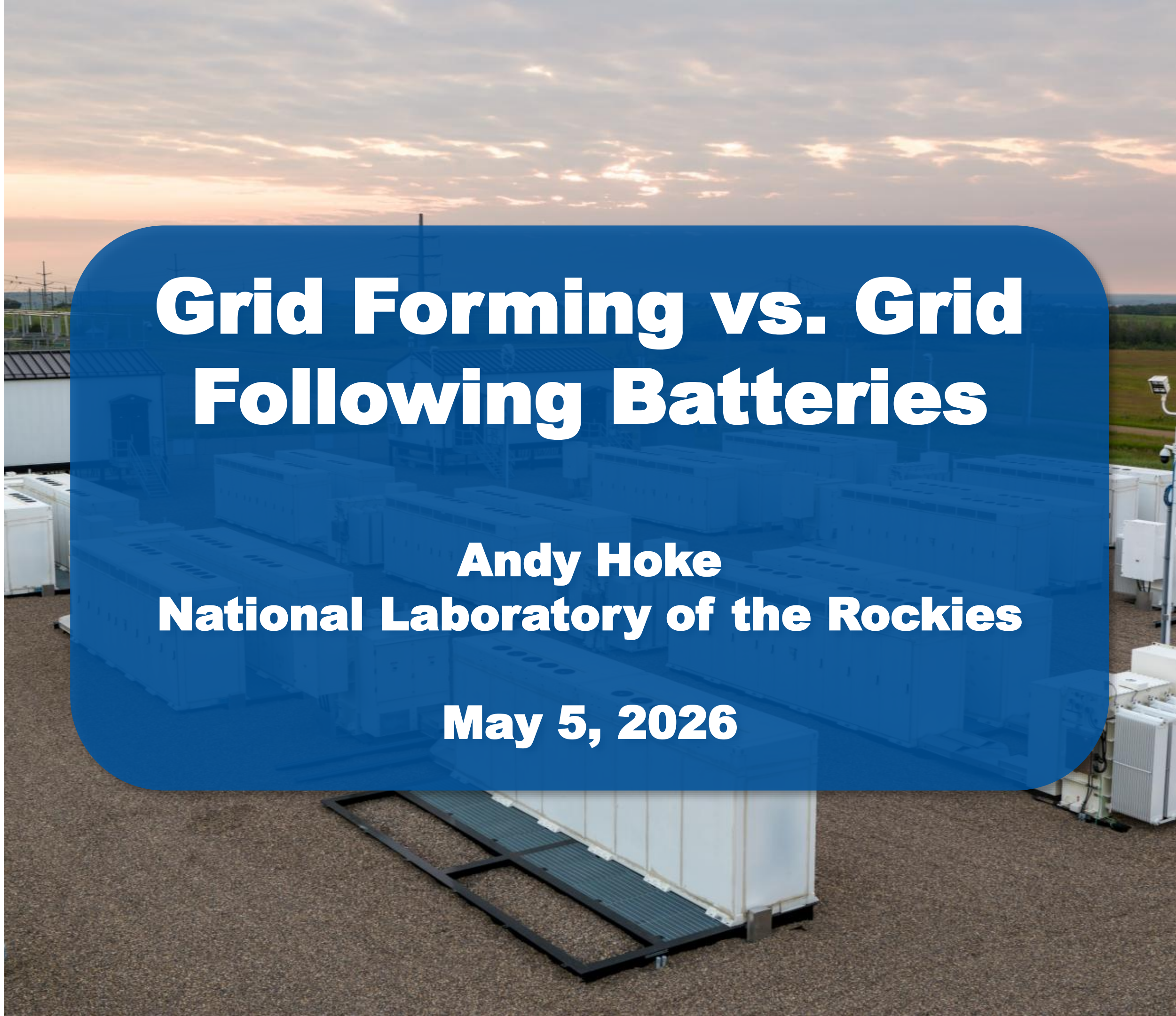


Grid Forming vs. Grid Following Batteries

Andy Hoke
National Laboratory of the Rockies

May 5, 2026

Antitrust Admonition

Because this event brings together market participants who may be viewed as actual or potential competitors, we must be mindful to conduct it in a manner that is consistent with the antitrust and competition laws. Participants should not disclose non-public, proprietary, or competitively sensitive information.

Attendees should exercise independent judgment and avoid even the appearance of discussions of agreements or concerted actions that may be viewed as restraining competition. Any questions on Texas RE's Antitrust Compliance Corporate Policy may be directed to Texas RE's General Counsel.

Upcoming Events at Texas RE

May 26, 2026

NERC Summer Assessment

June 3, 2026

2025 Texas Interconnection Reliability Performance

June 23, 2026

Integration of Large Loads

Upcoming Events at Texas RE

May 13, 2026

Q2 MRC, AGR&F, and Board Meetings

August 19, 2026

Winter Weatherization Workshop

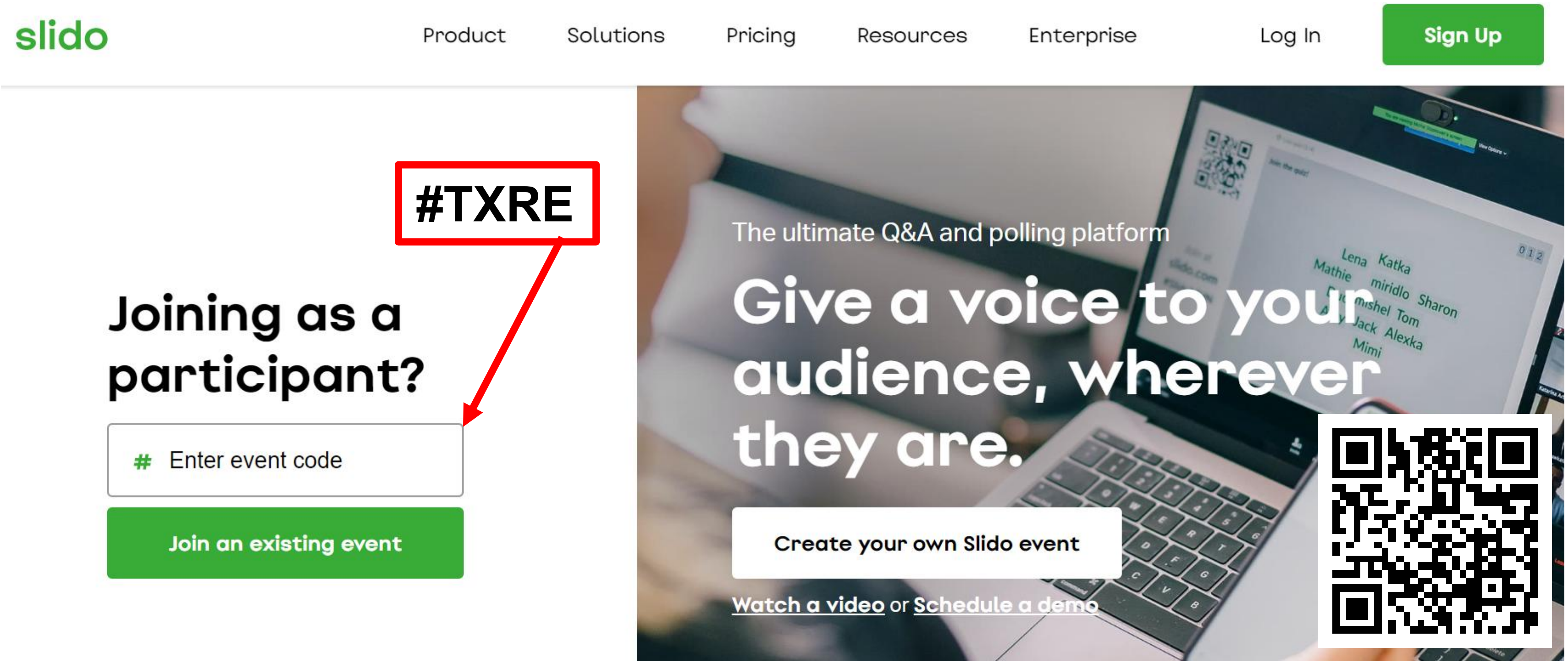
November 4, 2026

Fall Standards, Security, & Reliability Workshop

Upcoming ERO Enterprise Events

Date	Event
May 12-13, 2026	2026 MRO Reliability, Security, and CMEP Summit
May 12-14, 2026	SERC System Operator Technical Conference #2
May 18, 2026	Technical Talk with RF

Slido.com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National Laboratory of the Rockies

unifi consortium
universal interoperability for grid-forming inverters

Grid-Forming Technologies

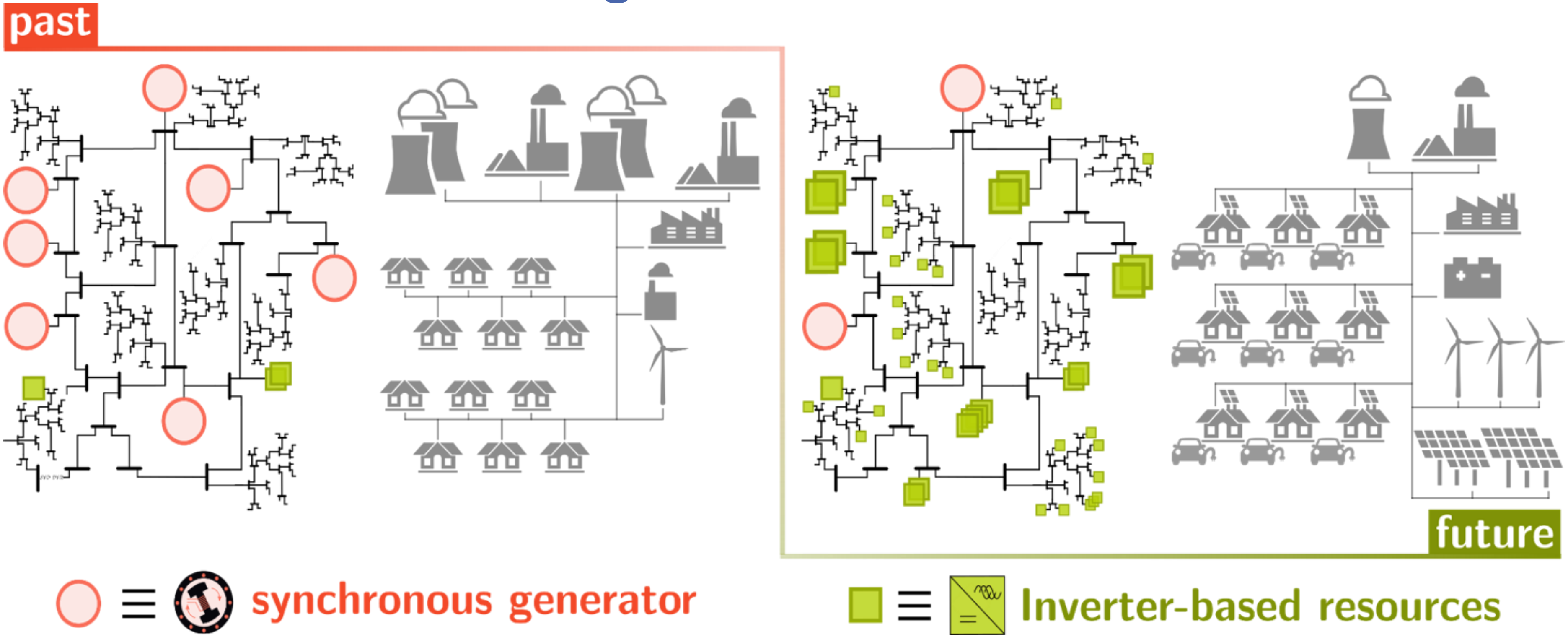
Andy Hoke
National Laboratory of the Rockies (formerly known as NREL)

Presentation to Texas RE, May 5, 2026

Outline

- Review of grid-forming (GFM) inverter technology
  - GFM vs grid-following (GFL)
  - GFM deployment status
  - Potential benefits of GFM for bulk power systems
- Overview of UNIFI Specification for GFM IBRs, Version 3 and IEEE P2800.1

More Inverter-based Resources are being integrated into the Grid



Difference between Synchronous Generators and Inverter-based Resources (IBRs)

Conventional power plants use large rotating synchronous generators to produce electricity

Coal, Natural Gas, Nuclear, Geothermal, and Hydro

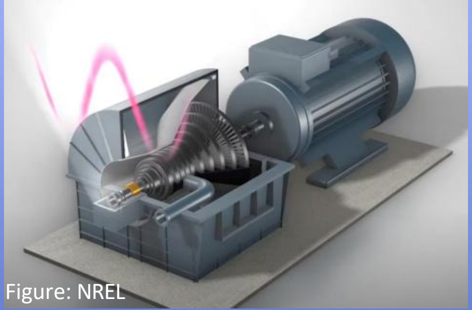
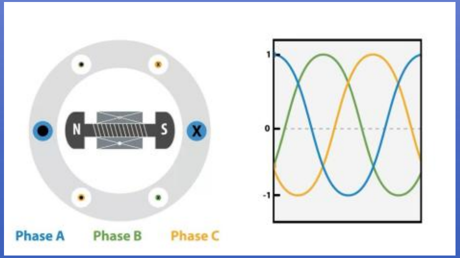


Figure: NREL



Learn more about generator inertia

Batteries, variable renewables, and HVDC stations use inverters to produce electricity

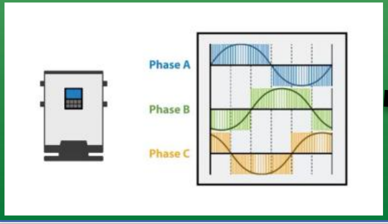
Batteries, Wind, Solar PV, and HVDC

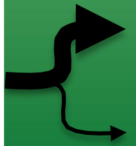
Figure: NREL

DC

AC

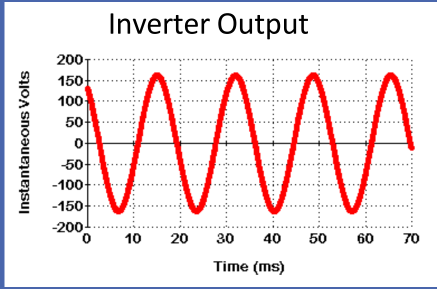
2 Types of IBR





Learn more about inverters

Grid Following (GFL) vs. Grid Forming (GFM)



- GFL IBRs control output **current** and can be responsive to grid disturbances
- Dependent on another source to synchronize to

- GFM IBRs control output **voltage,** which enables a quicker response to grid disturbances than GFL
- Can make its own voltage and frequency waveform (grid strength, blackstart)

Follower

Leader

Source: Lin, Yashen, Joseph H. Eto, Brian B. Johnson, Jack D. Flicker, Robert H. Lasseter, Hugo N. Villegas Pico, Gab-Su Seo, Brian J. Pierre, and Abraham Ellis. 2020. **Research Roadmap on Grid-Forming Inverters**. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-73476. https://www.nrel.gov/docs/fy21osti/73476.pdf.

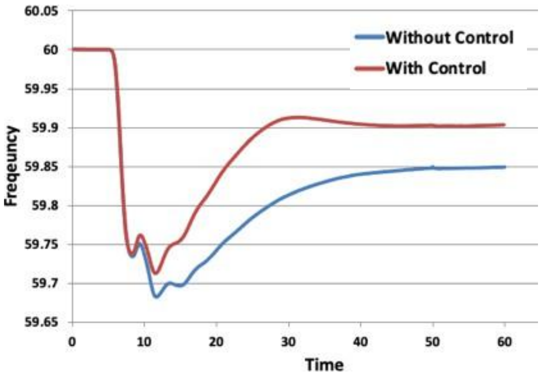
Technical Challenges and Solutions in Grids with Higher Inverter-based Resources

Challenge	Solution
Frequency and voltage stability	Responsive IBRs that provide grid support including fast frequency response
Protection	IBRs with negative sequence current and/or higher current output, sync condensers, new protection schemes
Blackstart	Grid-forming (GFM) inverters
System oscillations	Inverter control tuning and damping, GFM
Cybersecurity	Cyber standards for IBRs

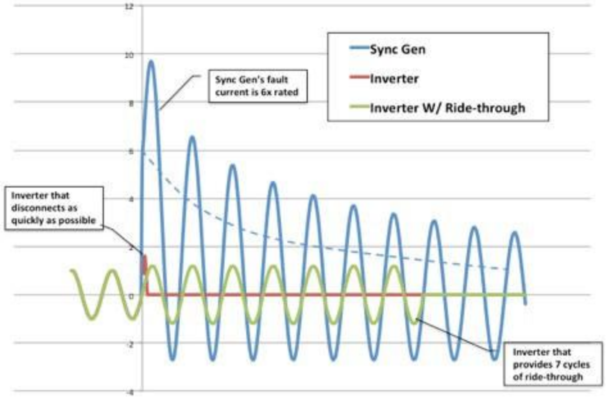
Source: B. Kroposki and A. Hoke, "Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," http://ieeexplore.ieee.org/document/7866938/

Source: Blackstart of Power Grids with Inverter- Based Resources, H. Jain, G. Seo, E. Lockhart, V. Gevorgian, B. Kroposki, 2020 IEEE Power and Energy General Meeting: https://www.nrel.gov/docs/fy20osti/75327.pdf

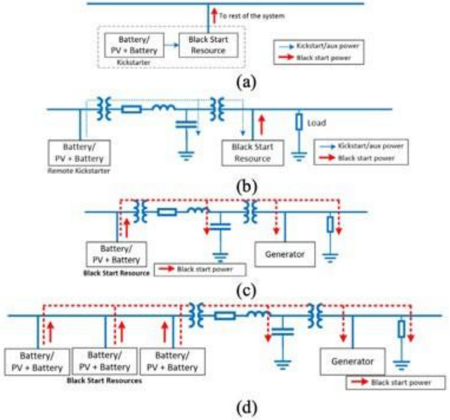
Grid Stability



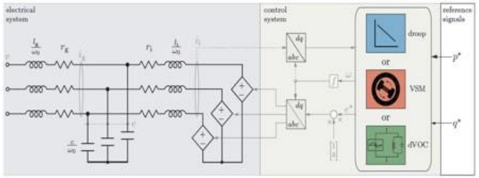
Protection

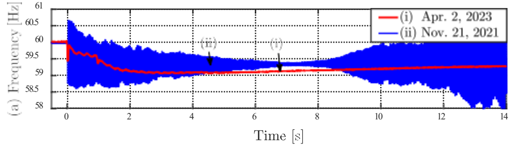


Blackstart and System Restoration

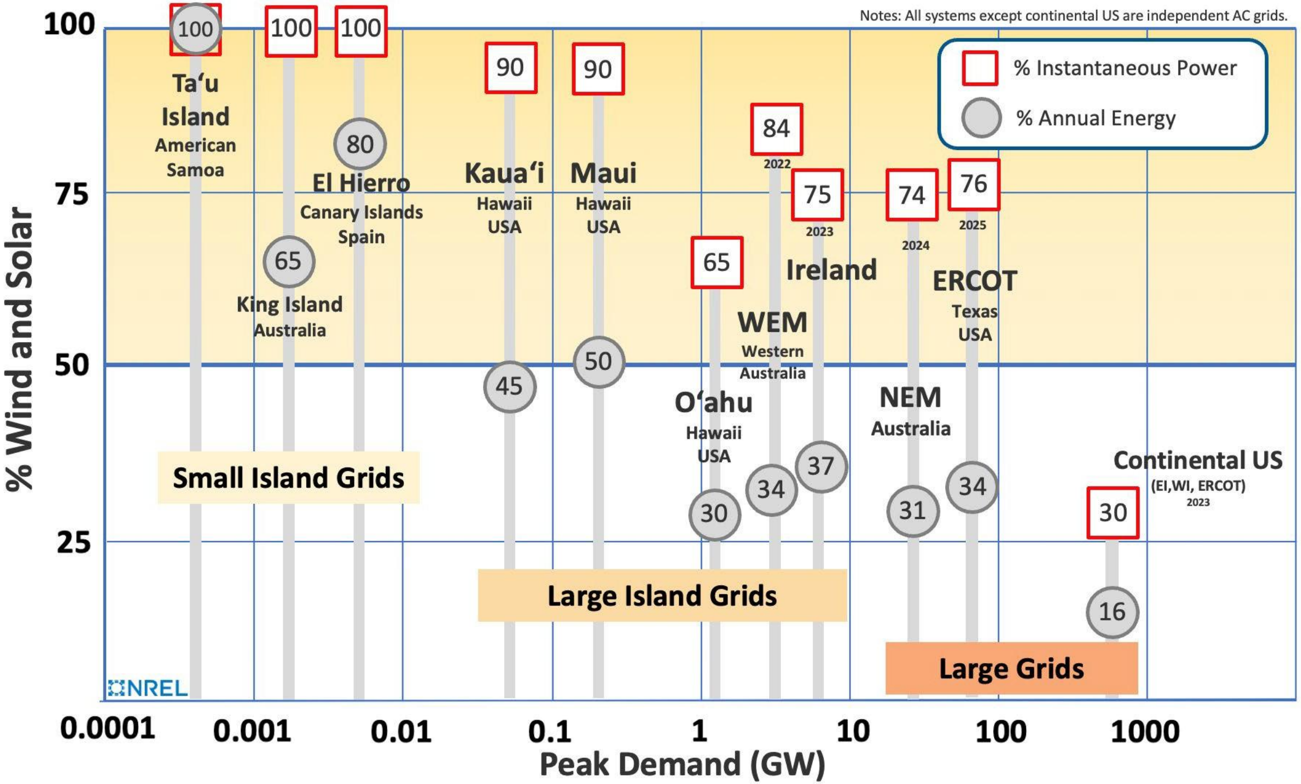


Control System Interactions and System Oscillations





Good news: We know how to operate power grids with high levels of inverter-based resources



Keys to Operating Grids with High IBR Levels (over 40% annually)

1) Ensure GFL IBRs are responsive to gid disturbances
2) Add GFM IBRs
3) Large amounts of energy storage

47% of ERCOT installed capacity is IBR

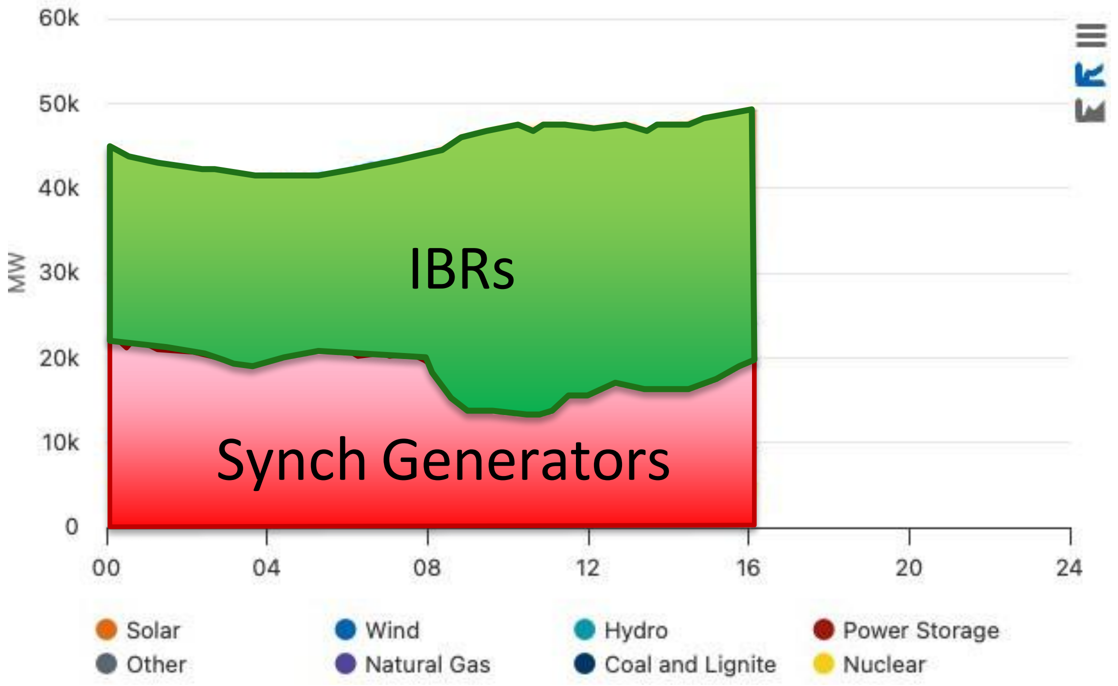
IBRs in ERCOT – February 15, 2026

Fuel Mix

Last Updated: Feb 15, 2026 16:11 CT

CURRENT GENERATION	MONTHLY CAPACITY
Solar 25,042 MW (51.0%)	36,437 MW
Wind 4,190 MW (8.5%)	40,588 MW
Hydro 20 MW (0.0%)	579 MW
Power Storage 26 MW (0.1%)	16,866 MW
Other 50 MW (0.1%)	667 MW
Natural Gas 10,388 MW (21.2%)	68,441 MW
Coal and Lignite 4,247 MW (8.7%)	13,705 MW
Nuclear 5,109 MW (10.4%)	5,268 MW

Lots of time operating over 50% IBRs

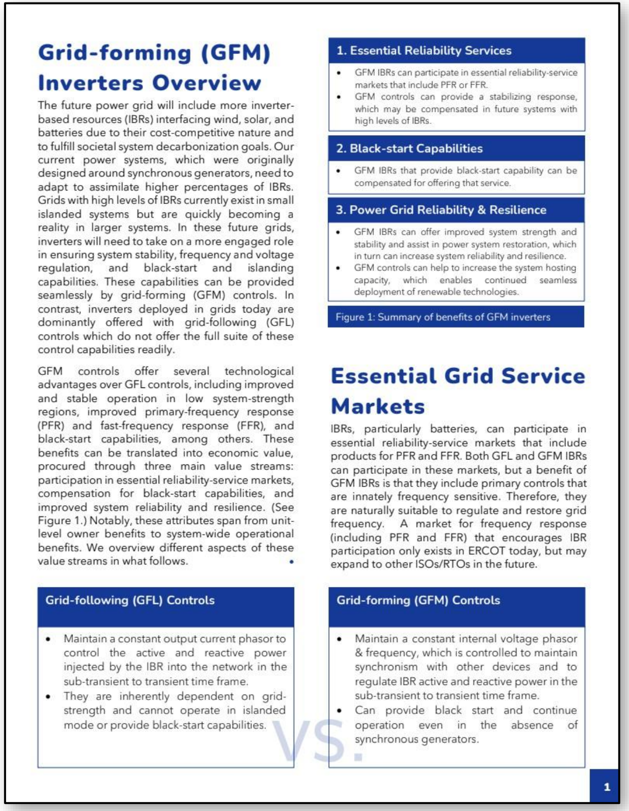


www.ercot.com

GFM Value Proposition

Value of Using Grid-forming Technologies

- Improved grid stability
  - Maintain system voltage
  - Very fast response to grid disturbances
- Essential reliability services
- Black-start capabilities for system restoration
- Improve power grid reliability and resilience



Grid-forming (GFM) Inverters Overview

The future power grid will include more inverter-based resources (IBRs) interfacing wind, solar, and batteries due to their cost-competitive nature and to fulfill societal system decarbonization goals. Our current power systems, which were originally designed around synchronous generators, need to adapt to assimilate higher percentages of IBRs. Grids with high levels of IBRs currently exist in small islanded systems but are quickly becoming a reality in larger systems. In these future grids, inverters will need to take on a more engaged role in ensuring system stability, frequency and voltage regulation, and black-start and islanding capabilities. These capabilities can be provided seamlessly by grid-forming (GFM) controls. In contrast, inverters deployed in grids today are dominantly offered with grid-following (GFL) controls which do not offer the full suite of these control capabilities readily.

GFM controls offer several technological advantages over GFL controls, including improved and stable operation in low system-strength regions, improved primary-frequency response (PFR) and fast-frequency response (FFR), and black-start capabilities, among others. These benefits can be translated into economic value, procured through three main value streams: participation in essential reliability-service markets, compensation for black-start capabilities, and improved system reliability and resilience. (See Figure 1.) Notably, these attributes span from unit-level owner benefits to system-wide operational benefits. We overview different aspects of these value streams in what follows.

1. Essential Reliability Services

- GFM IBRs can participate in essential reliability-service markets that include PFR or FFR.
- GFM controls can provide a stabilizing response, which may be compensated in future systems with high levels of IBRs.

2. Black-start Capabilities

- GFM IBRs that provide black-start capability can be compensated for offering that service.

3. Power Grid Reliability & Resilience

- GFM IBRs can offer improved system strength and stability and assist in power system restoration, which in turn can increase system reliability and resilience.
- GFM controls can help to increase the system hosting capacity, which enables continued seamless deployment of renewable technologies.

Figure 1: Summary of benefits of GFM inverters

Essential Grid Service Markets

IBRs, particularly batteries, can participate in essential reliability-service markets that include products for PFR and FFR. Both GFL and GFM IBRs can participate in these markets, but a benefit of GFM IBRs is that they include primary controls that are innately frequency sensitive. Therefore, they are naturally suitable to regulate and restore grid frequency. A market for frequency response (including PFR and FFR) that encourages IBR participation only exists in ERCOT today, but may expand to other ISOs/RTOs in the future.

Grid-following (GFL) Controls

- Maintain a constant output current phasor to control the active and reactive power injected by the IBR into the network in the sub-transient to transient time frame.
- They are inherently dependent on grid-strength and cannot operate in islanded mode or provide black-start capabilities.

VS.

Grid-forming (GFM) Controls

- Maintain a constant internal voltage phasor & frequency, which is controlled to maintain synchronism with other devices and to regulate IBR active and reactive power in the sub-transient to transient time frame.
- Can provide black start and continue operation even in the absence of synchronous generators.

1

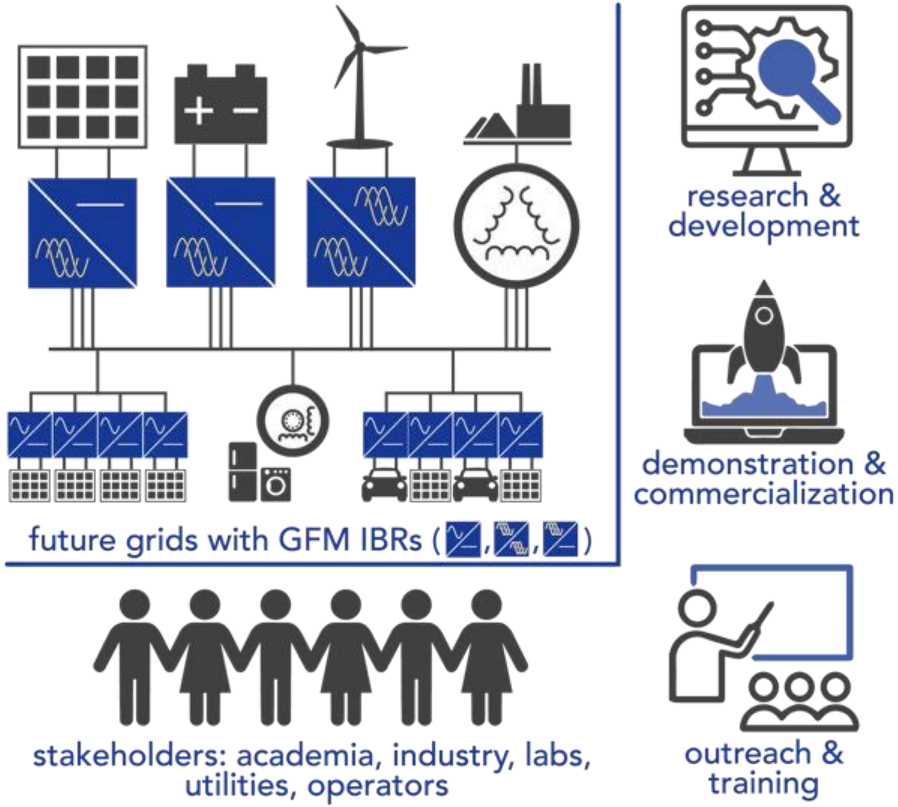
[GFM Value Proposition](#)

What is UNIFI ?

The **UNIFI Consortium** is a forum to address fundamental challenges in the seamless integration of grid-forming (GFM) inverter-based resources (IBR) into power systems of the future.

Bringing the industry together to <u>unify</u> the integration and operation of inverter-based resources and synchronous machines

Three major focuses:
- Research & Development
- Demonstration & Commercialization
- Outreach & Training



UNIFI Members - 49 Active Members

Utilities & System Operators

CAISO
TVA
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UAF
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ASU
NC State University
UNC Charlotte

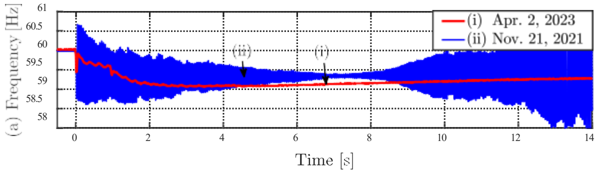
National Labs & Research Institutes

EPRI
National Laboratory of the Rockies
NPL
Sandia National Laboratories
PNNL
CanmetENERGY
NERGICA

UNIFI – Field Demonstrations

Kauai (80MW$_{peak}$) is the only place in the world with multiple 10MW+ GFM systems in operation paralleled to grid.

The grid operator (KIUC) is successfully operating the grid at 90% inverter-based resources at times which translate to around 45% annually.



2021 - One GFM operating

2023 - Two GFM operating

IEEE Spectrum - Grid-forming Inverters

Developing Field Demonstration Evaluation Process

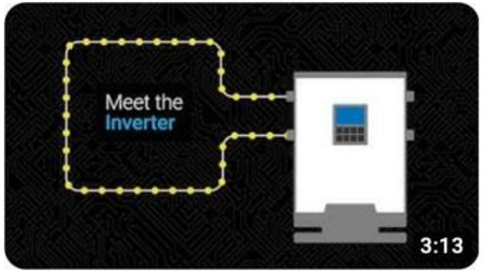
- Based on 1MW Demo Test plan
- Simplified based on equipment available for large sites (no grid simulators, no ability to change load, etc)
- Part of larger continuum of UNIFI work for GFM site implementation

Exus - 140-megawatt solar and 50-megawatt/200-megawatt-hour battery storage facility in Sandoval County, New Mexico

Workforce Development

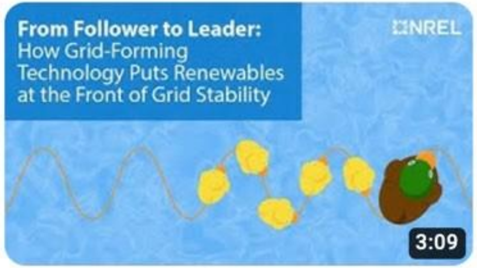
- 2,210+ Subscribers and 80,600+ Views
- 91 videos: archives of videos from UNIFI seminar series – continues in Spring 2026
- 16 videos with over 1,000 views

www.youtube.com/@UNIFIConsortium



[Meet the Inverter]

[Understanding Inertia]



[Grid-forming Inverters]

GFM Specifications around the Globe

https://www.esig.energy/working-users-groups/reliability/grid-forming/gfm-landscape/

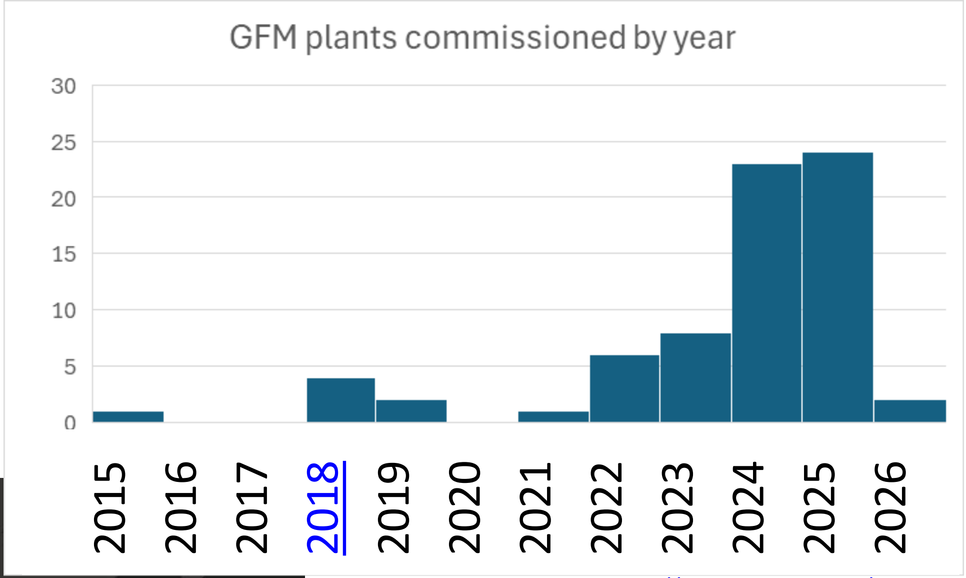
https://docs.nlr.gov/docs/fy26osti/98381.pdf

Interconnection Standard for GFM IEEE 2800.1

GFM Deployment

ESIG tracker lists:
- 72 GFM plants operational
- 24 GFM plants planned

https://unifi-consortium.github.io/GFM_Map/



https://www.esig.energy/working-groups/reliability/grid-forming-landscape/installed-and-planned-gfm-projects/

GFM plants by region

Operational GFM plants by technology:
- 51 GFM BESS
- 10 GFM STATCOMs
- 4 GFM HVDC systems
- 5 GFM hybrid plants
- 1 GFM PV plant

unifi consortium

universal interoperability for grid-forming inverters

UNIFI Specifications for GFM IBRs
Version 3

UNIFI Specifications for GFM IBRs – Version 2 – March 2024

unifi consortium

UNIFI Specifications for Grid-Forming Inverter-Based Resources

Version 2

For more information, visit: **unificonsortium.org**

The Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium is co-led by the National Renewable Energy Laboratory, the University of Texas-Austin, and the Electric Power Research Institute. This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number 38637.

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UNIFI Specifications for GFM IBRs – Version 2 – March 2024

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IBR Vendors/Developers

Utilities/System Operators

Research Labs

Universities

Summary of Comments on Version 2

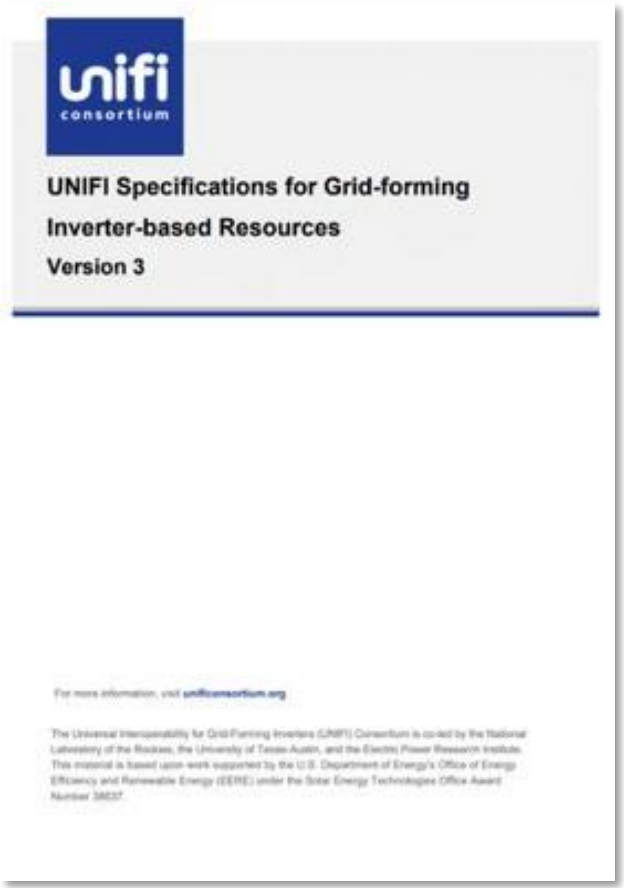
140 comments from 24 commenters representing 15 organizations:

Notable themes:

- **Clarifying IBR categories**
- **Frequency-domain characteristics**
- System strength
- Modeling
- **Test procedures**
- **Quantifying requirements**
- Definitions
- Fault current
- Ride-through
- Uniqueness of requirements to GFM
- Power sharing

Version 3 of UNIFI GFM Specification

- Published February 2026
- https://unificonsortium.org/resources/#toc_Specifications_v3
- Builds on Version 2
- Adds quantitative pass-fail test criteria
- Currently being used as the starting point for IEEE P2800.1, a new standard for GFM IBR equipment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UNIFI Specifications for Grid-forming Inverter-based Resources

Version 3

Overview of UNIFI Spec V3 content

- Introductory material
  - **Four tiers of GFM capability**
- **GFM requirements** (qualitative)
  - Under normal operating conditions
  - Outside normal operating conditions
- Modeling requirements (refers to IEEE P2800.2)
- **Time-domain tests** with quantitative criteria (similar to ERCOT, MISO, HECO, AEMO, Fingrid, etc)
- **Frequency-domain tests** with quantitative criteria (some new, some reference ESIG tests)

Why qualitative requirements and quantitative tests?

- Primary goal: Provide a standardized way for industry to know whether an IBR is GFM
- Tests with quantitative criteria are the shortest path to this goal
  - UNIFI currently includes time-domain tests and frequency-domain tests

Why qualitative requirements and quantitative tests?

- Defining quantitative requirements (as opposed to tests) raises many difficult questions
- For example, take the requirement to inject active power that resists phase jumps
  - Defining a quantitative requirement raises questions like:
    - How big is the phase jump? How much active power? What is the impedance between the phase jump location and the IBR? How do we deal with IBR current and power limits?
  - By defining a series of tests, we can answer all those questions for the specific test conditions without needing to answer them for all possible conditions

1 GFM Performance Tiers

GFM Tier	Key Function(s)	Examples of Resource Types	Notes
1	Voltage magnitude support	GFM STATCOM, GFM PV at night	
2	Tier 1 plus voltage angle/frequency support & minimum islanding capability	GFM E-STATCOM, GFM wind turbine (Type 3 and Type 4), GFM PV	Active power contribution is subject to complex intermittency, asymmetry, headroom, and resonance (for GFM IBRs with rotating machines) aspects.
3	Tier 2 plus extended islanding capability	GFM BESS	
4	Tier 3 plus black start	GFM BESS with black start	

2 Performance Requirements for GFM IBRs

2.1 Performance Requirements Within **Normal Grid Conditions**

Requirement	GFM has a unique requirement?	Could a quantitative pass-fail metric be applied?	Applicable test (Where no test is specified, a regional requirement may apply)
Autonomously Support the Grid	No	-	NA
Dispatchability of Power Output	No	-	NA
Provide Positive Damping of Voltage and Frequency Oscillations	Some GFL could comply depending on oscillation frequency	Yes	Frequency scan tests in Section 6 and Appendix A. Also spot-checked in various time-domain tests in Section 5.
Active and Reactive Power Sharing across Generation Resources	No	-	5.9: Loss of Grid Connection Test
Operation in Grids with Low System Strength	Yes, for very weak grids	Yes	5.3: System Strength Test
Operation under System Unbalance	Some GFL comply	Yes	5.4: Unbalance Step-Up Test

2 Performance Requirements for GFM IBRs

2.1 Performance Requirements **Outside Normal Grid Conditions**

Requirement	GFM has a unique requirement?	Could a quantitative pass-fail metric be applied?	Applicable test (Where no test is specified, a regional requirement may apply)
Voltage Ride-through Capability	No	Yes	Refer to relevant interconnection standard, e.g. IEEE 2800 or IEEE 1547
Performance During Symmetrical Faults	Some GFL comply	Yes	5.5: Fault Test (informative)
Performance During Asymmetrical Faults	Some GFL comply	Yes	5.5: Fault Test (informative)
Abnormal Frequency Ride-through Capability	No	-	Refer to relevant interconnection standard, e.g. IEEE 2800 or IEEE 1547
Performance in Response to Frequency Deviations	Yes, in subtransient timeframe.	Yes	5.6: Response to Frequency Change Test
Performance During Phase Jumps and Voltage Steps	Yes	Yes	5.7: Phase Angle Jump Test 5.8: Small Voltage Step Test

3 Additional GFM Capabilities and Considerations

Requirement	GFM has a unique requirement?	Could a quantitative pass-fail metric be applied?	Applicable test (Where no test is specified, a regional requirement may apply)
Intentional Islanding	Yes	Yes	5.9: Loss of Grid Connection Test
Black Start and System Restoration	Yes	Yes	Requirements are application-specific; no generic test provided here.
Regulating Voltage Harmonics	Some GFL comply at least partially	Yes	No consensus on quantitative GFM-specific requirement; no test provided here. Relevant interconnection standard applies.
Communications between System Operator and IBR Plant	No	-	NA
Secondary Voltage and Frequency Signal Response	No	-	NA
Constraints Due to Input Source	NA	-	NA

4 Modeling and Documentation

When designing and planning the integration of GFM IBR in power systems it is often helpful to be able to accurately model the behavior of the GFM IBR under a wide range of operating parameters. **The model should accurately represent all operational modes available in the IBR and the documentation should describe how to configure the modes and parameters.** The behavior of the GFM IBR when approaching or encountering physical limits is expected to be captured in the manufacturer's provided and validated electro-magnetic transient (EMT) model and phasor-domain transient (PDT) model to allow for accurate simulation of the GFM IBR's response to various events. For example, the EMT model should include fault current shaping behavior of the GFM IBR, such as the waveform of current during the fault and its duration if the fault current is designed to last only for a short period of time.

Because EMT simulations are a primary means of validating GFM performance, the EMT model of a GFM IBR should be validated. A validated EMT model is one whose output has been compared to hardware test data and shown to match sufficiently. IEEE P2800.2 contains hardware test procedures and model validation procedures; these can be leveraged for GFM IBR unit model validation. Annex G of IEEE 2800-2022 also includes recommendations for modeling IBR plants.

5 Time-domain conformity assessment procedures

- Focusing on GFM BESS (an example of "Tier 3 GFM") for now
  - Some tests could be applied to other Tiers; may need modification
- Tests rely on validated **EMT model of IBR unit**.
  - Could also be run as hardware tests, but not planning to require hardware testing
  - Some tests may also need plant controller in model
- Inverter model and plant controller model should be validated against hardware tests
  - For example, using IEEE P2800.2 procedures
- Most tests leverage existing test procedures from industry (HECO, NERC, AEMO, MISO, ERCOT, …)
  - E.g. https://www.ercot.com/files/docs/2024/09/16/ERCOT%20Advanced%20Grid%20Support%20ESR%20Test%20Requirement_.pdf
- **Join Subgroup 6 of IEEE IBR Interconnection WG to get involved**

Frequency-domain tests

- Characterize IBR **small-signal behavior** across a range of perturbation frequencies
- Currently focused on frequencies **below 40 Hz** (subsynchronous)
  - Many SMEs feel some requirement above nominal frequency should be required, but no consensus on requirement, so no requirement included
  - Harmonic requirements that apply to all IBRs also apply to GFM

- V3 proposes applying tests to **EMT model**
  - IEEE P2800.2 says frequency scan of EMT model should closely match scan of hardware

- Frequency-domain specs are relatively new. **Need broader industry input**

- **Join Subgroup 7 of IEEE IBR Interconnection WG to get involved**

Frequency-domain tests

- Specs leverage **dynamic droop coefficients** that capture the IBR's small-signal f-P and V-Q responses:

$$\begin{bmatrix} \Delta P(j\omega_p) \\ \Delta Q(j\omega_p) \end{bmatrix} = -\begin{bmatrix} m_p(j\omega_p) & \xi_q(j\omega_p) \\ \xi_p(j\omega_p) & m_q(j\omega_p) \end{bmatrix} \begin{bmatrix} \Delta\omega(j\omega_p) \\ \Delta V(j\omega_p) \end{bmatrix} \quad (1)$$

- m_p and m_q are frequency dependent droop coefficients including magnitude and angle
- Cross-coupling terms ξ_q, ξ_p assumed to be negligible. (May not be true at frequencies above 10-20 Hz)
- V3 also provides criteria based on other transfer functions that leverage GFM's voltage-source behavior: P/θ, V/Q, V/I
- https://www.esig.energy/gfm-performance-testing/
- V3 leaves readers to decide which of the various frequency-domain requirements to use

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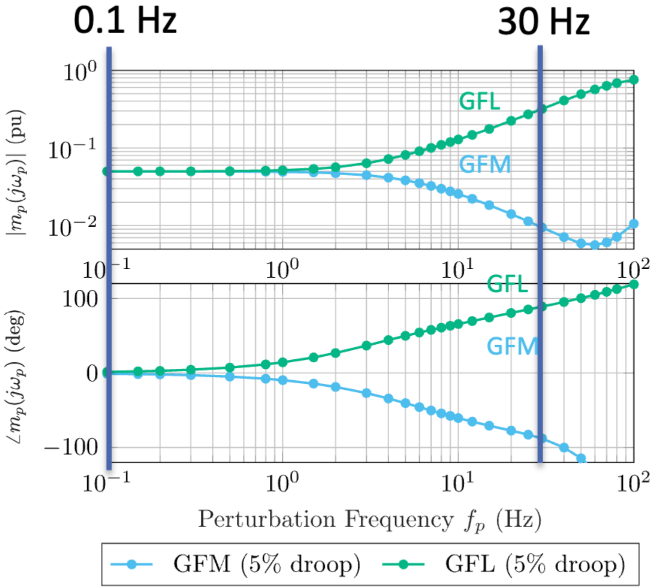
UNIFI Frequency Domain Specifications

Dominic Groß[1], Deepak Ramasubramanian[2], Dustin Howard[3], Phil Hart[3]



Frequency-domain criteria at lower frequencies (below a few Hz)

Table 5. Frequency-Domain Specifications for IBR Unit Capabilities Within the Continuous Operation Region Under Balanced Conditions—Applicable to GFM IBRs With Active Power Capability as Indicated in Last Column

Input / Output	Capability and applicable frequency range	Specifications: Frequency ω/P	Specifications: Voltage V/Q	Notes	Applicable GFM Tiers
Input: P, Q **Output:** ω, V Sometimes called 'dynamic droop' [a]	**Steady state droop** $f_p \in [f_{p,min}, f'_p]$ Approximately 0.01 Hz to 0.1 Hz, specified based on grid needs.	Upper bound on $\lvert\omega/P\rvert$ increases[§] from $m_p(0) + 0.01$ p.u. at $f_{p,min}$ to m''_p at f'_p with corresponding symmetric lower bound. Bound on $\lvert\angle\,\omega/P\rvert$ increase[§] from $5°$ at $f_{p,min}$ to $90° + \varepsilon_1$ * at f'_p	Upper bound on $\lvert V/Q\rvert$ increases[§] from $m_q(0) + 0.01$ p.u. at $f_{p,min}$ to m''_Q at f'_p with corresponding symmetric lower bound. Bound on $\lvert\angle\,V/Q\rvert$ increase[§] from $5°$ at $f_{p,min}$ to $90° + \varepsilon_1$ * at f'_p	Frequency bounds shift towards lower values for resources with large physical inertia, or VSM with large, emulated inertia time constants, and vice versa. * tolerance ε_1 to accommodate numerical/implementation aspects of control and test procedure [§] linear increase on log plot	V/Q: All GFM Tiers ω/P: Tier 3 and above
	Rate-of-change support $f_p \in [f'_p, f''_p]$ Approximately 0.1 Hz to 0.5 Hz, specified based on grid needs.	$\lvert\omega/P\rvert \le m''_p$ $\lvert\angle\,\omega/P\rvert \le 90° + \varepsilon_1$ *	$\lvert V/Q\rvert \le m''_Q$ $\lvert\angle\,V/Q\rvert \le 90° + \varepsilon_1$*		V/Q: All GFM Tiers ω/P: Tier 2 and above
	Low frequency oscillation damping $f_p \in [f''_p, f'''_p]$ Starting from approximately 0.5 Hz with upper limit f'''_p that depends on IBR characteristics.	$\lvert\omega/P\rvert$ below an upper bound that starts at m''_p at f''_p and decreases ten times for a ten times increase of f_p (straight line in log-log plot) $\lvert\angle\,\omega/P\rvert \le 90° + \varepsilon_1$*	$\lvert V/Q\rvert \le m''_Q$ $\lvert\angle\,V/Q\rvert \le 90° + \varepsilon_1$*		V/Q: All GFM Tiers ω/P: Tier 2 and above

[a] Groß, Dominic, Deepak Ramasubramanian, Benjamin Paz. December 2022. Universal input-output model of GFM functions and data-driven verification methods. UNIFI-2022-4-1.

In this frequency range, GFM is not very different from grid-following

Frequency-domain criteria at higher frequencies (above a few Hz)

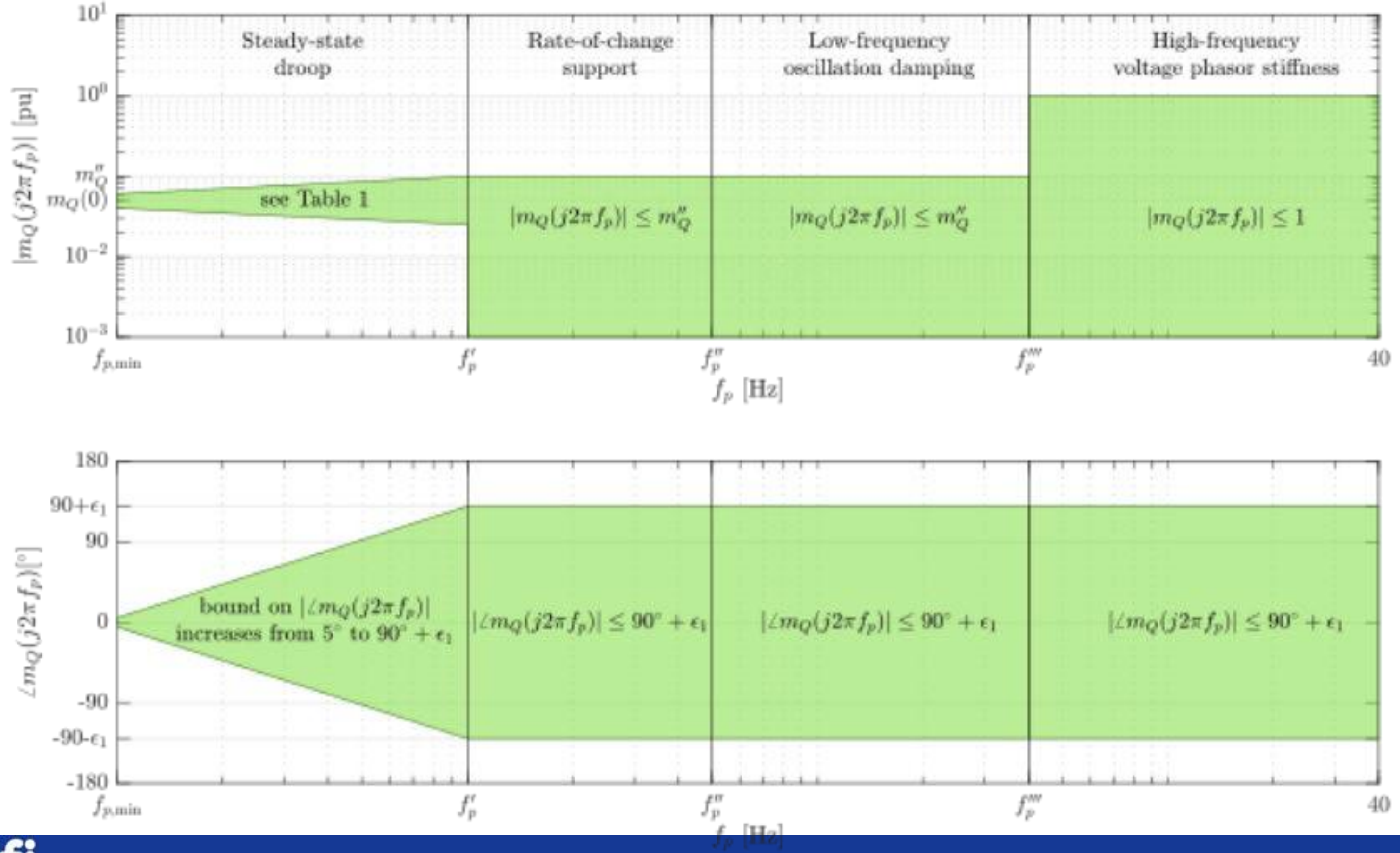
Table 6. Frequency-Domain Specifications for IBR Unit Capabilities Within the Continuous Operation Region Under Balanced Conditions—Applicable to All GFM IBRs

Input / Output	Capability and applicable frequency range		Specifications: Frequency ω/P	Specifications: Voltage V/Q	Notes
Input: P, Q **Output:** ω, V Sometimes called 'dynamic droop'	**Power synchronization** $f_p \in [f_{p,min}, f_p''']$ Starting from approximately 0.01 Hz with upper limit f_p''' that depends on IBR characteristics.		$\|\omega/P\|$ below an upper bound that is equal to m_p'' at f_p'' and decreases ten times for a ten times increase of f_p between $f_{p,min}$ and f_p''' (straight line in log-log plot) $\|\angle\omega/P\| \leq 90° + \varepsilon_1$*	All V/Q functions from Table 5	Synchronization through feedback from power to frequency without requiring steady-state droop. * tolerance to accommodate numerical/implementation aspects of control and test procedure
	High-frequency voltage phasor stiffness $f_p \in [f_p''', 40\text{ Hz}]$ Lower limit f_p''' that depends on IBR characteristics.	**"Passive"** Typical range for f_p''' is approximately 4 Hz to 10 Hz.	$\|\omega/P\|$ below an upper bound that increases[$] ten times for ten times increase of f_p (straight line in log-log plot) $\|\angle\omega/P\| \leq 90° + \varepsilon_1$*	$\|V/Q\| \leq 1$ p.u./p.u. $\|\angle V/Q\| \leq 90° + \varepsilon_1$*	* tolerance to accommodate numerical/implementation aspects of control and test procedure [$] starting from the gain at f_p'''
		"Low gain" Typical value for f_p''' is approximately 10 Hz.	$\|\omega/P\| \leq m_{low}$ no $\|\angle\omega/P\|$ phase specification	$\|V/Q\| \leq m_{low}$ no $\|\angle V/Q\|$ phase specification	

Input / Output	Capability	Active power P/θ	Reactive power Q/V	Impedance $Z = V/I$	Notes
Input: θ, V **Output:** P, Q Sometimes called 'power-domain scan' & **Input:** I **Output:** V Sometimes called 'impedance scan'	**"Voltage source behind impedance"** [7] Typical range for f_p''' consists of any values smaller than approximately 5 Hz, which provides a property like a voltage behind a reactor. One realization example recommends: $f_p''' = 4$ Hz	**Magnitude response**[†] $\|P/\theta\| > \|P/\theta\|_{min}$	**Magnitude response**[†] $\|Q/V\| > \|Q/V\|_{min}$	**Equivalent inductance** estimated using positive-sequence impedance, Z within $f_{nom} \pm f_{Z,width}$ frequency range, except for within $f_{nom} \pm f_{Z,exception}$	[†] The magnitude response of P/θ and Q/V should be almost constant over the prescribed frequency range. No index is given to check this property.
		Phase response $\|\angle P/\theta^{**} - 180°\| < \varepsilon_2$*	**Phase response** $\|\angle Q/V^{**} - 180°\| < \varepsilon_2$*	estimated inductance $L \leq L_{max}$	* permissible magnitude of phase angle error. **wrapped angle within [0, 360°]

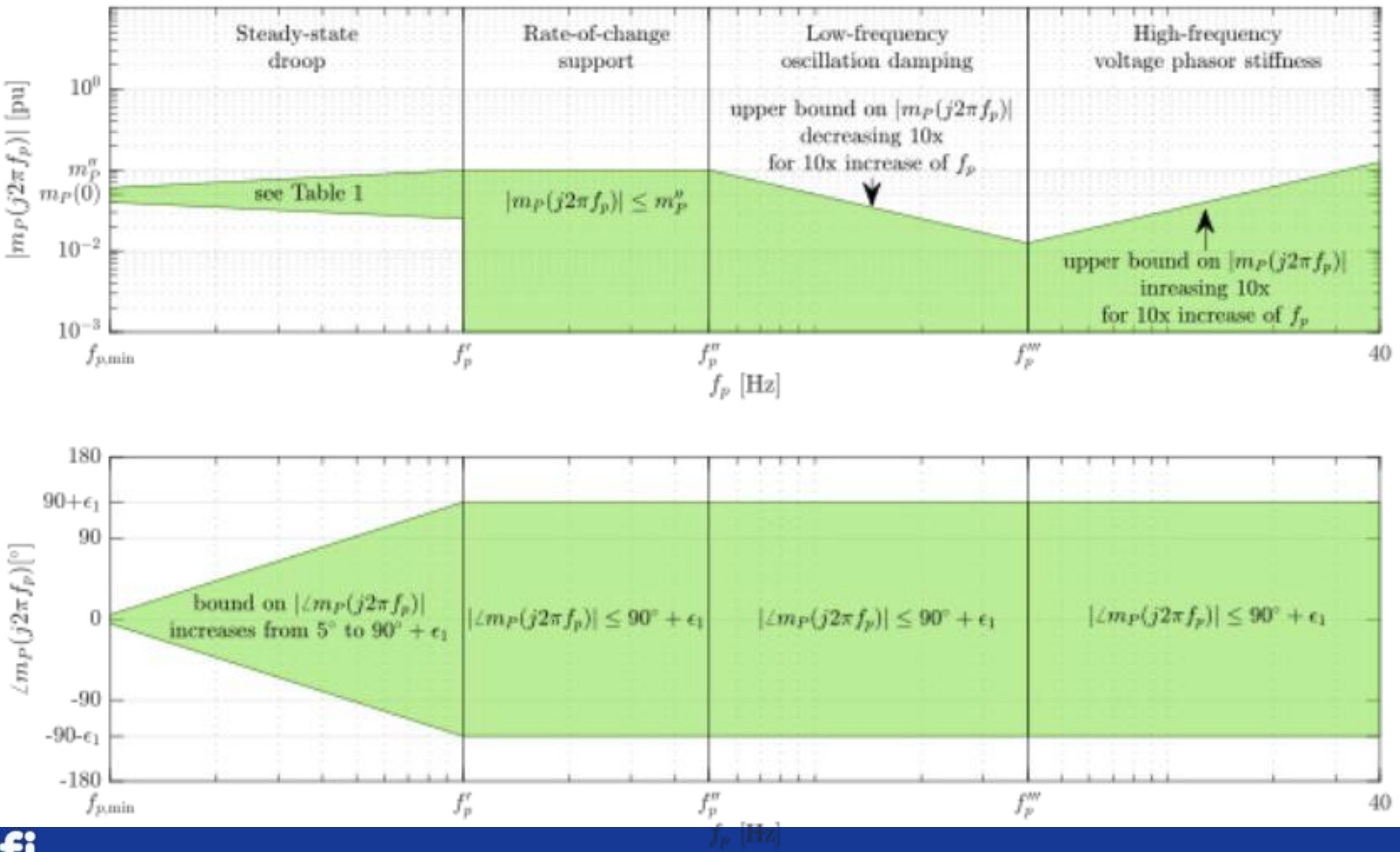
This is the frequency range where GFM differentiates itself from GFL

Visualizing frequency-domain criteria – Tier 3 (GFM BESS) – option 1



m_Q: Transfer function from Q to $|V|$

Visualizing frequency-domain criteria – Tier 3 (GFM BESS) – option 1



m_P: Transfer function from P to $\Delta\delta$

Leveraging UNIFI Specifications into an IEEE Standard for GFM

- UNIFI Specs V3 are the basis for new IEEE P2800.1
- IEEE P2800.1 focuses:
  - Transmission-connected GFM BESS (most mature)
  - Device-level specifications
- Recommended practice (less prescriptive than a standard)
- In parallel, an amendment to IEEE 2800 will remove barriers to GFM, leveraging UNIFI analysis

A potential timeline… Can we go this fast?

Q3/Q4 2025	Q4 2025/ Q1 2026	Q1/Q2 2026	Q2-Q4 2026	2027	2028
Submit PAR for P2800.1	Form WG/TF	Begin WG drafting	Revise in WG	IEEE-SA balloting	Publication of P2800.1

IEEE 2800-series Projects

Project	Type	Scope	PAR Approval Date	Date of SA Initial Ballot	Date of Submittal to RevCom	Publication Date
P2800a	Standard	Removal of barriers to GFM from 2800	December 2025	Q4 2026 (Goal)	2027 (Goal)	Q3/Q4 2027 (Goal)
P2800.1	Recommended Practice	GFM IBR equipment	December 2025	Q4 2026 (Goal)	2027 (Goal)	Q3/Q4 2027 (Goal)
P2800 R1	Standard	IBR plant interconnection requirements (Revison)	December 2025	March 2028 (Goal)	Late 2028 (Goal)	April 2029 (Goal)
2800.2-2026	Recommended Practice	Conformity assessment (testing)	May 2021	May 2025	December 2025	Spring 2026 (expected)

Mandatory
(Standard, "shall")

Optional
(Recommended Practice, "should")

Slide modified from Jens Boemer, EPRI/GPST

Global Power System Transformation Consortium

Key Questions Facing IEEE P2800.1

- Tradeoff between timeline and scope:
  - Do we include tests for non-BESS GFM (GFM STATCOMs, E-STATCOMs, HVDC, PV, wind, etc.?)
    - Also potential conflict with other IEEE groups' scopes
  - Use UNIFI Spec V3 with only minor edits? Or make significant edits?
  - Quantify requirements?
  - Adapt time-domain tests for Tier 1 and 2?
  - Are frequency-domain tests mature enough? Are pass-fail criteria appropriate?

Summary and final thoughts

- GFM IBRs enable reliable operation of high-IBR power grids
  - Adds system strength in weak grid regions
- GFM BESS inverters are widely available and add little cost
- UNIFI GFM Spec V3 has simple tests for GFM capability

- Industry is starting to understand GFM benefits
- Some grid operators are starting to require BESS be GFM
- Other regions are slower to adopt
- IEEE P2800.1 will establish standard requirements for GFM inverters and tests to demonstrate GFM capability

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Thank you

Visit the UNIFI website: unificonsortium.org

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