Next-Generation Frequency and Voltage Control using Inverter-Based Resources

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NREL Workshop on Resilient Autonomous Energy Systems

September 7, 2021
Control + Opt of Microgrids

Feedback-Based Optimization

Robust Methods for Power Flow Analysis

Automatic Generation Ctrl.
Motivation

Selected Trends/Challenges in Grid Modernization:

1. reliability concerns from decreased inertia & new RES, DERs
2. inadequate legacy monitoring/control architectures (e.g., SCADA)

Required Advances for Next-Grid Control:

1. use of high-bandwidth closed-loops (e.g. 10+ samples/sec)
2. online coordination of heterogeneous inverter-based resources (IBRs)
3. distributed hierarchical controls for (i) integration of many devices, (ii) local situational awareness, (iii) low-latency localized response

EPRI Whitepaper: “Next-Generation Grid Monitoring and Control: Toward a Decentralized Hierarchical Control Paradigm”
Enabling Fast Control via Inverter-Based Resources
Objectives and design constraints

**Big Picture:** fully leverage IBR capabilities for freq./volt. control

1 Design Objectives

- Fast and localized compensation of disturbances
- Hierarchical/decentralized architecture (min. delay, scalability)
- State/control variable constraint satisfaction

2 Design Constraints

- Premium on simplicity in design and implementation
- Integrable with legacy controls
- Uses realistically available model info.
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Outline of Talk

1. Frequency controller design
2. Voltage controller design
3. Joint frequency/voltage design
Review: Frequency Control in the Bulk Grid

![Diagram of frequency control](image)

**Fundamentals of frequency control:**

1. **Inertial** response: fast response of rotating machines
   
   *Time scale:* immediate

2. **Primary** control: turbine-governor control for *stabilization*
   
   *Time scale:* seconds. *Spatial scale:* local control, global response

3. **Automatic Generation Control (AGC):** multi-area control which eliminates *generation-load mismatch* within each area
   
   *Time scale:* minutes. *Spatial scale:* area control, area response.
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Overview of Proposed Frequency Controller

Bulk grid divided into small **local control areas** $A_1, \ldots, A_N$ (e.g., a few substations each)

Measurements and resources locally available within each LCA

1. **Stage 1:** LCA-decentralized controllers $C_k$ redispachtch local IBRs

2. **Stage 2:** Centralized coordination for severe contingencies

**Conceptual goal:** very fast and localized secondary-like response
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Philosophy: quickly estimate and compensate all local imbalance

IBRs: can have local $f/P$ droop curve, but must accept a provided set-point

1. **Disturbance Estimator:** real-time estimate of gen.-load mismatch
2. **Detuning (if needed):** lower bandwidth to ensure robust stability
3. **Power Allocator:** compute (constrained) power set-points for IBRs
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An application of classical internal model control (IMC) ...

1. A crude/aggregate LCA model, e.g.,

\[ 2H\Delta \dot{\omega} = -(D + \frac{1}{R_l})\Delta \omega + \Delta P_m - \Delta P_u - \Delta P_{\text{inter}} + \Delta P_{\text{ibr}} \]

\[ T_R \Delta \dot{P}_m = -\Delta P_m - R_g^{-1}(\Delta \omega + T_R F_H \Delta \dot{\omega}), \]

where \( \Delta x = (\Delta \omega, \Delta P_m) \) and \( \Delta P_u = \) unknown gen/load mismatch

2. Assume: \( \Delta \omega \) measured, \( \Delta P_{\text{inter}} \) measured (subj. to. delays)

3. Discretize LCA model & augment with disturbance/delay models

\[ \Delta P_u(k+1) = \Delta P_u(k), \quad \Delta \omega_m(k) = \Delta \omega(k - \tau_d), \ldots \]

4. Design observer (e.g., Kalman) to estimate \( \Delta \hat{x}(k) \text{ and } \Delta \hat{P}_u(k) \)
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**Detuning (optional):**

low-pass filter

\[ F(z) = \frac{1 - e^{-T/\tau}}{z - e^{-T/\tau}} \]

for lowering controller bandwidth

**Power Allocator:** Allocate disturbance estimate \( \Delta \hat{P}_u \) to compute IBR set-points \( P_{ik} \) within the \( i \)th LCA:

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\begin{align*}
\text{minimize} & \quad f_i(\{P_{ik}\}) + \lambda_i |\varphi_i| \\
\text{subject to} & \quad \sum_{k \in I_i} (P_{ik} - P_{ik}^{\text{dispatch}}) + \varphi_i = \Delta \hat{P}_{u,i}
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Case Study: Three-LCA System
Simplified Model Response vs. True Nonlinear Model

- LCA model parameters set via simple inertia/droop gain aggregation and using largest turbine-gov time constant (very crude!)
- 63 MW load increase in Area 2
Scenario: 63 MW Disturbance, Area 2

Localized Response: IBRs in Area 2 ramp quickly; IBRs in Areas 1/3 don’t need to react, so they don’t.
Stage 2: Centralized Coordinator Design

What if local IBR capacity is **insufficient** to meet the disturbance? Then IBRs in **electrically close** areas should respond.

- mismatch variable $\varphi_i$ from Stage 1 will be **non-zero**
- total IBR adjustments $a_i$ computed as

$$\text{minimize} \quad \sum_{i \in A} q_i a_i^2$$

s.t.  
$$0 = \sum_{i \in A} (a_i - \varphi_i^*)$$

$$0 \leq a_i \cdot \text{sign}\left(\sum_{i \in A} \varphi_i^*\right), \quad i \in A$$

$$a_i + \sum_{j \in I_i} P_{ij}^* \in [\text{lower}, \text{upper}], \quad i \in A.$$ 

**Solution method matters!** Centralized vs. privacy-preserving ADMM.
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Scenario: 130MW Disturbance, Area 2

IBRs in Area 2 hit limits; Stage 2 forces Area 1/3 response.
Conclusions for Frequency Control

Summary:

- Two-stage design: local area control & global coordination
- Design enables fast frequency control via IBRs
- Response is localized to the contingency
- Inherent robustness against model imperfections

Ongoing:

- remove even the crude model requirement via data-driven control
- extend to incorporate distribution-integrated DERs

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Overview of Proposed Voltage Controller (One-Area)

Control resources:
- SGs: \( v_g^{\text{ref}} \rightarrow q_g \)
- SVCs: \( v_s^{\text{ref}} \rightarrow q_s \)
- IBRs: \( q_i^{\text{ref}} \rightarrow q_i \)
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Model:
\[
\begin{align*}
\dot{x} &= f(x, u, w) \\
y &= (v, q) = h(x, u, w)
\end{align*}
\]

minimize \( f(q) \) subject to voltage limits power limits
Steady-State Optimization Problem (One-Area)

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\text{minimize} \quad \text{Priority}(q_g, q_s, q_i) + \text{PenaltyFcn}(q_g, q_s, \nu) := F(u, y)
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- vector \( y \) assumed to be **measurable** in real-time
- \( \pi = \) steady-state grid model from power flow eqns.
- approximate sensitivities \( \Pi \approx \frac{\partial \pi}{\partial u} \) computable via load flow model
Feedback Implementation of Voltage Controller

- approximate gradient method steps can be evaluated using **real-time system measurements** leading to a **feedback controller**

\[ u_{k+1} = \text{Proj}_U \left\{ u_k - \alpha \left( \nabla_u F(u_k, y_k) + \Pi^T \nabla_y F(u_k, y_k) \right) \right\} \]

- nonlinear controller implemented on a nonlinear dynamic transmission system; **stability analysis** is non-trivial

**Theorem:** Assume grid is nominally “stable” and “well-behaved”. If

\[ u \mapsto \nabla_u F(u, \pi(u, w)) + \Pi^T \nabla_y F(u, \pi(u, w)) \]

is a **strongly monotone** operator, then CLS is stable for all sufficiently small controller gains \( \alpha > 0 \).
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Add-Ons and Extensions for Voltage Controller

The base controller is flexible and admits various modifications

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2. **Faster/Slower Unit Responses:** replace \( \alpha \) with diagonal matrix \( \alpha = \text{blkdiag}(\alpha_{\text{ibr}}, \alpha_{\text{sfc}}, \alpha_{\text{sg}}) \) and tune elements as desired

3. **Improved Recovery to Pre-Fault Operating Voltages:** integrate term proportional to \( \| \Delta v_{\text{sg}} \|_2^2 \) into objective function

4. **Increased Transient Response:** integrate term proportional to \( y_k - y_{k-1} \) into controller (“derivative” action)
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The base controller is flexible and admits various modifications

\[ u_{k+1} = \text{Proj}_\mathcal{U}\left\{ u_k - \alpha \left( \nabla_u F(u_k, y_k) + \Pi^T \nabla_y F(u_k, y_k) \right) \right\} \]

1. **Multi LCA Systems:** use one-area controller in each LCA

2. **Faster/Slower Unit Responses:** replace \( \alpha \) with diagonal matrix \( \alpha = \text{blkdiag}(\alpha_{ibr}, \alpha_{svc}, \alpha_{sg}) \) and tune elements as desired

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Scenario: 120 MVAR Disturbance (SG Priority)

solid: with proposed controller       dotted: without

Voltage (p.u.)

Time (s)

Load buses

Voltage (p.u.)

Time (s)

IBRs

Reactive power (100 Mvar)

Time (s)

SVC

Reactive power (100 Mvar)

Time (s)

SGs

Reactive power (100 Mvar)

Time (s)
Scenario: 180 MVAR Disturbance (G2/IBR Priority)

solid: with proposed controller    dotted: ignore
Scenario: 180 MVAR Disturbance (IBR Priority)

solid: with proposed controller  
dotted: ignore

---

**SG and SVC buses**

- Voltage (p.u.)
  - Ranges from 0.9 to 1.1
  - Graph shows voltage changes over time (s)
  - Bus markers: bus1, bus2, bus3, bus6

**Load buses**

- Graph shows voltage changes over time (s)
  - Bus markers: bus4, bus7, bus9, bus5, bus8
  - Colored lines indicate different buses

---

**IBRs**

- Reactive power (100 Mvar)
  - Ranges from 0 to 1
  - Graph shows reactive power changes over time (s)
  - Markers: IBR1, IBR2

**SVC**

- Reactive power (100 Mvar)
  - Ranges from 0 to 1
  - Graph shows reactive power changes over time (s)
  - Marker: SVC

**SGs**

- Reactive power (100 Mvar)
  - Ranges from 0 to 1
  - Graph shows reactive power changes over time (s)
  - Markers: G1, G2, G3
Conclusions for Voltage Control

Summary:
- Local area control based on local model/meas.
- Flexible design allows operator to set device priority
- Bus voltage and device output constraint satisfaction
- More scenarios: line trips, 3ϕ-fault, multi-areas, etc. . . .

Ongoing:
- combine with online least-squares sensitivity estimation (model-free)
- integration with frequency controller

Paper: https://www.control.utoronto.ca/~jwsimpson/

IEEE TPWRS: “Measurement-Based Fast Coordinated Voltage Control for Transmission Grids”
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Integration of Freq. and Volt. Controllers

The two controllers can operate simultaneously.

1. Allocate IBR capacity priority

   ![Diagram showing Allocation of IBR capacity priority]

   **A)** $FC > VC$
   
   - $P_{\text{lim}}$
   - $S_{\text{IBR}}$
   - $P_{\text{IBR}}$
   - $\sqrt{S_{\text{IBR}}^2 - P_{\text{IBR}}^2}$
   - $Q_{\text{lim}}$
   - $Q_{\text{IBR}}$
   - $P_{\text{IBR}}$
   - $\sqrt{S_{\text{IBR}}^2 - Q_{\text{IBR}}^2}$

   **B)** $VC > FC$
   
   - $P_{\text{lim}}$
   - $S_{\text{IBR}}$
   - $P_{\text{IBR}}$
   - $\sqrt{S_{\text{IBR}}^2 - P_{\text{IBR}}^2}$
   - $Q_{\text{lim}}$
   - $Q_{\text{IBR}}$
   - $P_{\text{IBR}}$
   - $\sqrt{S_{\text{IBR}}^2 - Q_{\text{IBR}}^2}$

2. Dynamic cross-couplings between controllers:
   - **voltage-sensitivity** of (e.g., impedance) loads
   - **PSS** and VC both operate through SG AVR systems
Scenario: 150MW/80MVAR Disturbance (FC Priority)

solid: with proposed controller  dotted: without

- Frequency (Hz)
- Active power (MW)

![Graph showing frequency and active power over time for different generators with and without the proposed controller.]
Scenario: 150MW/80MVAR Disturbance (FC Priority)

solid: with proposed controller  dotted: without

SG buses

Load buses

IBRs

SGs
Collaborators

**UWaterloo**: Etinosa Ekomwenrenren (PhD), Zhiyuan Tang (PDF), JWSP

![Collaborator Photos](images)

**EPRI**: Evangelos Farantatos, Mahendra Patel, Hossein Hooshyar, Aboutaleb Haddadi

![Collaborator Photos](images)
Questions

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Comparison with Traditional Frequency Control

Traditional frequency control:

1. very fast inertial response of machines limits ROCOF
2. primary layer (droop) provides “fast” & global stabilizing response
3. secondary layer (AGC) provides slow & “localized” response

Traditional frequency control + next-gen IBR controller:

1. very fast inertial response of machines limits ROCOF
2. Stage 1 (local IBR redispatch) provides fast & localized response

   Ideally, minimal activation of SG turbine-govs

3. Stage 2 (global IBR redispatch) provides fast & semi-local response
4. AGC cleans up any remaining mismatch on minutes time-scale
Frequency Scenario: Robustness Test

- Introduce large (50%–100%) errors in parameters \((H, T, R, \ldots)\) used for LCA disturbance estimator designs.
Scenario: 150MW/80MVAR Disturbance (VC Priority)
Scenario: 150MW/80MVAR Disturbance (VC Priority)