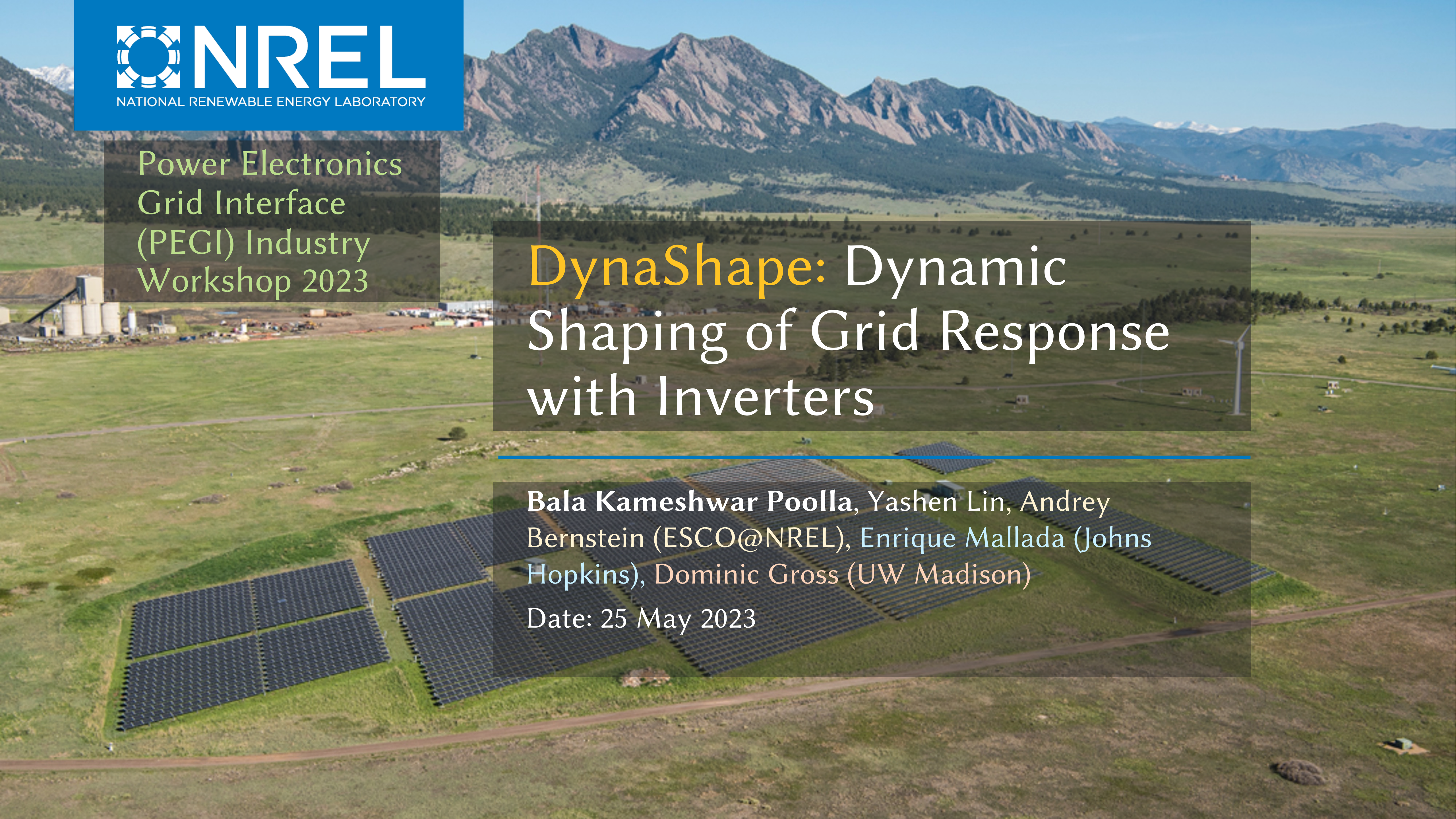

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Power Electronics Grid Interface (PEGI) Industry Workshop 2023

DynaShape: Dynamic Shaping of Grid Response with Inverters

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Date: 25 May 2023

Outline

1. What is “DynaShape” all about and why it is necessary?
2. What do we aim to achieve with “DynaShape”?
3. What is the approach we follow?
4. Analysis & Simulation Results
5. What comes next?
6. What more can be done? Industry Collaboration
7. Conclusions

Why DynaShape?

Grid-following

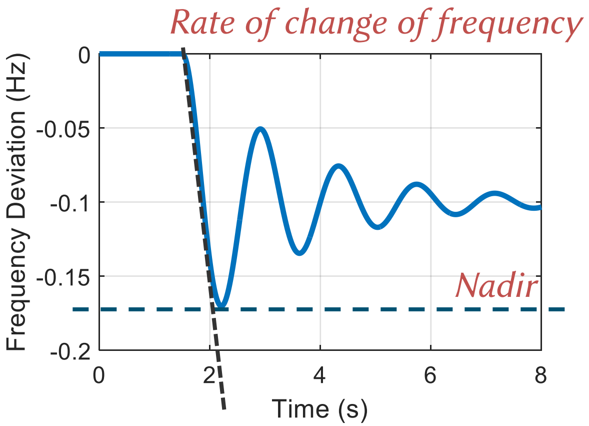
- IBRs follow grid voltage
- Large transient, PLL delay

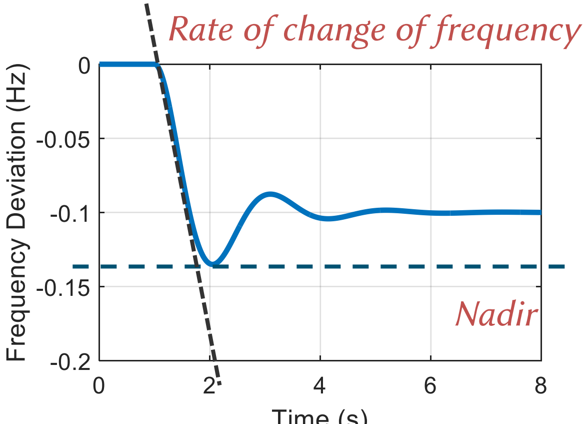
Grid-forming

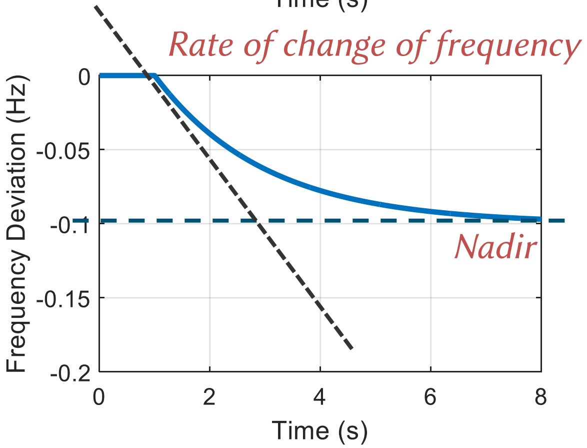
- IBRs mimic synchronous generators
- Typical oscillatory behavior-leading to power losses on lines

DynaShape

- IBRs “shape” the grid to desired system behavior





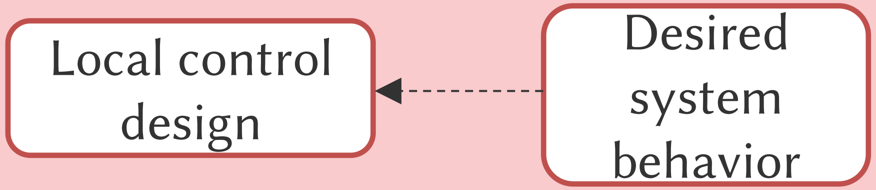


- “State-of-the art” Device level focus:

The existing controls do NOT leverage full potential of IBRs for operating future grids.

We need a new system level control design philosophy.

- “Dyna-Shape” System level view:



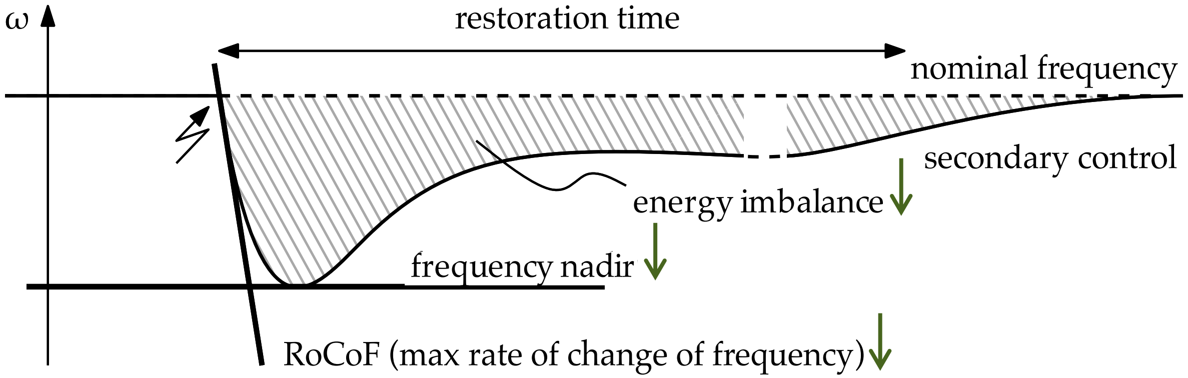
- Beyond the limitation of synchronous generators

What we aim to achieve?

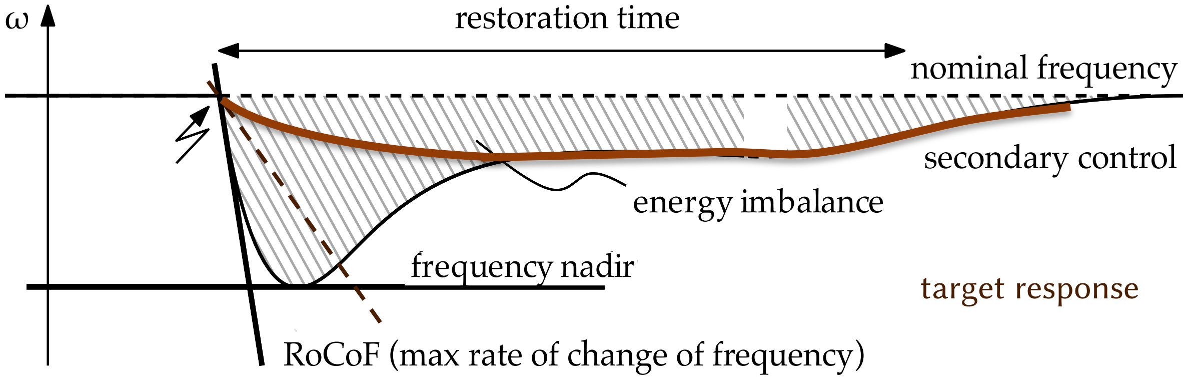
- Develop "grid-shaping" inverter control for IBR-integrated systems, that does not hinge on synchronous machine emulation.
- Design controller that achieves "desirable" grid behavior.

Additional features:

- Interoperability with various inverters, synchronous generators, and other legacy devices
- Adaptive control modify the control by analyzing the impact of "incorrect knowledge" of network parameters on system performance.



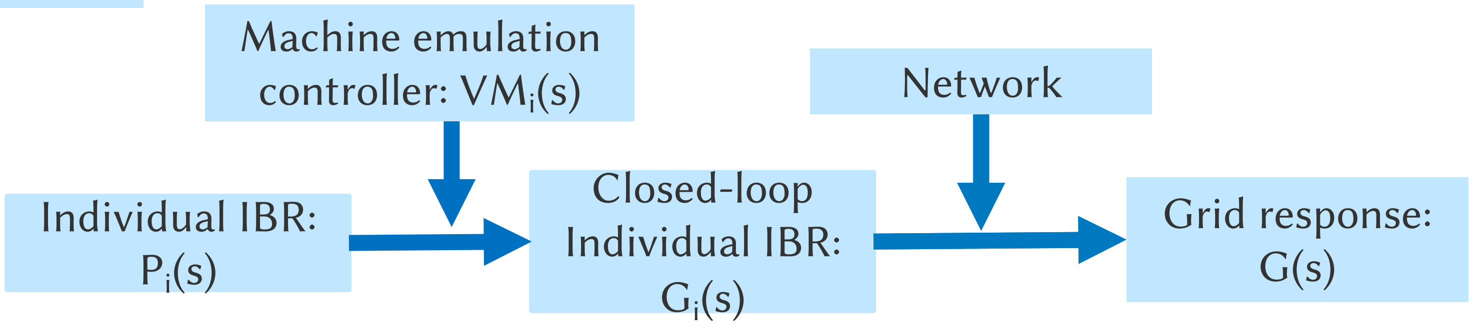
Typical power system metrics considered for post-disturbance stability analysis



Target response for post-disturbance stability analysis

Approach followed

Standard: Forward design



Machine emulation controller: $VM_i(s)$

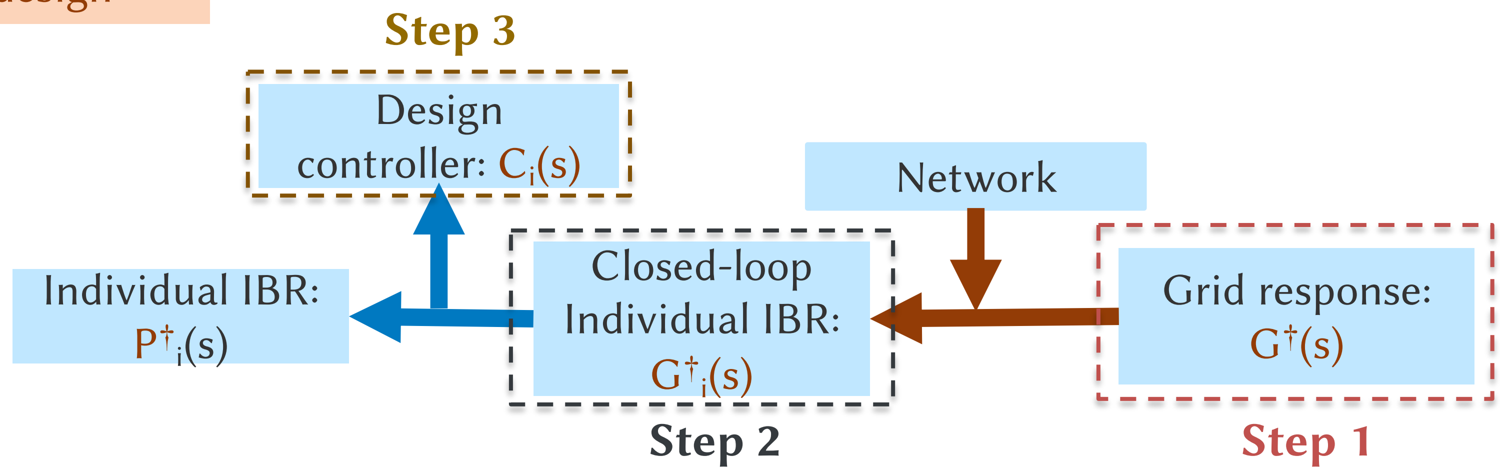
Network

Individual IBR: $P_i(s)$

Closed-loop Individual IBR: $G_i(s)$

Grid response: $G(s)$

DynaShape: Reverse design



Step 3

Design controller: $C_i(s)$

Network

Individual IBR: $P^\dagger_i(s)$

Closed-loop Individual IBR: $G^\dagger_i(s)$

Step 2

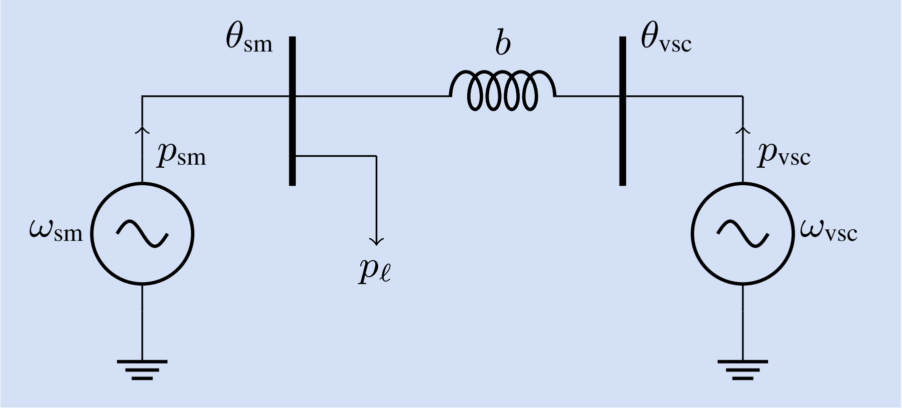
Grid response: $G^\dagger(s)$

Step 1

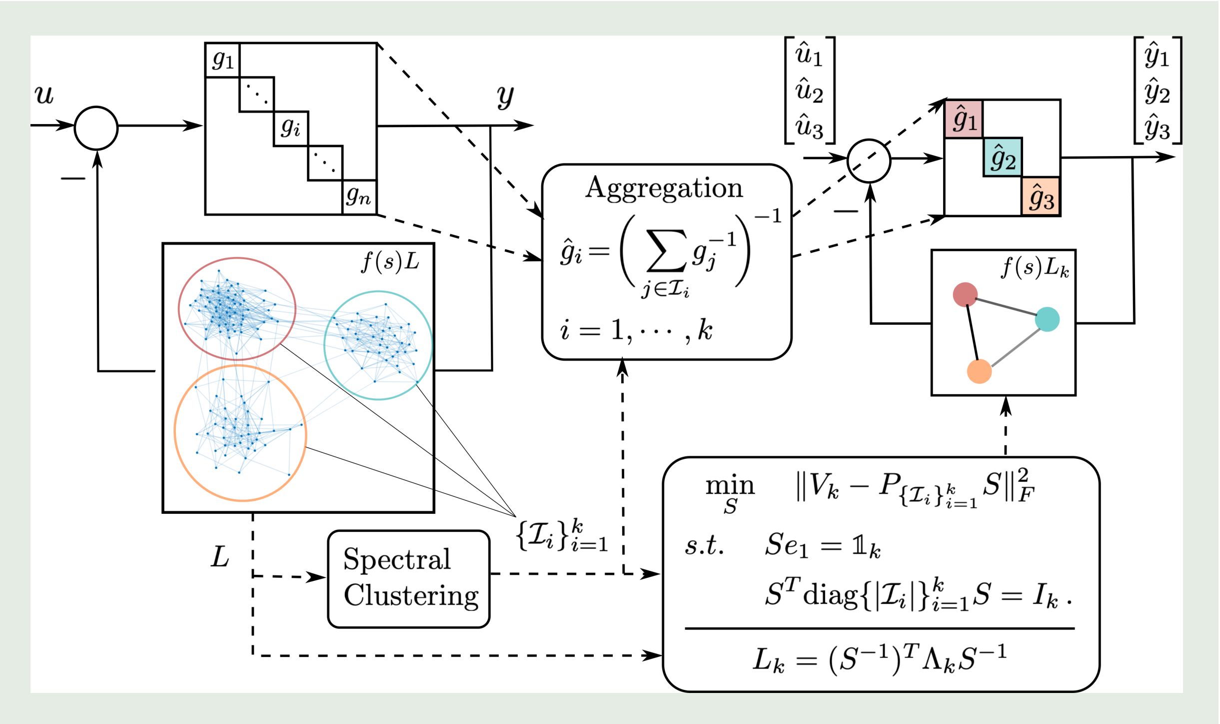
Analysis

The problem can be studied under multiple settings:

- Single IBR device coupled with an aggregate synchronous machine under both grid-forming and grid-following implementations.
- Star/Delta connected IBR devices with an aggregate synchronous machine at the point of common coupling.
- Large-scale networks with multiple IBR devices and synchronous machines. Such networks can be aggregated and reduced to coherent clusters.

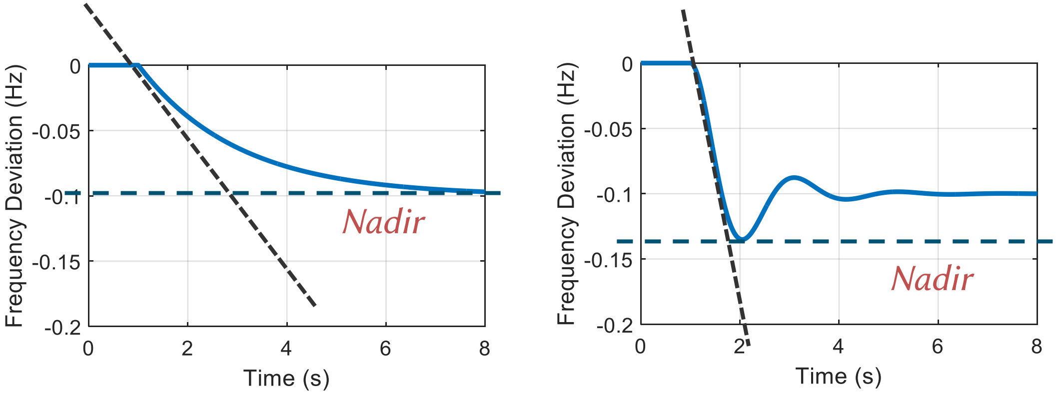


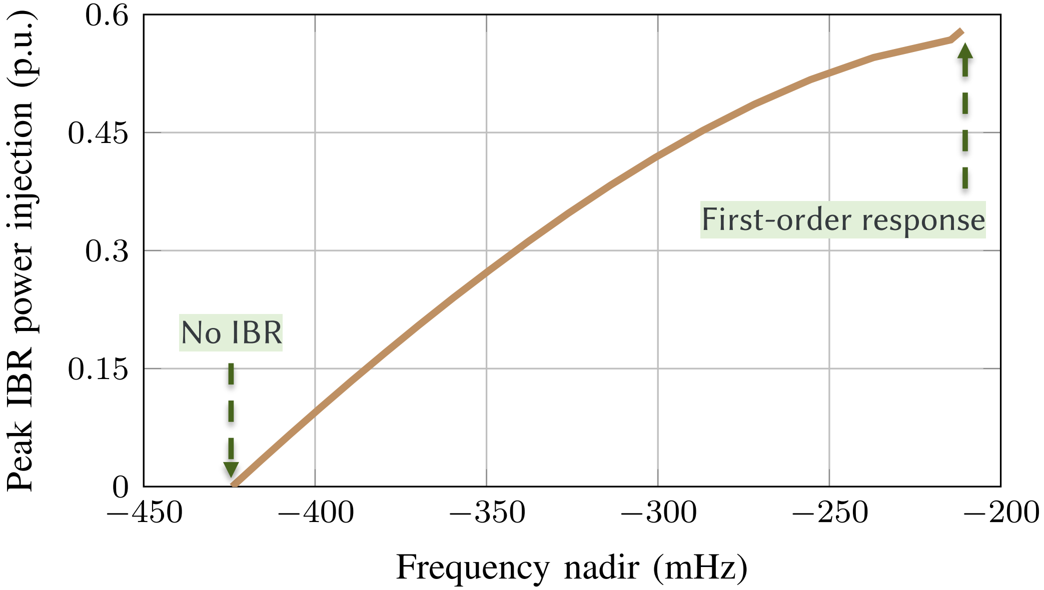
One IBR (Grid forming)-aggregated synchronous machine



Multi-IBR, multi-machine network (Source: Enrique Mallada)

Simulations Step1





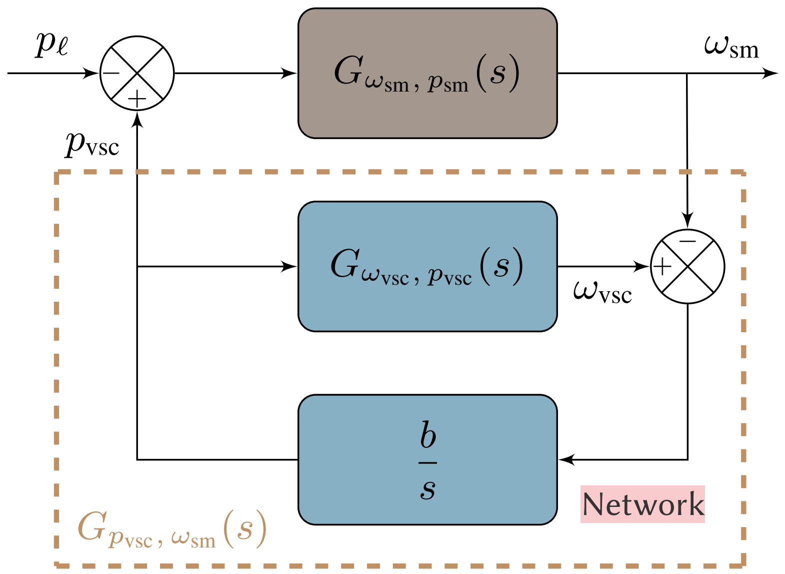
- Grid Response Characteristics $G^{\dagger}(s)$: Frequency Nadir, Rate of change of Frequency (RoCoF), peak IBR power injection, among others.
- First-order overall response of the system:
  - Improves frequency nadir
  - Fails to reduce peak IBR power injection
- Consider a second-order response instead to reduce peak power.
- We evaluate/provide a pareto-front for peak IBR power v/s maximum frequency violation and determine the corresponding IBR transfer function.
- Grid operator decides an acceptable (nadir, peak power) set-point.
- Subsequently, we delve into physically realizing the transfer functions.

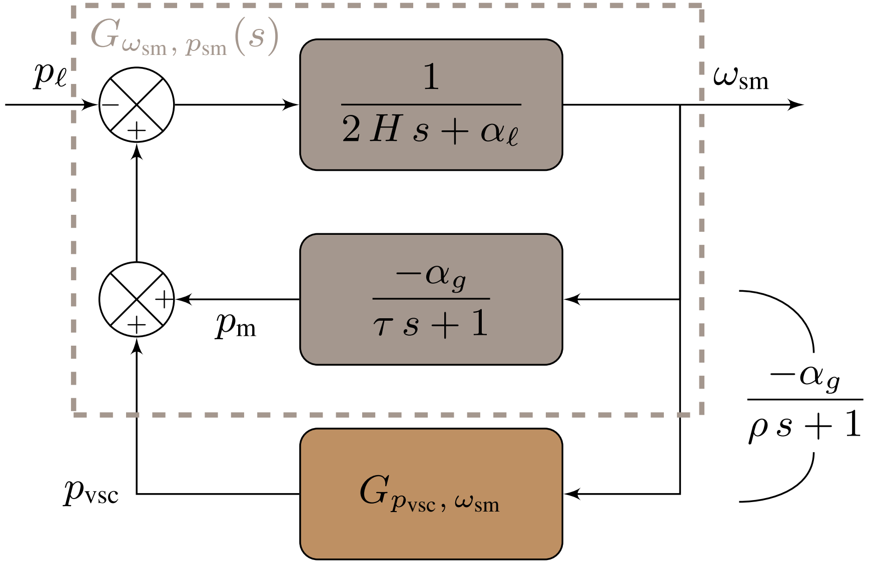
Simulations Step2

- Consider a single IBR device coupled with an aggregate synchronous machine setting.
- Design the IBR response, such that overall design behaves as a synchronous machine with faster turbine dynamics ρ.
- Re-write the dynamics with IBR modeled as a feedback.

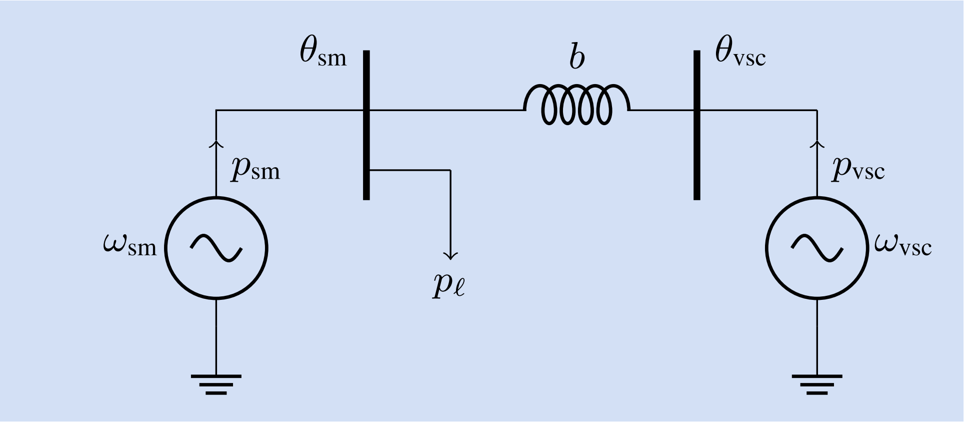
$$p_{\mathrm{vsc}}(s) = \frac{\alpha_g\, s\,(\tau - \rho)}{(s\,\tau + 1)(s\,\rho + 1)}\, G^{\mathrm{cl}}_{\omega_{\mathrm{vsc}},\, p_\ell}(s)\, p_\ell(s)$$

$$\begin{aligned} \min_{\rho} \quad & |p_{\mathrm{vsc}}|_\infty \\ \text{s.t.} \quad & |\omega_{\mathrm{sm}}|_\infty \le \bar{\omega}_{\mathrm{sm}} \end{aligned}$$

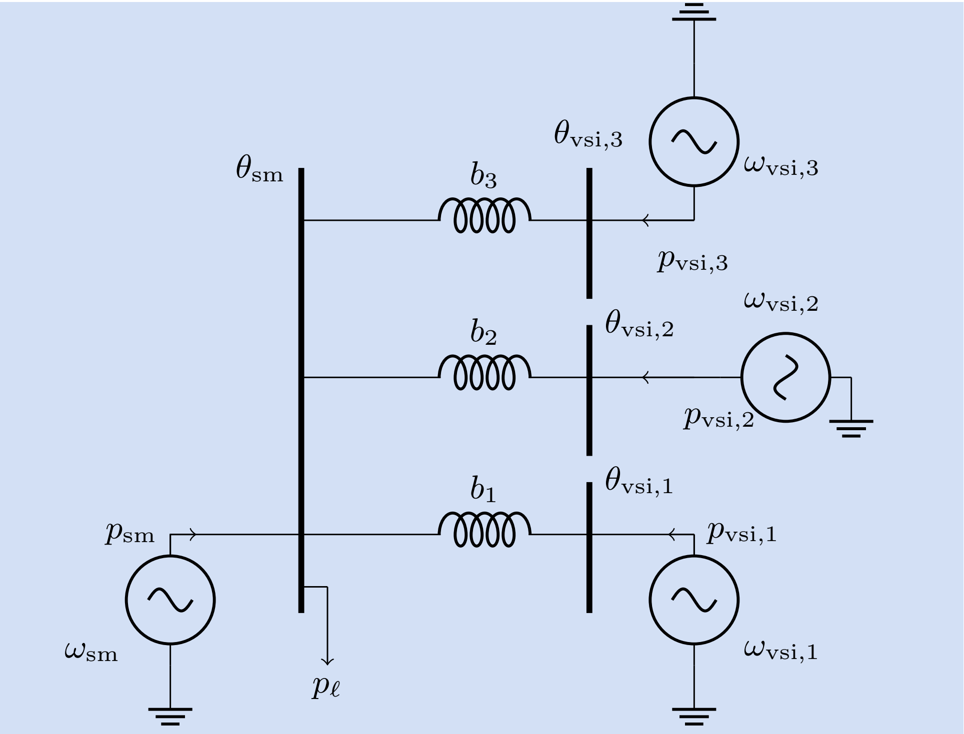




Simulations Step3



Grid-forming implementations



Preliminary investigation hints at greater flexibility for grid-forming IBRs.

$$\frac{s}{b} + G_c(s) = \frac{(s\,\tau + 1)(s\,\tau' + 1)}{\alpha_g\, s\,(\tau - \tau')}$$

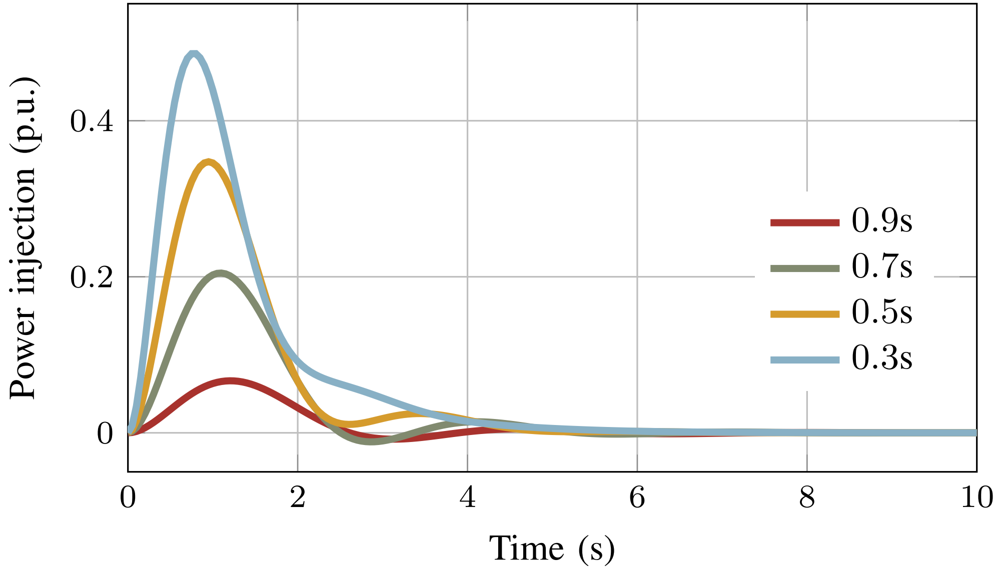
$$\text{Let } G_c(s) = k_p^{GFM} + \frac{k_i^{GFM}}{s} + k_d^{GFM}\, s$$

Analogous results for multi-component star system

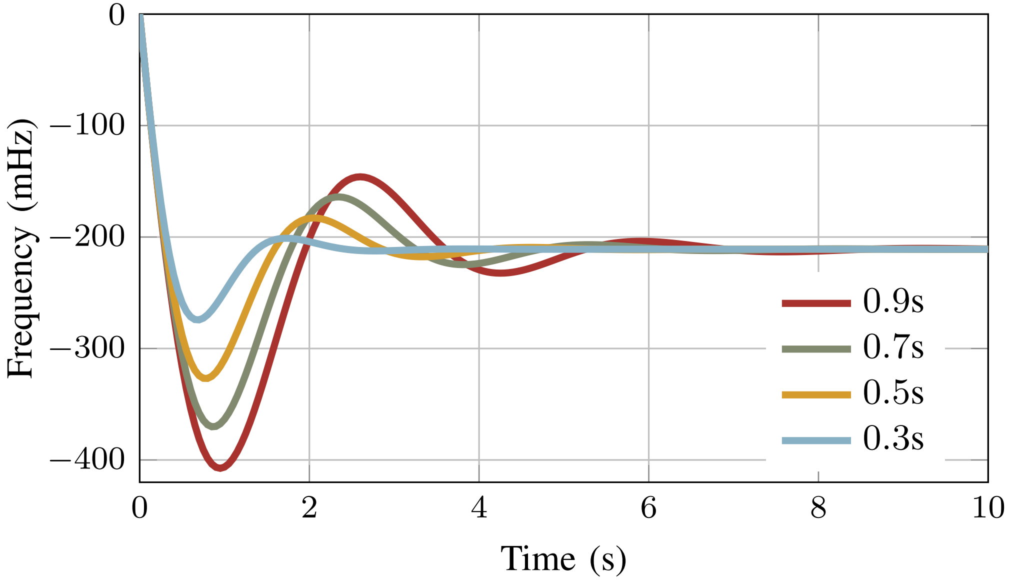
$$\omega_{\mathrm{sm}}(s) = -\frac{G_{\omega_{\mathrm{sm}},\,p_{\mathrm{sm}}}(s)}{1 + \frac{G_{\omega_{\mathrm{sm}},p_{\mathrm{sm}}}}{\frac{s}{b_1} + G_{\omega_{\mathrm{vsi},1},\,p_{\mathrm{vsi},\,1}}(s)} + \frac{G_{\omega_{\mathrm{sm}},p_{\mathrm{sm}}}}{\frac{s}{b_2} + G_{\omega_{\mathrm{vsi},\,2},\,p_{\mathrm{vsi},\,2}}(s)} + \dots}\, p_\ell(s),$$

$$p_{\mathrm{vsi},1}(s) + p_{\mathrm{vsi},2}(s) + \dots \overset{!}{=} -\frac{\alpha_g\, s\,(\tau - \rho)}{(s\,\tau + 1)(s\,\rho + 1)}\,\omega_{\mathrm{sm}}(s),$$

Simulations

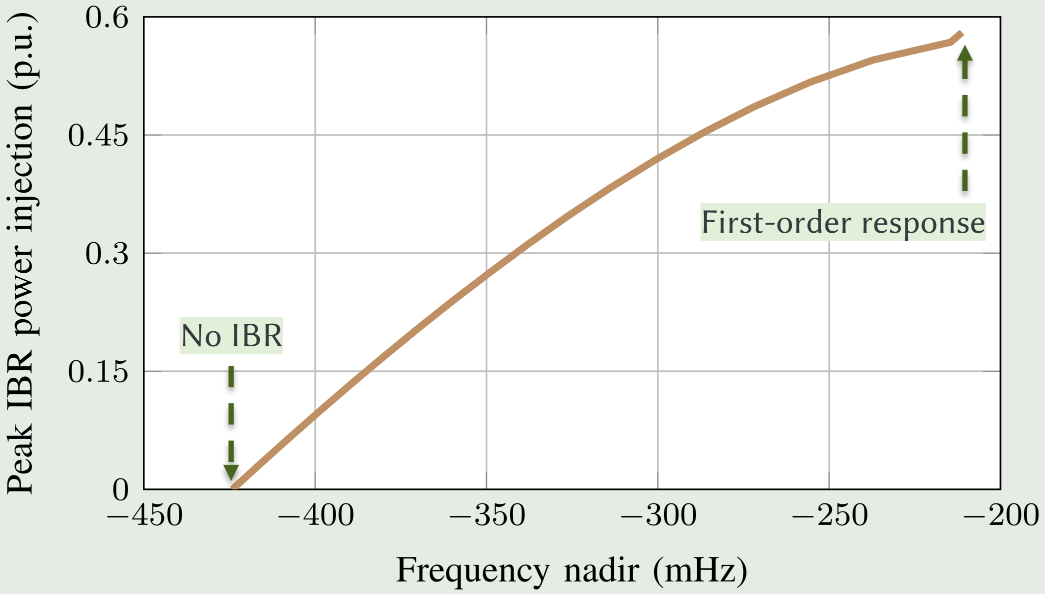


IBR power injection for a 1 p.u. load step

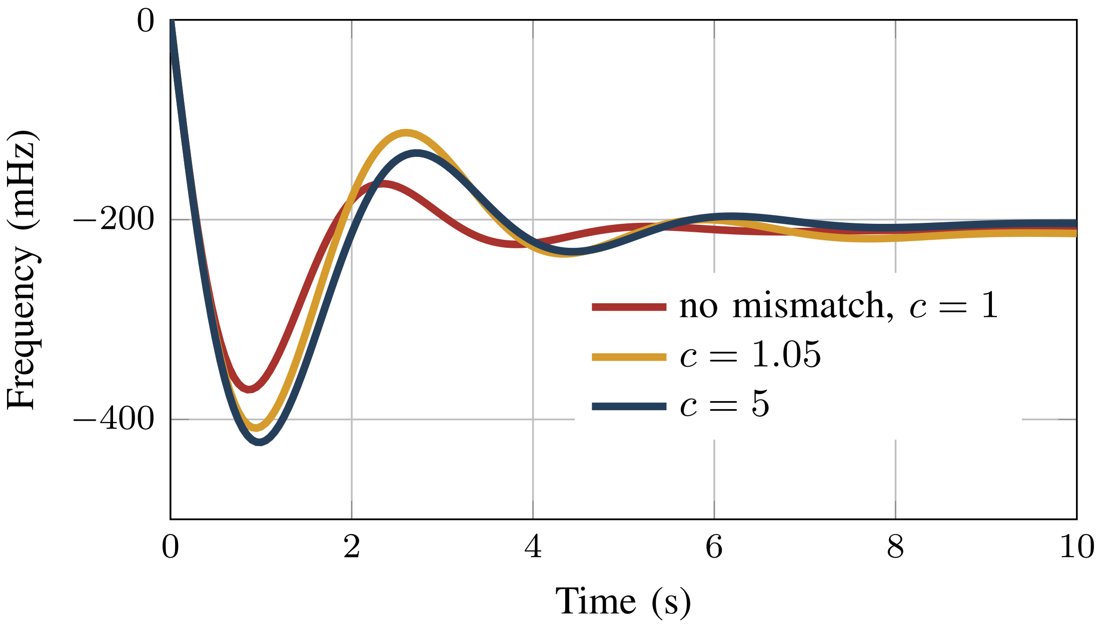


Frequency response for a 1 p.u. load step

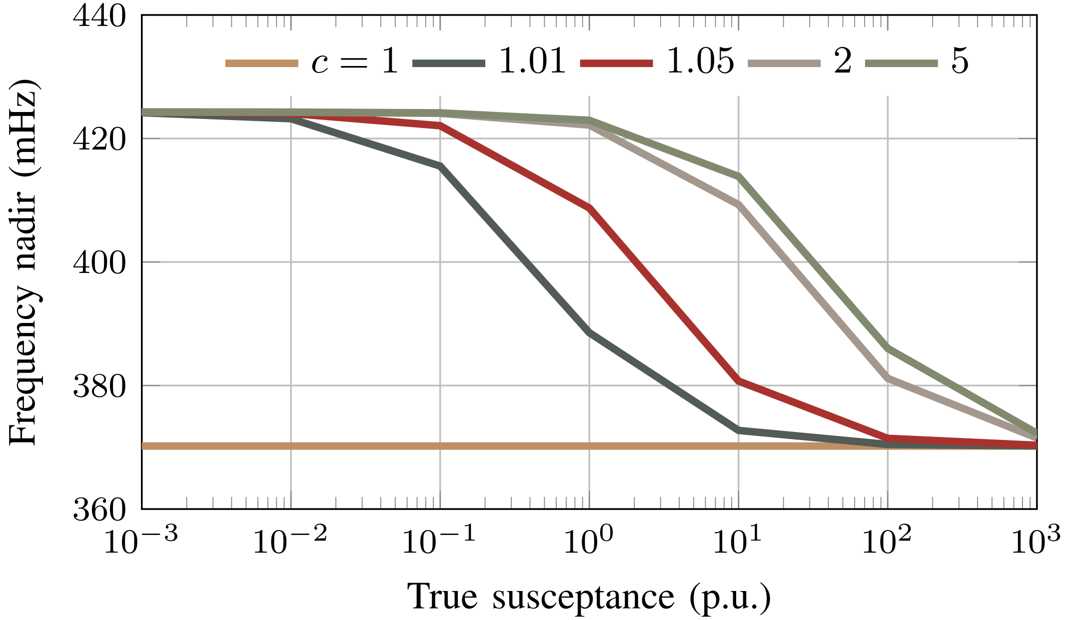
- Grid Response Characteristics $G^{\dagger}(s)$: Frequency Nadir, Rate of change of Frequency (RoCoF), peak IBR power injection, among others.
- First-order overall response of the system:
  - Improves frequency nadir
  - Fails to reduce peak IBR power injection

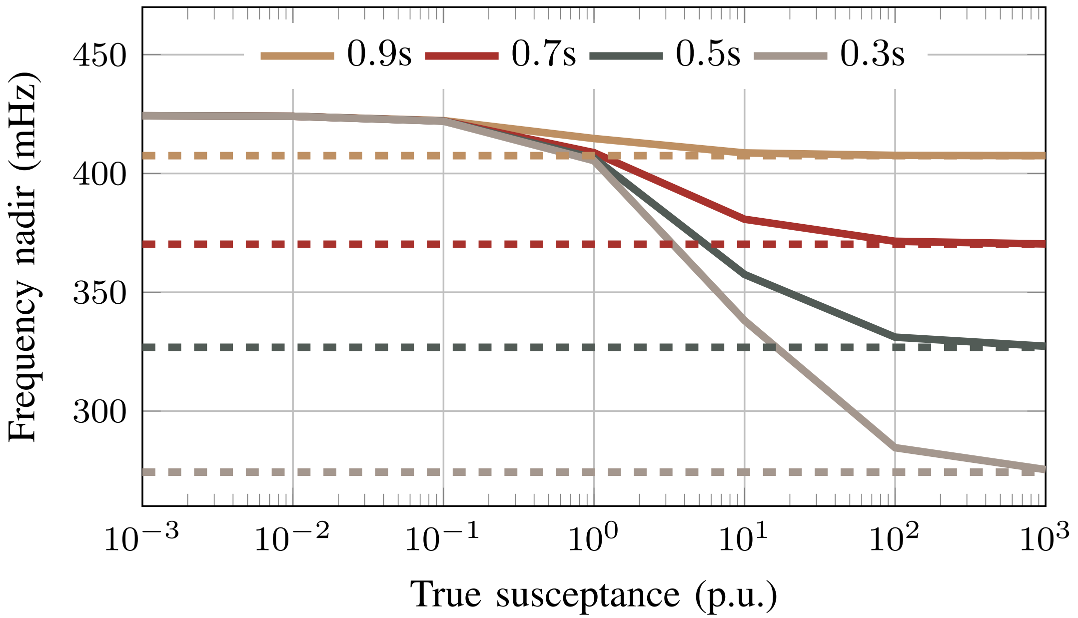


Adaptive Control



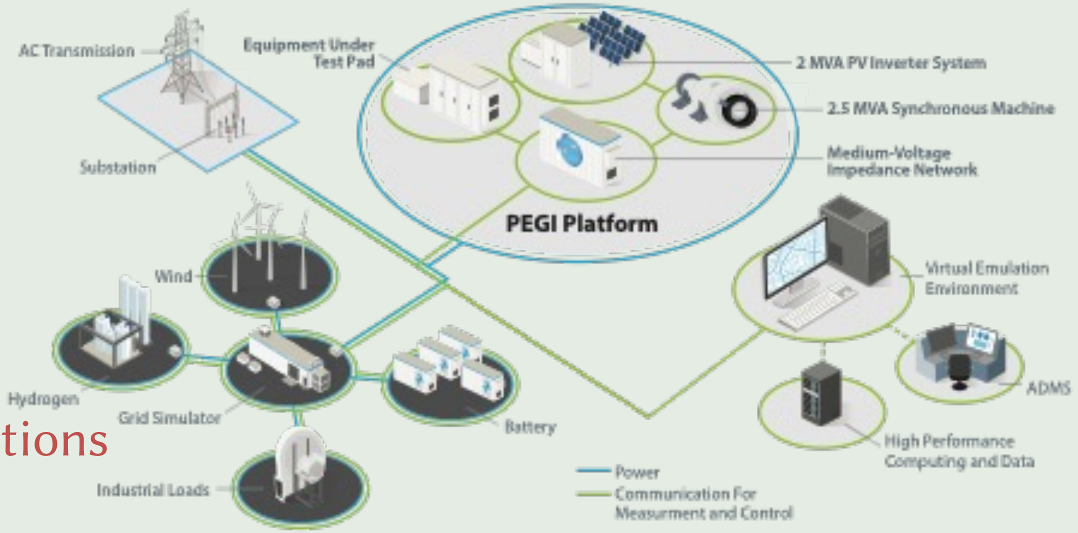
- Major drawback: controller requires knowledge of the changing network parameters (line admittance).
- Solution: Adaptive/robust design quantifying the worst-case behavior for incorrect estimates of parameters.
- Characteristics: Stable controller, the design is amenable to incorporate new estimates of the network parameters.





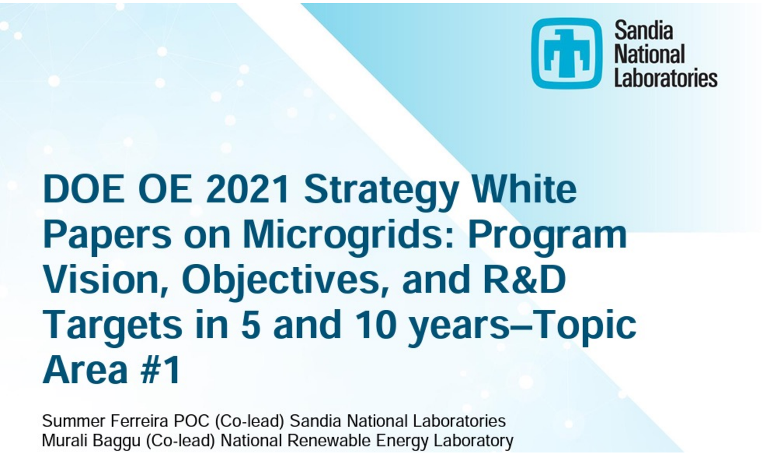
What comes next?

- Analyze large-scale multi-IBR/multi-machine systems
- Is a more generic target performance achievable?
  - Which transfer functions to shape?
  - Frequency @ nodes of interest?
- Sources behind the IBR: Wind/PV
  - Incorporate detailed models of sources
  - Leverage their inherent characteristics
- Effect of line-dynamics, non-linear/EMT simulations
- Coordination with other services from IBRs?
  - Capacity constraints
- Hardware Performance Evaluation
  - Hardware-in-loop Test-bed implementation/evaluation of controls with heterogeneous IBRs
  - Real-world demonstration for large-scale systems with partners



Conclusions

- "DynaShape" aims to advance foundational science in control of IBR-integrated power systems.
- Develop controls which do not replicate synchronous machine dynamics in weakly-coupled grids.
- Three-step structured approach for designing controls
- Suitable for adaptation to larger networks through clustering/aggregation
- Aligns with the missions of OE and EERE.
  - OE Microgrids program developed strategy white papers on interconnected microgrids with IBRs.
  - Universal interoperability for grid-forming inverters (UNIFI)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DOE OE 2021 Strategy White Papers on Microgrids: Program Vision, Objectives, and R&D Targets in 5 and 10 years–Topic Area #1

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Thank You

This work was authored in part by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was supported by the Laboratory Directed Research and Development (LDRD) Program at NREL. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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Please contact Bala Kameshwar Poolla (bpoolla@nrel.gov) with feedback/questions/comments.

The corresponding LCSS publication is available at https://ieeexplore.ieee.org/iel7/7782633/7912304/09983802.pdf

Q&A