Grid Shaping Control for High-IBR Power Systems

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Panel on Future electricity systems: How to handle millions of power electronic-based devices and other emerging technologies
Acknowledgements

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The Future Grid

Present grid
- dispatchable generation
- high inertial response
- strong voltage support
- well known physics

Future
- variable and distributed generation
- limited inertia levels
- weak voltage support
- proprietary control laws (black box)

The Future Grid

Selected challenges
- increased system **uncertainty**
- **sensitivity** to disturbances
- new forms of **instabilities**, induced by inverter-based resources
- need to compensate for the limited number of SGs remaining

Research questions:
- How should we control a grid with limited inertial/voltage support?
- Should we try to mimic SGs response? Or find new and more efficient control paradigms, suitable for IBRs?

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Outline

• Merits and trade-offs of low inertia
  • Control Perspective: Lighter systems are easier to control!

• Analysis of IBR-rich Coherent Networks
  • Generalized Center of Inertia captures IBR dynamics

• Grid Shaping Control
  • Grid-following/forming control framework for future girds
Merits and Trade-offs of Inertia

\[
\ddot{\theta} = -\frac{d}{m} \dot{\theta} - g \sin \theta + \frac{f}{m}
\]
Merits and Trade-offs of Inertia

\[ \ddot{\theta} = -\frac{d}{m} \dot{\theta} - g \sin \theta + \frac{f}{m} \]

Pros: Provides natural disturbance rejection

Cons: Hard to regain steady-state
Merits and Trade-offs of Low Inertia

\[ \ddot{\theta} = -\frac{d}{m} \dot{\theta} - g \sin \theta + \frac{f}{m} \]

**Cons:** Susceptible to disturbances

**Pros:** Regains steady-state faster

What happens when one adds control?
Control of Low Inertia Pendulum

Virtual Mass Control: \[ m\ddot{\theta} = -d\dot{\theta} - mg\sin\theta + f - \nu\dot{\theta} \]

Pros:
Provides disturbance rejection

Cons:
Hard to regain steady-state + excessive control effort
Control of Low Inertia Pendulum

Dynamic Droop:

\[ m\ddot{\theta} = -d\dot{\theta} - mg \sin \theta + f + x \]
\[ \tau' \dot{x} = -x - (r_1^{-1} \dot{\theta} + \tau' \nu' \ddot{\theta}) \]

Dynamic Droop Control in Low-Inertia Power Systems

Yan Jiang, Richard Pates, and Enrique Mallada, Senior Member, IEEE

Dynamic Droop Benefits

- Overshoot Elimination in Nadir
- Noise Attenuation
- Disturbance Rejection
- Reduce Inter-area Oscillations

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Coherence in Power Systems

Studied since the 70s
• Podmore, Price, Chow, Kokotovic, Verghese, Pai, Schwepppe,…

Enables aggregation/model reduction
• Speed up transient stability analysis

Many important questions
• How to identify coherent modes?
• How to accurately reduce them?
• What is the cause?

Many approaches
• Timescale separations (Chow, Kokotovic,)
• Krylov subspaces (Chaniotis, Pai ’01)
• Balanced truncation (Liu et al ‘09)
• Selective Modal Analysis (Perez-Arriaga, Verghese, Schwepppe ’82)

Question: What is the role of IBRs in determining the coherent response?
Coherence in Power Systems

**System response:** Is affected by SG dynamics, network, disturbances,...
Problem Setup:

- Linearized power flows $L_{ij}$
- Bus $i$: arbitrary siso tf:
  \[ \omega_i = g_i(s) \Delta P_i \text{ (SGs or IBRs)} \]
1. Coherence can be understood as a low rank property the closed-loop transfer matrix

2. It emerges as the effective algebraic connectivity $\frac{1}{s_0} \lambda_2$ increases

3. The coherent dynamics is given by the harmonic sum of bus dynamics

$\hat{g}(s) = \left( \sum_{i=1}^{n} g_i^{-1}(s) \right)^{-1}$

1. When does this network exhibit coherence?

2. What is the exact coherent response of this network?

[CDC 19] Min, M. Dynamics concentration of large-scale tightly-connected networks. CDC 2019

Generalized Center of Inertia [CDC 19, ArXiv 23]

\[
\hat{g}(s) = \left( \sum_{i=1}^{n} g_i^{-1}(s) \right)^{-1}
\]

**Coherent Dynamics: \( \hat{g}(s) \)**
- Representation of aggregate response
- Accuracy of approximation:
  - is frequency dependent
  - increases with network connectivity
- Provides excellent template for reduced order models (via balance-truncations)
- More details [LCSS 20]

[CDC 19] Min, M. Dynamics concentration of large-scale tightly-connected networks. CDC 2019
[LCSS 20] Min, Paganini, M. Accurate reduced-order models for heterogeneous coherent generators. IEEE LCSS 2020
Weakly-Connected Coherent Networks \[\text{[L4DC 23]}\]

\[\Delta P \rightarrow g_1 \rightarrow \ldots \rightarrow g_i \rightarrow \ldots \rightarrow g_n \rightarrow \omega \]

\[\frac{1}{s}L\]

[Min, M. Learning coherent clusters in weakly-connected network systems. L4DC 2023]
Weakly-Connected Coherent Networks [L4DC 23]

Three coherent groups:
- High intra-group connectivity
- Low inter-group connectivity

Min, M. Learning coherent clusters in weakly-connected network systems. L4DC 2023
Approximate the network by a reduced network of three aggregate nodes

We need to:

- Identify the coherent groups
- Find the right interconnection for the reduced network

Min, M. Learning coherent clusters in weakly-connected network systems. L4DC 2023
Weakly-Connected Coherent Networks \[\text{[L4DC 23]}\]

- Spectral clustering on graph Laplacian identifies coherent groups
- Spectral embedding refinement finds the interconnection
- Structure-preserving model reduction

\[\Delta P \]
\[\omega \]
\[\hat{\omega}_1\]
\[\hat{\omega}_2\]
\[\hat{\omega}_3\]

\[\hat{\omega}_1 \hat{\omega}_2 \hat{\omega}_3 \]

\[\hat{\Delta P}_1 \hat{\Delta P}_2 \hat{\Delta P}_3 \]

\[\hat{g}_1 \hat{g}_2 \hat{g}_3 \]

\[\frac{1}{s} L \]

\[\frac{1}{s} L_k \]

\[\{\mathcal{I}_i\}_{i=1}^k \]

\[\min_S \quad \| V_k - P_{\mathcal{I}_i}^k S \|_F^2 \]

\[\text{s.t.} \quad S e_1 = 1_k \]
\[S^T \text{diag}\{\mathcal{I}_i\}_{i=1}^k S = I_k . \]
\[L_k = (S^{-1})^T \Lambda_k S^{-1} \]

\[\Lambda_k: \text{bottom } k \text{ eigenvalues} \]
\[V_k: \text{bottom } k \text{ eigenvectors} \]

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Grid Shaping Control

Use model matching control to shape SGs response

Grid-following IBRs  Grid-forming IBRs
Grid-shaping with GFL IBRs [TPS 21]

Tunable Performance:

\[
\text{RoCoF} = \frac{1}{a} \Delta P, \quad \Delta \omega = \frac{1}{b} \Delta P
\]

[TPS 21] Jiang, Cohn, Vorobev, M. Storage-based frequency shaping control TPS 2021
Grid-shaping with GFL IBRs [TPS 21]

\[ \frac{1}{\alpha s + b} \]

\[
\omega = \frac{1}{a} \Delta P, \quad \omega = \frac{1}{b} \Delta P
\]

Tunable Performance:

\[
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Grid-shaping with GFL IBRs

\[ P_L = \frac{1}{as + b} \]

Tunable Performance:

\[ \text{RoCoF} = \frac{1}{a} \Delta P, \quad \Delta \omega = \frac{1}{b} \Delta P \]

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Grid Shaping Control

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Grid-following IBRs

Grid-forming IBRs

Tunable Performance:

\[ \text{RoCoF} = \frac{1}{a} \Delta P, \quad \Delta \omega = \frac{1}{b} \Delta P \]
Grid-shaping with GFM IBRs [LCSS 20]

\[ \sum_i \Delta P_i \rightarrow \left( \sum_{i \in \text{SG}} g_i^{-1}(s) + \sum_{i \in \text{IBR}} g_i^{-1}(s) \right)^{-1} \rightarrow \omega_{\text{COI}} \]

\[ \sum_i \Delta P_i \rightarrow \frac{1}{as + b} \rightarrow \omega_{\text{COI}} \]

Tunable Performance: RoCoF = \( \frac{1}{a} \Delta P \), \( \Delta \omega = \frac{1}{b} \Delta P \)

Grid Shaping Control

Use model matching control to shape SGs response

Grid-following IBRs

Grid-forming IBRs

Tunable Performance: RoCoF = \frac{1}{a} \Delta P, \Delta \omega = \frac{1}{b} \Delta P
Summary

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Thanks!