

IMPERIAL

IBR-driven Sub-synchronous Oscillation (SSO)

How to get to the bottom of these oscillations?

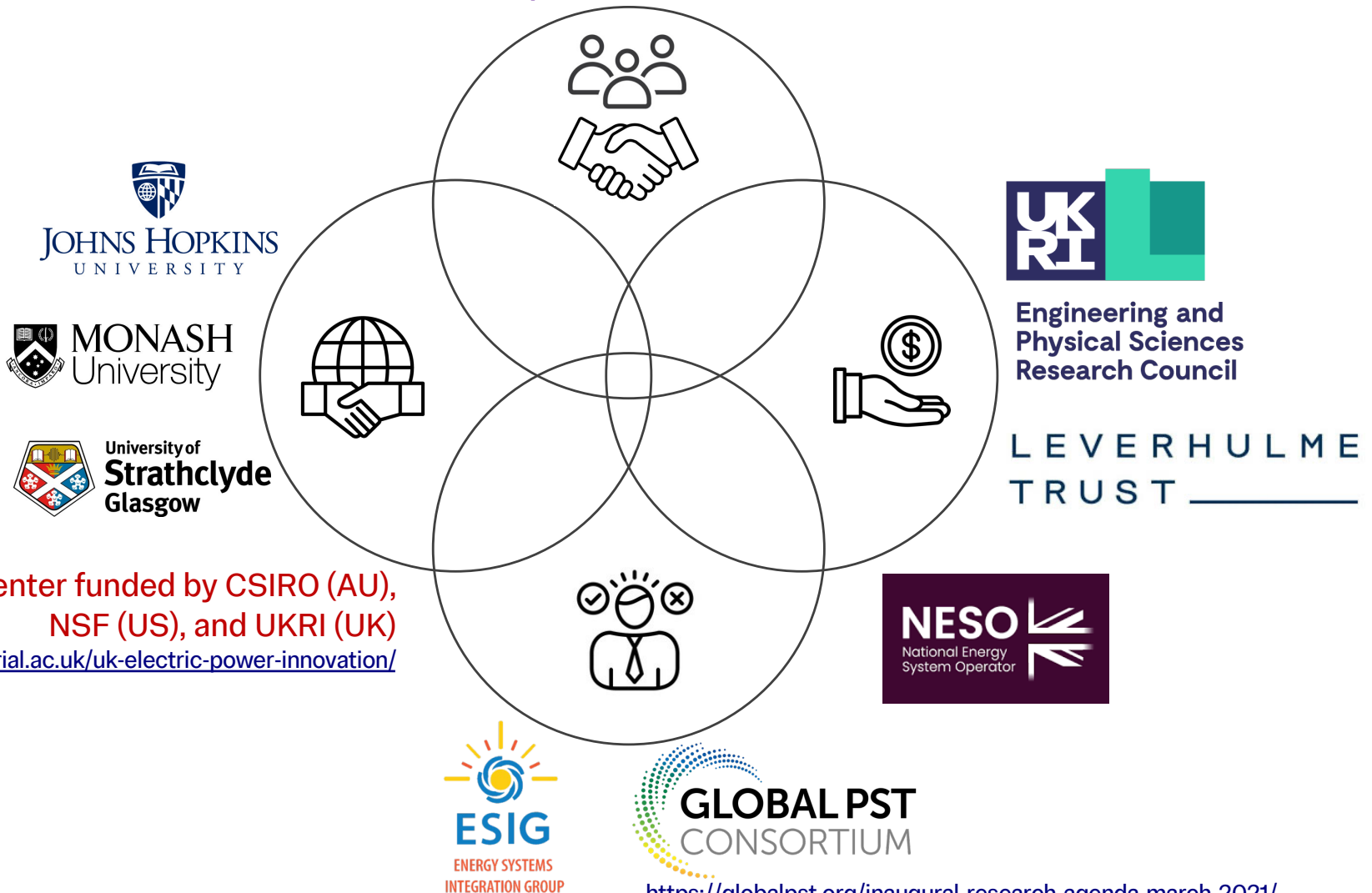
Balarko Chaudhuri

b.chaudhuri@imperial.ac.uk

Acknowledgement

Research on stability of IBR-dominated grids

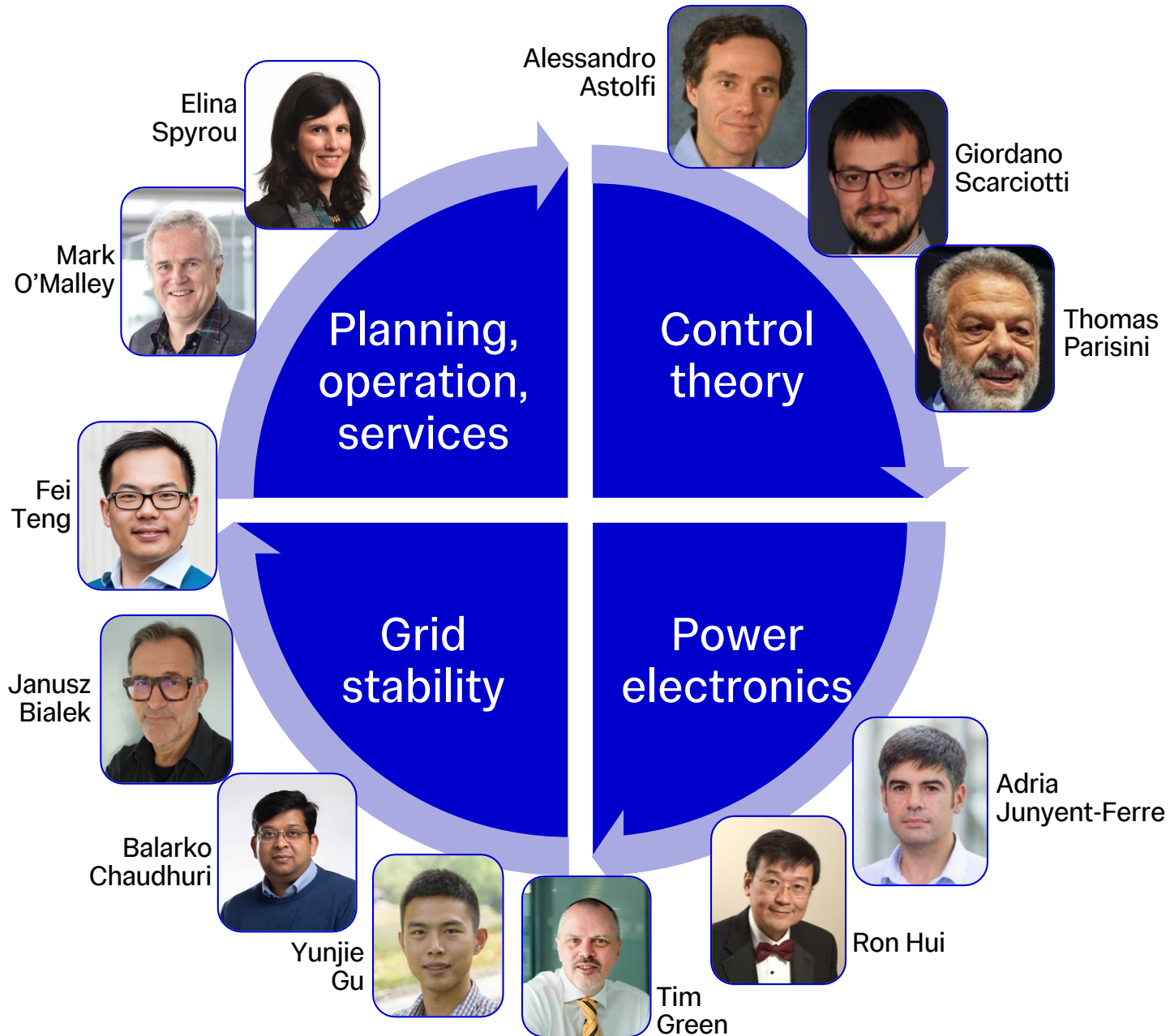
Researchers and colleagues
at Imperial (next slide)



EPICS global center funded by CSIRO (AU),
NSF (US), and UKRI (UK)
<https://www.imperial.ac.uk/uk-electric-power-innovation/>

<https://globalpst.org/inaugural-research-agenda-march-2021/>

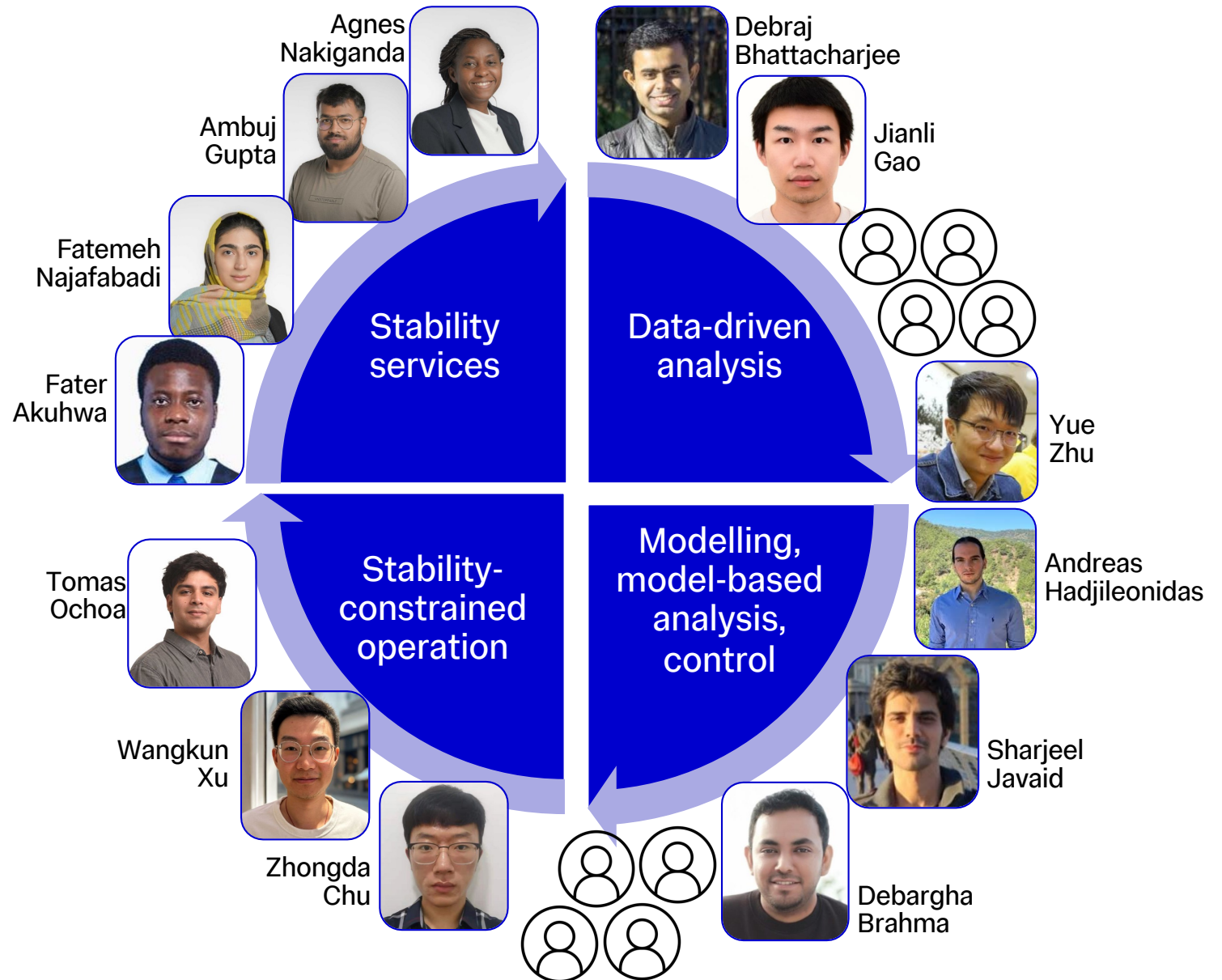
Team of academics



Researchers

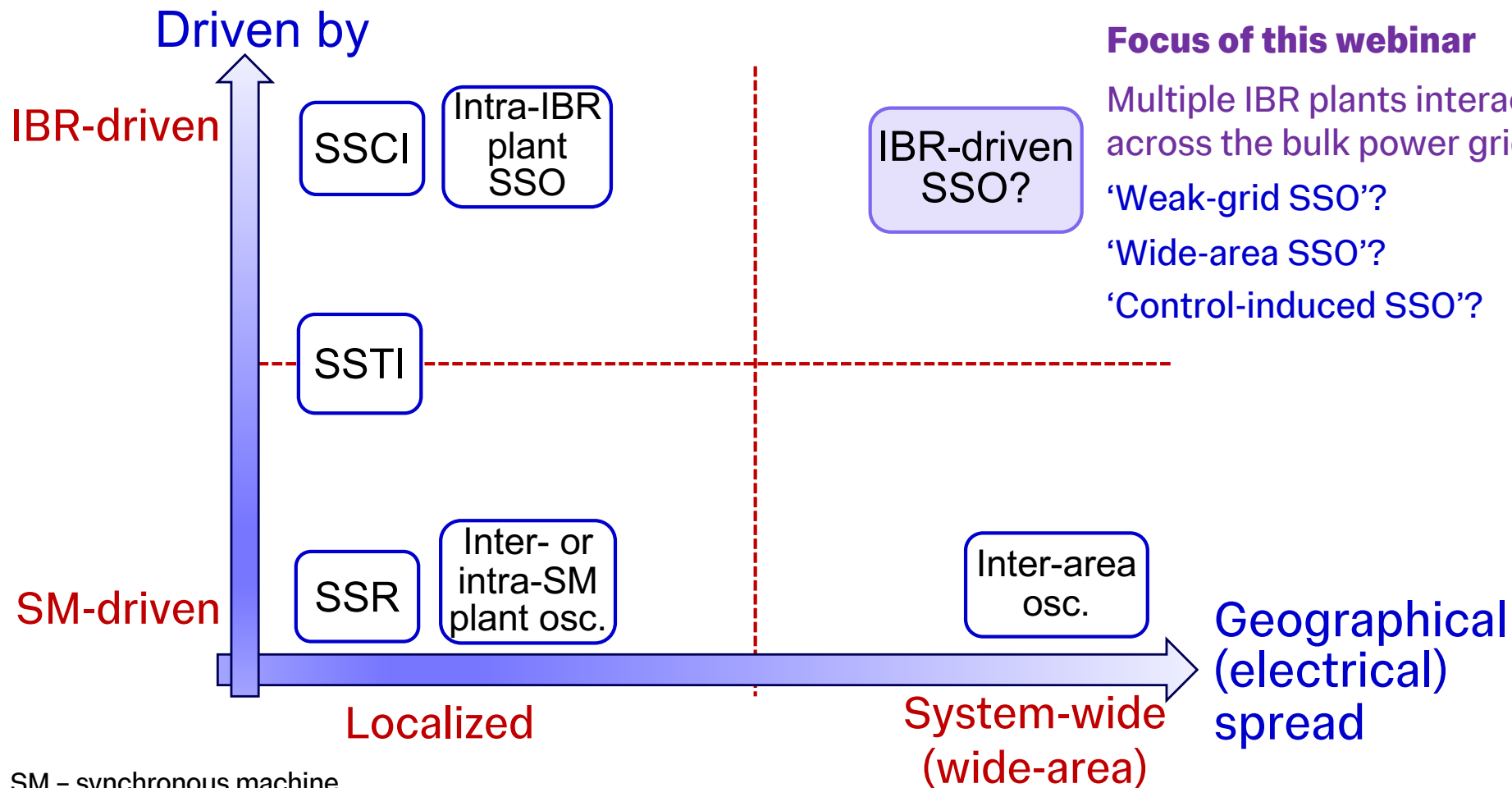
On stability of IBR-dominated grids

Recruitment of 8 post-docs underway



Sub-synchronous oscillation (SSO)

Oscillation frequency less than 50/60 Hz



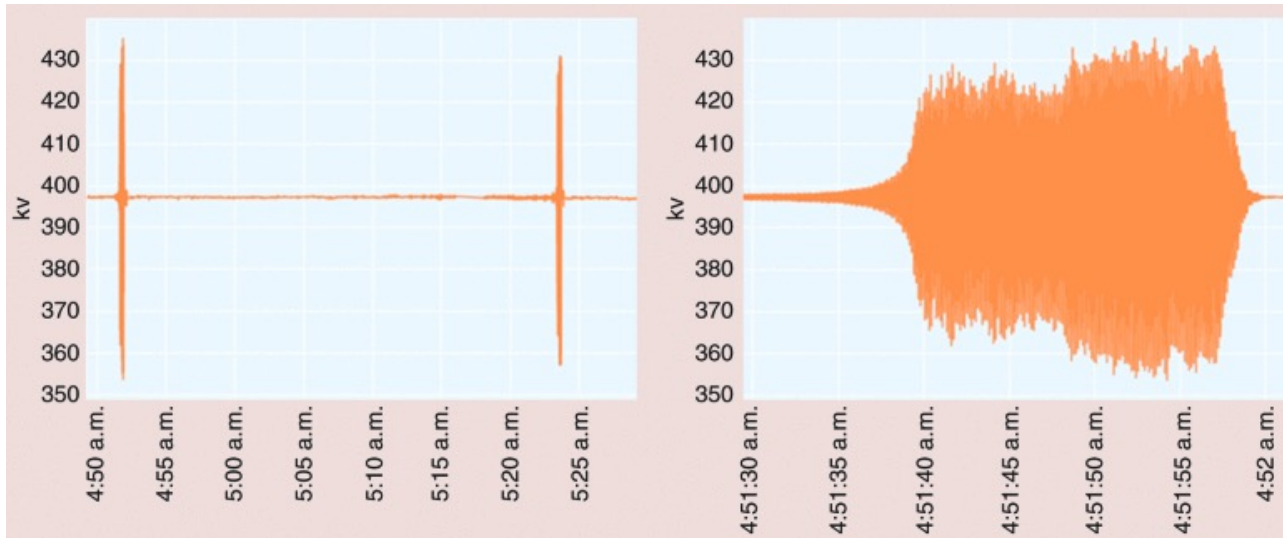
SM – synchronous machine
 IBR – inverter-based resource
 SSR – sub-synchronous resonance
 SSTI – sub-synchronous torsional interaction
 SSCI – sub-synchronous control interaction (series capacitor SSO)
 SSO – sub-synchronous oscillation

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

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

IBR-driven SSO

Getting more frequent in IBR-dominated parts of the system



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

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

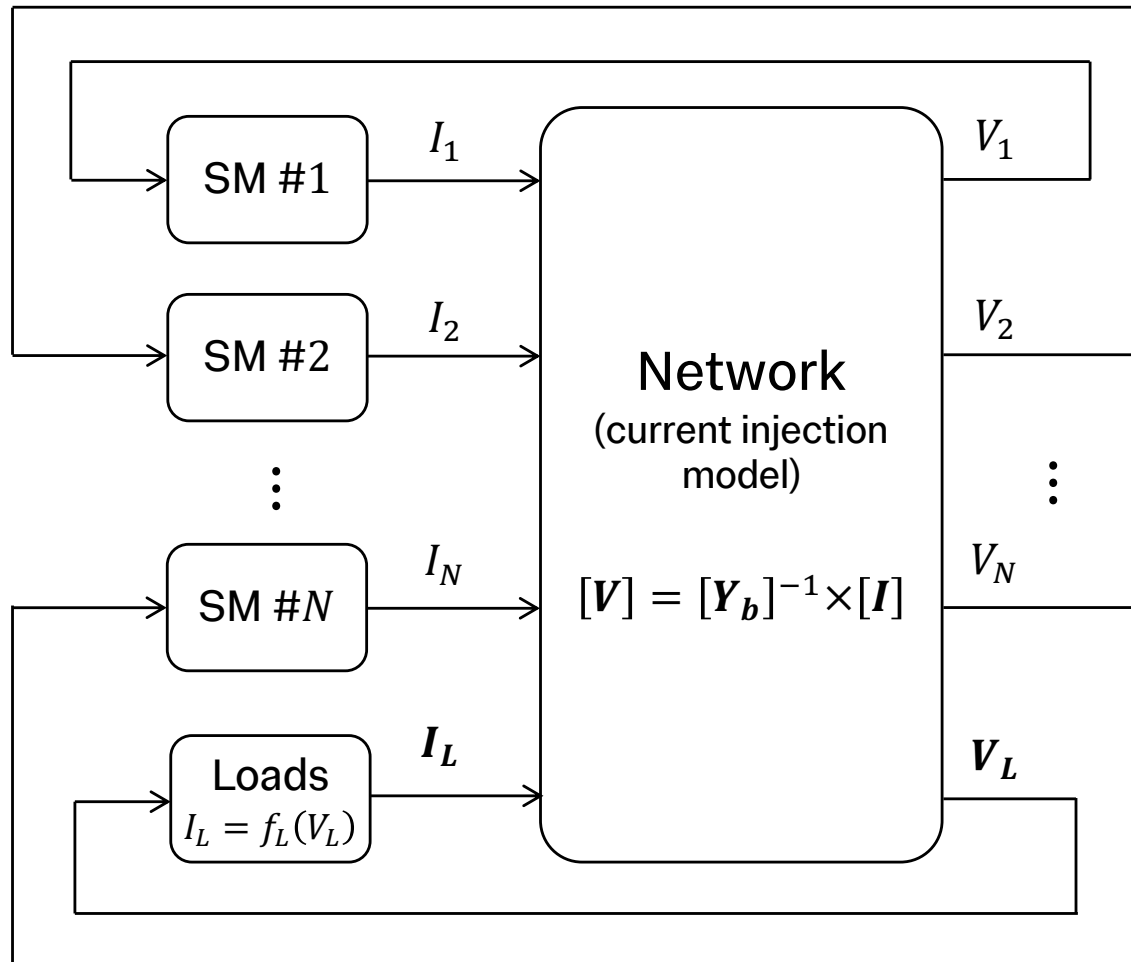
Miller et. al, "Diagnosis and Mitigation of Observed Oscillations in IBR-Dominant Power Systems: A Practical Guide" ESIG Stability TF, 2024

8 Hz SSO in Scotland, 2021 (source NESO)

- 1) Can such oscillations be foreseen? – not always!
 - a) IBR connection compliance process
 - b) Modelling adequacy (IBR – vendor-specific vs. generic; RMS, EMT, hybrid)
- 2) When such oscillations are seen in (EMT) simulation (or in real world) how to analyze and find the root cause for effective mitigation?

How is it done for inter-area oscillations?

Established modelling and analysis framework



Synchronous machine (SM)

$$\dot{x}_i = f_i(x_i, y_i, p_i)$$

$$0 = g_{Gi}(x_i, y_i, p_i)$$

standard model structure $f(\cdot), g_G(\cdot)$
and established parameter range p

DAE model of overall system

$\dot{x} = f(x, y)$ - all SMs, other dynamic components

$0 = g(x, y)$ - network, static loads, SM stator

Linearized state-space around an equilibrium (x_0, y_0)

$$\Delta \dot{x} = \left[\left(\frac{df}{dx} \right)_0 - \left(\frac{df}{dy} \right)_0 \left(\frac{dg}{dy} \right)_0^{-1} \left(\frac{dg}{dx} \right)_0 \right] \Delta x$$

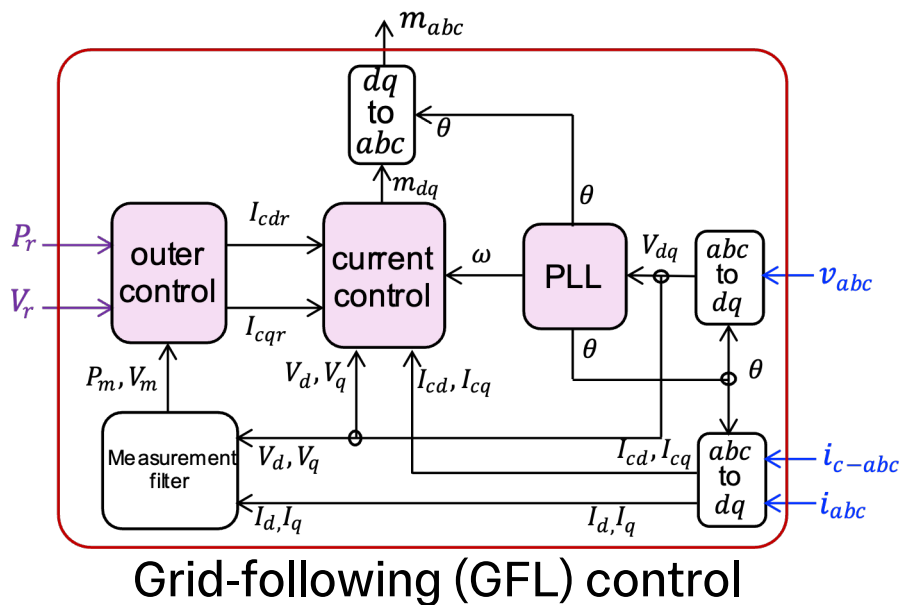
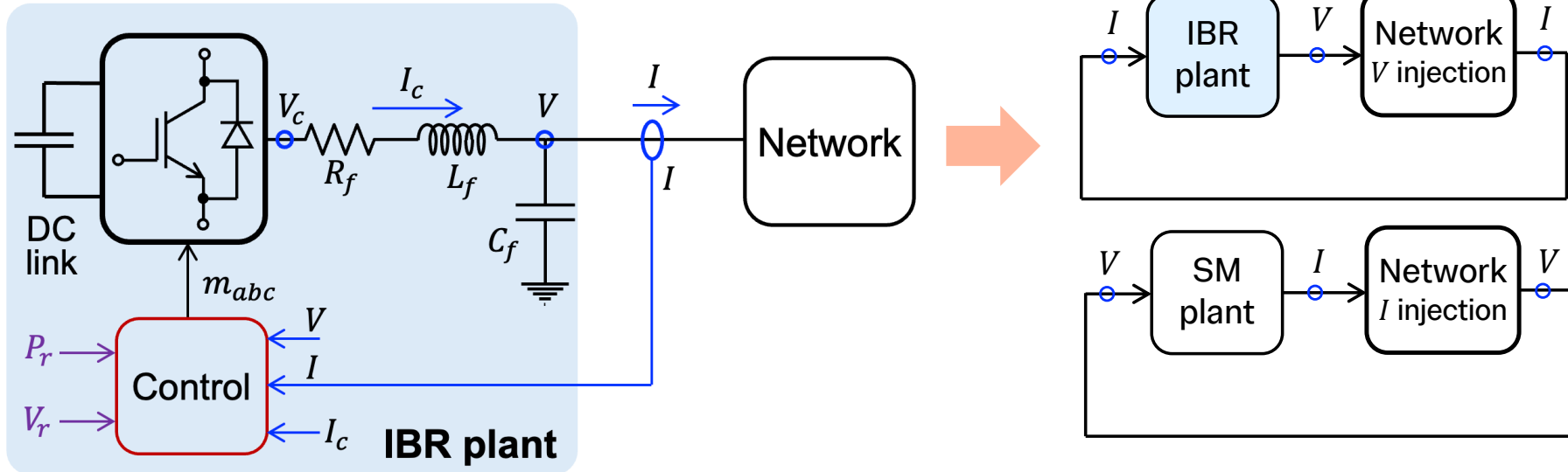
$$\Delta \dot{x} = [A]_0 \Delta x$$

Small-signal stability analysis based on linearized state matrix $[A]_0$ of overall system around an operating point (x_0, y_0) Suffix '0' denotes an operating point

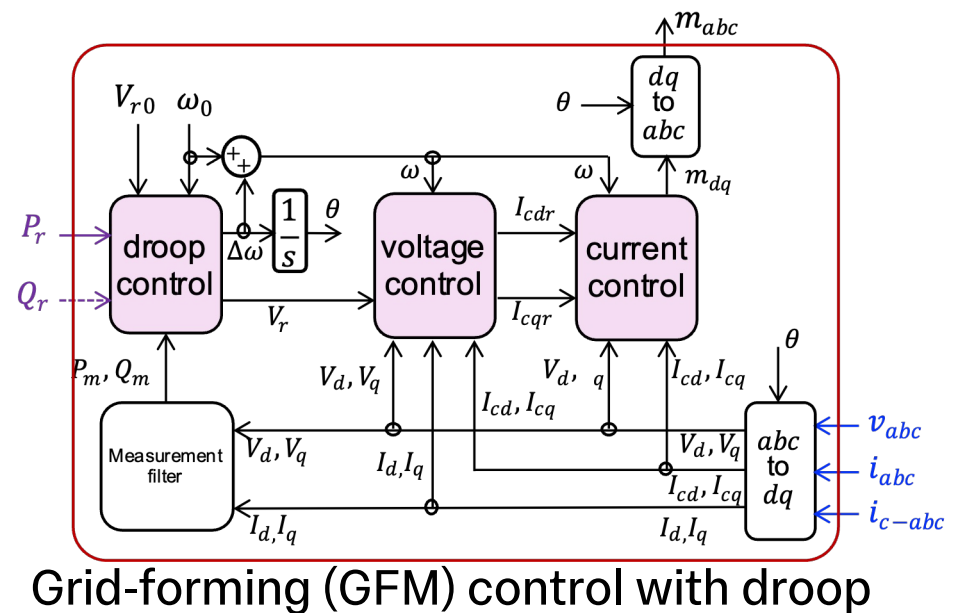
IBR model

aggregated at plant level

IBR - network interface



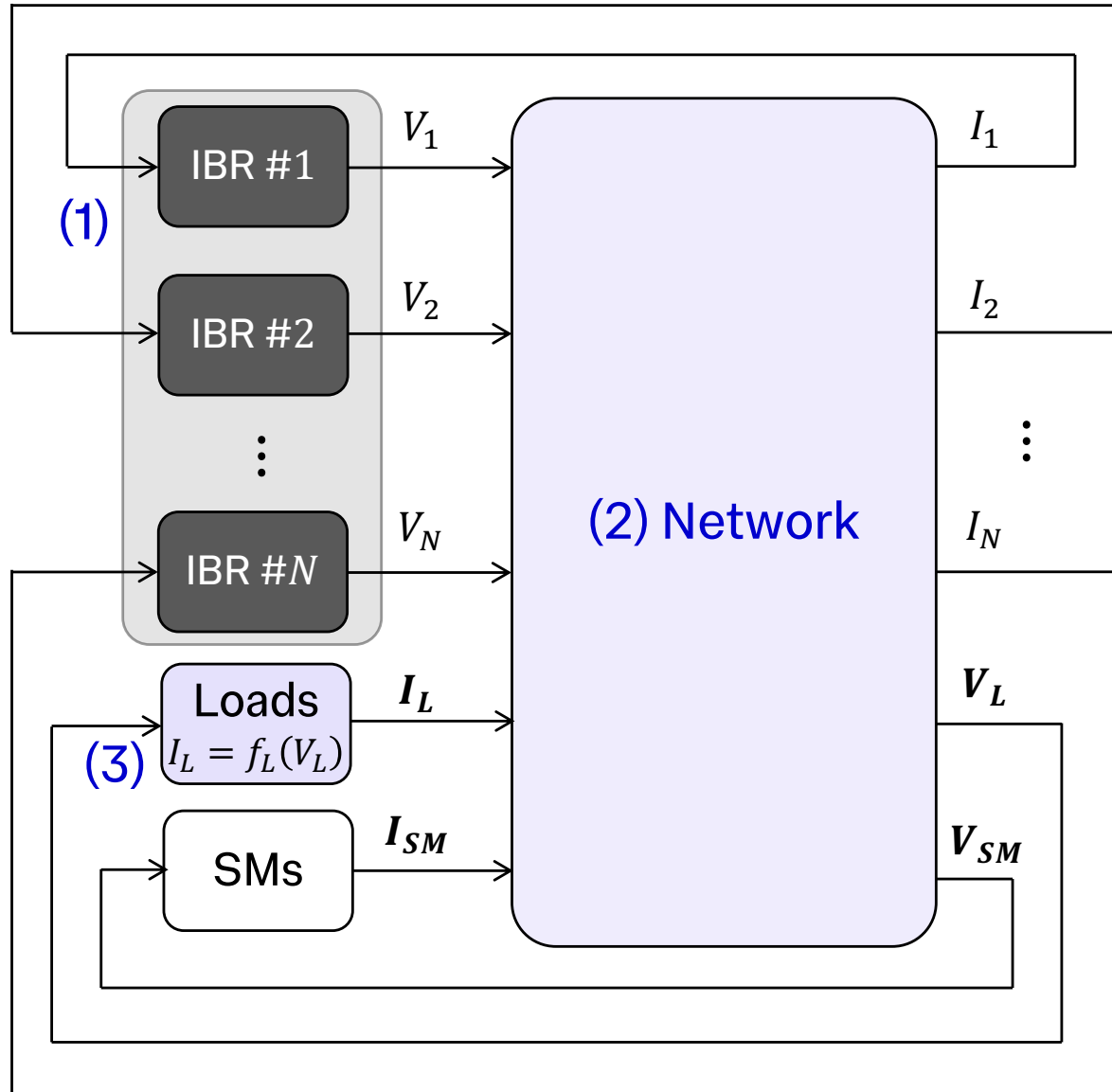
Grid-following (GFL) control



Grid-forming (GFM) control with droop

IBR-dominated system

How to obtain overall state matrix to analyze IBR-driven SSO?



(1) IBR plant model

$$\dot{x}_i = f_i(x_i, y_i, p_i)$$

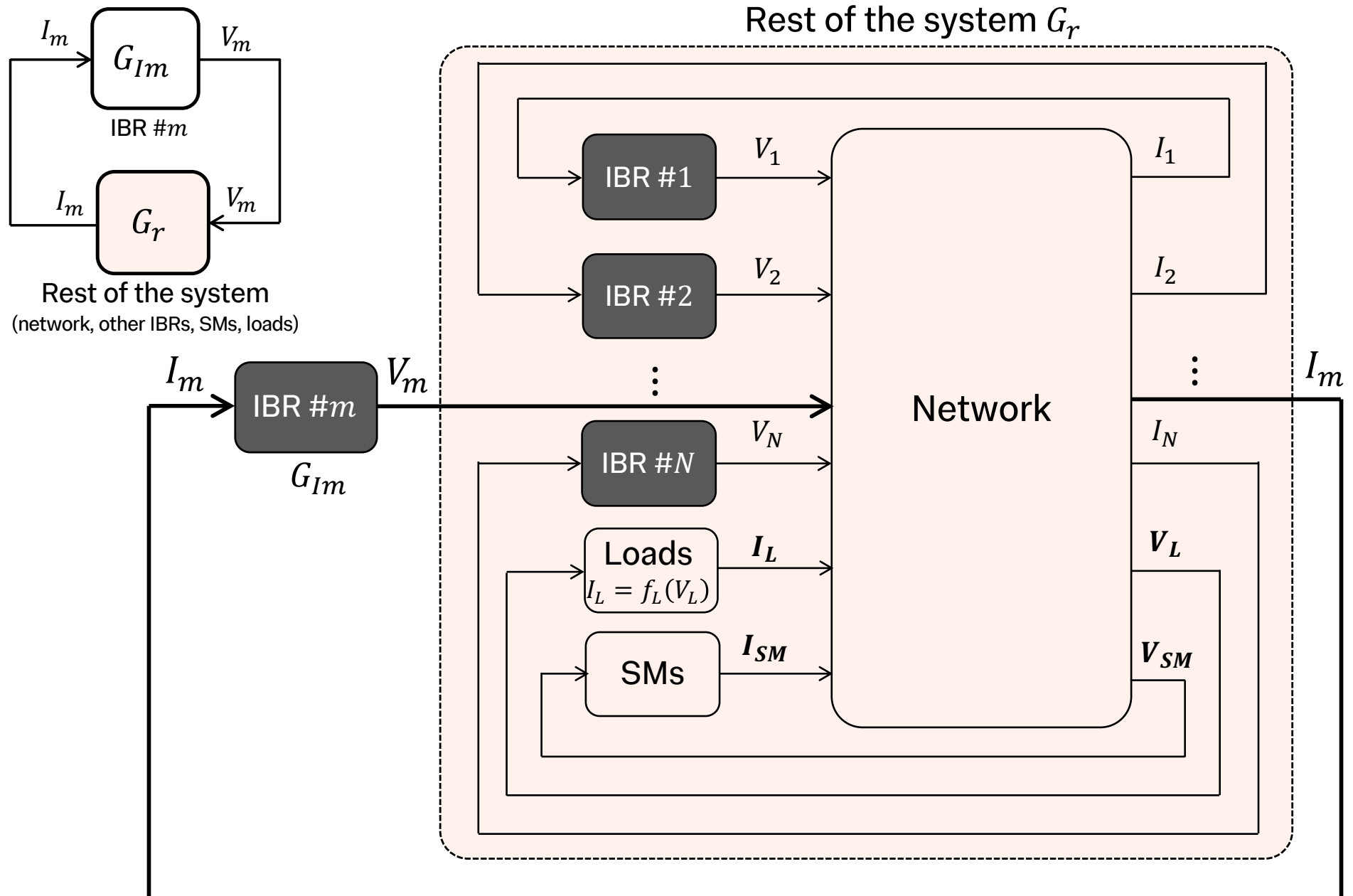
- Vendor-specific proprietary ('black-box') structure $f_i(\cdot)$
- Generic model $f_i(\cdot)$ available but parameterization (p) challenging
- Track operating point $(x_{i,0}, y_{i,0})$ dependency of IBR linearized model

(2) Network and SM stator model

- Static/algebraic (RMS tools)
- Dynamic/differential (EMT tools)

(3) Aggregated load model

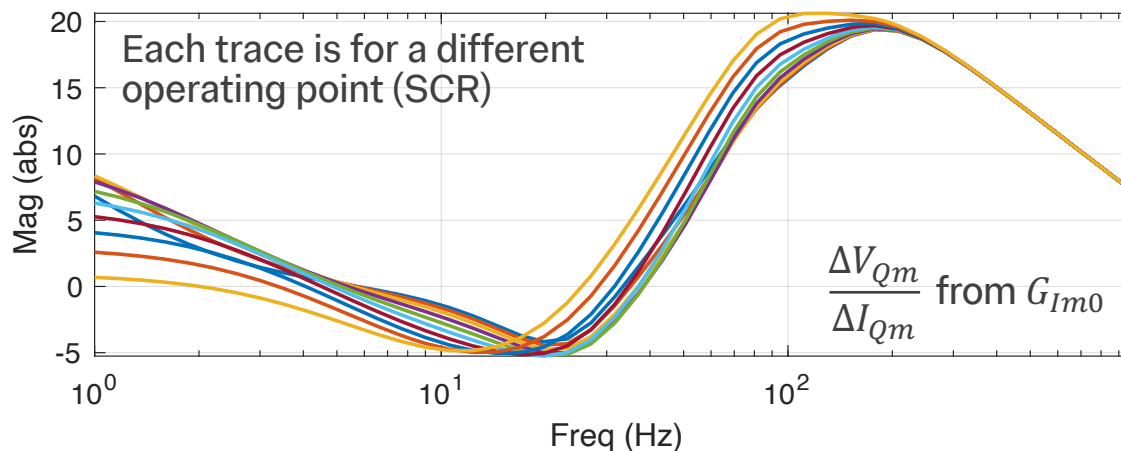
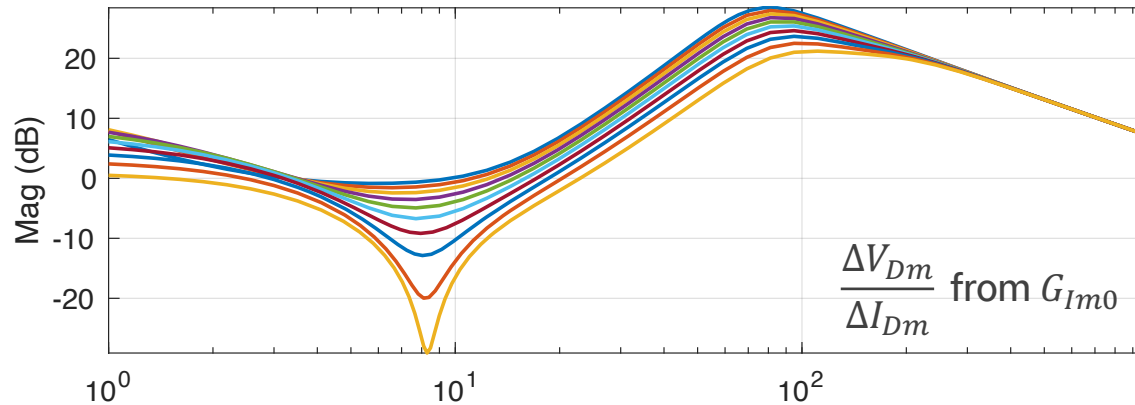
Consider a particular IBR



Frequency response of a GFL (open loop)

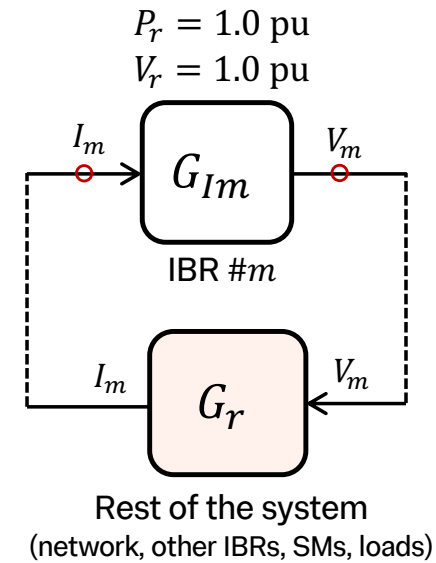
Standalone GFL plant for different operating points

Frequency response of IBR # m from model



Each trace is for a different operating point (SCR)

How to estimate linearised model G_{Im0} of an IBR for a given operating point?



$$I_m = \begin{bmatrix} I_{Dm} \\ I_{Qm} \end{bmatrix}, V_m = \begin{bmatrix} V_{Dm} \\ V_{Qm} \end{bmatrix}$$

$$1.1 \leq \text{SCR} \leq 5.0$$



$$11.5^\circ \leq \theta_{m,0} \leq 63^\circ$$

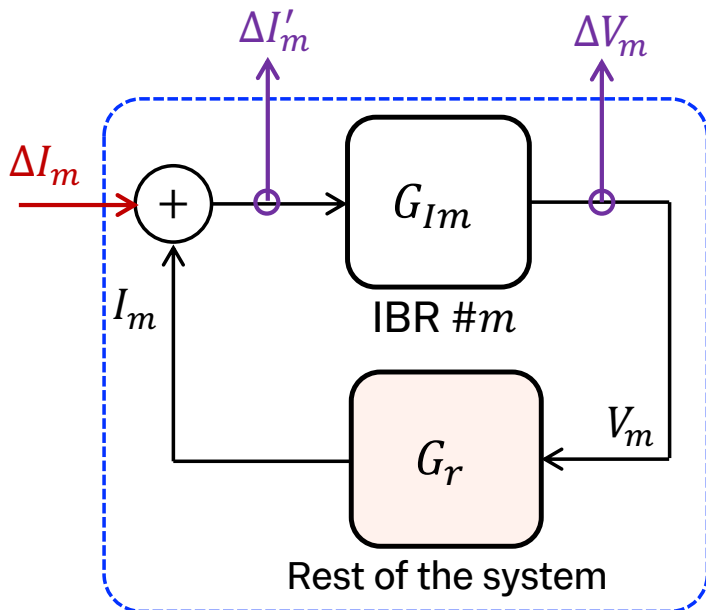
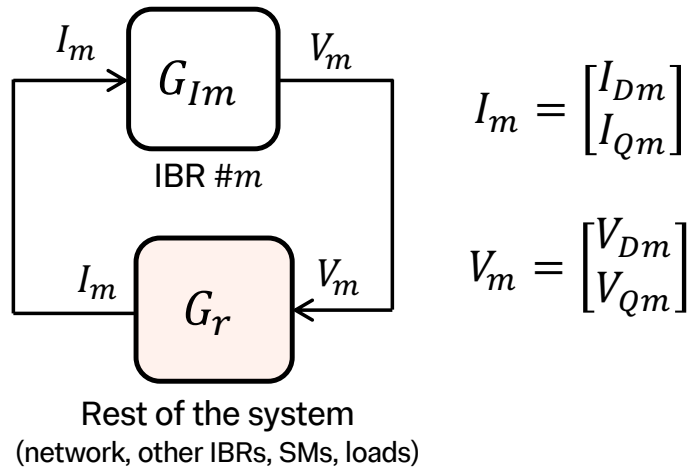
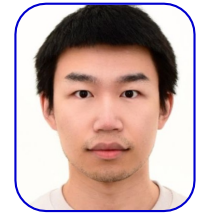
$$0.46 \text{ pu} \leq V_{Dm,0} \leq 0.98 \text{ pu}$$

$$0.20 \text{ pu} \leq V_{Qm,0} \leq 0.89 \text{ pu}$$

$$0.88 \text{ pu} \leq I_{Dm,0} \leq 0.98 \text{ pu}$$

$$0.20 \text{ pu} \leq I_{Qm,0} \leq 0.67 \text{ pu}$$

Estimation of IBR plant model



Simulation model

- Inject current perturbation ΔI_m at IBR # m and obtain perturbed $\Delta I'_m$ and ΔV_m at its terminal
- Estimate model $G_{est1,0}$, $G_{est2,0}$ between perturbed ΔV_m , $\Delta I'_m$, and perturbation ΔI_m

$$G_{est2,0} = \frac{\Delta V_m}{\Delta I_m}$$

$$G_{est1,0} = \frac{\Delta I'_m}{\Delta I_m}$$

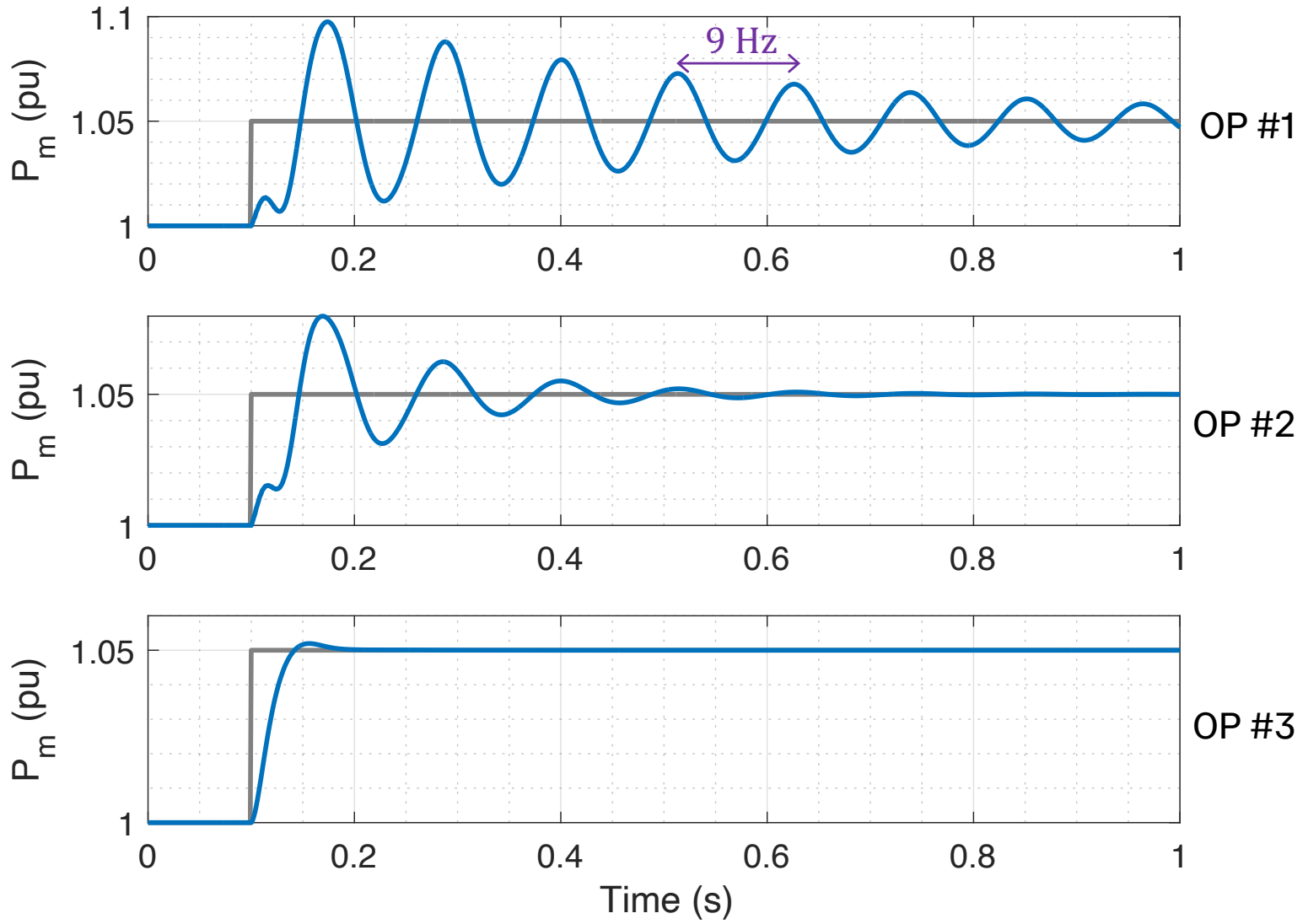
$$G_{est2,0} \times (G_{est1,0})^{-1} = \frac{\Delta V_m}{\Delta I_m} \times \frac{\Delta I_m}{\Delta I'_m} = G_{Im0-est}$$

- Estimated linearized model of IBR # m

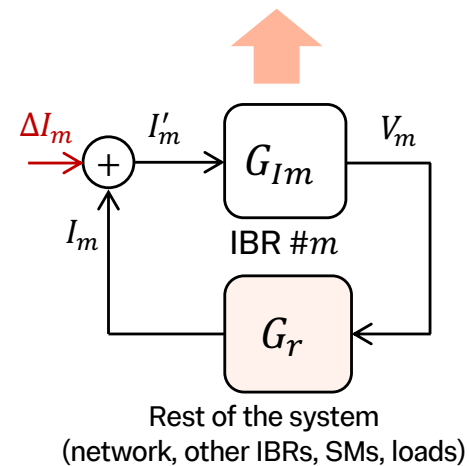
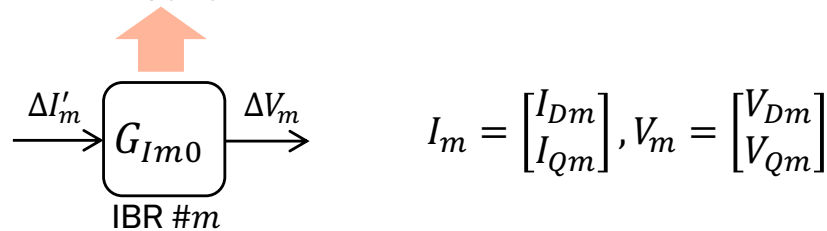
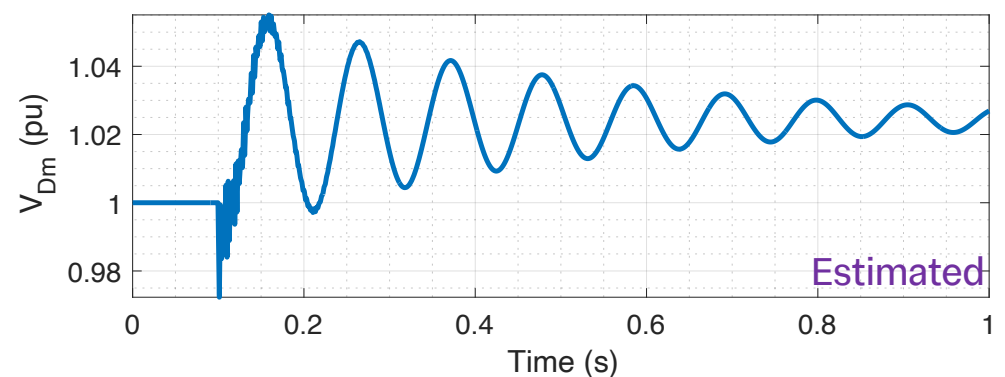
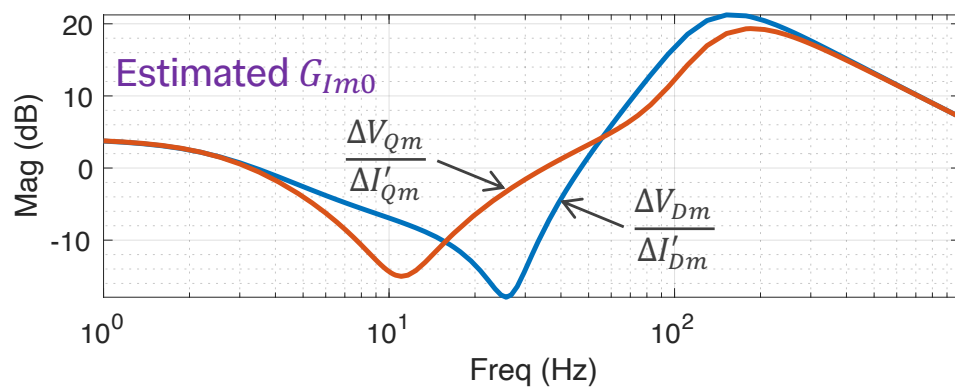
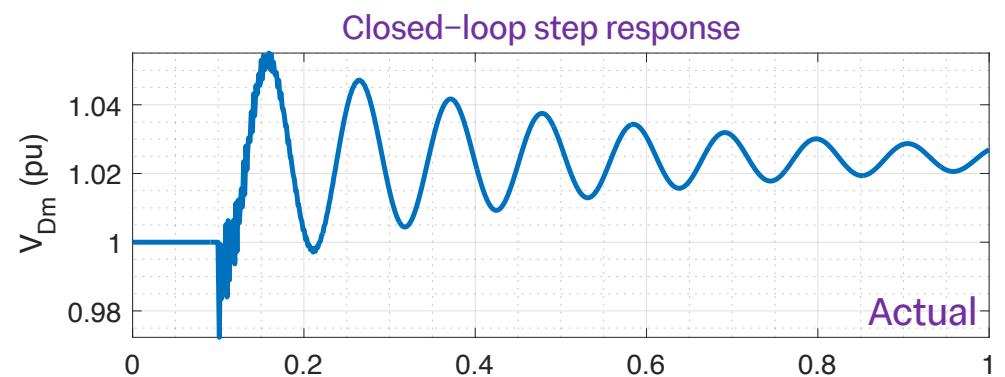
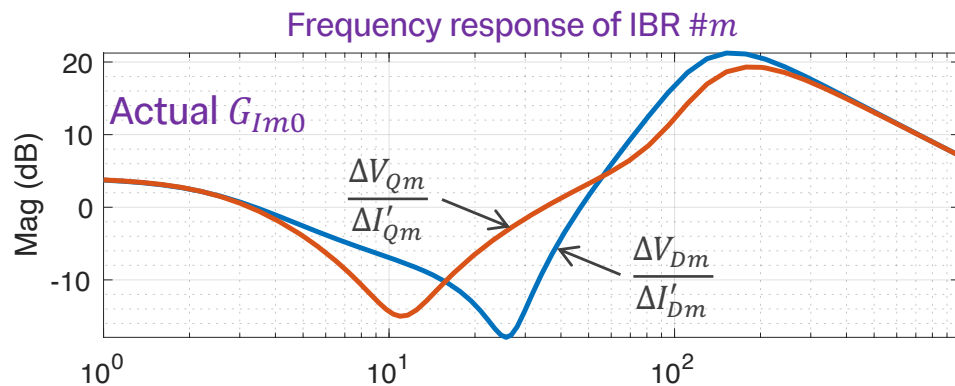
$$G_{Im0-est} = G_{est2,0} \times (G_{est1,0})^{-1}$$

- $G_{est1,0}$ is invertible as $G_{est1,0} \cdot D \neq 0$
- Perturbation signal key to estimation accuracy

Validation - 3 operating points



Validation: OP #1 (poorly damped)

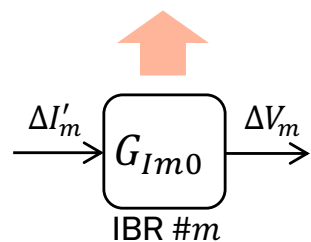
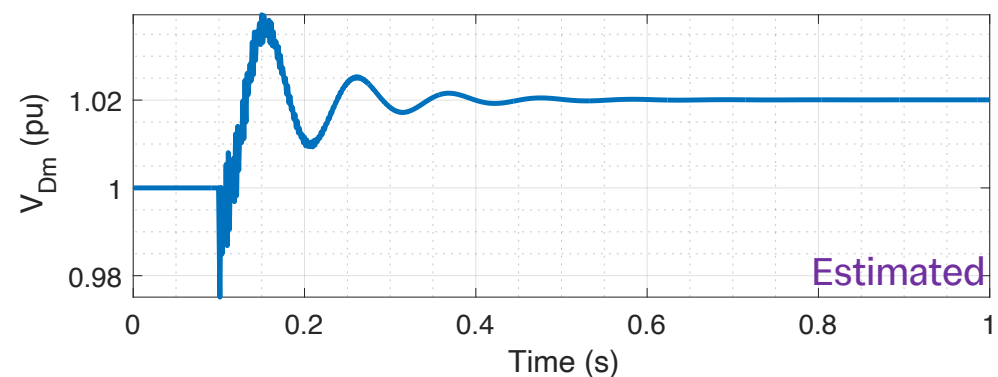
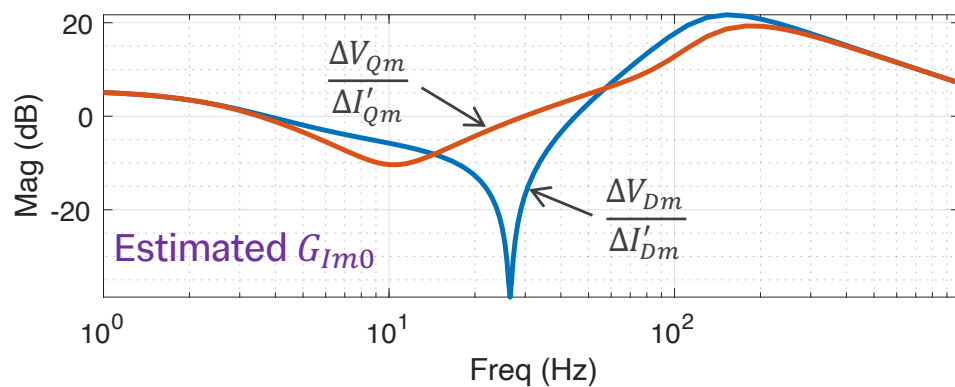
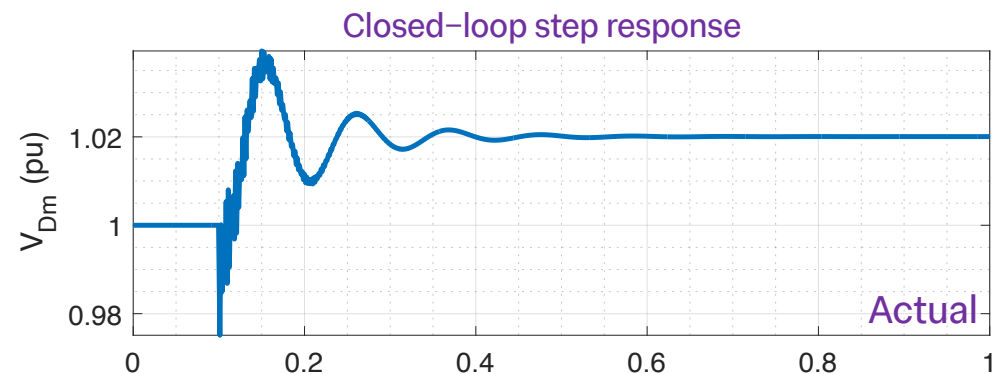
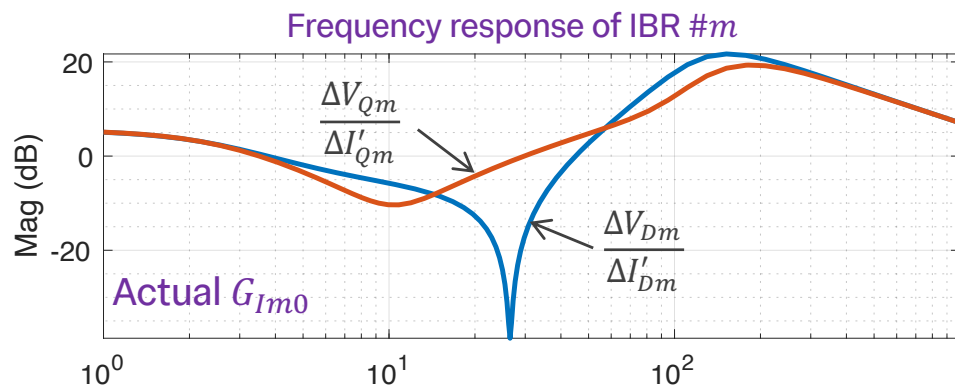


Accuracy of estimated model is high if:

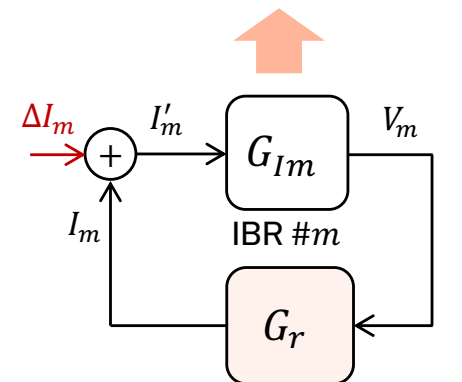
- perturbation signal is 'rich' and sufficiently exciting
- response stays within 'linear' zone (close to the operating point)

Both are relatively easy to achieve in a simulation environment

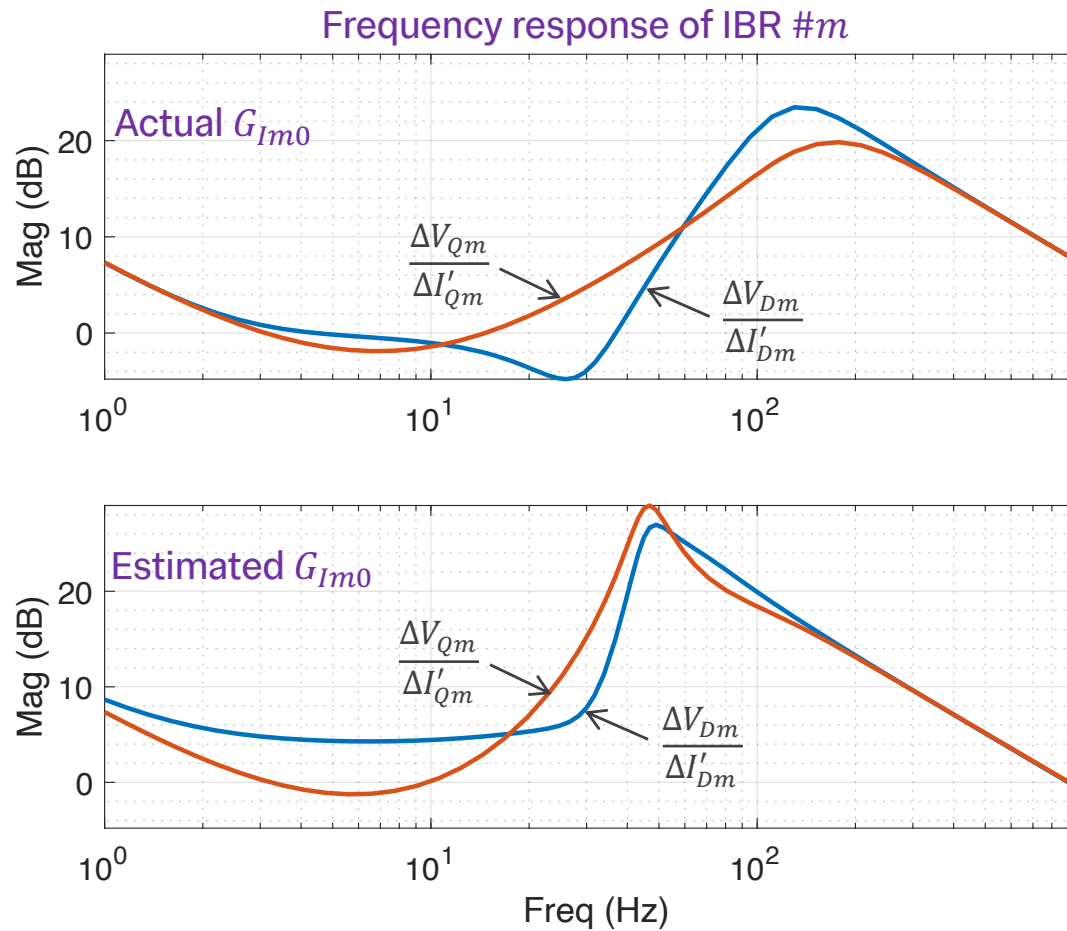
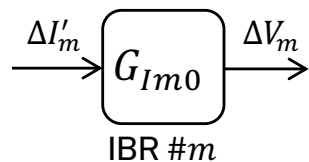
Validation: OP #2 (well damped)



$$I_m = \begin{bmatrix} I_{Dm} \\ I_{Qm} \end{bmatrix}, V_m = \begin{bmatrix} V_{Dm} \\ V_{Qm} \end{bmatrix}$$

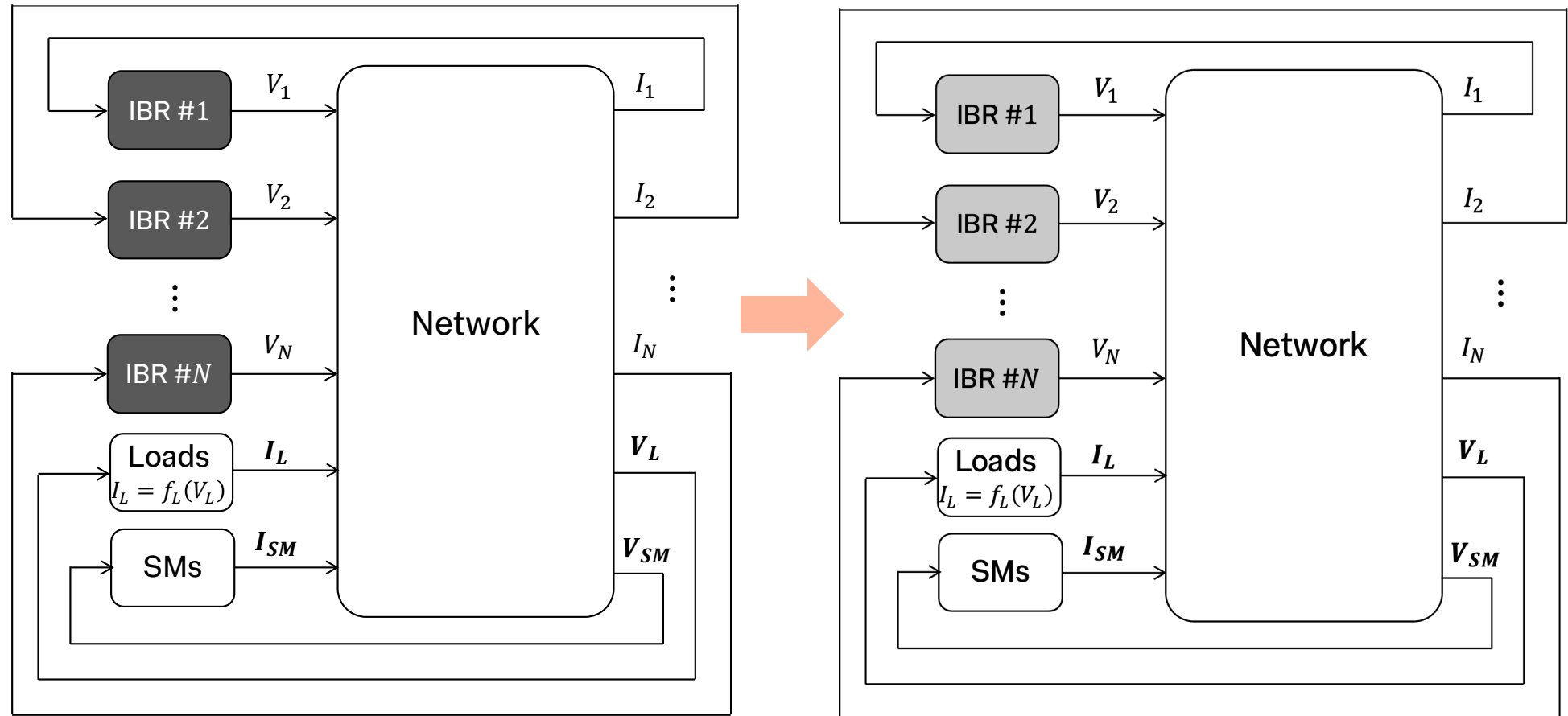


Validation: OP #3 (critically damped)



Estimated IBR model **inaccurate** for critically damped response

'Black-box' to 'Gray-box' IBR



- Overall, system state-space matrix $[A]_0$ formed with **estimated** linearized model of IBRs ($G_{Im0-est} \forall m = 1, 2, \dots, N$) and **known** SMs, loads and network models
- Eigen vectors of $[A]_0$ provides contribution (participation) of each IBR plant in poorly damped SSO mode(s) and oscillation pathway (modeshape)

Challenges

- Sequential vs. simultaneous
 - System identification with structure?
- Perturbation
 - Richness of perturbation signal?
 - Perturb IBR references?
- Scale-up for large systems?
 - Model order vs dominant modal response
- Effect of noise (NESO funded DOME project)



2) Network model for SSO studies

Static (algebraic) or dynamic (differential)?

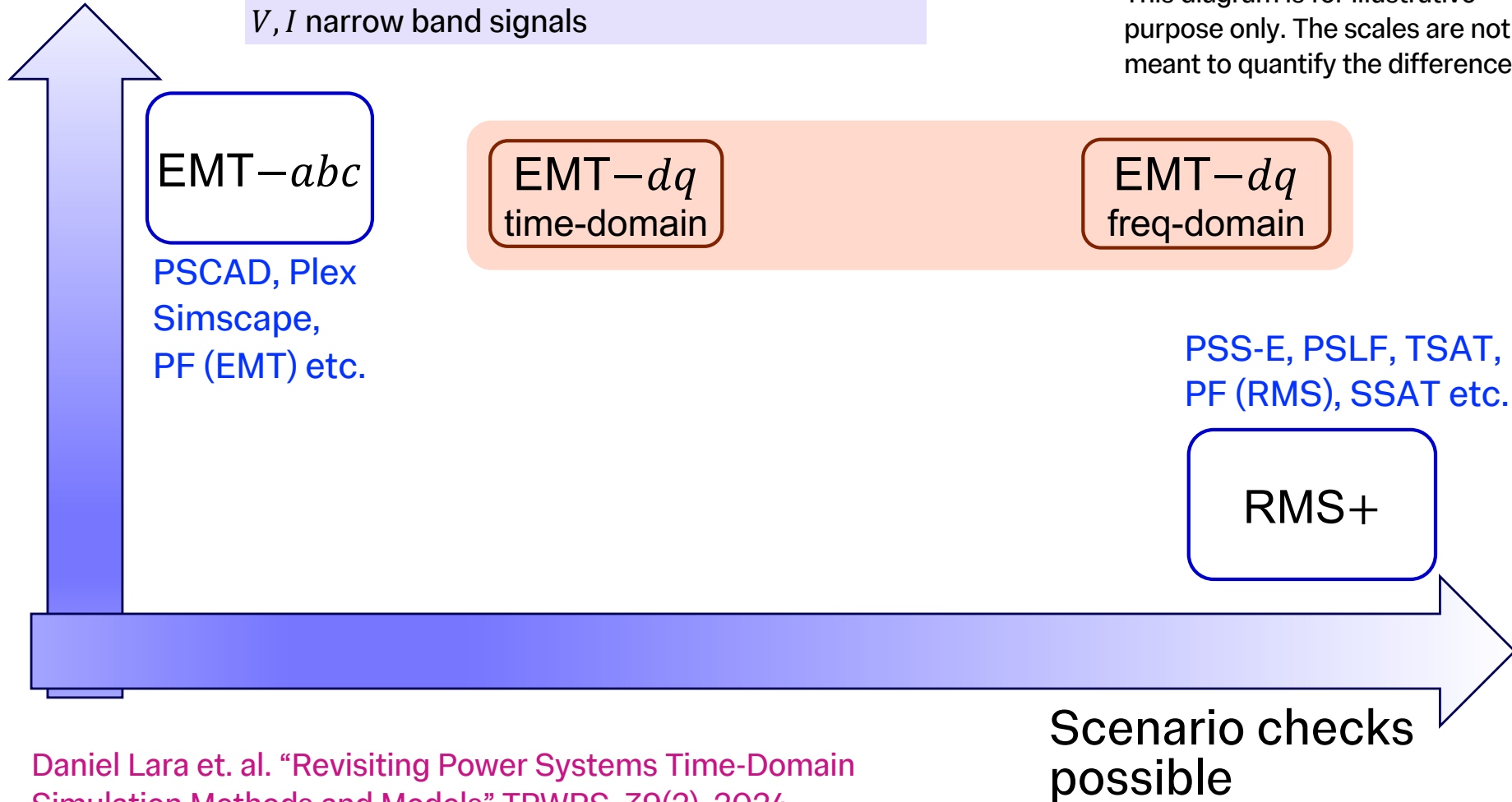


Accuracy
for SSO

Scope

Small-signal stability
No large disturbance (faults, frequency events)
 V, I narrow band signals

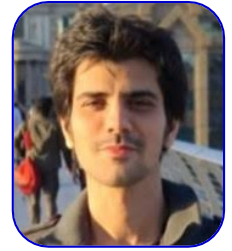
This diagram is for illustrative purpose only. The scales are not meant to quantify the difference



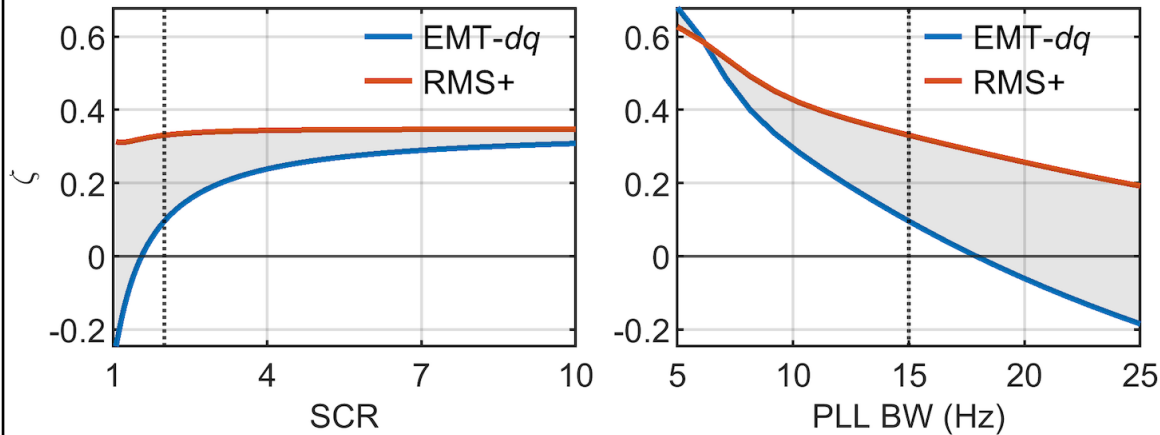
Daniel Lara et. al. "Revisiting Power Systems Time-Domain Simulation Methods and Models" TPWRS, 39(2), 2024

EMT vs. RMS for GFL

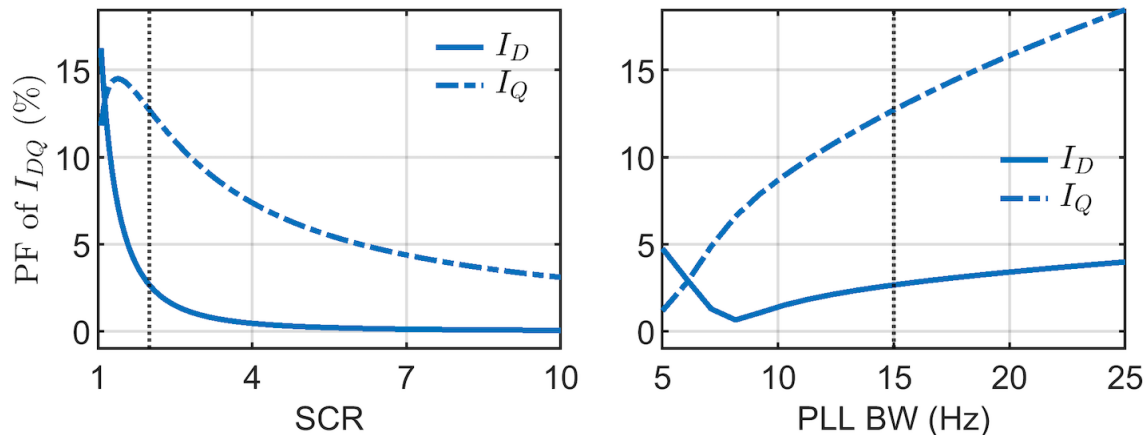
Grid-following (GFL)



Damping ratio (ζ) of SSO mode



Participation of network state in SSO mode



Network dynamic model in DQ frame

$$v_{\Delta DQ} = R i_{LDQ} \mp \omega L i_{LDQ} + L \frac{di_{LDQ}}{dt}$$

$$i_{\Delta DQ} = \mp \omega C_b v_{DQ} + C_b \frac{dv_{DQ}}{dt}$$

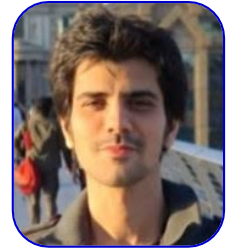
Difference between EMT and RMS more pronounced for

- higher oscillation frequency $\frac{d(\cdot)}{dt}$ (usually at higher control BW)
- higher L and C_b (i.e., lower SCR)
- higher participation of network states

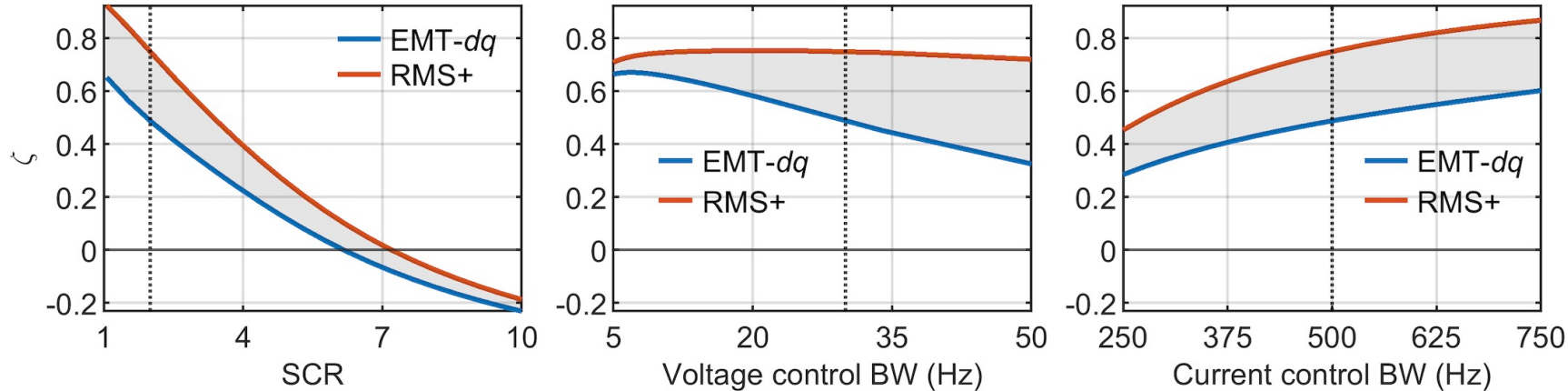
- 1) RMS generally shows higher damping than EMT
- 2) Difference between EMT and RMS is more at low SCR (weak grid) and higher PLL bandwidth

EMT vs. RMS for GFM

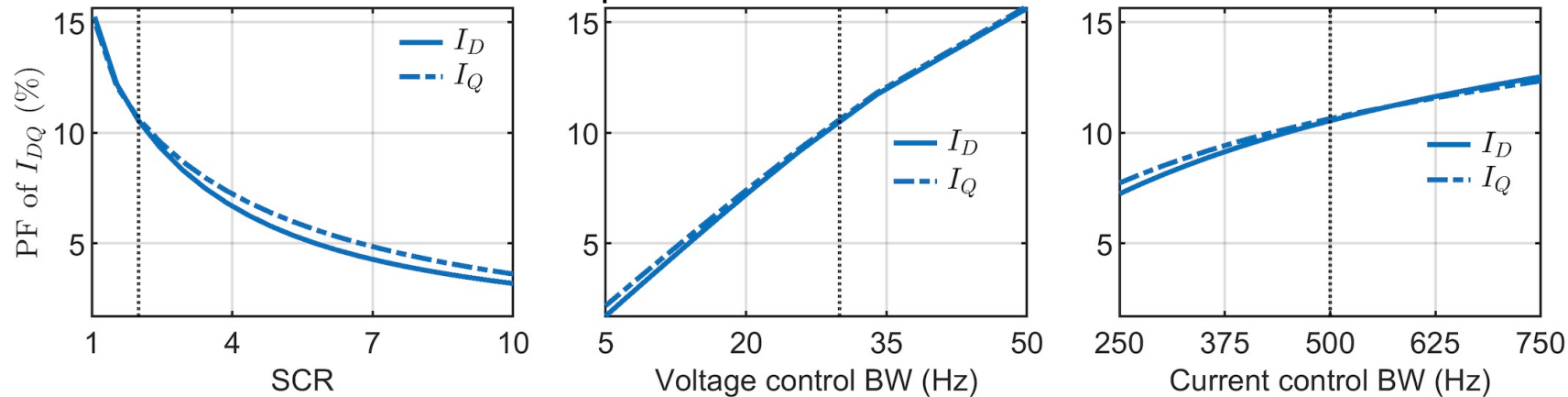
Grid-forming (GFM)



Damping ratio (ζ) of SSO mode



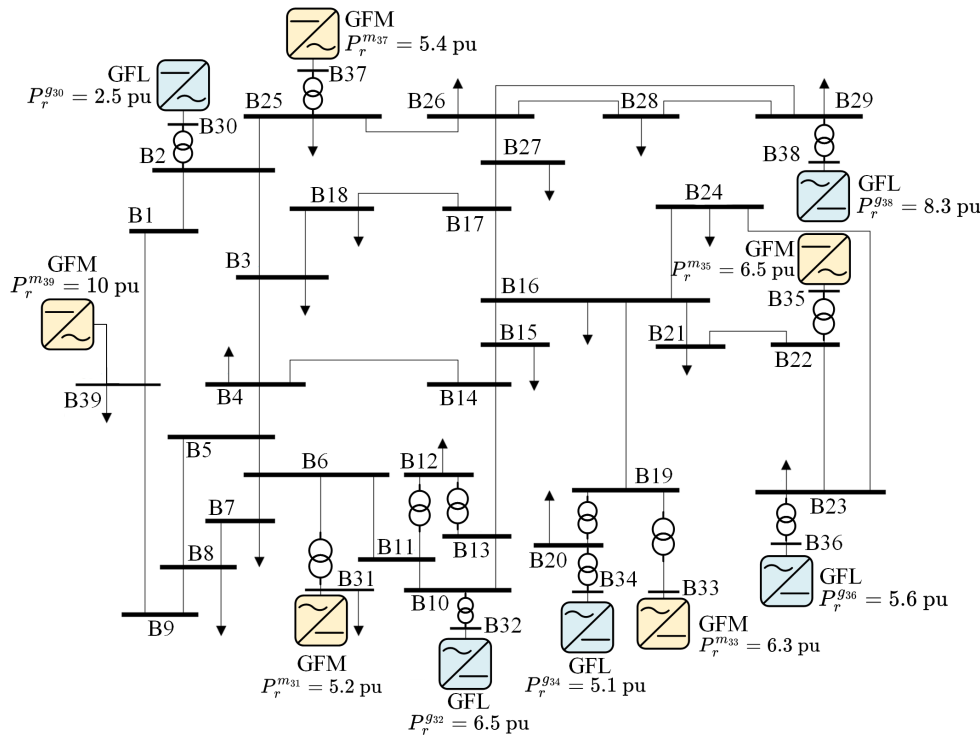
Participation of network state in SSO mode



- 1) RMS shows higher damping than EMT unless GFM voltage control is slow and/or network is strong (high SCR)
- 2) Stability assurance with RMS could be misleading!

39-bus test system with 100% IBRs

EMT vs. RMS

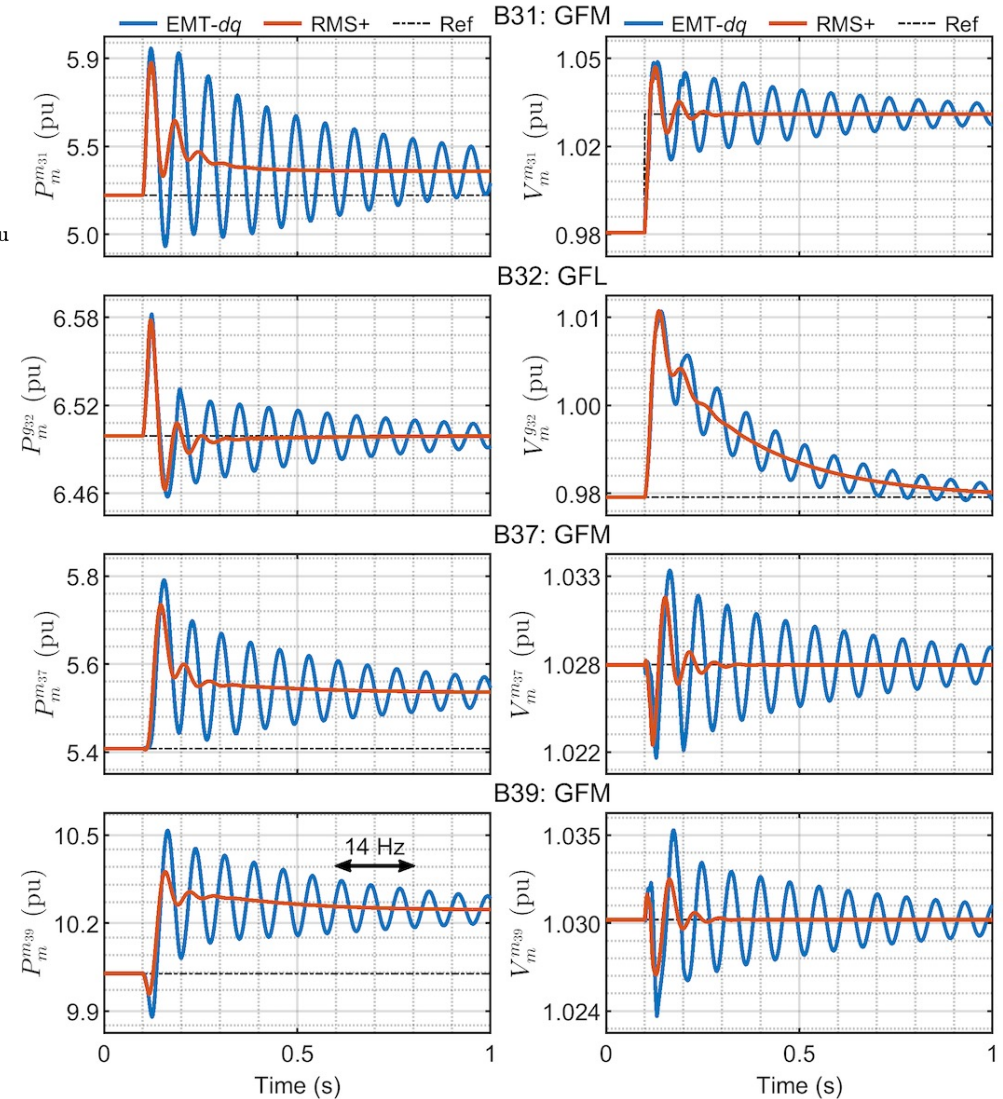


Step change at 0.1 s - P_r of GFL at bus 30 reduced by 10%, V_r of the GFM at bus 31 increased by 5%

45% GFL and 55% GFM

Difference between EMT and RMS response depends on:

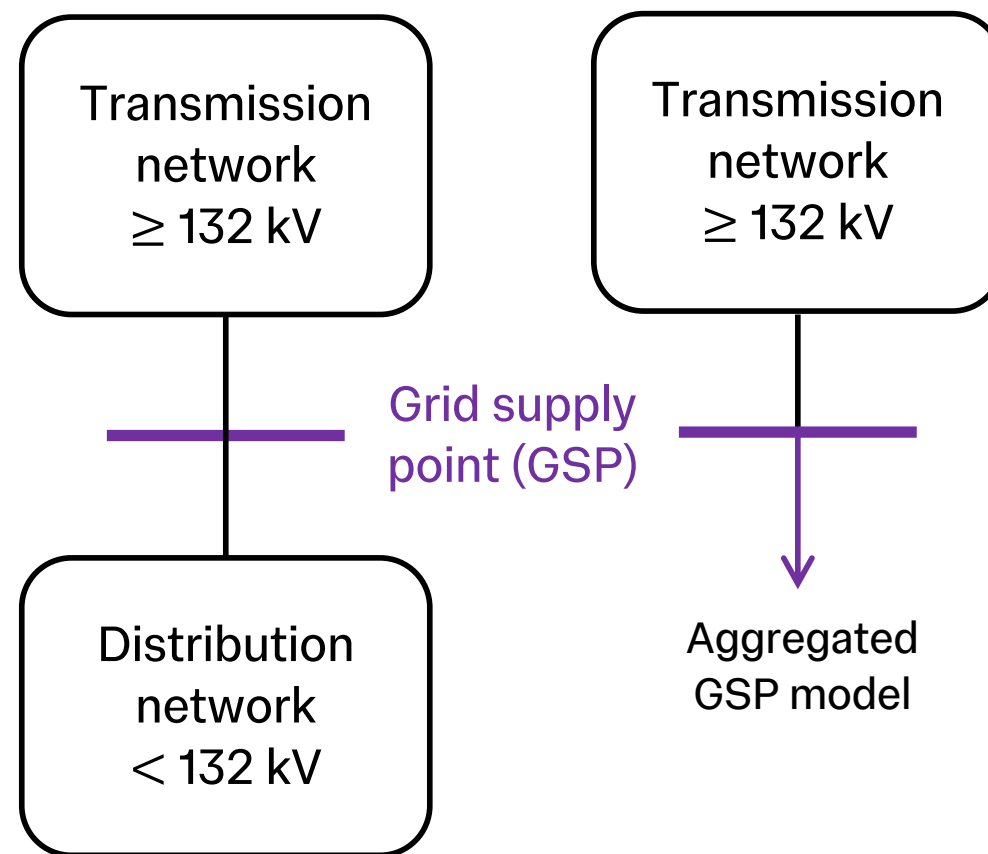
- 1) Relative share of GFL and GFM
- 2) GFL and GFM control bandwidths



3) Aggregated model at GSPs

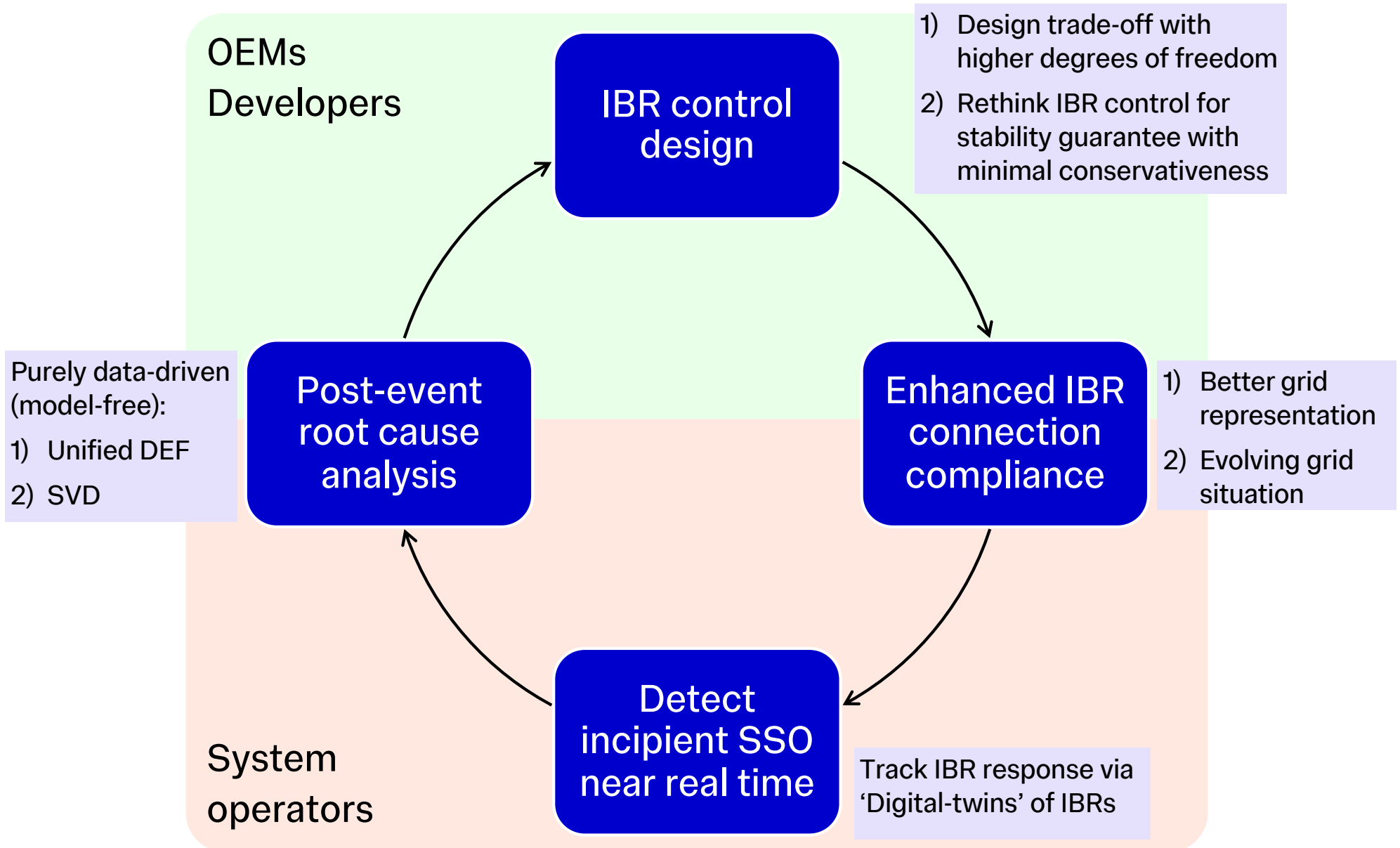
Project with SSEN-T in collaboration with SSEN-D

- Basis
 - DNO test data at distribution substations
 - Composite load model (WECC)
- Aggerate at GSPs bottom-up
- Active distribution with DERs
- Impact on stability
- Recommendation for field tests



Four-layer defense against SSO

Ongoing research with NESO and EPICS global center



Take away...

Work in progress

- IBR model could be estimated around an operating point to analyze their effect on SSO
- For SSO studies, RMS tools are not generally adequate
 - depends on GFL-GFM mix, their relative location and control bandwidths
- Revisit aggregated load model
- Four-layer defense against SSO



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