Recent Advances in Experiments and Modeling of Grid-forming Systems

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My Lab Activities
Acknowledgements

Contributions from my postdocs and 6 grad students

and generous support from DOE & NSF for my research on:

- Grid-forming systems
- Power electronics
- UNIFI Consortium
- Engineering challenges grow with system size and complexity
- Need scalable, robust, and resilient methods for system operation
A Vision for the Future Grid
A Vision for the Future Grid
A Vision for the Future Grid

Present

Future

current source

generator

inverter

generator

inverter
A Vision for the Future Grid

Achieving 2 goals simultaneously:

- Break down barriers that limit adoption of renewable energy
- Realize a bottom-up system that works resiliently at any scale
Desired Characteristics of a GFM Inverter

- Can operate in standalone or with many other GFMs
- Proportional power sharing among units
- Works when connected to a stiff or weak grids
- Automatic synchronization
- Exogenous signals can adjust power delivery
- Has current limiter to prevent overcurrents
- Integrates with dc-side controls
The inverter shall:

- NOT regulate voltage
- TRIP under abnormal voltage/frequency

An Evolving Regulatory Landscape
An Evolving Regulatory Landscape

IEEE 1547 approved

2003

IEEE 1547.1 published

2004

GFL unit acts as passive current injection & disconnects abruptly

2014

2018
An Evolving Regulatory Landscape

- Assist voltage regulation
- Ride-through abnormal voltage/frequency

IEEE 1547 approved

2003

IEEE 1547.1 published

2004

IEEE 1547A amendment 1

2014

IEEE 1547A amendment 2

2018
An Evolving Regulatory Landscape

IEEE 1547 approved

2003

IEEE 1547.1 published

2004

GFL supplemented with functions for grid support

2014

IEEE 1547A amendment 1

2018

IEEE 1547A amendment 2
An Evolving Regulatory Landscape

- IEEE 1574 approved (2003)
- IEEE 1574A amendment 1 (2014)
- IEEE 1574A amendment 2 (2018)

Moving to 100% renewables by 2020s

Full-fledged grid-forming (GFM) functionality needed to realize ambitious renewable targets[1]

[1] List of territories, states, cities, communities committed to 100% renewable energy: www.sierraclub.org/ready-for-100
Remaking the Electric Power Industry

The organization that will bring GFM technologies onto grids:

- **Duration**: 2022-2027
- **Co-Leads**: UW, NREL, EPRI
- **Total Funds**: $34.9M
- **Federal Funds**: $25M
- **Membership**:
  - 12 universities
  - 4 national labs
  - 25 industry members

Funded by: US Department of Energy
Unifying Technologies Across All Scales

- New & Old (GFM with GFL + Machines)
- Local & Global (controls)
- Slow & Fast (timescales of operation)
- Big & Small (inverters to aggregations)
- Solar, Wind, & Storage (technologies)
A Team with Crosscutting Perspectives Across the Electric Power Industry

- National Labs & Research Institutes
  - NREL
  - EPRI
  - Sandia National Laboratories
  - PNNL

- Universities
  - Texas
  - NC State University
  - GT
  - Cal
  - I
  - UAF
  - VT

- Industry
  - Siemens
  - GE
  - Danfoss
  - SMA
  - Analog Devices
  - EATON
  - Ørsted
  - Hitachi Energy
  - OPAL-RT Technologies
  - Typhoon HIL

- Utilities & System Operators
  - Southern California Edison
  - Hawaiian Electric
  - New York Power Authority
  - ComEd
  - CAISO
  - PacifiCorp
  - ISO New England
A Team with Crosscutting Perspectives Across the Electric Power Industry

These + many others will need to work towards consensus
Universal Interoperable Operation is Essential

Seeking inspiration from Bluetooth®
& cultivating an ecosystem of innovation

Interoperable GFM controls will

- Enable all manufacturers to innovate
- Coexist with proprietary functions
- Streamline first-principles-based standards
- Be black-box testable for certification
Interoperability

Self-organizing GFM Networks
Interoperability

Self-organizing GFM Networks
Reference Frame Basics for Three-phase Systems

\[
\begin{bmatrix}
\cos \delta & \sin \delta \\
-\sin \delta & \cos \delta
\end{bmatrix}
\]

R(\delta)

\[
\begin{bmatrix}
\cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\
-\sin \theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3})
\end{bmatrix}^{\frac{2}{3}}
\]

\[
\begin{bmatrix}
\cos \theta & -\sin \theta \\
\cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\
\cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3})
\end{bmatrix}
\]
We Begin with a Humble Little Circuit

The simple harmonic oscillator lies at the heart of modern GFM control

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} =
\begin{bmatrix}
0 & -\omega_0 \\
\omega_0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix}
\]

\[\varepsilon = \sqrt{\frac{L}{C}}\]

The van der Pol oscillator is a stepping-stone towards a power application.
Early Oscillator Models with Self-regulating Limit Cycles

Andronov’s oscillator gives harmonic-free waveforms useful for high power quality

Aleksandr Andronov 1901-1952

Approach #1: Dispatchable Virtual Oscillator Control

- Transformed oscillator gives model here
- Newest GFM type in existence

Approach #1: Dispatchable Virtual Oscillator Control

Control equations are given by

\[
\omega = \omega_0 + \frac{\omega_0 \kappa_1}{V^2} \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P \end{bmatrix},
\]

\[
\dot{V} = \omega_0 \kappa_2 V (V_0^2 - V^2) + \frac{\omega_0 \kappa_1}{V} \begin{bmatrix} 0 & 1 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P \end{bmatrix}.
\]
Illustrating Versatile Performance on Hardware with dVOC Control

Dr. Minghui Lu
Rahul Mallik

- $v_1$, $v_2$, $v_3$:
  - Green: ON
  - Red: OFF

- $P_1$, $P_2$, $P_3$:
  - Inverters
  - Grid

- 60 Hz
Approach #2: Droop Control

- Oldest GFM method in existence
- Inspired by machine droop laws

Control equations are given by

$$\omega = \omega_0 + \frac{1}{d_t} \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix},$$

$$V = V_0 + \frac{1}{d_c} \begin{bmatrix} 0 & 1 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix},$$

$$\frac{1}{\omega_c} \begin{bmatrix} \dot{P}_m \\ \dot{Q}_m \end{bmatrix} = - \begin{bmatrix} P_m \\ Q_m \end{bmatrix} + \begin{bmatrix} P \\ Q \end{bmatrix}.$$
Approach #3: Virtual Synchronous Machine Control

- Emulate machine dynamics digitally
- Popular due to familiar behavior


Control equations are given by

\[
J \ddot{\omega} = -\omega + \omega_0 + \frac{d_4}{d_f} (\omega_g - \omega) + \frac{1}{d_f} \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P \\ Q^* - Q_m \end{bmatrix},
\]

\[
V = V_0 + \frac{1}{d_v} \begin{bmatrix} 0 & 1 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P \\ Q^* - Q_m \end{bmatrix},
\]

\[
\frac{1}{\omega_0} \dot{\eta} = \begin{bmatrix} 0 & 1 \end{bmatrix} R(\alpha)R(\delta)T(\omega_0 t)v,
\]

\[
\frac{1}{\omega_0} \dot{\alpha} = \frac{k_p}{\omega_0} \dot{\eta} + k_1 \eta,
\]

\[
\frac{1}{\omega_c} \dot{Q}_m = -Q_m + Q.
\]
A Universal & Unified GFM Model

All 3 GFM types can be boiled down to

\[
\frac{d\omega}{dt} = -\omega + \omega_0 + \kappa_d (\omega_g - \omega) \\
+ \kappa_f \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix},
\]

\[
\frac{dV}{dt} = f_v(V) + \kappa_v \begin{bmatrix} 0 & 1 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix},
\]

\[
\frac{1}{\omega_0} \frac{d\eta}{dt} = \begin{bmatrix} 0 & 1 \end{bmatrix} R(\alpha) R(\delta) T(\omega_0 t) v,
\]

\[
\frac{1}{\omega_0} \frac{d\alpha}{dt} = \frac{k_p}{\omega_0} \dot{\eta} + k_1 \eta,
\]

\[
\tau_p \begin{bmatrix} \dot{P}_m \\ \dot{Q}_m \end{bmatrix} = - \begin{bmatrix} P_m \\ Q_m \end{bmatrix} + \begin{bmatrix} P \\ Q \end{bmatrix}.
\]


A Universal & Unified GFM Model

All 3 GFM types can be boiled down to

\[
\frac{d\omega}{dt} = -\omega + \omega_0 + \kappa_d (\omega_g - \omega) + \kappa_f \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix},
\]

\[
\frac{dV}{dt} = f_v(V) + \kappa_v \begin{bmatrix} 0 & 1 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - p_m \\ q^* - q_m \end{bmatrix},
\]

\[
\frac{1}{\omega_0} \frac{d\eta}{dt} = \begin{bmatrix} 0 & 1 \end{bmatrix} R(\alpha)R(\delta)T(\omega_0 t) v,
\]

\[
\frac{1}{\omega_0} \frac{d\alpha}{dt} = \frac{k_p}{\omega_0} \dot{\eta} + k_1 \eta,
\]

\[
\tau_p \begin{bmatrix} \dot{P}_m \\ \dot{Q}_m \end{bmatrix} = - \begin{bmatrix} P_m \\ Q_m \end{bmatrix} + \begin{bmatrix} P \\ Q \end{bmatrix}.
\]

where the parameters are

<table>
<thead>
<tr>
<th>(\tau_f)</th>
<th>(\tau_v)</th>
<th>(\tau_p)</th>
<th>(\kappa_d)</th>
<th>(\kappa_f)</th>
<th>(\kappa_v)</th>
<th>(f_v(e^*))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0)</td>
<td>(0)</td>
<td>(\frac{1}{\omega_c})</td>
<td>(0)</td>
<td>(\frac{1}{d_f})</td>
<td>(\frac{1}{d_v})</td>
<td>(-V + V_0)</td>
</tr>
<tr>
<td>(VSM)</td>
<td>(J)</td>
<td>(\frac{1}{\omega_c})</td>
<td>(\frac{d_d}{d_f})</td>
<td>(\frac{1}{d_f})</td>
<td>(\frac{1}{d_v})</td>
<td>(-V + V_0)</td>
</tr>
<tr>
<td>(dVOC)</td>
<td>(0)</td>
<td>(\frac{1}{\omega_0})</td>
<td>(0)</td>
<td>(\frac{\omega_0 \kappa_1}{V^2})</td>
<td>(\frac{\kappa_1}{V})</td>
<td>(\kappa_2 (-V^2 + V_0^2) V)</td>
</tr>
</tbody>
</table>

Steady-state Performance of GFM Types

-inductive lines \( \psi = \frac{\pi}{2} \)

-resistive lines \( \psi = 0 \)


Unifying 25+ Years of GFM Technologies

1993
Control of Parallel Connected Inverters in Standalone ac Supply Systems
Mukul C. Chandorkar, Student Member, IEEE, Deepakraj M. Divan, Member, IEEE, and Rambabu Adapa, Senior Member, IEEE

Abstract—A scheme for controlling parallel-connected inverters in a standalone ac supply system is presented in this paper. This scheme is suitable for control of inverters in distributed source environments such as in isolated ac systems, large and small distributed energy resources, and microgrids.

2007
Virtual Synchronous Machine
Prof. Dr.-Ing. Hans-Peter Beck
Clausthal University of Technology
Institute of Electric Power Technology (IEE)
Clausthal-Zellerfeld, Germany
info@iee.tu-clausthal.de

2014
Synchronization of Parallel Single-Phase Inverters With Virtual Oscillator Control
Brian B. Johnson, Member, IEEE, Sairaj V. Dhople, Member, IEEE, Abdallah O. Hamadeh, and Philip T. Kein, Fellow, IEEE

Abstract—A method to synchronize and control a system of parallel single-phase inverters without communication is presented. Inspired by the phenomenon of synchronization in networks of coupled oscillators, we propose that each inverter be controlled proportion to their ratings. Focused on these challenges, this paper presents a method to synchronize and control a system of parallel single-phase inverters without communication. It is important to clarify that synchronization can occur in systems with

A unified model

\[ \frac{d\omega}{dt} = -\omega + \omega_0 + \kappa_d (\omega_k - \omega) + \kappa_r [1 \ 0] R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix} \]

\[ \frac{dV}{dt} = f_\alpha(V) + \kappa_v [0 \ 1] R(\psi - \frac{\pi}{2}) \begin{bmatrix} p^* - p_m \\ q^* - q_m \end{bmatrix} \]

\[ \frac{1}{\omega_0} \frac{d\omega_0}{dt} = [0 \ 1] R(\alpha)R(\delta) T(\omega_0 t) v, \]

\[ \frac{1}{\omega_0} \frac{d\omega_0}{dt} = k_p \eta + k_i \eta_i, \]

\[ \tau_p \begin{bmatrix} P_m \\ Q_m \end{bmatrix} = - [P_m] + [P] \]

[Diagram and equations related to virtual synchronous machine and synchronization]
Showing Interoperability with a Mix of Control Types

Weiqian Cai
Interoperability

Self-organizing GFM Networks
A Single-phase GFM Commercial Product

Features of the inverter building block
- 300 VA single-phase with droop-based GFM controls
- Bidirectional converter can interface PV or batteries

Over 39M+ Enphase inverters shipped for 12 GW of capacity as of September 2021
Building Three-phase Systems with Single-phase GFM Units

Can swarms of decentralized single-phase GFMs self-organize into a three-phase system?

Could this system maintain phase balancing when islanded?
From Industry Challenges to Foundational Research

Industry partners have already prioritized three-phase system operation with single-phase units.
Single-phase Inverter Model

The $\ell \in 1, 2, 3$ inverter has the droop laws

$$V_\ell = V_{\text{nom}} - m_q \left( Q_{\text{avg},\ell} - Q^*_\ell \right),$$

$$\omega_\ell = \omega_{\text{nom}} - m_p \left( P_{\text{avg},\ell} - P^*_\ell \right),$$

where

$$\dot{P}_{\text{avg},\ell} = \omega_c \left( P_\ell - P_{\text{avg},\ell} \right),$$

$$\dot{Q}_{\text{avg},\ell} = \omega_c \left( Q_\ell - Q_{\text{avg},\ell} \right),$$

and slopes $m_q = 0.05 \frac{V_{\text{nom}}}{S_{\text{rated}}}$, $m_p = \frac{2\pi \times 0.5}{S_{\text{rated}}}$. This gives the following in steady-state:

A single-phase droop-controlled inverter
A Common Framework For Various Load Configurations

inverters with Δ & Υ loads

circuit model with mesh loops
A System Circuit Model

Circuit laws + control dynamics give

\[ V_\ell = V_{\text{nom}} - m_q \sum_{k=1}^{3} \frac{V_k V_\ell}{|Z_{\text{loop}}|} \sin (\theta_{k\ell} - \phi), \]

\[ \dot{\theta_\ell} = \omega_{\text{nom}} - m_p \sum_{k=1}^{3} \frac{V_k V_\ell}{|Z_{\text{loop}}|} \cos (\theta_{k\ell} - \phi). \]

where \( Z_{\text{loop}} = 3\overline{Z} \) and \( \phi = \tan^{-1} (X/R) \). Next, focus on angle difference dynamics

\[ \dot{\theta}_{21} = \dot{\theta}_2 - \dot{\theta}_1, \]

\[ \dot{\theta}_{31} = \dot{\theta}_3 - \dot{\theta}_1. \]
Nonlinear Angular Dynamics

Algebra gives us

$$\dot{\theta}_{21} = \frac{m_p V_2 V_1}{|Z_{\text{loop}}|} \cos (\theta_{21} - \phi) + \frac{m_p V_3 V_1}{|Z_{\text{loop}}|} \cos (\theta_{31} - \phi)$$

$$- \frac{m_p V_2 V_3}{|Z_{\text{loop}}|} \cos (\theta_{32} - \phi) - \frac{m_p V_2 V_1}{|Z_{\text{loop}}|} \cos (\theta_{12} - \phi),$$

$$\dot{\theta}_{31} = \frac{m_p V_3 V_1}{|Z_{\text{loop}}|} \cos (\theta_{31} - \phi) + \frac{m_p V_2 V_1}{|Z_{\text{loop}}|} \cos (\theta_{21} - \phi)$$

$$+ \frac{m_p V_2 V_3}{|Z_{\text{loop}}|} \cos (\theta_{23} - \phi) + \frac{m_p V_1 V_3}{|Z_{\text{loop}}|} \cos (\theta_{13} - \phi).$$

circuit model with mesh loops
Angle Difference Dynamics

Substitute voltage droop laws, ignore $m_p^2, m_q^2, m_p m_q$ terms, and let $K = m_p V_{nom}^2 / |Z_{loop}|$ to get:

$$\dot{\theta}_{21} \approx K(2 \sin \theta_{21} + \sin \theta_{31} + \sin (\theta_{21} - \theta_{31})) \sin \phi + K(\cos \theta_{31} - \cos (\theta_{21} - \theta_{31})) \cos \phi,$$

$$\dot{\theta}_{31} \approx K(2 \sin \theta_{31} + \sin \theta_{21} + \sin (\theta_{31} - \theta_{21})) \sin \phi + K(\cos \theta_{21} - \cos (\theta_{31} - \theta_{21})) \cos \phi.$$
Angle Difference Dynamics

The equilibria are below, where $\sigma_1 = 2\pi + 2\tan^{-1}(-3\tan \phi)$, $\sigma_2 = 2\tan^{-1}(3\tan \phi)$.

\[
(\theta_{21,\text{eq}}, \theta_{31,\text{eq}}) = \left\{ \left( \frac{2\pi}{3}, \frac{4\pi}{3} \right), \left( \frac{4\pi}{3}, \frac{2\pi}{3} \right) \right\},
\]

\[
(\theta_{21,\text{eq}}, \theta_{31,\text{eq}}) = \{(0, 0)\},
\]

\[
(\theta_{21,\text{eq}}, \theta_{31,\text{eq}}) = \{(0, \sigma_1), (\sigma_1, 0), (\sigma_2, \sigma_2)\},
\]

Small-signal Modeling

The linearized system is

\[
\begin{bmatrix}
\Delta \dot{\theta}_{21} \\
\Delta \dot{\theta}_{31}
\end{bmatrix} = \mathcal{J}(\theta_{21,eq}, \theta_{31,eq}) \begin{bmatrix}
\Delta \theta_{21} \\
\Delta \theta_{31}
\end{bmatrix},
\]

where

\[
\mathcal{J}(\theta_{21,eq}, \theta_{31,eq}) = K \begin{bmatrix}
(2 \cos \theta_{21,eq} + \cos (\theta_{21,eq} - \theta_{31,eq})) \sin \phi + \sin (\theta_{21,eq} - \theta_{31,eq}) \cos \phi & (\cos \theta_{31,eq} - \cos (\theta_{21,eq} - \theta_{31,eq})) \sin \phi + (\sin (\theta_{31,eq} - \theta_{21,eq}) - \sin \theta_{31,eq}) \cos \phi \\
(\cos \theta_{21,eq} - \cos (\theta_{31,eq} - \theta_{21,eq})) \sin \phi + (\sin (\theta_{21,eq} - \theta_{31,eq}) - \sin \theta_{21,eq}) \cos \phi & (2 \cos \theta_{31,eq} + \cos (\theta_{31,eq} - \theta_{21,eq})) \sin \phi + \sin (\theta_{31,eq} - \theta_{21,eq}) \cos \phi
\end{bmatrix},
\]

and the eigenvalues for all equilibria within \( \phi \in (0, \pi/2] \) are

\[
\lambda_{1,2} = -\frac{3}{2} K (\sin \phi \pm j \cos \phi), \quad \Re(\lambda_{1,2}) < 0 \quad \text{stable},
\]

\[
\lambda_{1,2} = 3K \sin \phi, \quad \Re(\lambda_{1,2}) > 0 \quad \text{unstable},
\]

\[
\lambda_1 = -3K \sin \phi, \quad \lambda_2 = 9K \frac{1 + \tan^2 \phi}{1 + 9 \tan^2 \phi} \sin \phi, \quad \Re(\lambda_1) < 0 \quad \text{and} \quad \Re(\lambda_2) > 0 \quad \text{saddle}.
\]

Self-balancing Single-phase GFM Hardware Results

Dr. Minghui Lu
Thanks for Your Attention!

My other work building & analyzing future energy systems at all scales

electromechanics  medium-voltage electronics

multiphysics modeling  dc-dc converters  system dynamics