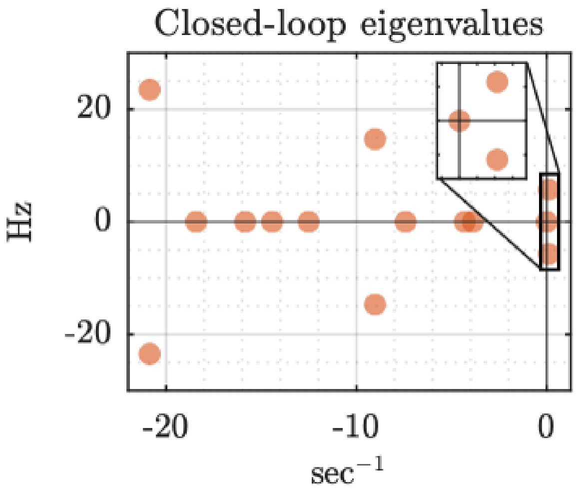
IEEE 39-bus test system with 3 upcoming GFLs





All 3 local Nyquist compliance test passed but overall system unstable



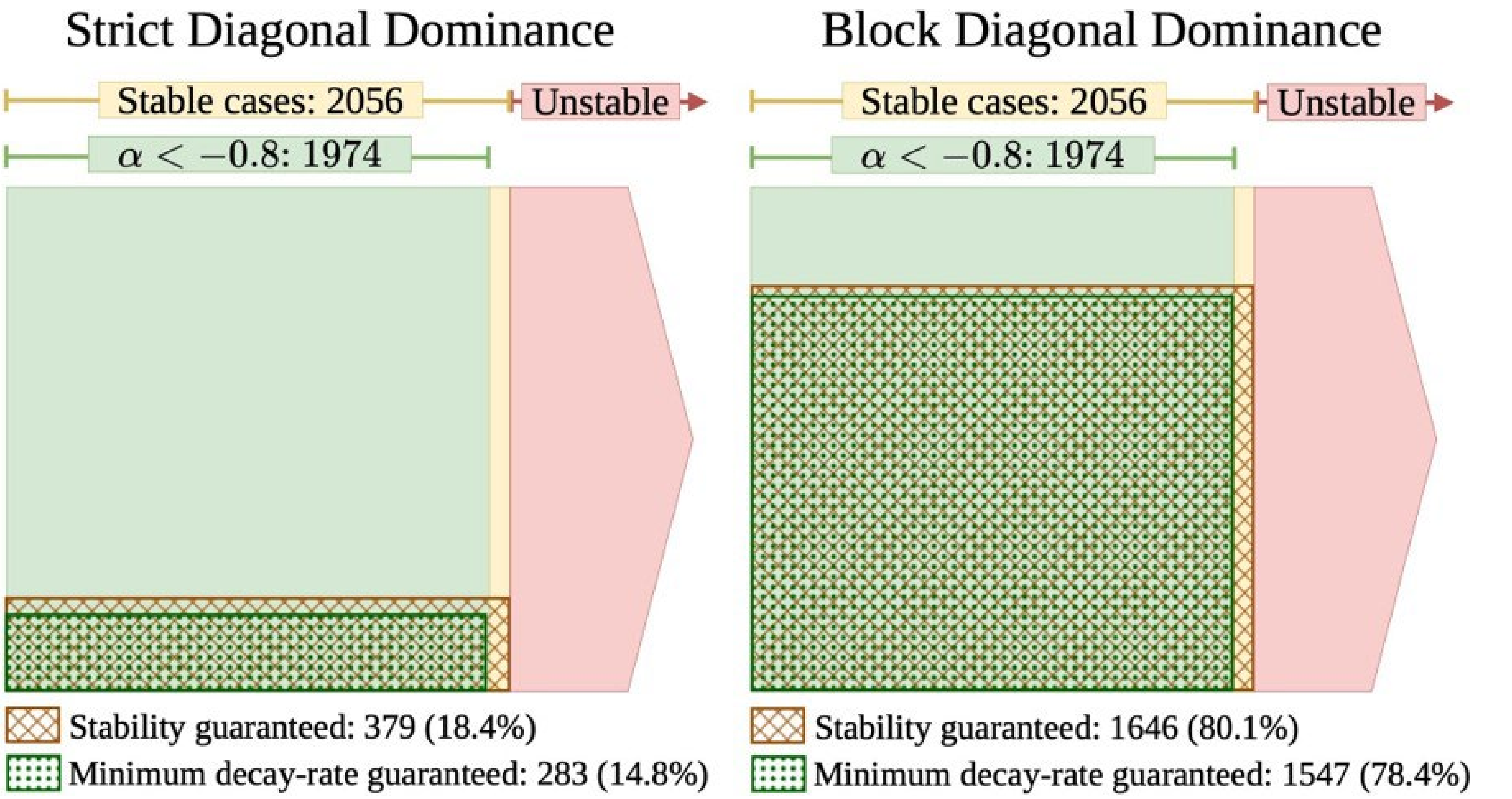


IBR 33 failing BDD test would have flagged potential instability

Chen, Tan, Javaid, Angeli, and Chaudhuri, "Decentralized Stability of IBR-dominated Power Grids Using Block Diagonal Dominance," https://arxiv.org/abs/2606.28023

Conservativeness of BDD

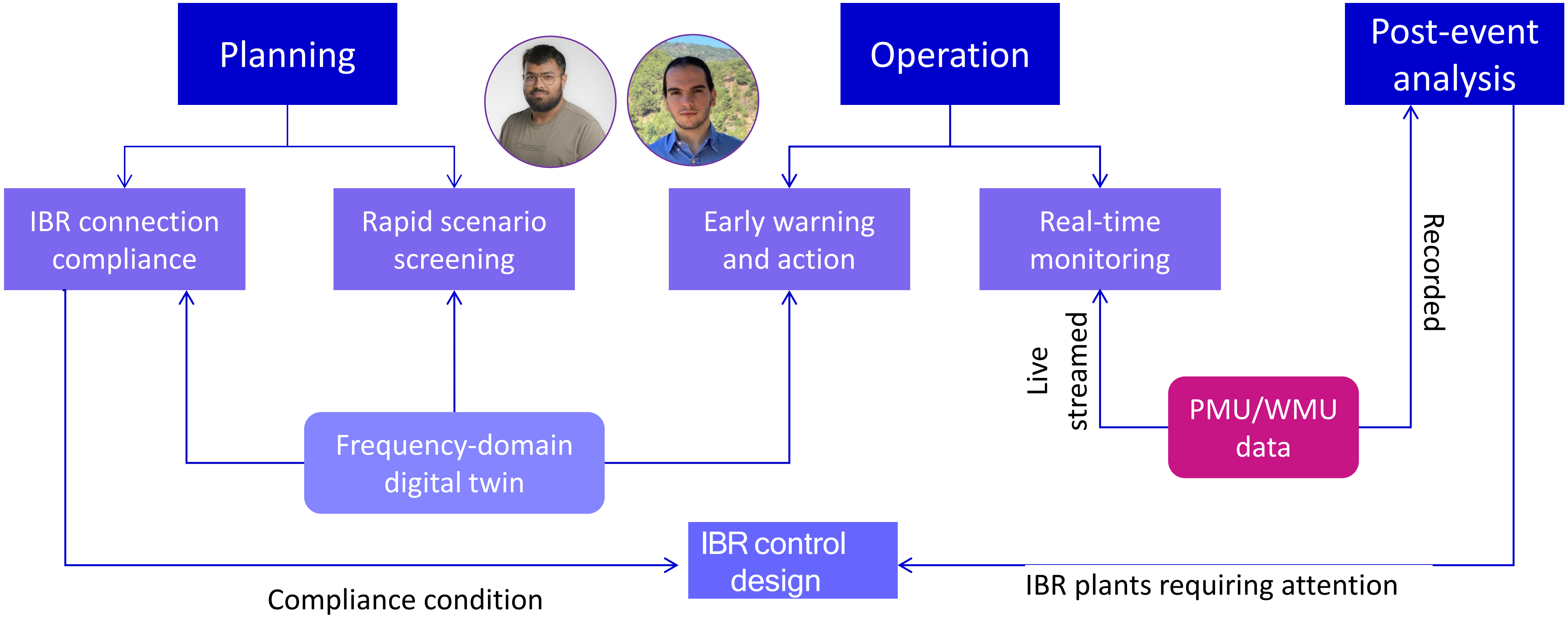
Monte-Carlo study on IEEE 39-bus system with 100% IBRs



Chen, Tan, Javaid, Angeli, and Chaudhuri, "Decentralized Stability of IBR-dominated Power Grids Using Block Diagonal Dominance," https://arxiv.org/abs/2606.28023

Identify and mitigate SSO risk

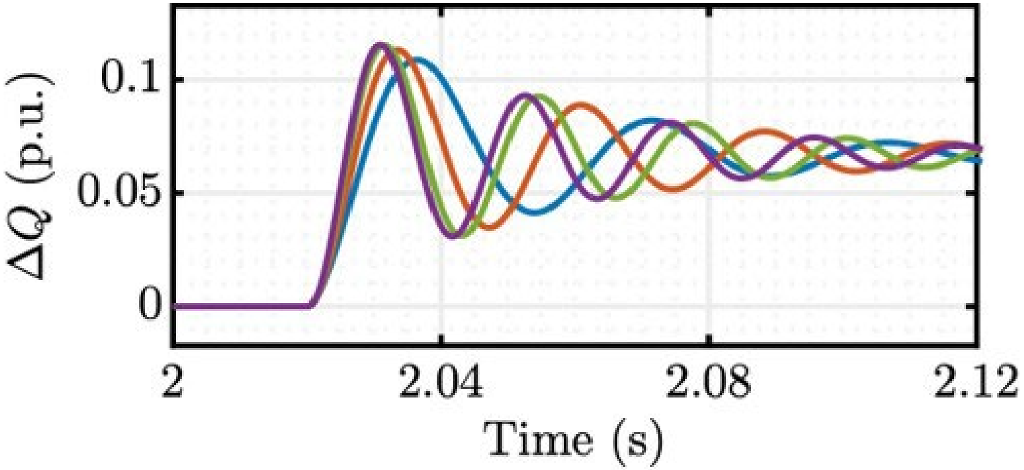
Multi-layered defense & attack

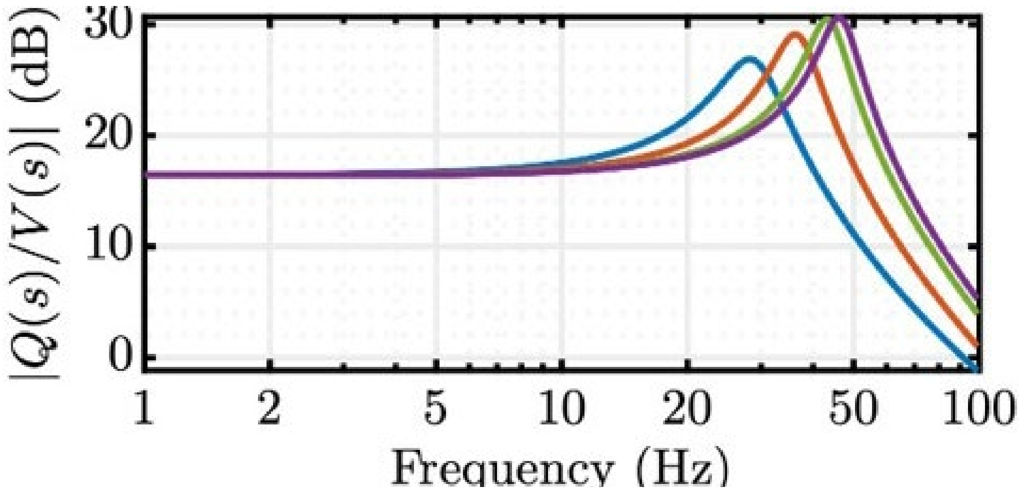


System strength metric for SSO risk screening

Jacobian voltage stiffness metric (JVSM)

- JVSM stems from GFM voltage stiffness characterization
- Captures both magnitude and speed of response





$$\mathrm{JVSM}_V = \frac{\displaystyle\int_{f_{\min}}^{f_{\max}} \left|\frac{Q(s)}{V(s)}\right| \log_{10}(f)\, df}{\displaystyle\int_{f_{\min}}^{f_{\max}} \log_{10}(f)\, df}$$

$$\mathrm{JVSM}_\theta = \frac{\displaystyle\int_{f_{\min}}^{f_{\max}} \left|\frac{P(s)}{\theta(s)}\right| \log_{10}(f)\, df}{\displaystyle\int_{f_{\min}}^{f_{\max}} \log_{10}(f)\, df}$$

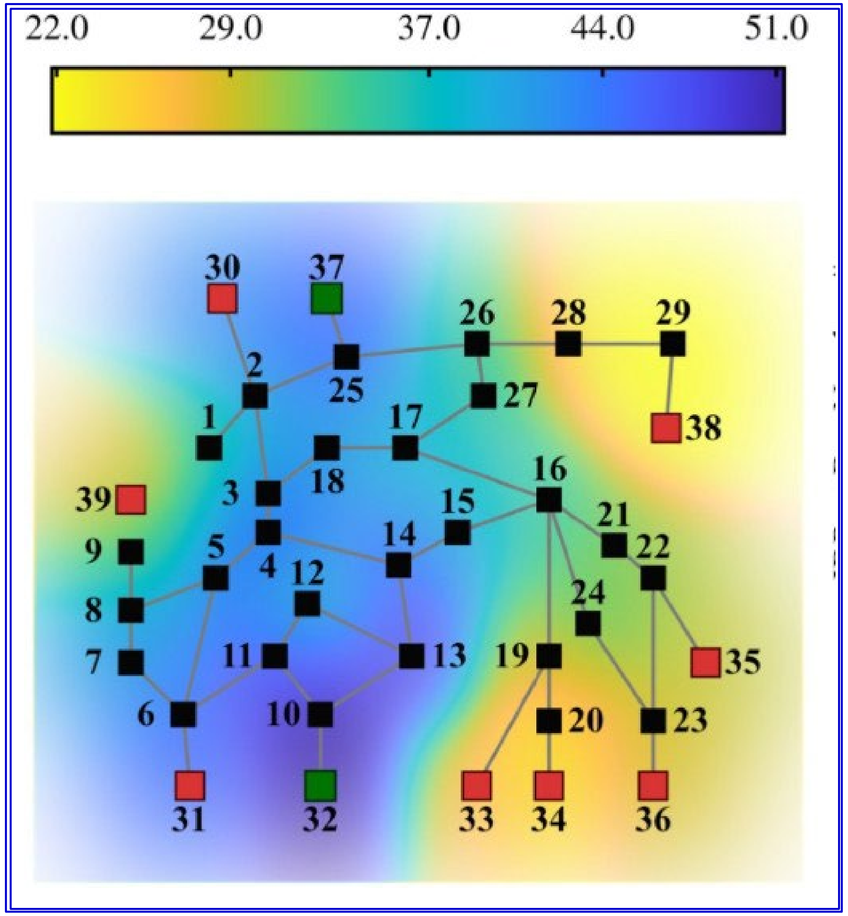
$$\mathrm{JVSM} = \sqrt{\frac{\mathrm{JVSM}_\theta^2 + \mathrm{JVSM}_V^2}{2}}$$

Researcher: Ambuj Gupta

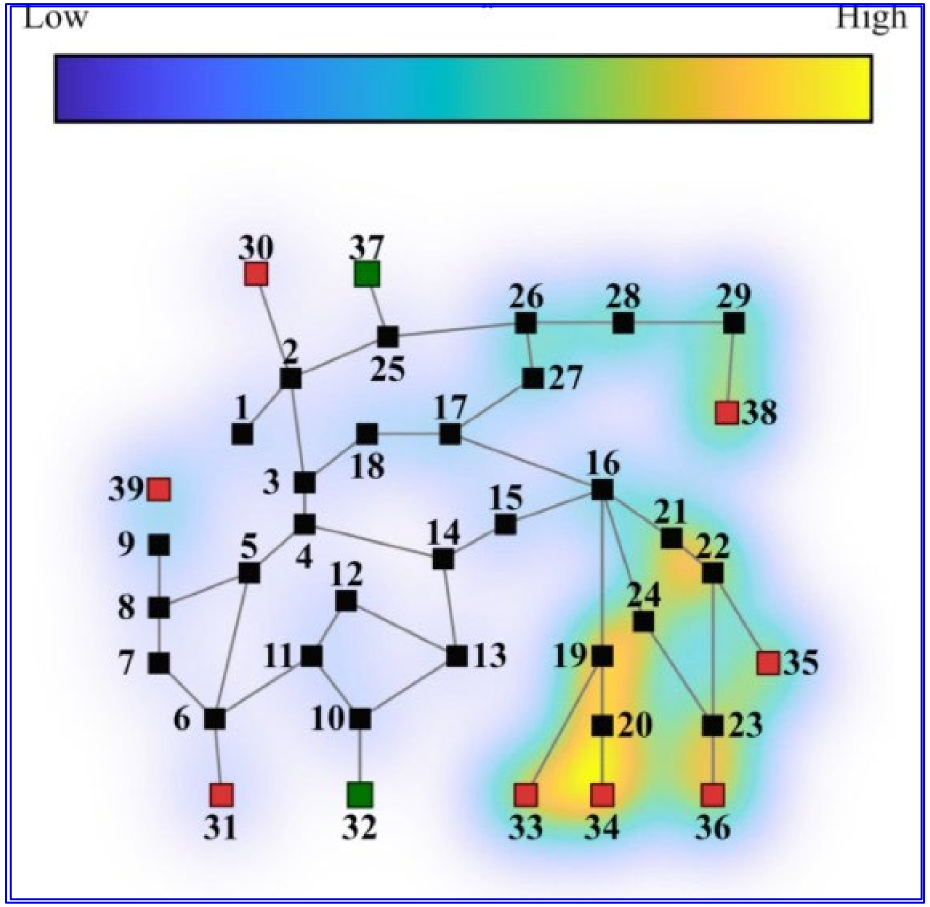
Gupta, Chaudhuri, and O'Malley, "Jacobian Voltage Stiffness Metric - A Measure of Grid-Forming Capability and System Strength in IBR-Dominated Grids," https://arxiv.org/abs/2607.09249

JVSM – an effective proxy of SSO risk

Validation on IEEE 39-bus test system with 100% IBRs



JVSM



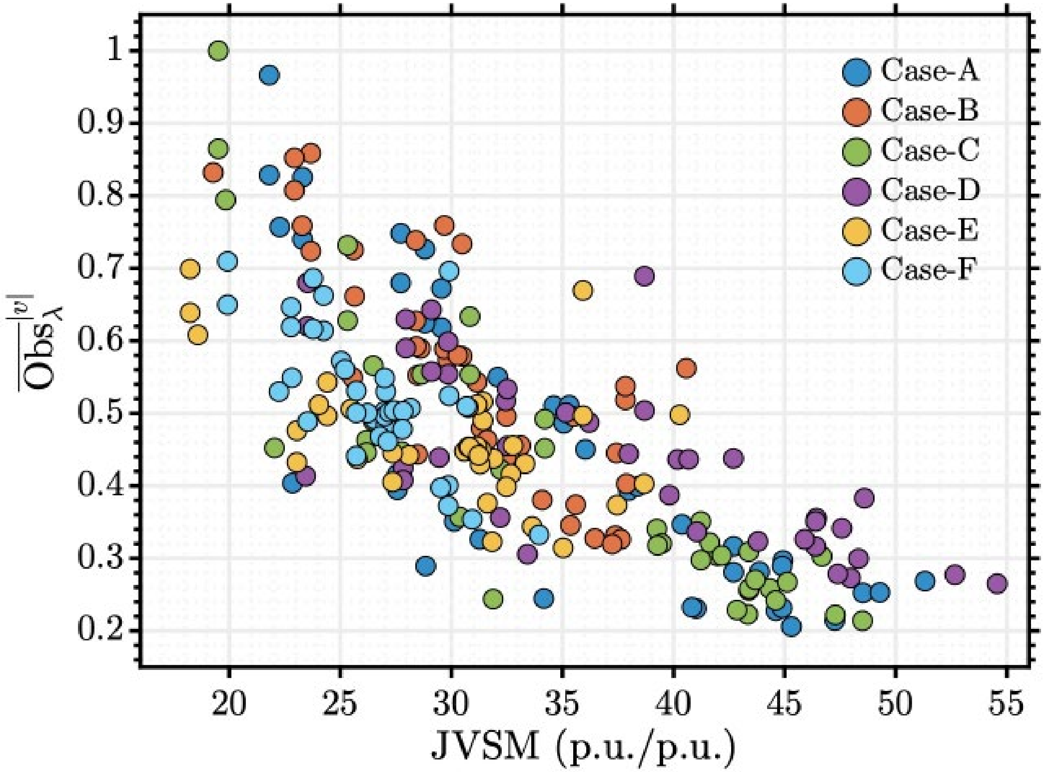
Observability of bus voltage

Where JVSM is low (high), SSO is more (less) pronounced

Gupta, Chaudhuri, and O'Malley, "Jacobian Voltage Stiffness Metric - A Measure of Grid-Forming Capability and System Strength in IBR-Dominated Grids," https://arxiv.org/abs/2607.09249

Validate JVSM for different scenarios

Case / Bus	30	37	39	31	32	33	34	35	36	38
Case-A	GFL	**GFM**	GFL	GFL	**GFM**	GFL	GFL	GFL	GFL	GFL
Case-B	GFL	GFL	**GFM**	GFL	GFL	GFL	GFL	**GFM**	GFL	GFL
Case-C	GFL	GFL	**GFM**	GFL	GFL	GFL	GFL	GFL	GFL	**GFM**
Case-D	GFL	GFL	GFL	**GFM**	GFL	GFL	GFL	**GFM**	GFL	GFL
Case-E	GFL	GFL	GFL	**GFM**	GFL	GFL	GFL	GFL	GFL	**GFM**
Case-F	GFL	GFL	GFL	GFL	GFL	GFL	GFL	GFL	**GFM**	**GFM**



- Mean voltage-magnitude observability of worst-damped modes vs. bus-wise JVSM for the six cases/scenarios
- Higher JVSM values correspond to lower observability
- Consistent inverse trend demonstrates JVSM as a pre-screening tool for identifying weak buses vulnerable to SSO

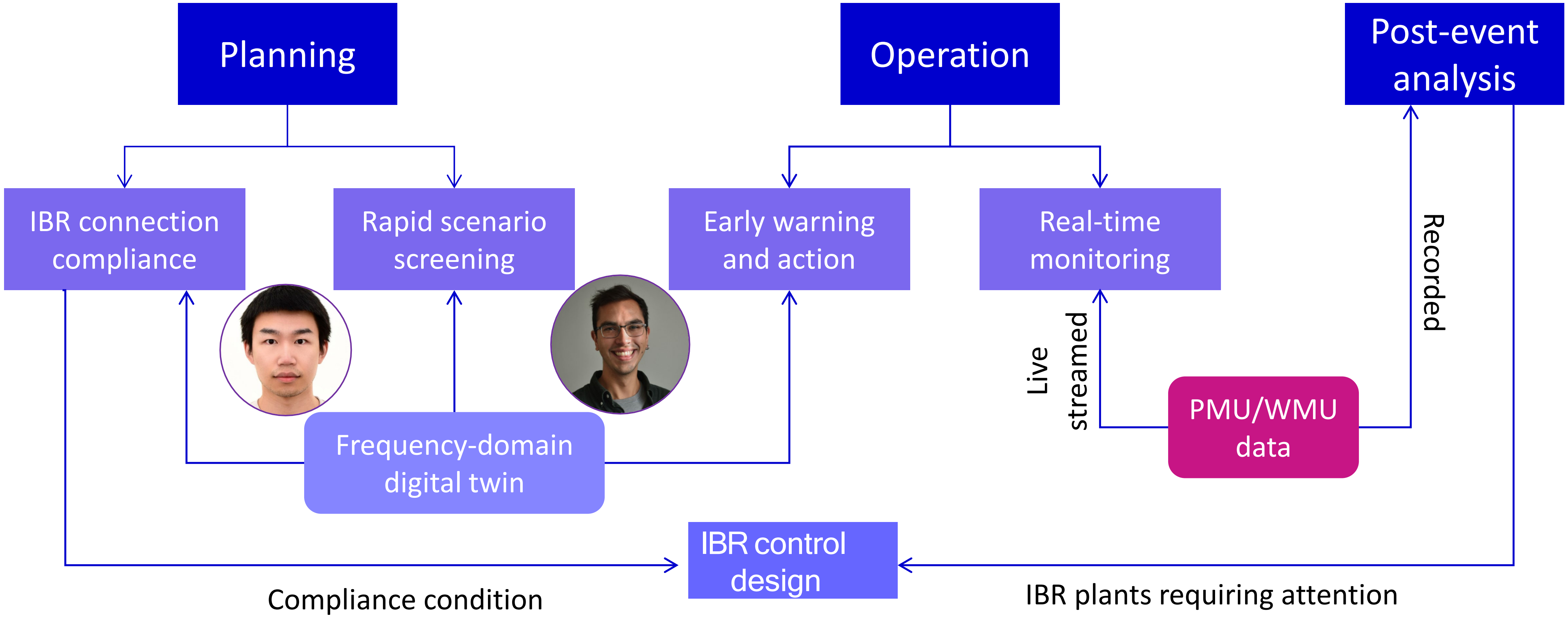
Gupta, Chaudhuri, and O'Malley, "Jacobian Voltage Stiffness Metric - A Measure of Grid-Forming Capability and System Strength in IBR-Dominated Grids," https://arxiv.org/abs/2607.09249

JVSM overcomes the drawbacks of existing metrics

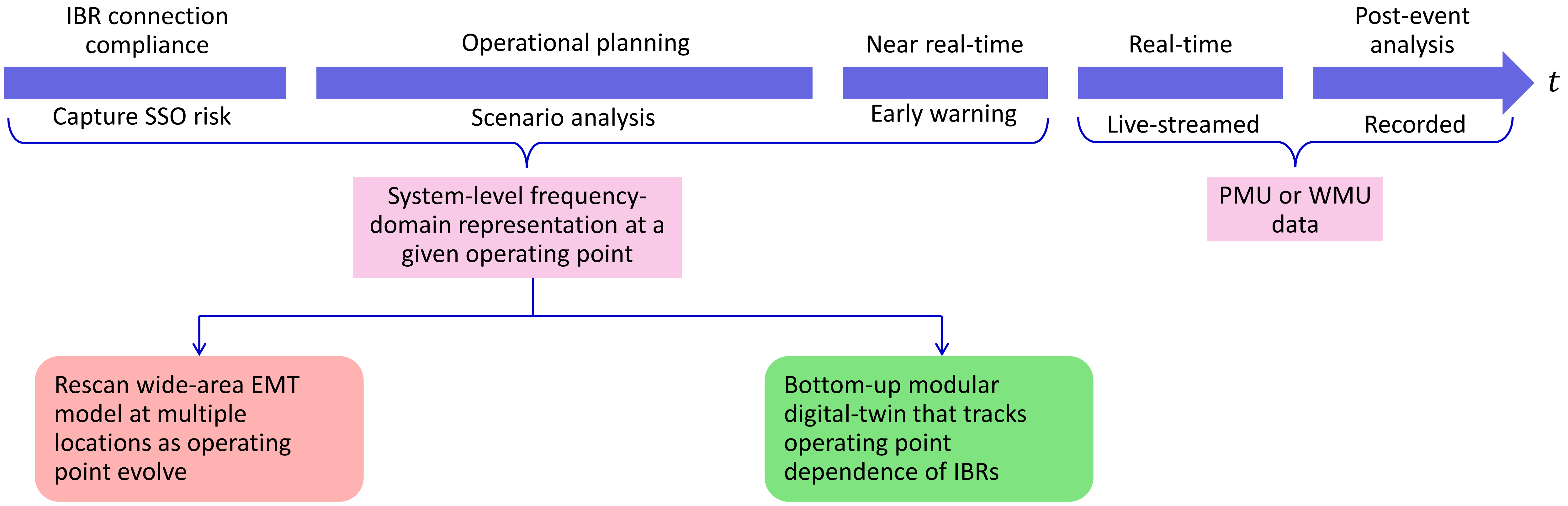
Metric	Single strength value	No ideal-VSBI assumption	Captures frequency dynamics	No reference impedance needed	Grid-impedance independent	No Vector Fitting, eigenvalue or singular-value analysis	Preserves coupling dynamics
gSCR	✓	✗	✗	N/A	N/A	✗	✓
IMR / AM	✗	✓	✓	N/A	N/A	✗	✓
DZM / NSCR / dSCR	✓	✗	✗	✓	✓	✓	✓
GSIM / DSI	✗	✓	✓	✗	✓	✗	✗
FI	✗	✓	✓	✓	✗	✗	✗
JVSM	✓	✓	✓	✓	✓	✓	✓

Identify and mitigate SSO risk

Multi-layered defense & attack



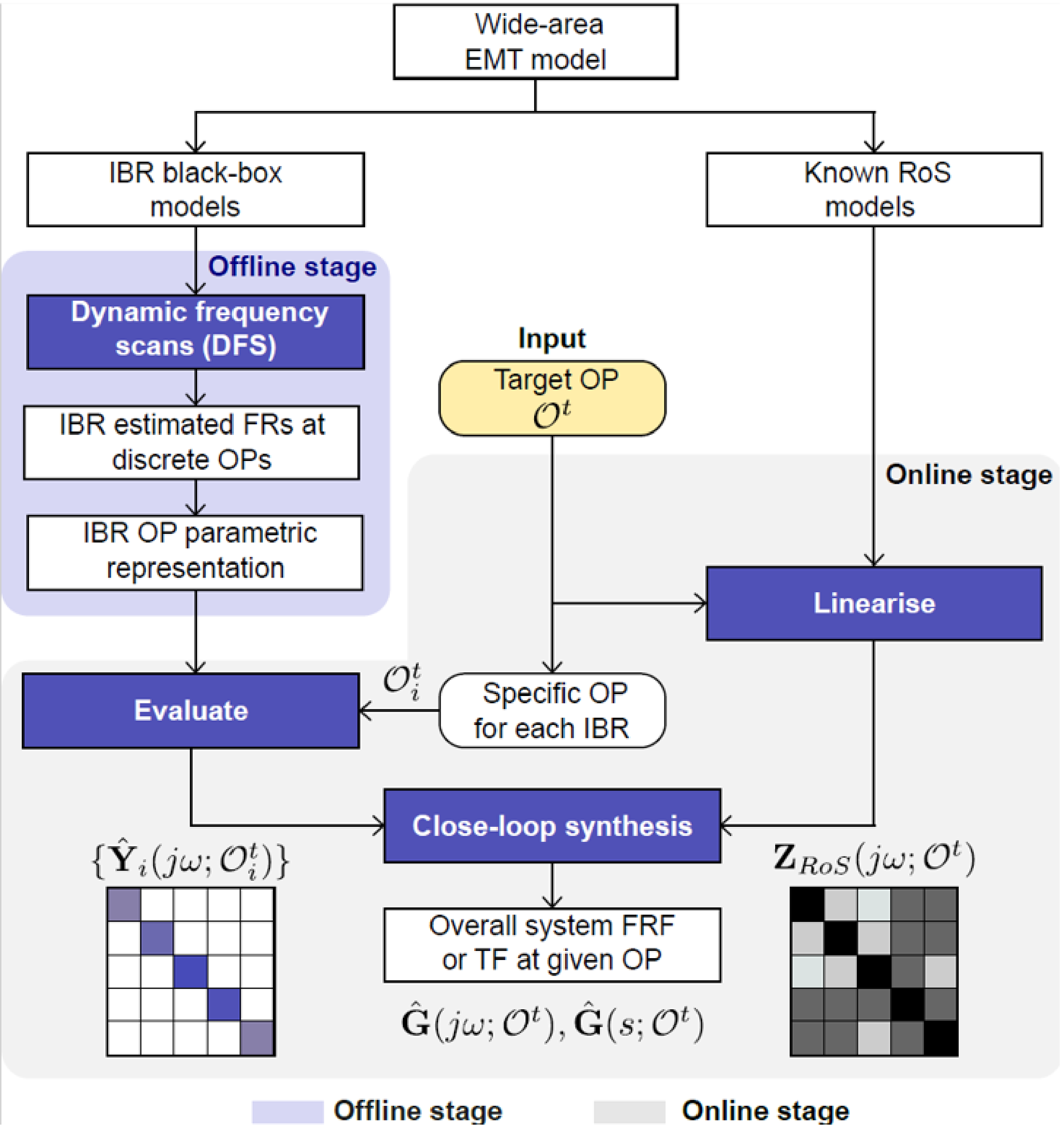
Frequency domain digital twin



- Needs wide-area EMT model
- System-level scan at different locations
- Repeat as operating point evolve
- Computationally intensive
- Component saturation

- IBR frequency scans across its operating range provided by vendors /developers
- Parameterise IBR operating point dependence
- Readily obtain system level frequency response (or transfer function) at a given operating point

Frequency-domain digital twin

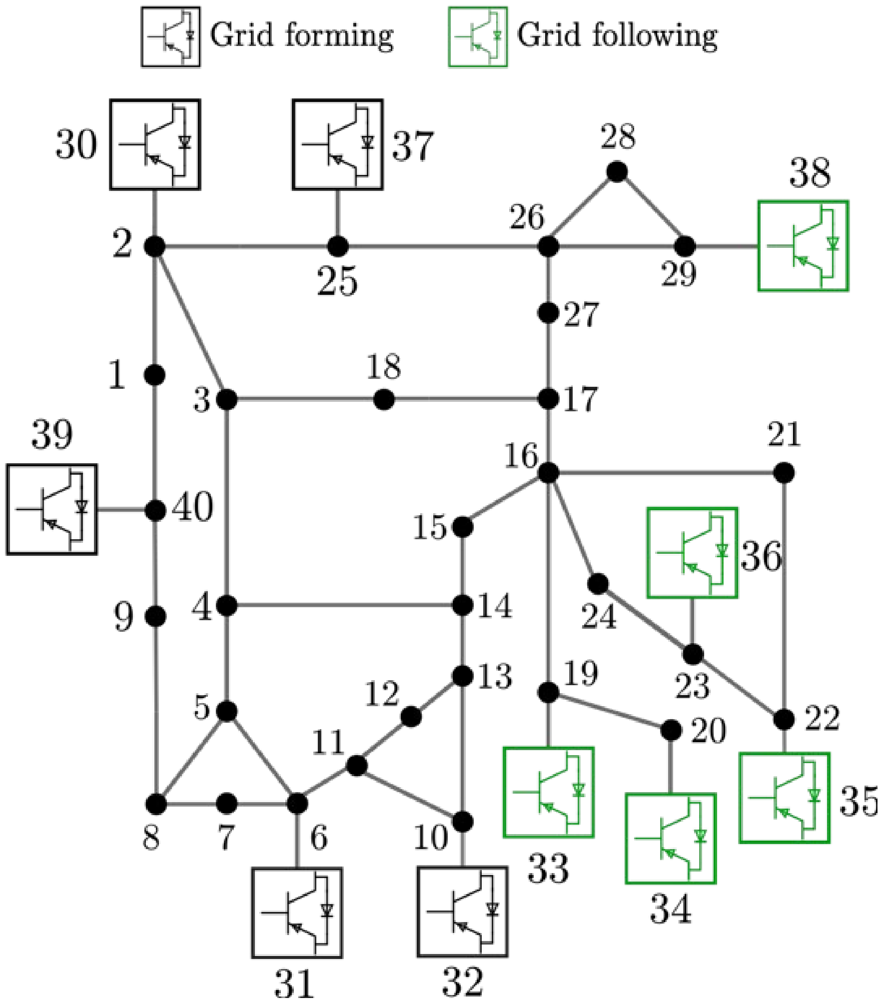


Researcher: Gabriel Covarrubias Maureira

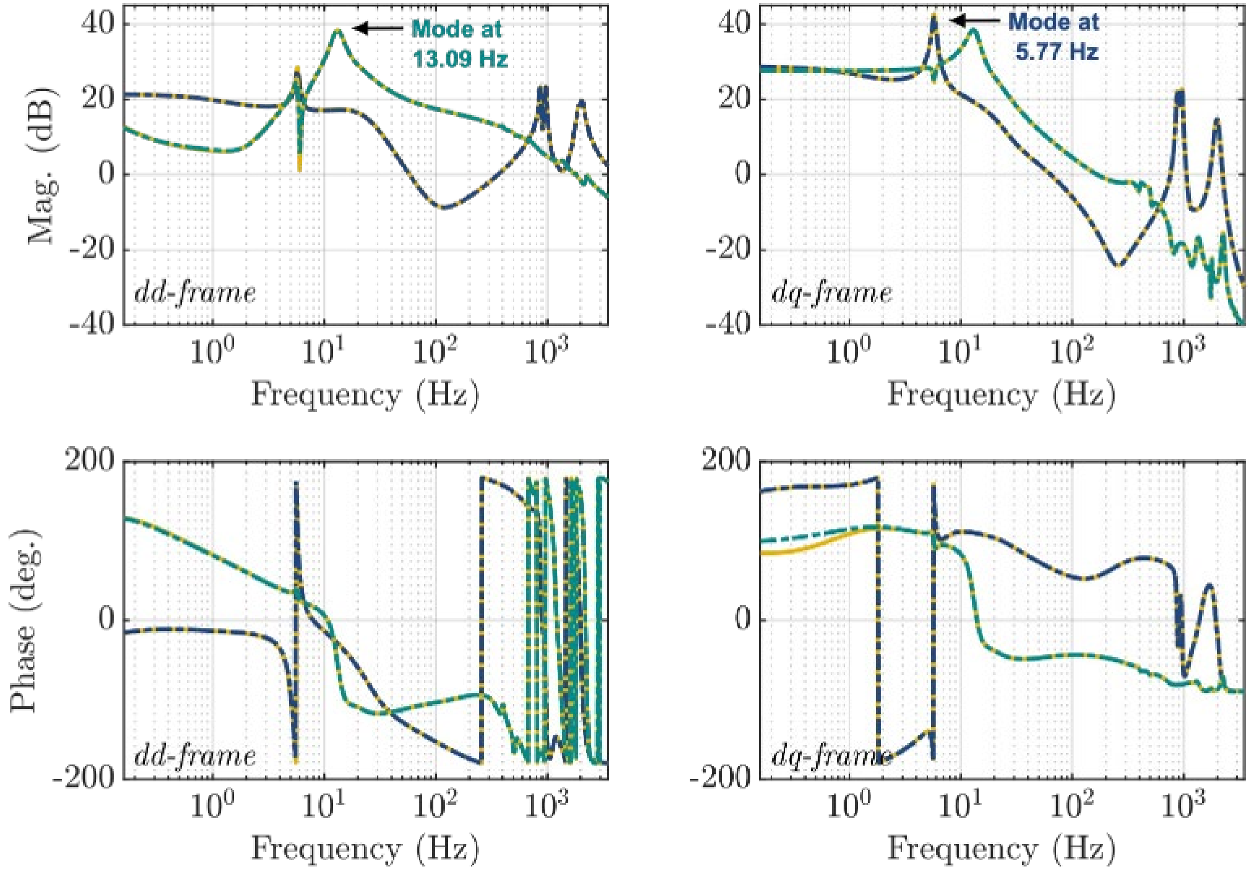
Covarrubias Maureira, Chaudhuri, and O'Malley, "Parameterizing Operating-Point-Dependent IBR Using Coherent Operating Regions for Sub-synchronous Oscillation Analysis," https://arxiv.org/abs/2607.00216

Validation of digital twin

Modified IEEE 39-bus test system with 100% IBRs



Frequency responses at bus 6 (green) and 22 (blue) compared against actual model-based (yellow)

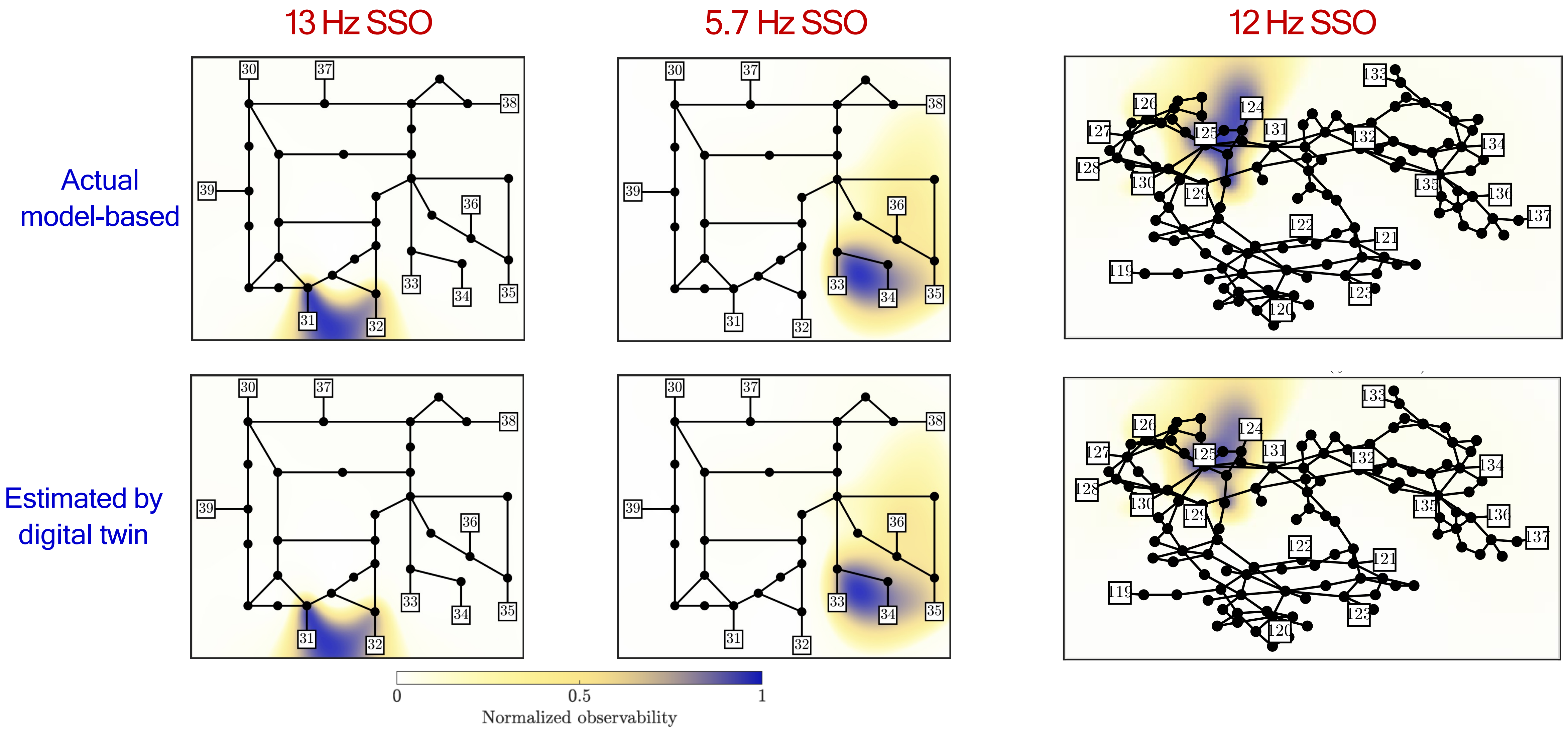


Covarrubias Maureira, Chaudhuri, and O'Malley, "Parameterizing Operating-Point-Dependent IBR Using Coherent Operating Regions for Sub-synchronous Oscillation Analysis," https://arxiv.org/abs/2607.00216

Geographic spread of SSO

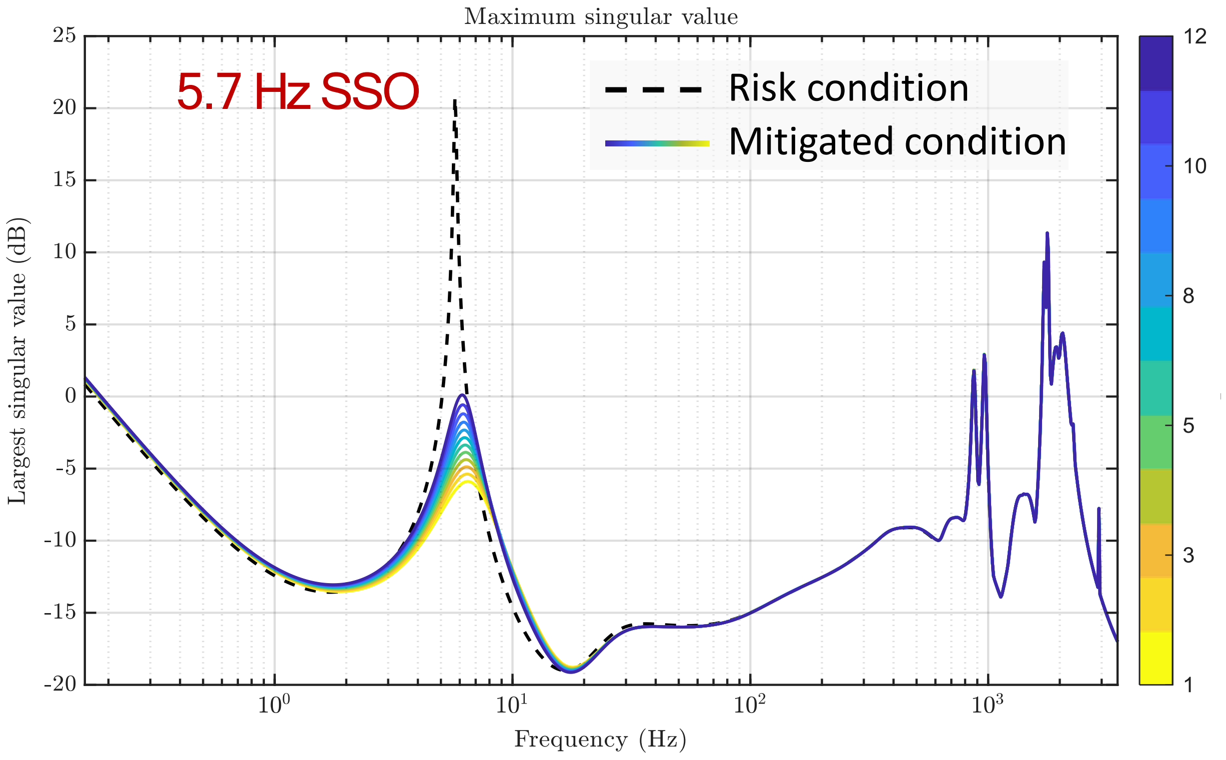
Based on estimated modal observability

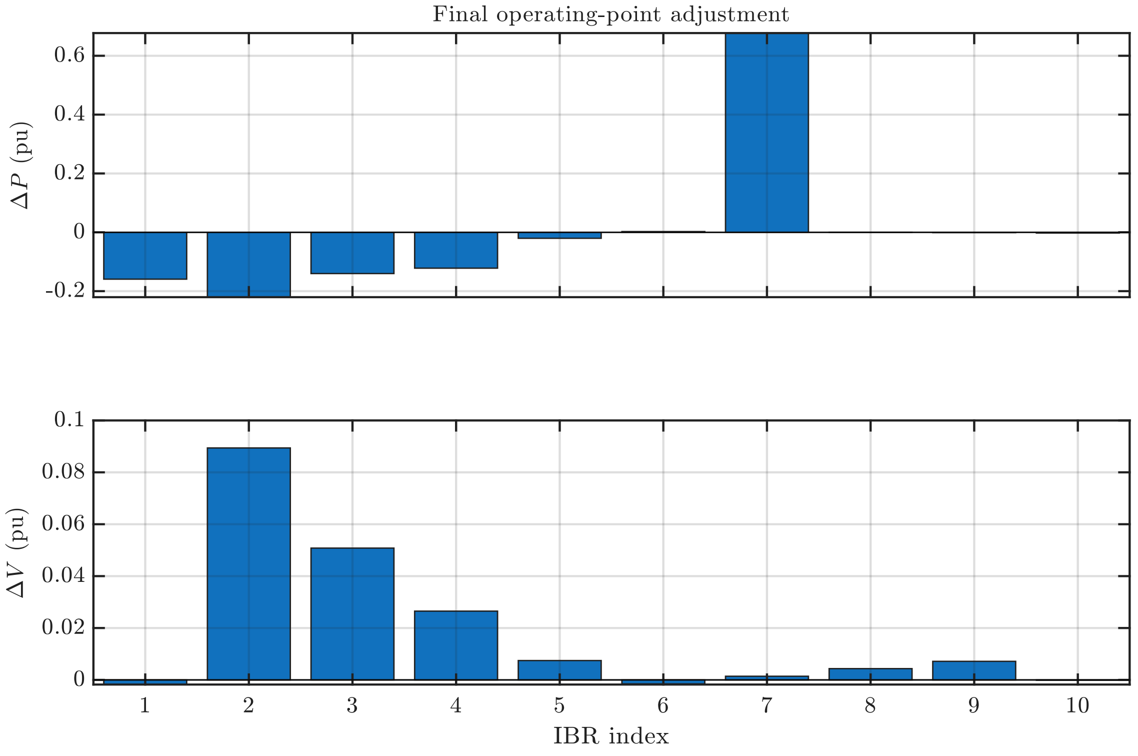
Covarrubias Maureira, Chaudhuri, and O'Malley, "Parameterizing Operating-Point-Dependent IBR Using Coherent Operating Regions for Sub-synchronous Oscillation Analysis," https://arxiv.org/abs/2607.00216



Mitigation actions

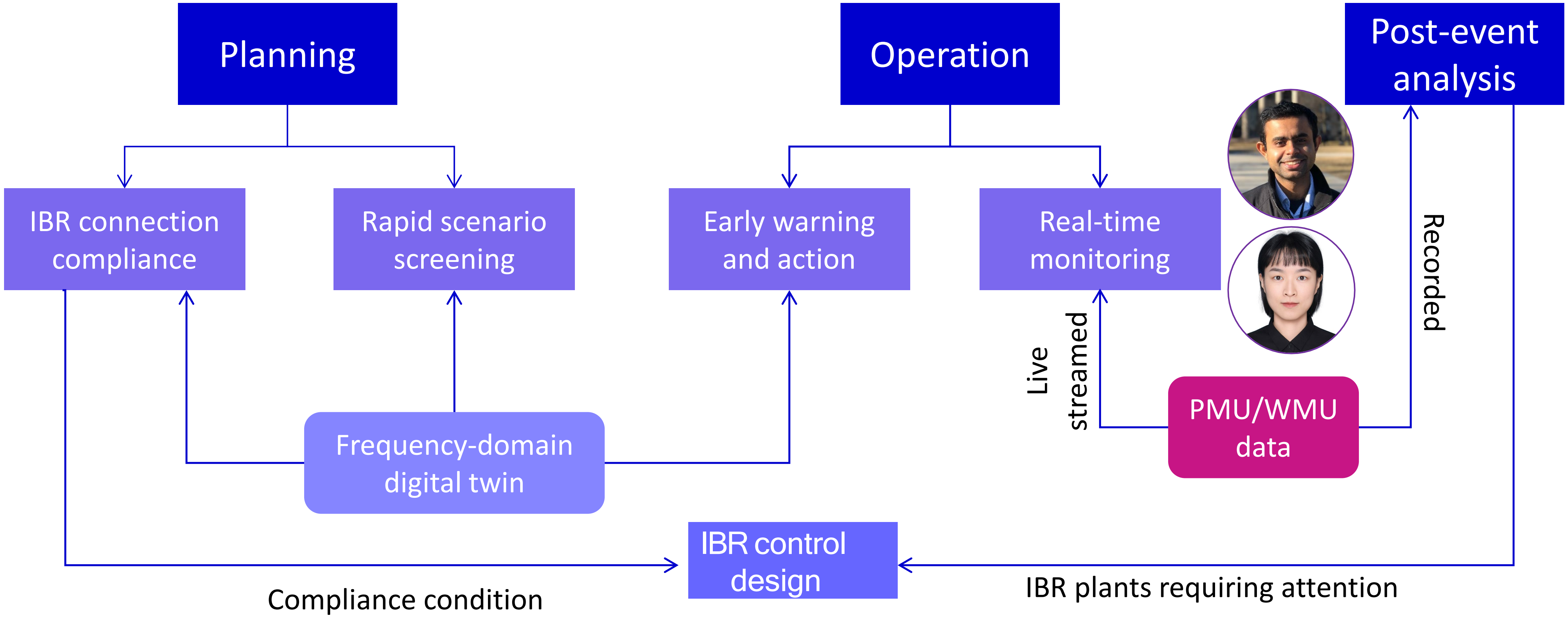
Operating point adjustment





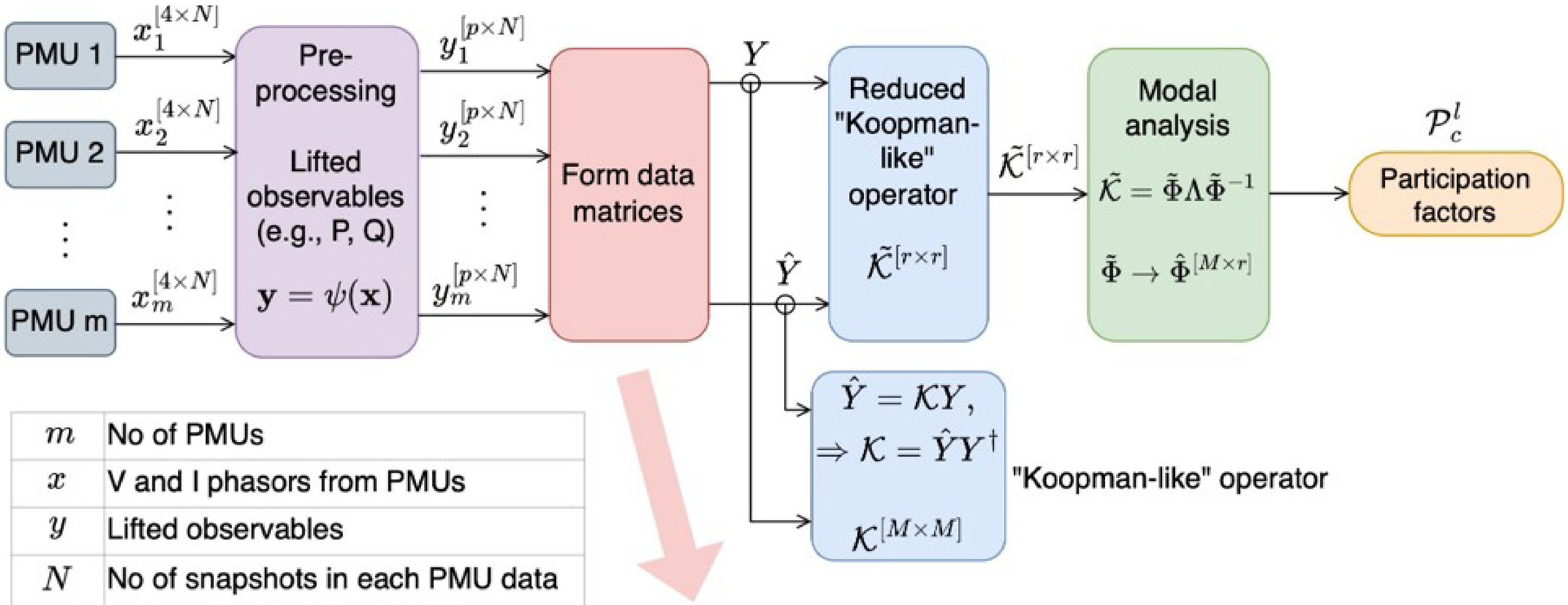
Identify and mitigate SSO risk

Multi-layered defense & attack



Post-event SSO analysis based on PMU/WMU data

Extended Dynamic Mode Decomposition (EDMD)



m	No of PMUs
x	V and I phasors from PMUs
y	Lifted observables
N	No of snapshots in each PMU data
p	No of lifted observables per PMU
Y	Data matrix
$\hat{Y}$	Shifted data matrix
$\mathcal{K}$	"Koopman-like" operator
$\mathcal{P}_c^l$	Participation of mode *c* at location *l*

Form data matrices

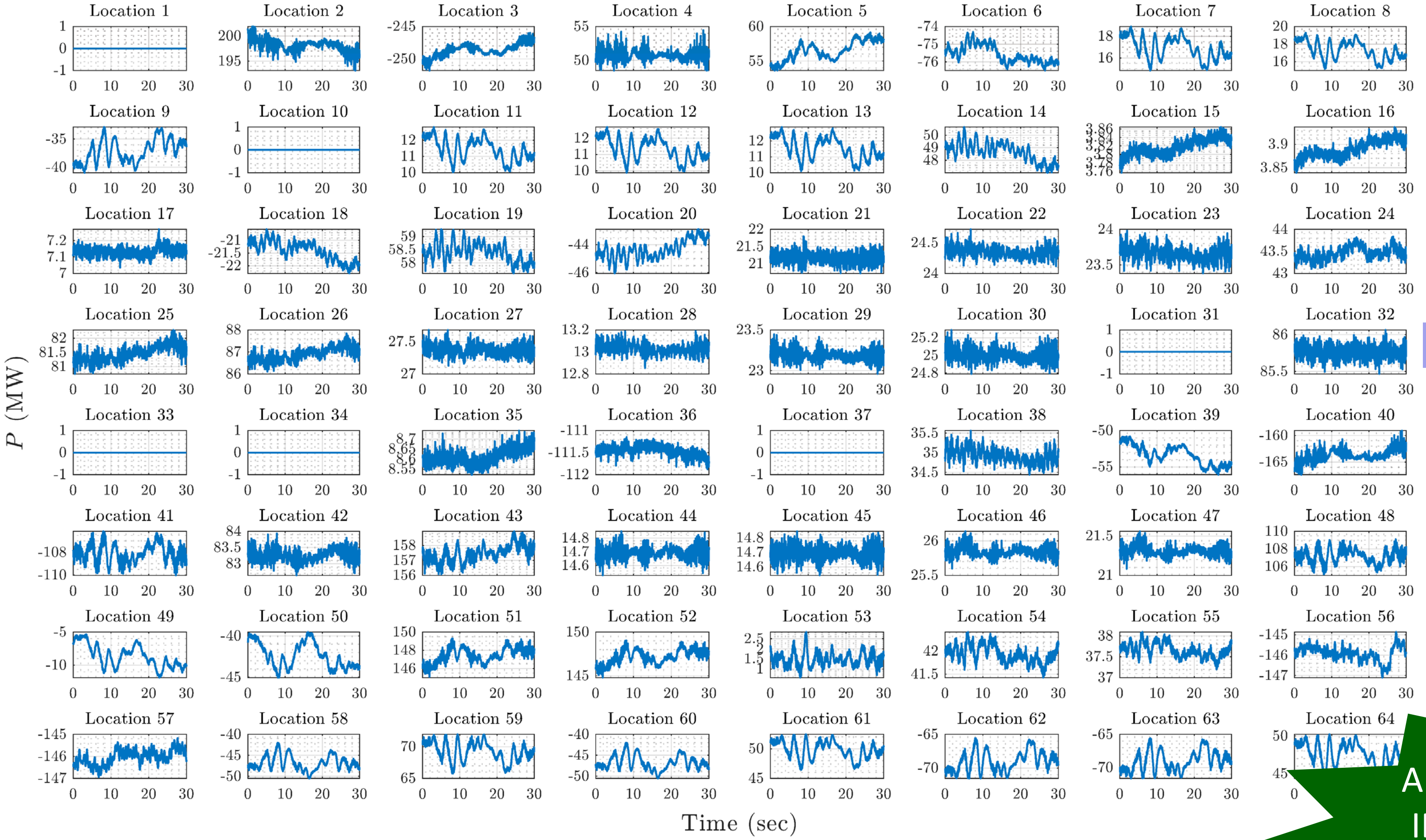
$$Y^{[M\times(N-1)]} = \begin{bmatrix} | & | & & | \\ \bar{y}_{t1} & \bar{y}_{t2} & \cdots & \bar{y}_{t(N-1)} \\ | & | & & | \end{bmatrix}, \hat{Y}^{[M\times(N-1)]} = \begin{bmatrix} | & | & & | \\ \bar{y}_{t2} & \bar{y}_{t3} & \cdots & \bar{y}_{tN} \\ | & | & & | \end{bmatrix}$$

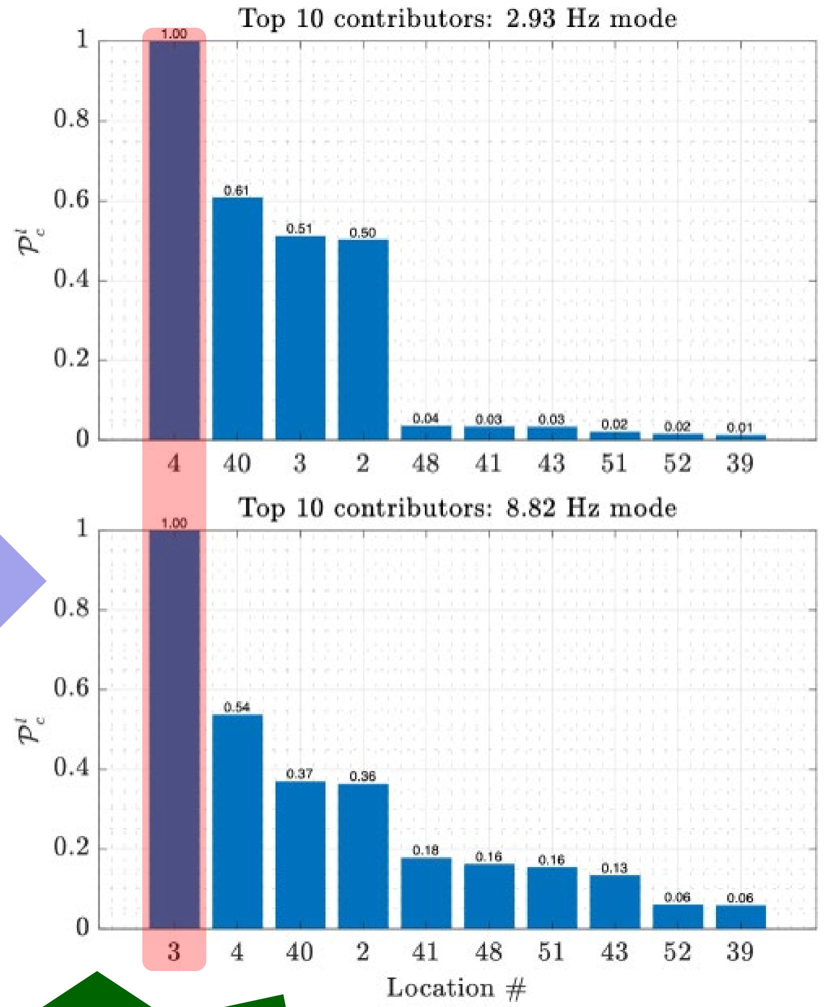
$$\bar{y}_{ti}^{[M\times 1]}, \text{where } M = m \times p$$

Researchers: Youhong Chen, Debraj Bhattacharjee, Jia Lu

SSO event in South Australia

PMU data from 64 locations from an SSO event in Australia in Aug 2025





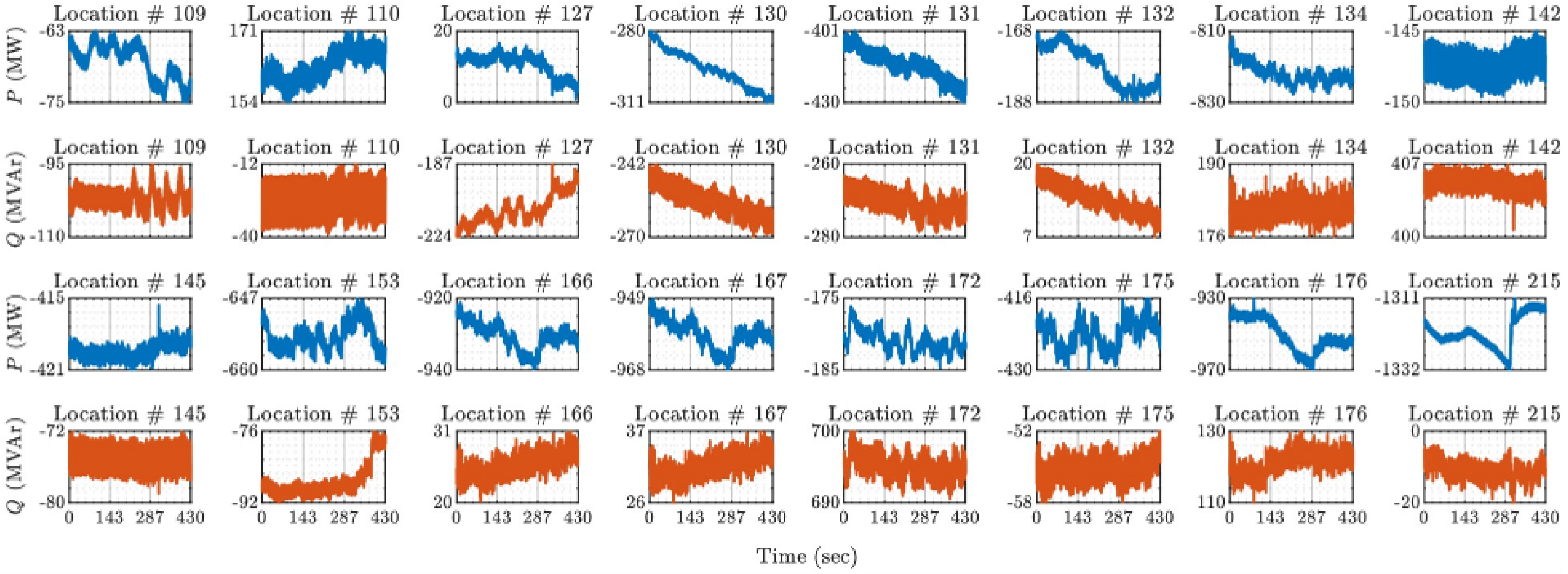
Where is the root cause of SSO?

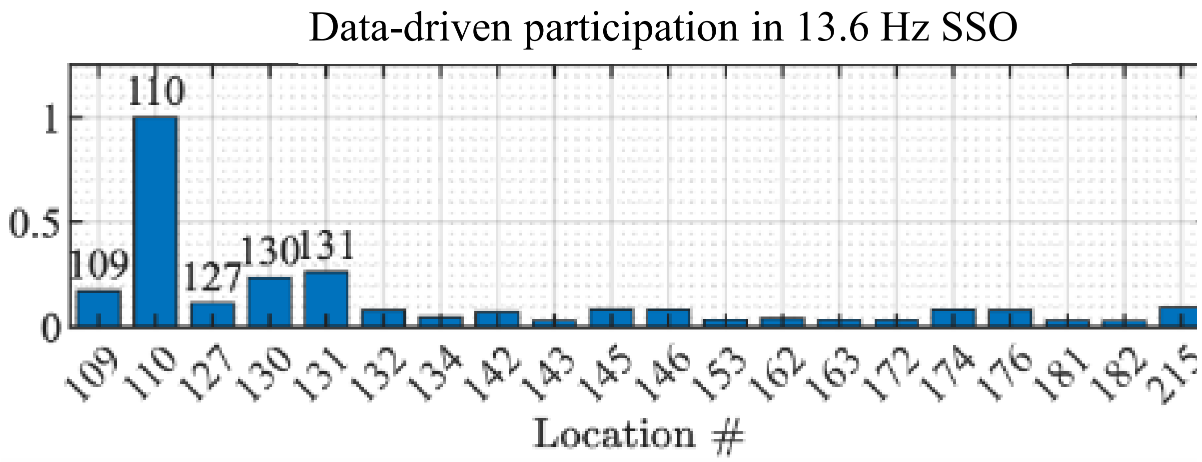
AEMO later confirmed IBR plants at location 4 and 3 as top contributors

Researchers: Youhong Chen, Debraj Bhattacharjee, Jia Lu
Thanks to Maddy Binet and Campbell Linden from AEMO

SSO event in north-east Brazil

PMU data from 222 locations during an SSO event in Brazil in Feb 2026





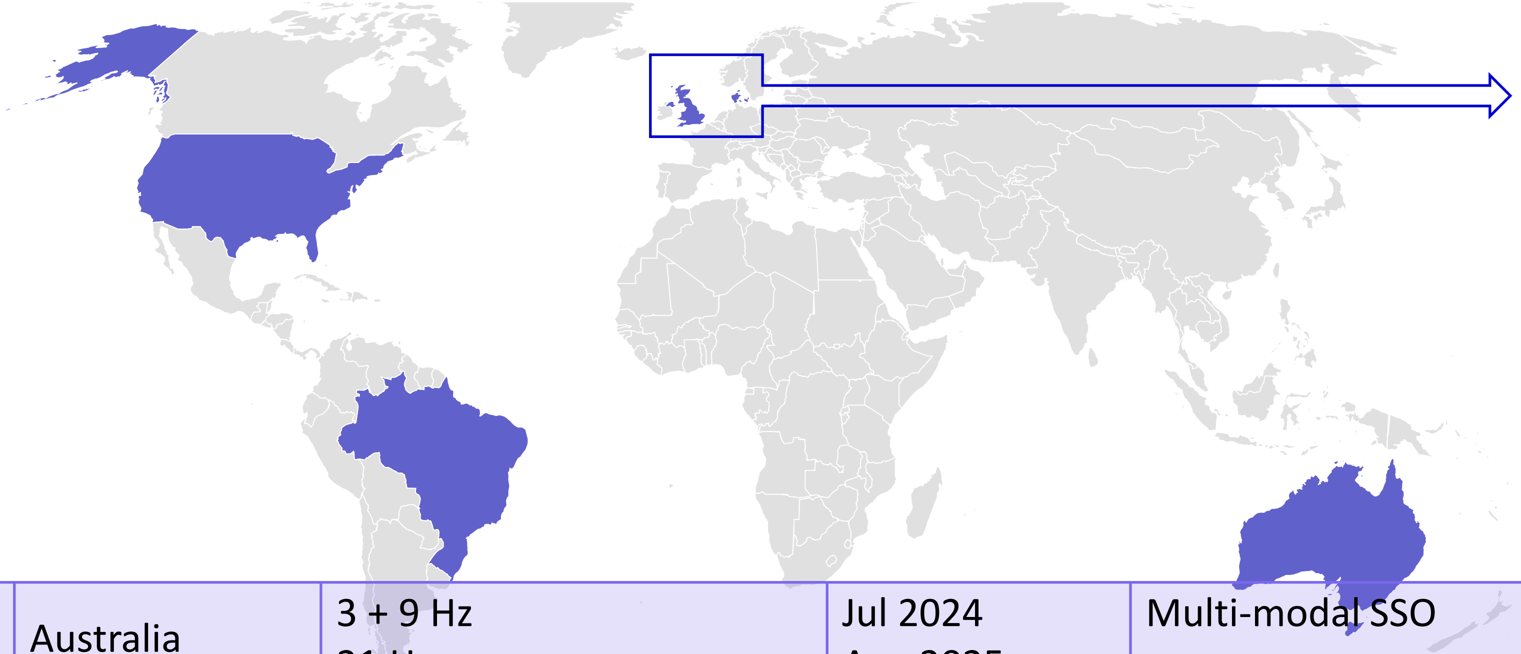
16 representative locations out of 222 shown here

Where is the root cause of SSO?

ONS later confirmed network element at 110 lead to widespread 13.6 Hz SSO

Researchers: Youhong Chen, Debraj Bhattacharjee, Jia Lu
Thanks to Bruno Pestana Rosa and other colleagues from ONS

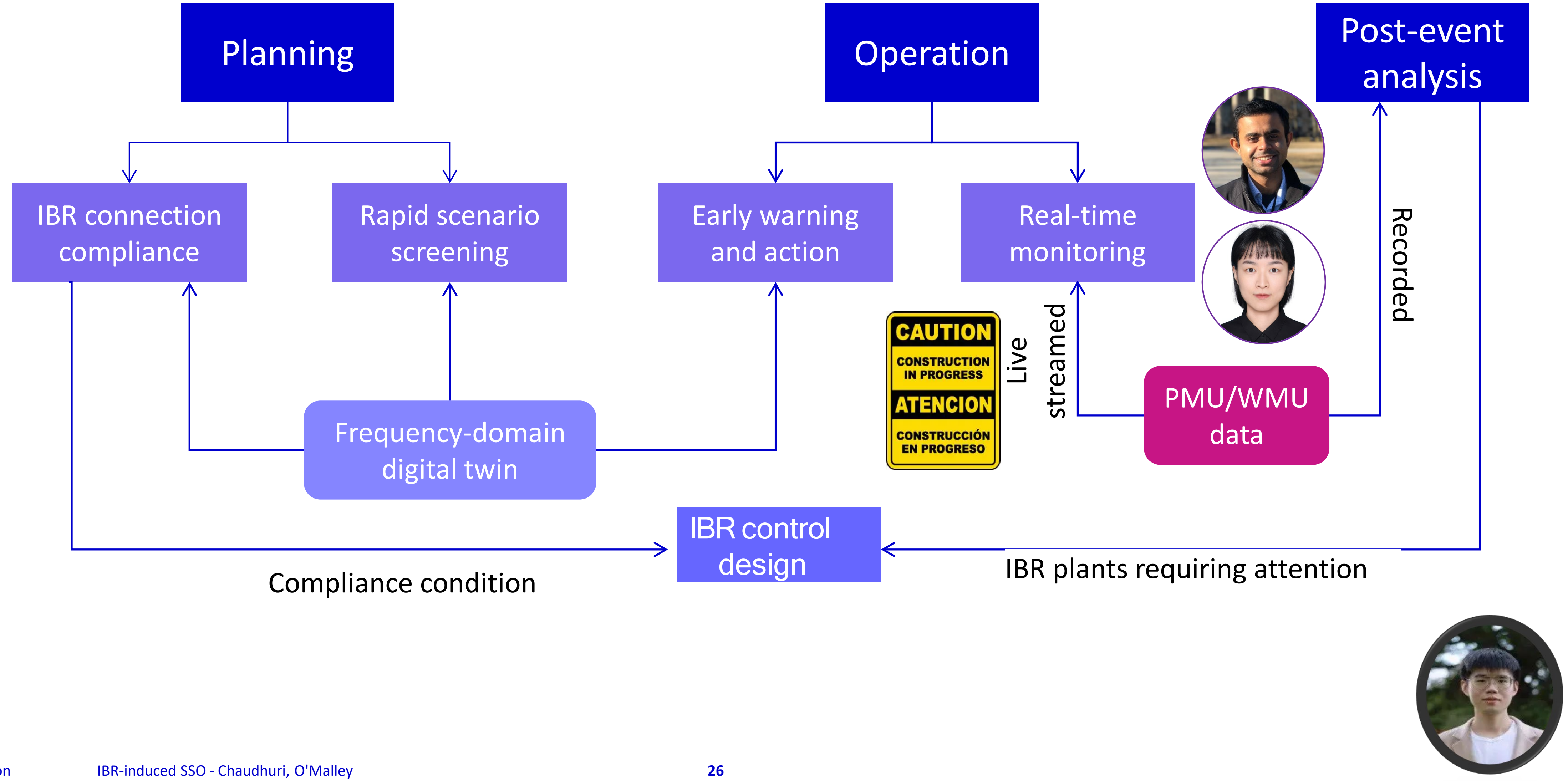
Validation on real SSO events



AEMO	Australia	3 + 9 Hz 21 Hz	Jul 2024 Aug 2025	Multi-modal SSO
Energinet	Denmark	0.16 Hz 2.8 Hz	Aug 2025 Jun 2025	Low frequency SSO Multi-stage SSO
ISO-NE	United States	0.27 Hz, 1.13 Hz, 0.25 Hz 0.08 + 0.15 + 0.31 Hz	Jun 2017 – Jun 2019	Electromechanical oscillation Multi-modal
ONS	Brazil	13.6 Hz 5 + 15 Hz	Feb 2026 Apr 2026	Resonance Multi-modal SSO
SPEN	Great Britain	37.5 Hz	Dec 2024	High frequency SSO – WMU data

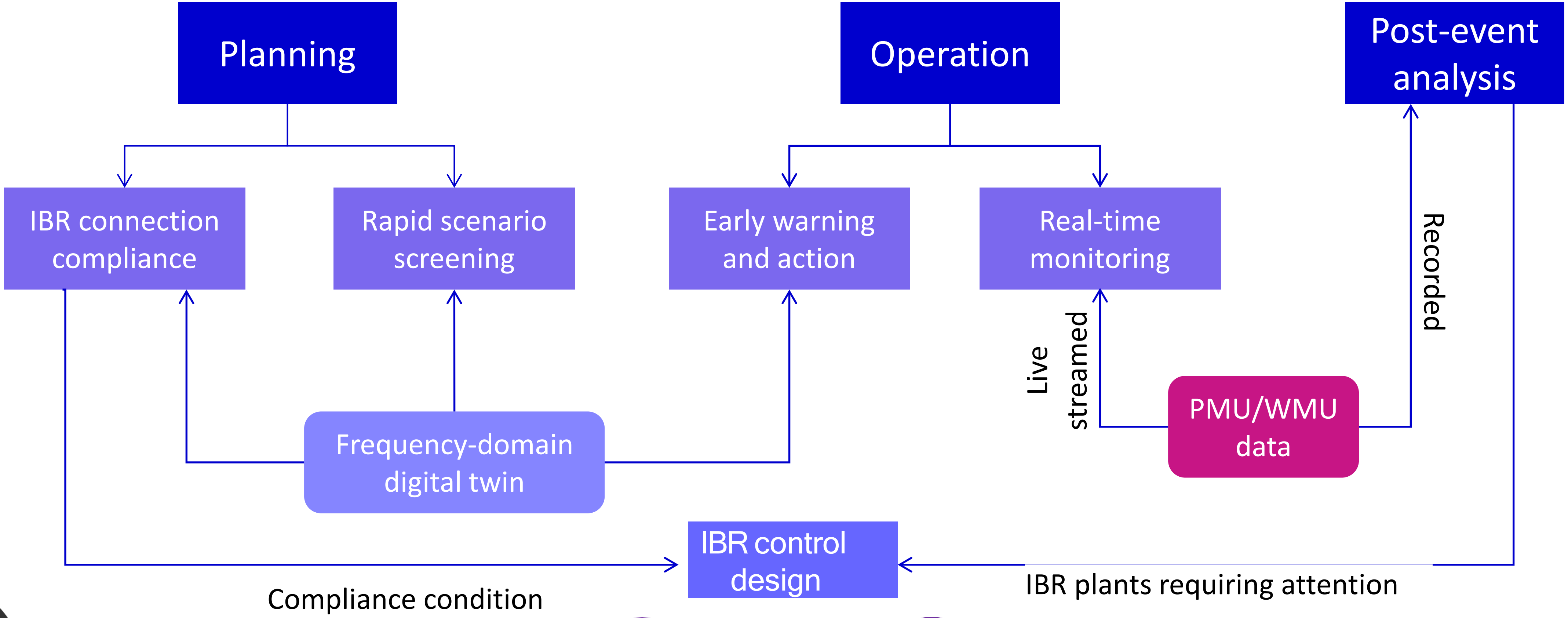
Identify and mitigate SSO risk

Multi-layered defense & attack



Identify and mitigate SSO risk

Multi-layered defense & attack

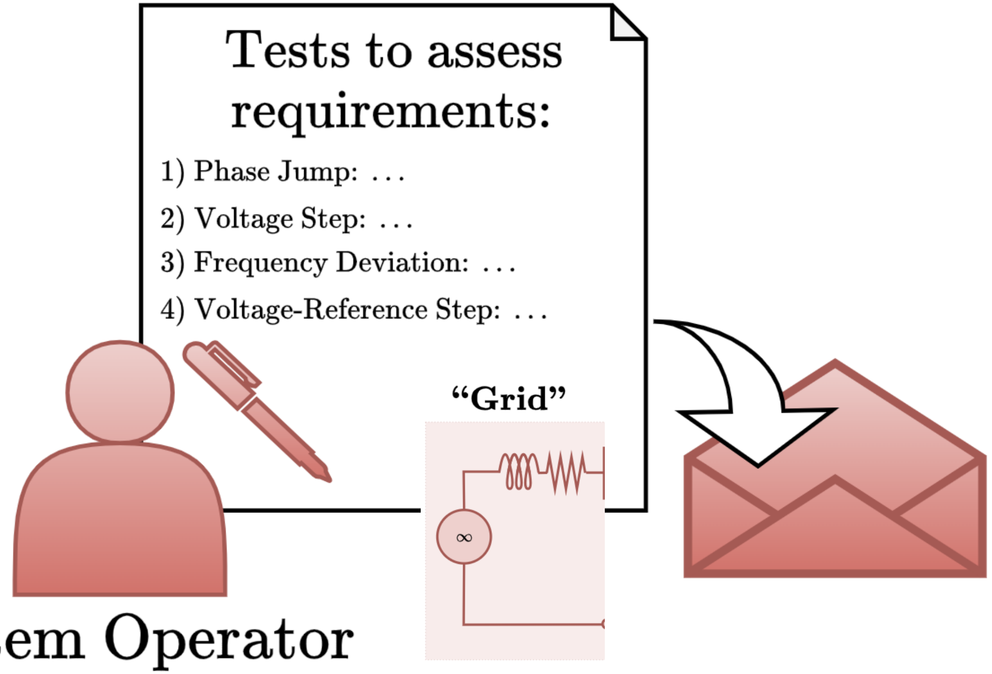


Designing Control Around Grid Requirements

Summary of GFM-specific qualitative compliance requirements

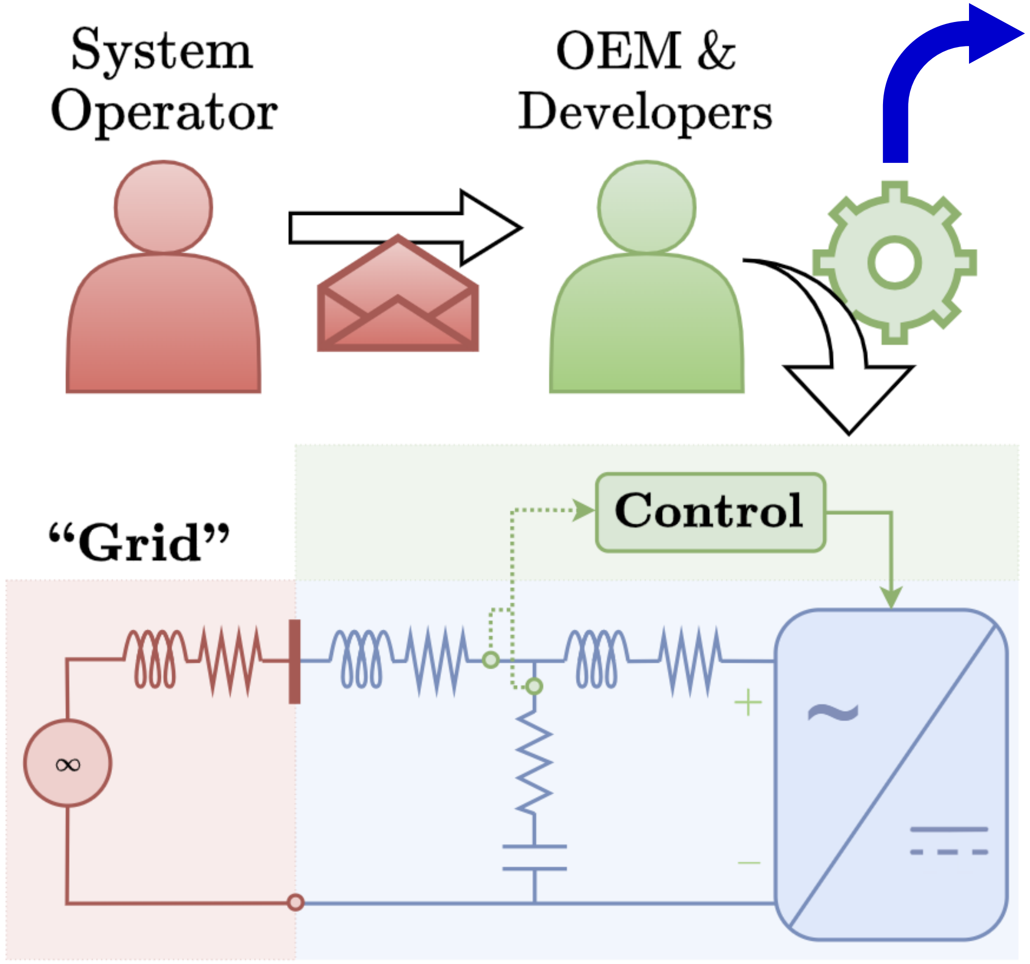
Requirement	ERCOT [1] (USA)	MISO [2] (USA)	AEMO [3] (Australia)	NERC [4] (USA)	UNIFI [5] (USA)	ENTSO-E [6] (Europe)	CEN [7] (Chile)	Energinet [8] (Denmark)	FNN/VDE [9] (Germany)	Fingrid [10] (Finland)	NESO [11] (GB)
Provide voltage & frequency oscillations damping	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Active & reactive power sharing across resources	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓
Operation in grids with low system strength	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Performance in response to frequency deviations	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Performance during phase jumps & voltage steps	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Intentional islanding	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Black start & system restoration	✗	✗	✗	✓	✓	✗	✓	✓	✗	✓	✓

specify how requirements are going to be assessed…



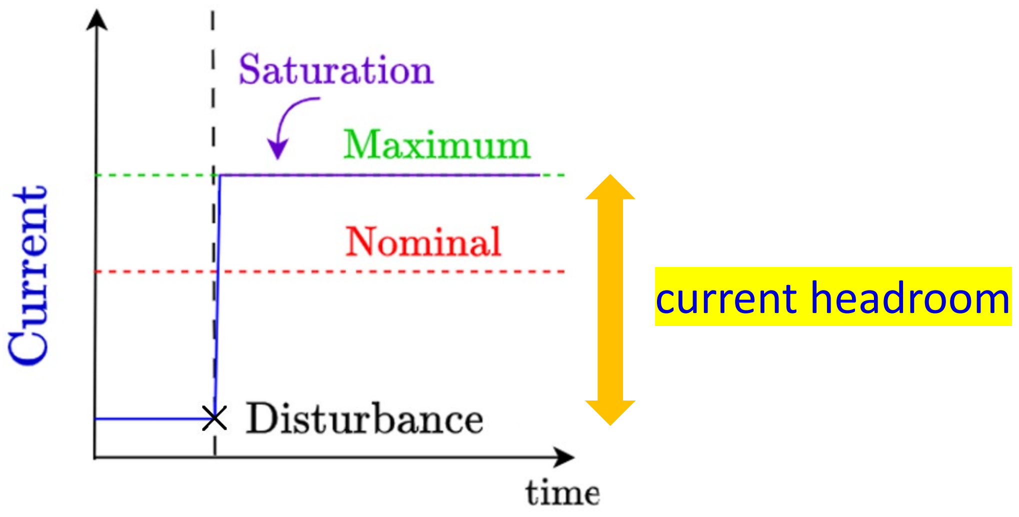
Designing Control Around Grid Requirements

Be compliant – how to assess the resource



Our work: **Optimal control design** subject to compliance requirements.

Objective: To deliver the required grid-support services with minimum additional current headroom.



Why? Headroom is created by either

a) **oversizing the inverter** (increasing capital cost) or

b) **operating below rated limit** (reducing energy-market participation)

Case Study

Considered GFM control structures

The proposed compliance-aware control design method is evaluated under three **control structures**.

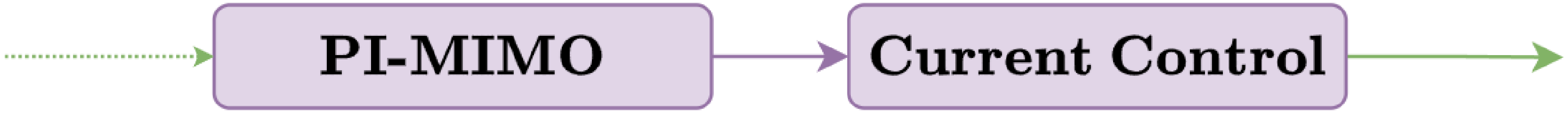
Conventional droop structure:

1) with fixed control parameters (Benchmark)

2) with optimized control parameters (Droop)

Coupled structure (+ cross-coupling among power, voltage, and frequency channels):

PI-MIMO: Proportional-Integral Multi-Input Multi-Output

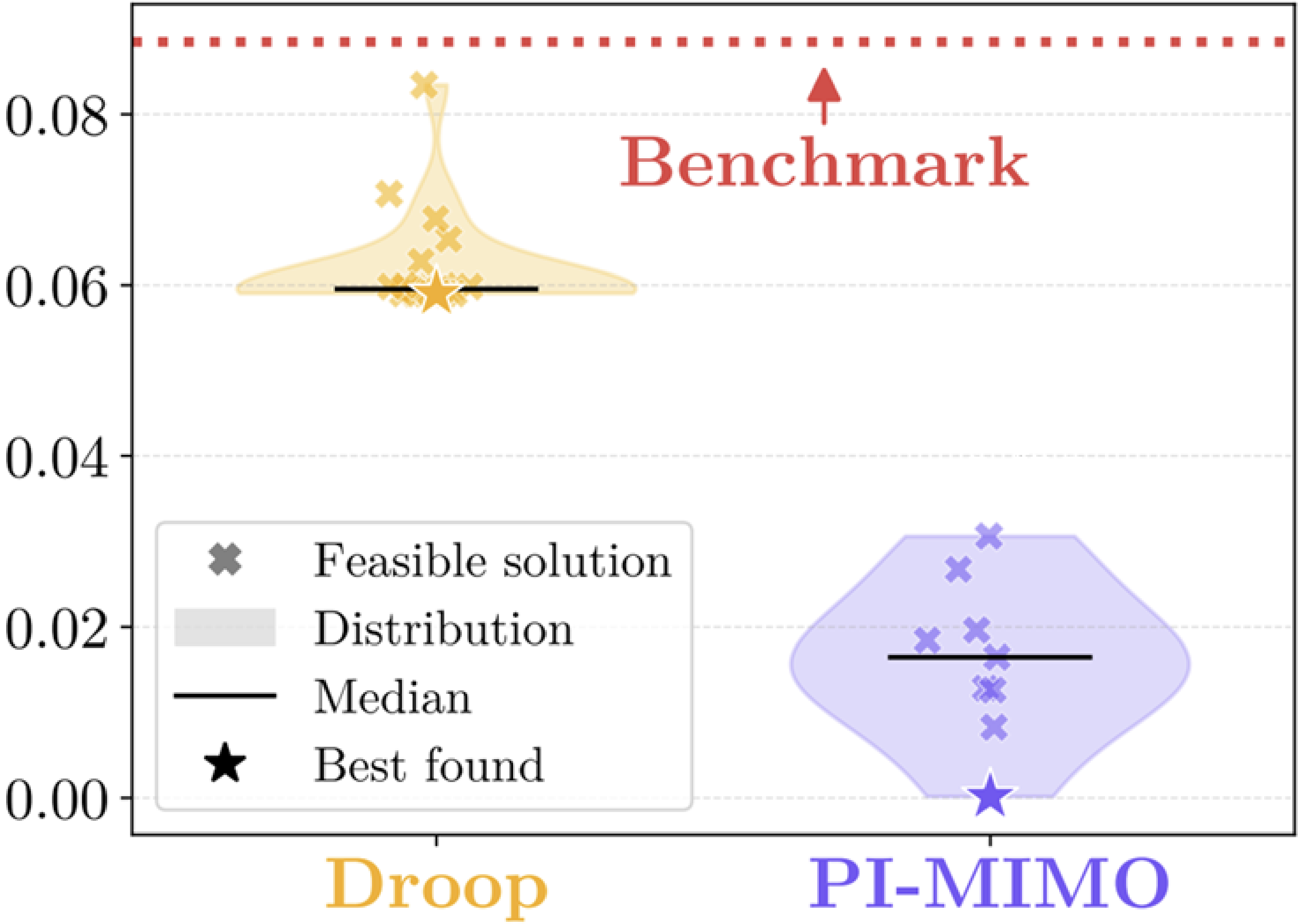


3) with optimized control parameters (PI-MIMO)

Results

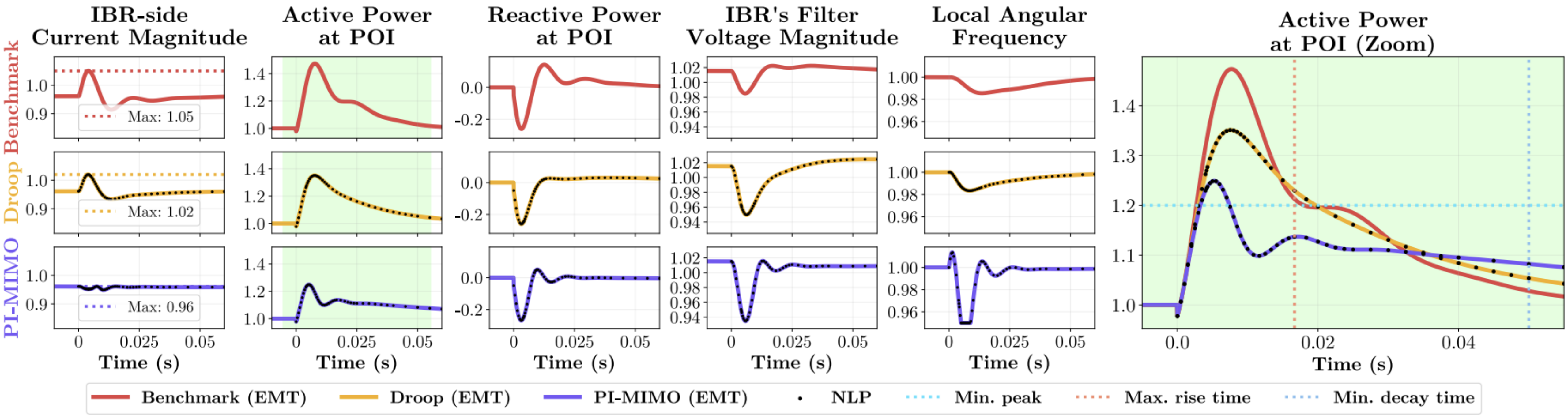
Optimization results across multiple initializations

current headroom

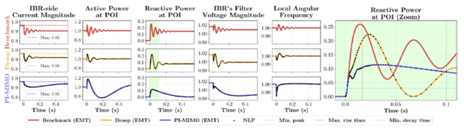


Results

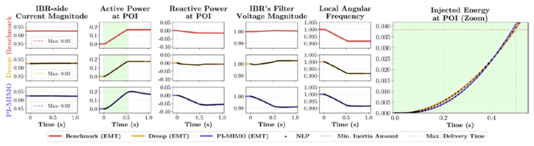
Across compliance tests (for best-found control design solution per structure)



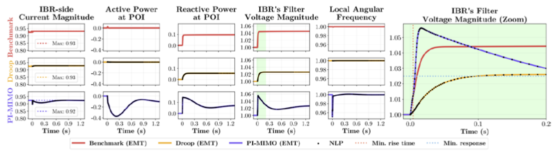
Test 1: Phase Jump



Test 2: Voltage Step.

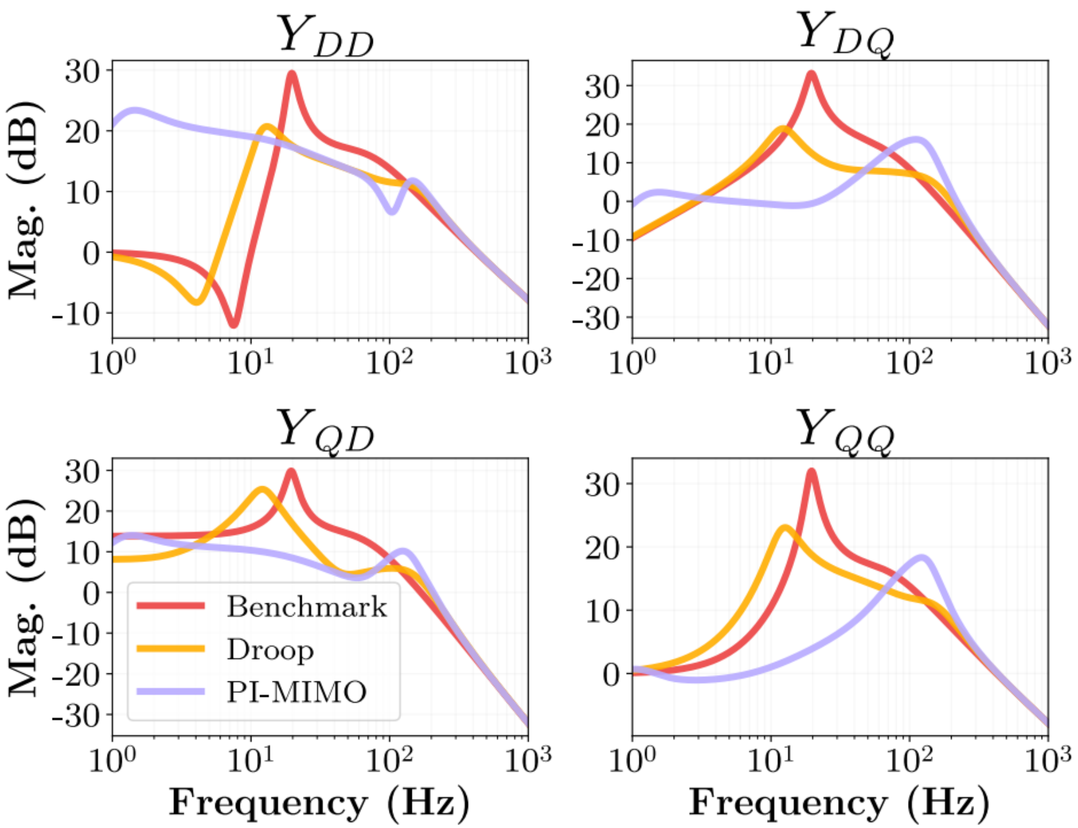


Test 3: Frequency Deviation



Test 4: Voltage-Reference Step.

Bode Diagrams and Voltage-Stiffness Characteristics



Controller	JVSM
Benchmark	6.731
Droop	3.020
PI-MIMO	2.832

↑ JVSM = ↑ Voltage-source like behaviour

General compliance requirements preserve room for innovation

but watchout! OEM's may "add water to the milk" to pass tests with the bare minimum…

departing from SO's expected behaviour.

Identify and mitigate SSO risk – defence & attack – post game review

IBR connection compliance

- Existing process overlooks SSO risk
- Locally verifiable decentralised stability condition
- Balance conservativeness and SSO risk

Digital twin of IBR-dominated grid

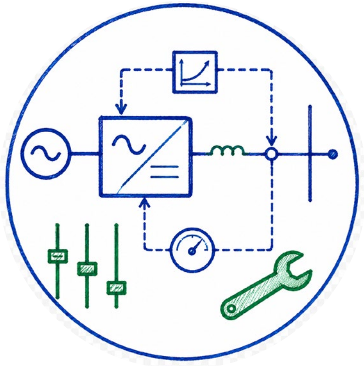
- Track operating point dependence of black-box IBRs
- Fast scenario screening and early warning
- Frequency-domain insights for targeted mitigation

Real-time SSO monitoring

- Beyond damping and frequency estimation
- Live PMU/WMU data-driven spatiotemporal characterisation
- Identify dominant SSO contributors

Post-event analysis of SSO

- Recorded PMU/WMU data from SSO events
- Batch window spatiotemporal characterisation



IBR control design, retuning

- Decentralised control design
- Informed by enhanced IBR compliance condition
- Post-event studies pointing to IBRs requiring retuning

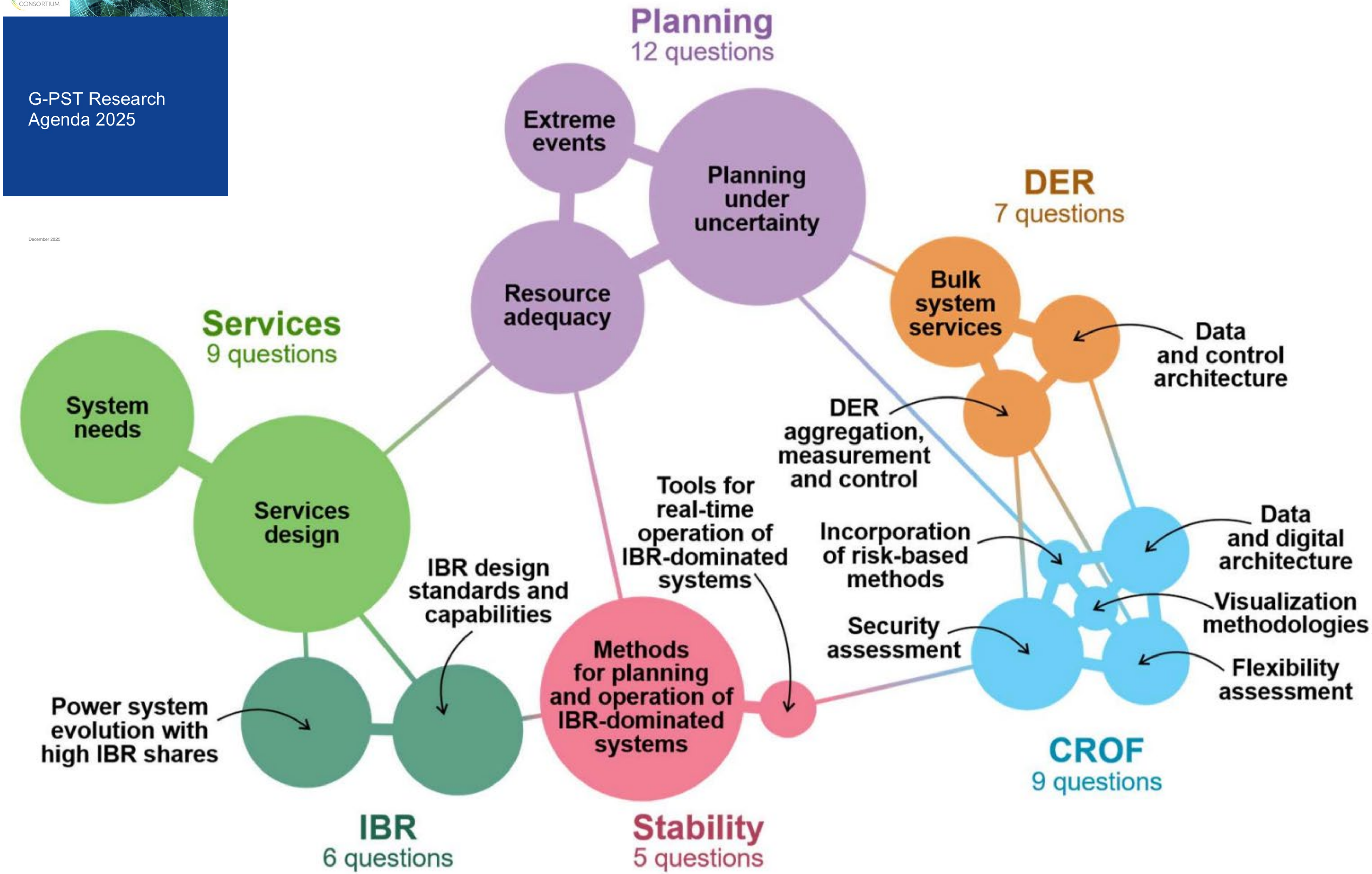
Global Power System Transformation Consortium Research Agenda

https://globalpst.org/wp-content/uploads/G-PST_Research_Agenda_2025_FINAL.pdf

#	Stability	Sub Programs
7	What approaches can be taken to track the dynamic response of IBR-dominated systems near real time and detect any emerging stability problems?	Tools for real-time operation of IBR-dominated systems
8	What methods, including data types, and analyses can be used to identify the risk of poorly damped IBR-induced oscillations in planning studies and trace their root cause?	Methods for planning and operation of IBR-dominated power systems
9	What analytical tools and models should be provided to planners and operators for robust assessment of system performance in IBR-dominated power grids?	
10	What methods and tools should be used in planning and/or operation to determine the appropriate mix, location, and capabilities of grid-forming and grid-following inverters to mitigate stability problems for a given power system?	
11	In what form and fidelity should the original equipment manufacturers/developers and system operators exchange the IBR and grid models for comprehensive stability assurance of IBR-dominated grids?	

G-PST Research Agenda 2025

December 2025



#	IBR Research	Sub Programs
1	What is the future of active power balance as the synchronous generation fraction reduces? For example, might tightened or loosened frequency (or similar proxy for active power balance) limits lead to a more reliable, secure, lower-cost IBR-based power system?	Power system evolution with high IBR shares
2	How will protection systems need to change to accommodate high penetrations of IBRs, and what possible actions might an inverter take during a fault that would help fault detection and location?	
3	How could the IBR control paradigm change from replicating synchronous machines to exploiting wider IBR flexibility without introducing integration challenges during the transition?	
4	What are the appropriate inverter capabilities and, consequently, control design methods for operation in grids with high percentages of IBRs, and are standard configurations and combinations of services helpful in simplifying operational decision-making?	IBR design standards and capabilities
5	What recommendations for standard IBR frequency characteristics and responses should be identified to help system design? For example, should a contribution to damping be mandatory at certain frequencies?	
6	What requirements (e.g. impedance) should be placed on IBRs to control negative sequence currents for protection and harmonics suppression?	

#	Control room of the future
19	How can the capabilities of grid-enhancing technologies (such as FACTS, SPS, RAS, DLR, PFC, WAMPAC) be integrated into the operational decision-making process?
20	How can grid topology be flexibly adapted to be reliably integrated into the operational decision-making process with outage scheduling, transfer limit increase, and post contingency remedial actions?
21	What applications are required to assess adequate flexibility from all resources, including those on the transmission, distribution and coupled energy systems (e.g., heat, electric vehicles, etc.) in the near term, and how can these resources be applied to address uncertainty during real-time applications?
22	What type of digital architecture is best placed to enable modularity and the variety of software required to operate a control room in real time, near-real time, and in auto pilot mode?
23	What is the best way to integrate large datasets, streaming information, and historical system performance to create actionable operational insights in an increasingly complex environment with multiple phenomena occurring within overlapping timescales?
24	How can the risk of high-impact low-probability events (weather-related and otherwise) be incorporated into security assessments in real time and operations planning?
25	What metrics and their definitions (system strength, inertia, or others) need to be appropriately monitored or calculated to assess system dynamic behavior in real time, and what monitoring capabilities are necessary to support these assessments?
26	What improvements can be made to predictive tools and visualization methodologies in operational applications within the control room to support decision-making in real-time operations?
27	How can risk-based methods (e.g. probabilistic forecasting techniques) be better incorporated into operational decision-support tools and used consistently across multiple stages (e.g., real-time, day-ahead, intraday planning)?

#	Services	Sub Programs
28	What system services are needed across different timescales and to the extent that services coexist within the same timescale, how should these services be designed to avoid competition and overlap?	System needs
29	What are the needs of a power system expressed in technologically neutral form and how do these needs map to services that any resource (including data centers, other IBRs, DERs, high-voltage direct current links, etc.) can provide?	
30	How can system performance requirements be translated into reliable new technology solutions?	
31	For each service, how feasible is it to provide from IBR, what “cost” does it add, what limitations exist on its magnitude and duration and what are the tradeoffs between the provision of services?	
32	How should system restoration services be structured and organized in systems with few or no synchronous machines, relying on IBR technologies and variable energy resources?	Services design
33	How should the definitions of services for IBR-dominated grids be structured and can standard services and standard characteristics be defined as reasonable for large and small IBRs and across variable renewable energy, storage, demand response interfaces and for differing procurement mechanisms?	
34	What methods could determine the need, sufficiency, and locational nature of IBR voltage control and system strength services for a given area?	
35	What models and methods, including testing, are necessary to quantify the ability of variable renewable energy to provide essential reliability services to the grid, and how do system operators quantify the value of these reliability services (for example, as an input to system-specific market/incentive design questions)?	
36	What system services can be designed to enable response from IBRs that can be a substitute for inertia (i.e. very fast frequency response)?	

Conclusions

- Imperial has a full team (critical mass) in SSOs
- End to end game plan to SSOs
- Addresses many aspects of the G-PST research agenda

- Good success to date but many open questions
  - Offline model bank adequacy for digital twin
  - Operating point dependence - especially, for connection compliance and model-based IBR control design
  - Spatiotemporal characterisation of SSO in real-time
  - Post-event source location of SSO amplified and spread due to resonance
  - etc.

- Other team members (System operators) needed – real world validation
- Other team members (researchers) needed as many other research questions to be addressed

IMPERIAL

GLOBAL PST CONSORTIUM

December 2025


happytoast

Thanks for listening,

Q&A

Our ecosystem