G-PST/ESIG Webinar Series

Understanding Grid-forming Inverter Specifications

Ben Kroposki
UNIFI Organizational Director

February 2023

universal interoperability for grid-forming inverters

U.S. DEPARTMENT OF ENERGY

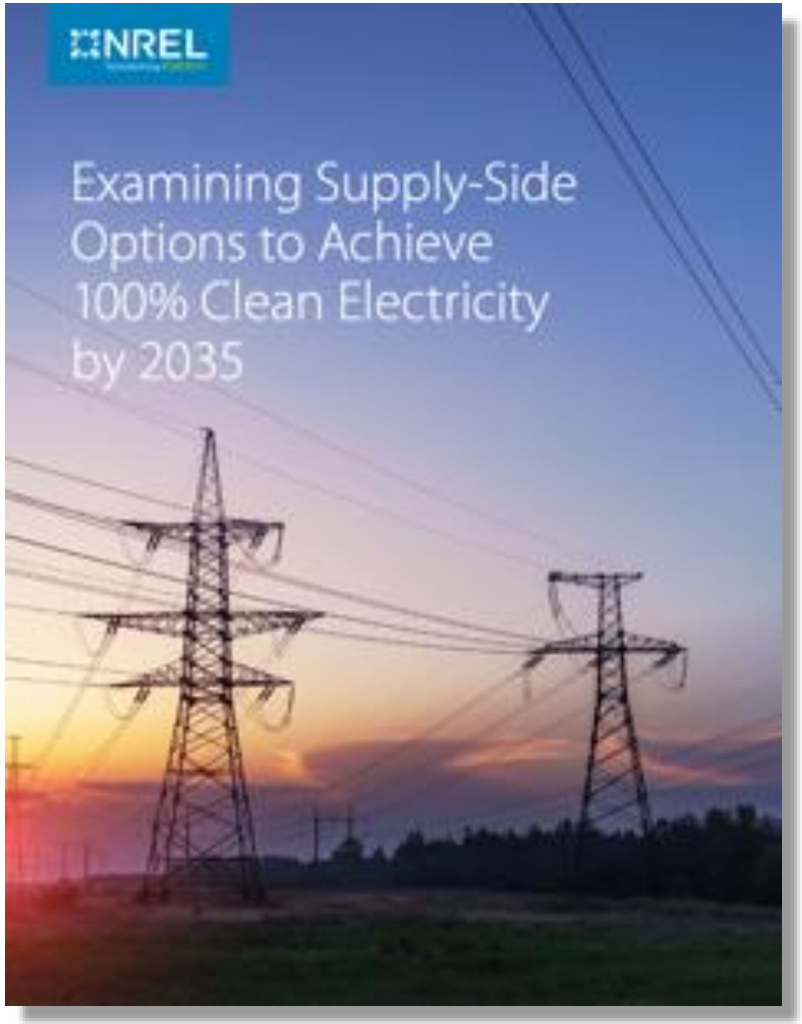
unifi consortium — universal interoperability for grid-forming inverters

The Need for Grid-forming Inverters

NREL 100% Clean Energy by 2035 Study

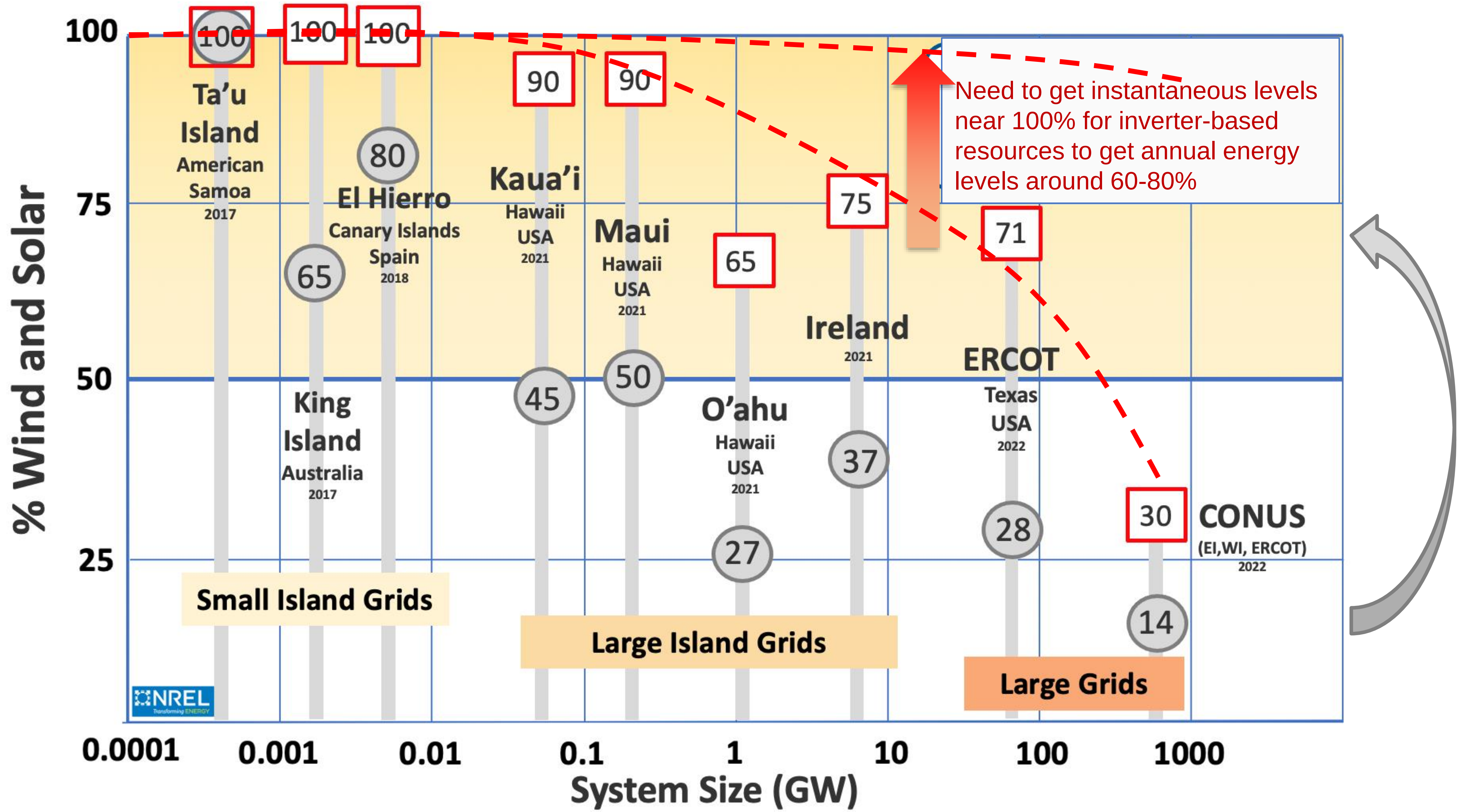
- In all modeled scenarios, new clean energy technologies are deployed at an unprecedented scale and rate to achieve 100% clean electricity by 2035.

- As modeled, **wind and solar energy provide 60%–80% of generation** in the least-cost electricity mix in 2035, and the overall generation capacity grows to roughly three times the 2020 level by 2035—including a **combined 2 terawatts of wind and solar**.



Denholm, Paul, Patrick Brown, Wesley Cole, et al. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035*. Golden, CO: National Renewable Energy Laboratory. NREL/TP- 6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf

To get closer to 100% IBR, you need grid-forming (GFM)



How to better Understand System Needs

$$\text{Instantaneous \% IBR} = \frac{\text{Total IBR Output (MVA)}}{\text{Total Generation (MVA)}} \quad \text{(at any point in time)}$$

Inertia Constant:

$$\frac{\text{Synchronous Machine Rotational Kinetic Energy (MVA·s)}}{\text{Total Online Generation Capacity (MVA, Including IBRs)}}$$

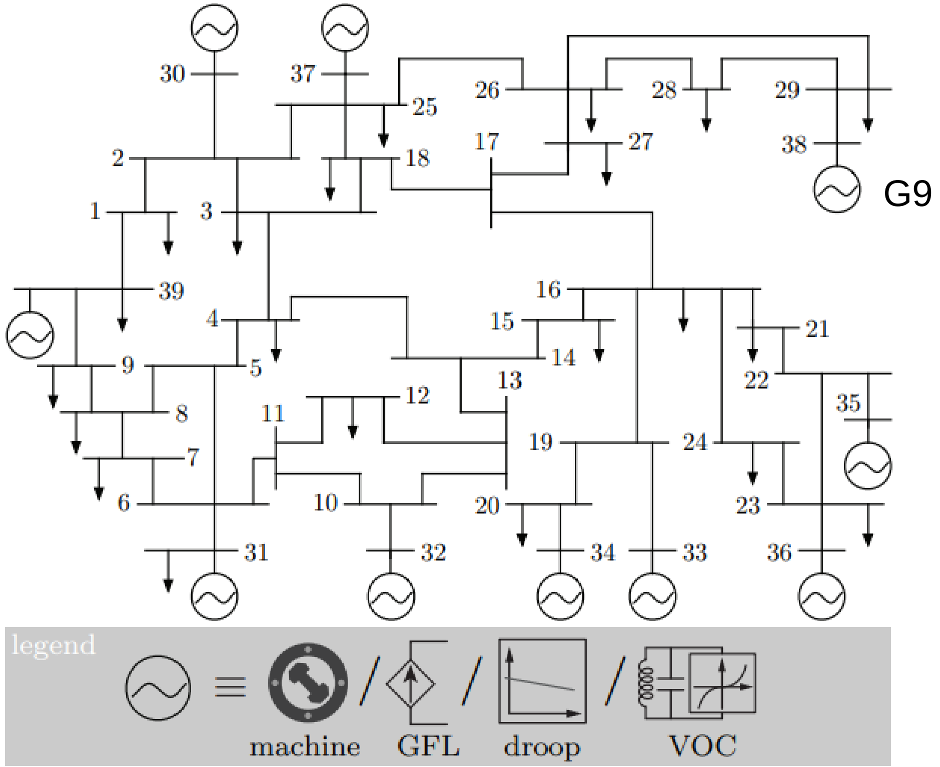
Voltage-Forming Ratio:
A metric for power system stability?

$$\frac{\text{Synchronous Machine Rotational Kinetic Energy (MVA·s)} + A_1 \cdot \text{Grid-Forming IBR Capacity of Type 1 (MVA)} + \cdots + A_k \cdot \text{Grid-Forming IBR Capacity of Type } k \text{ (MVA)}}{\text{Total Online Generation Capacity (MVA, Including IBRs)}}$$

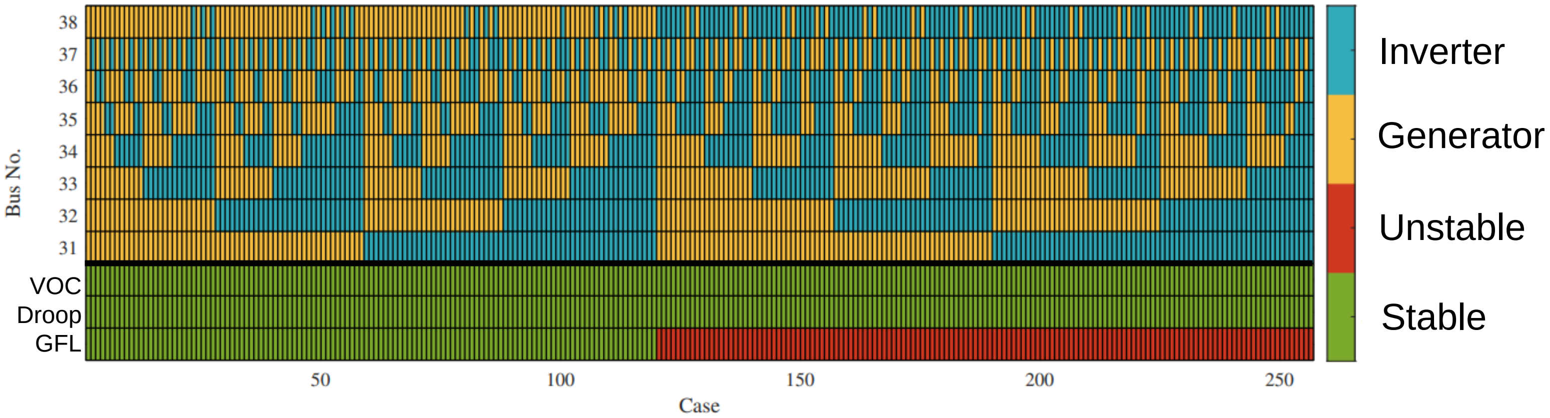
This new metric could be called the voltage-forming ratio because it would quantify the ratio of the voltage-forming capacity (synchronous generators, synchronous condensers, and grid-forming IBRs) to the total apparent power capacity (synchronous generators, synchronous condensers, and all IBRs).

Source: **Thoughts and Hypotheses on the Metrics and Needs for the Stability of Highly Inverter-Based Island Systems**, A. Hoke and G. Gevorgian, *IEEE Electrification Magazine*, September 2022

When do we need GFM and How much do we need?



IEEE 39-bus test system



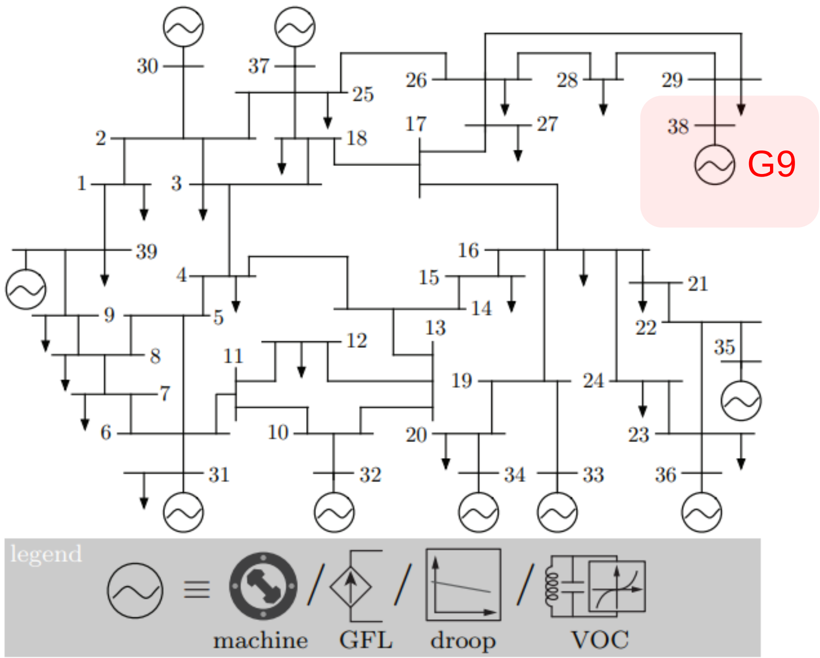
Stable and unstable configurations with an exhaustive combination of:

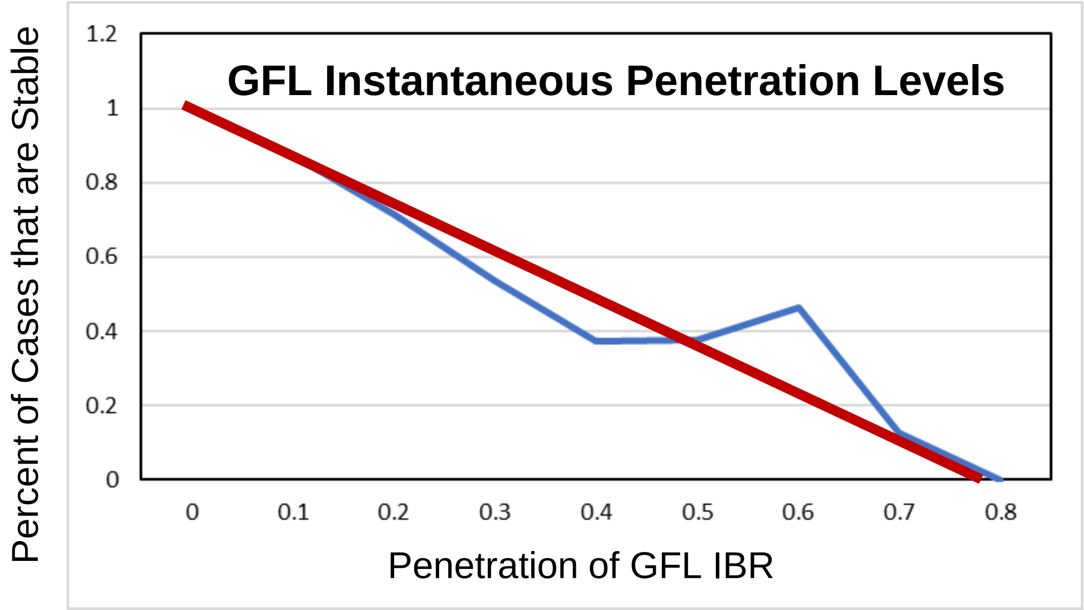
- **synchronous generators**
- **droop-controlled grid-forming inverters**
- **virtual oscillator control (VOC) grid-forming inverters**
- **grid-following inverters**

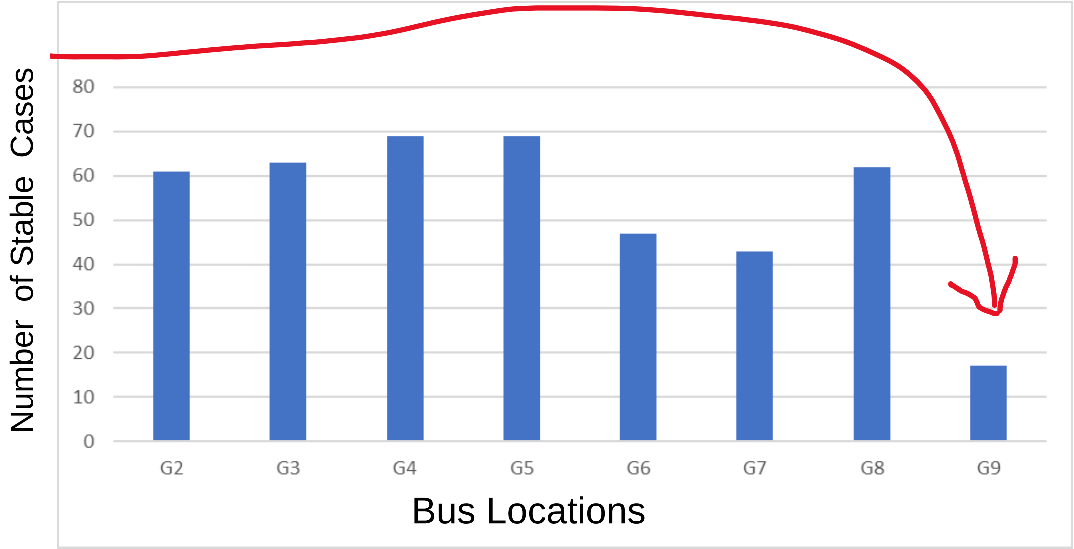
GFM controls showed no instability

Source: Lin, Seo, Vijayshankar, Johnson, Dhople, "Impact of Increased Inverter-based Resources on Power System Small-signal Stability," IEEE PESGM, 2021

When do we need GFM and How much do we need?





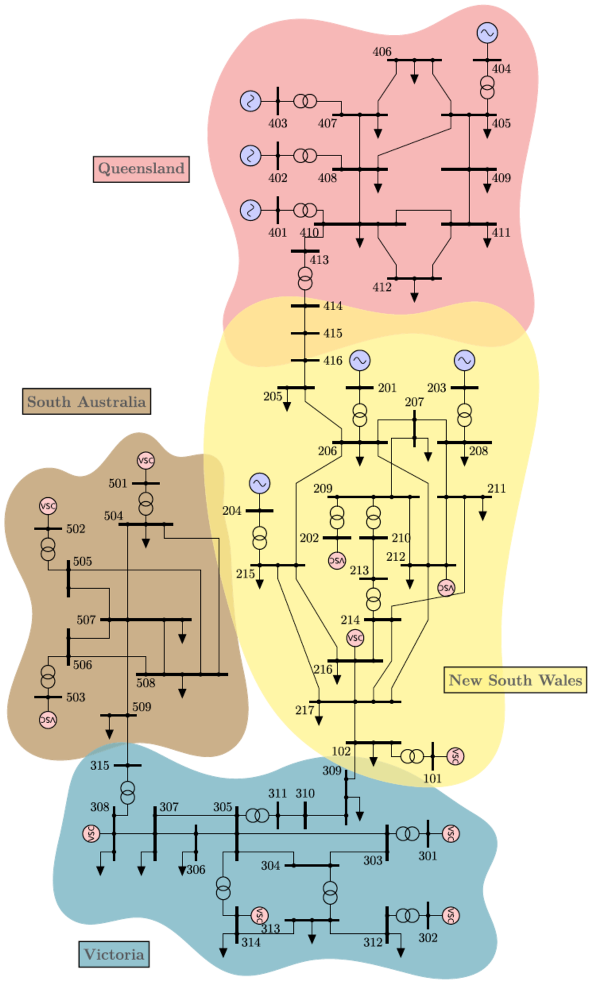


- Depends on system characteristics, types of disturbances, nominal V/f ranges
- Stability issues increase as GFL IBR penetration increases – especially above 60% instantaneous
- Systems can have corner cases at low IBR penetrations – especially in weak parts of the system
- GFM can play an important role in maintain grid stability

Source: Lin, Seo, Vijayshankar, Johnson, Dhople, "[Impact of Increased Inverter-based Resources on Power System Small-signal Stability](),” IEEE PESGM, 2021

When do we need GFM and How much do we need?

Similar Results on the Australian NEM System



- Stability issues increase as GFL IBR penetration increases – especially above 60% - 70% instantaneous levels
- GFM can increase stability levels dramatically
- Location of GFM in systems is a significant contributor to system stability – GFM need to be placed at weak points in grid

Source: U. Markovic, et al., "Understanding Small-Signal Stability of Low-Inertia Systems," IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 36, NO. 5, SEPTEMBER 2021

Technical Challenges with Higher Inverter-based Resources

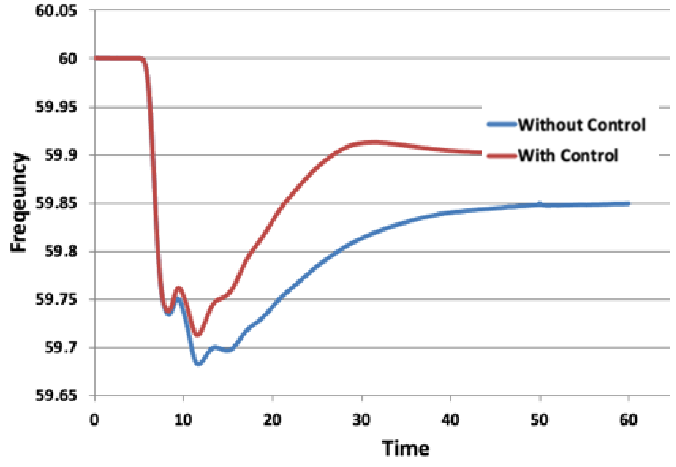
Challenges:

- Frequency Stability (Lower System Inertia)
- Voltage Stability and Regulation
- System Protection
- Grid Forming capability
- Black Start capability
- Control system interactions and resonances
- Cybersecurity

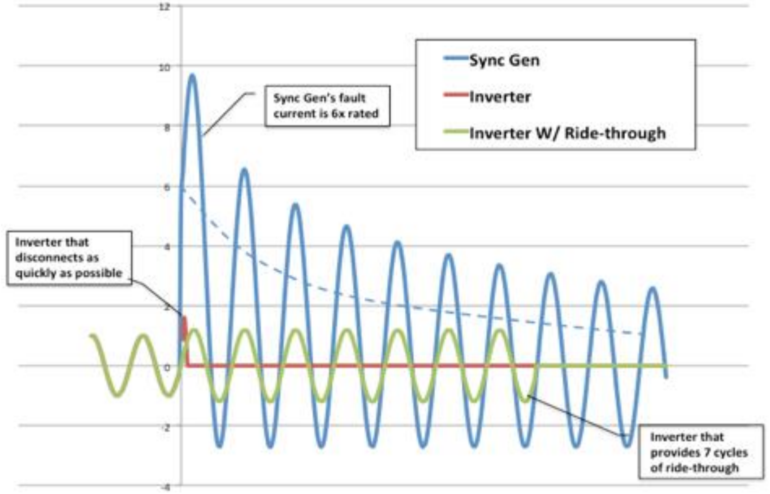
Source: B. Kroposki et al., "Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," http://ieeexplore.ieee.org/document/7866938/

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

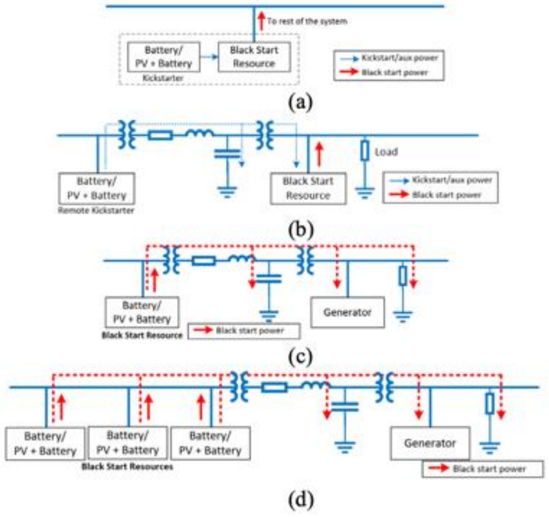
Stability



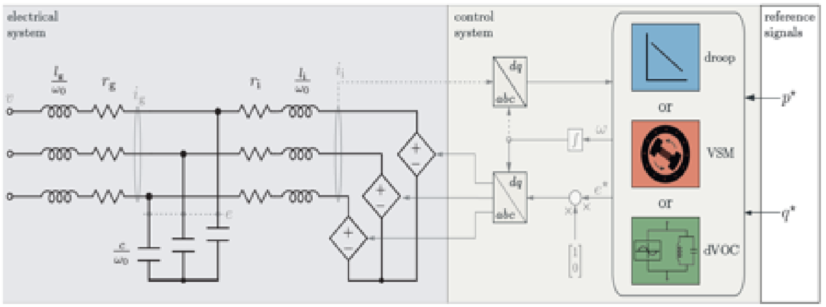
Protection



Grid-forming/Blackstart



Control system interactions and resonances



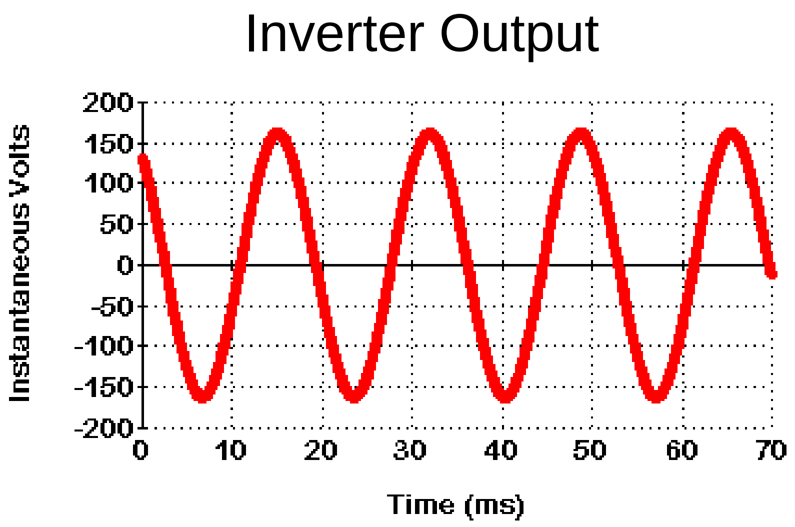
Power System Oscillations

GFL vs. GFM

Grid Following (GFL)

vs.

Grid Forming (GFM)



- GFL IBR controls output **Current**
- Is dependent on another source to synchronize to

- GFM IBR controls output **Voltage**
- Can make its own voltage waveform

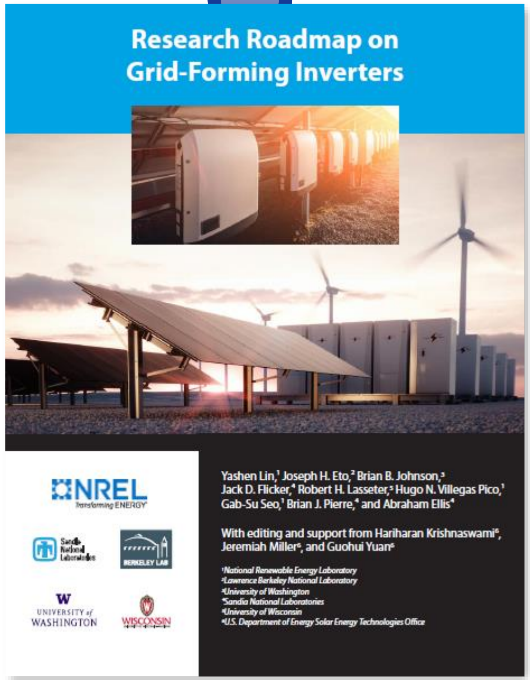
Source: Lin, Yashen, Joseph H. Eto, Brian B. Johnson, Jack D. Flicker, Robert H. Lasseter, Hugo N. Villegas Pico, Gab-Su Seo, Brian J. Pierre, and Abraham Ellis. 2020. **Research Roadmap on Grid-Forming Inverters**. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-73476. https://www.nrel.gov/docs/fy21osti/73476.pdf.

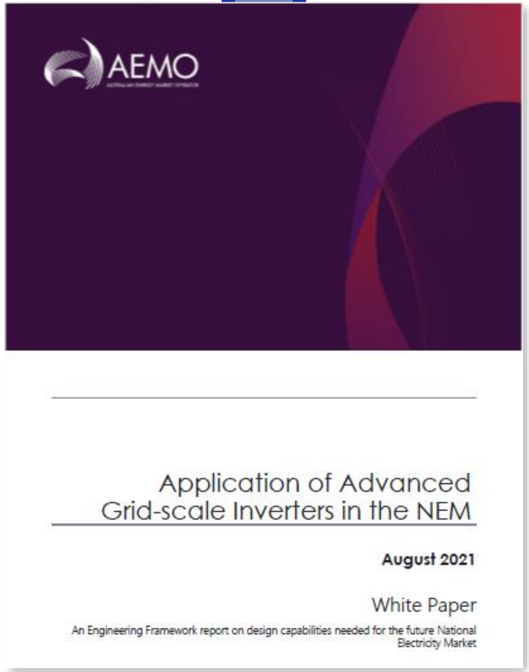
Benefits to Using Grid-forming (GFM) IBR

- Can maintain system voltage
- Very fast response to disturbances
- Blackstart capability
- Enable higher levels of wind and solar to be integrated in grids
- Improved system reliability and resilience
- Added economic value from providing essential grid reliability services

Global Landscape

Grid codes and roadmaps around the world recognize the role for (and of) grid-forming (GFM) inverter-based resources (IBRs)





Challenges

- Poor definitions of capability and functionality across technologies; lack of standardization
- Limited-to-no consensus on expected performance from unit and system levels
- Vendors/Manufacturers and Utilities/Operators appear to be locked in circular death spirals

Solution (@ a snapshot)

- Interoperability drove interconnections in the past
- Interoperability will drive innovation into the future

unifi

consortium

universal interoperability
for grid-forming inverters

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

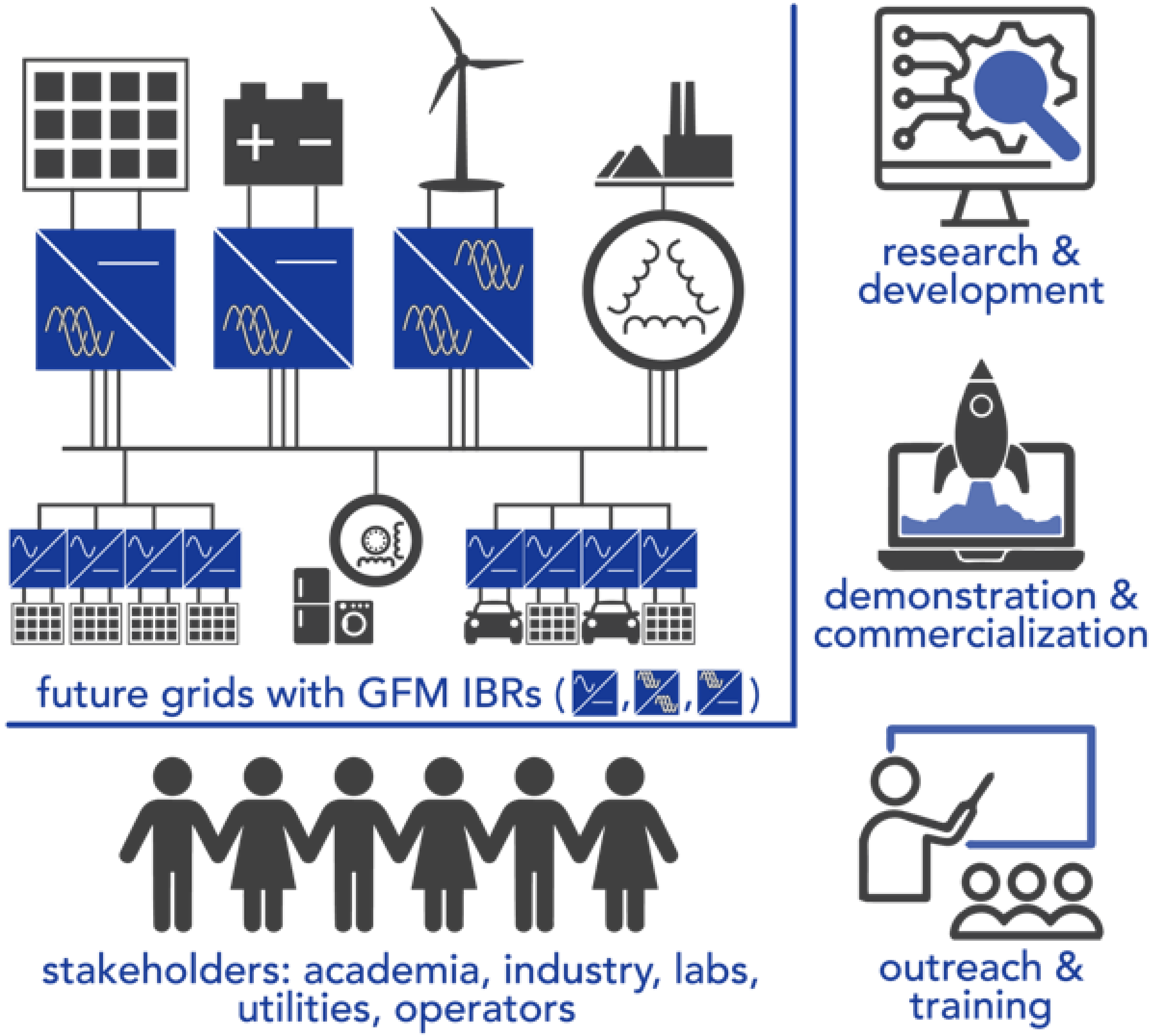
Three major focuses:

- Research & Development
- Demonstration & Commercialization
- Outreach & Training

Started in January 2022 with DOE Funding

UNIFI has:

- 22 Industry Participants (Manufacturers, utilities, system operators, system integrators,)
- 5 Research Labs
- 12 Universities



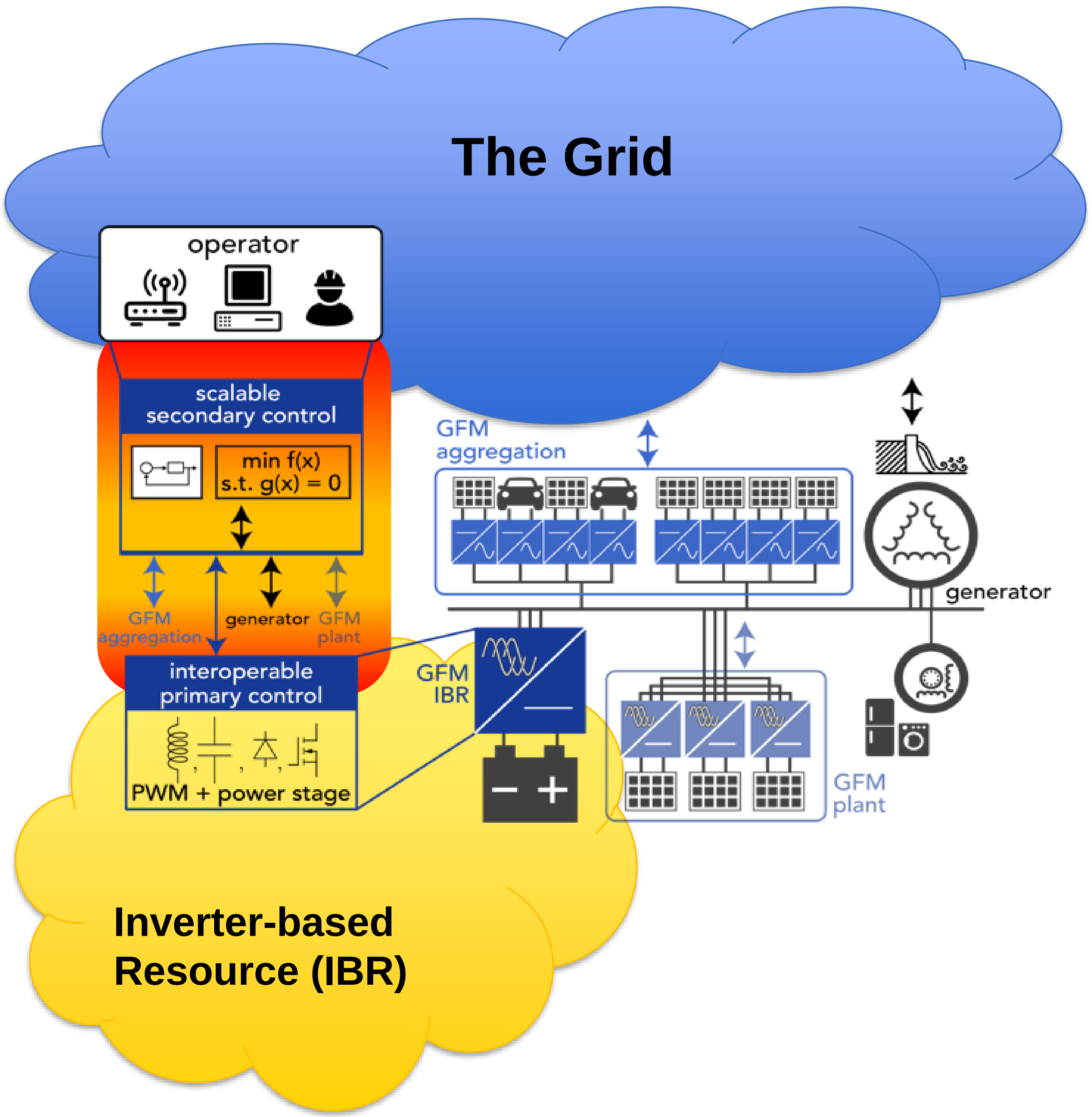
UNIFI Goals

Curate vendor- and technology-agnostic ***"UNIFI Specifications for GFM"*** that standardize performance and benchmark capabilities of GFM technologies across scales

- ***System Level - Guidelines*** *- that promote the coordinated and seamless operation of GFM technologies from multiple vendors while ensuring stable and reliable power grids*
- ***Inverter Level - Requirements*** *– that define GFM-IBR capabilities which are specified in a vendor-agnostic fashion to satisfy all system-level interoperability guidelines*

Convene continuous collaboration between inverter manufacturers (on one end) and system operators and utilities (on the other) to bridge gaps between power-systems and power-electronics industries

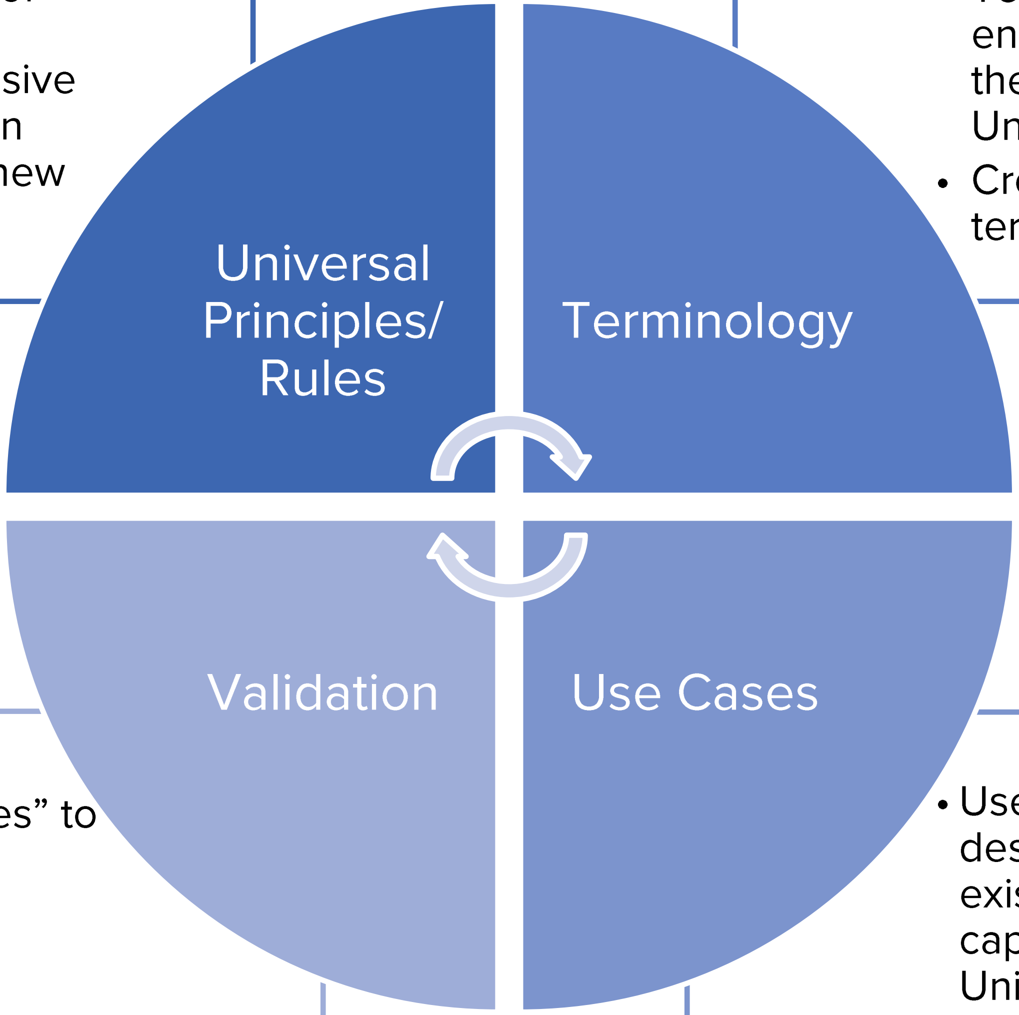
Cultivate inclusive culture and leverage member cooperation for sustained innovation



UNIFI Universal Principles/Rules Importance & Challenges

- Forward-looking description of the desired functionality of a future grid (needs to be inclusive of existing principles unless in direct conflict with what the new principles require)

- Terminology and definitions to ensure everyone understands the terms used in the Universal Principles
- Create a bridge to existing terminology and definitions



- Convert “Universal Principles/Rules” to metrics that are measurable from outside the inverter to verify if an inverter is compliant to the UNIFI principles/rules

- Use cases demonstrate desired functionality, including existing capabilities and new capabilities, resulting from the Universal Principles

Universal Objectives for Grid-Connected Inverters

First – Agree on what we think we need GFM to do.

1. Supports Seamless Transition between Grid-connected and Islanded/Microgrid Mode
2. Uses System Frequency as a Universal Power Sharing Parameter
3. Dynamic Exchange of Energy to realize appropriate "Inertia" & “Damping”
4. Passivity, damping, and interactions with other devices, even after severe transient/faults
5. Maintain System Balancing, Stability & Strength necessary for proper grid operation
6. Supports Ability to Connect/Disconnect on Command
7. Provide System Support & IBR Trip if necessary
8. Cyber-secure Communications & Real-time Must-run Grid: Black Starting Capabilities
9. Dispatch-mode & Droop on Average Frequency/Voltage
10. Support Grid Interconnection Codes and Fault Current Injection
11. Provides Good Power Quality

Next step, convert these objectives to specifications

UNIFI Specifications for GFM Technologies

Quick Link to UNIFI Specs

- The UNIFI Specifications for Grid-forming Technologies establish functional requirements and performance criteria for integrating GFM IBRs in electric power systems at any scale.
- Provide uniform technical requirements for the interconnection, integration, and interoperability of GFM IBR units and plants

Contents

Mapping of Universal Objectives to Specifications

Universal Objectives	UNIFI Specification Section
Seamless Transition between Grid-connected and Islanded/Microgrid Mode	Section 2.2.5
Universal Power Sharing Parameter	Section 2.1.4
Dynamic Exchange of Energy with the System to realize appropriate "Inertia" & “Damping”:	Section 2.1.3 and Section 2.2.4
Passivity, damping, and interactions with other devices, even after severe transient/faults	Section 2.1.3
System Balancing, Stability & Strength	Section 2.1.5
Ability to Connect/Disconnect on Command	Section 2.2.5, Section 3.3
System Support & IBR Trip	Section 2.1.1
Cyber-secure Communications & Real-time Must-run Grid	Section 3.3
Black Starting Capabilities	Section 3.1
Dispatch-mode & Droop on Average Frequency/Voltage	Section 2.1.2 and Section 2.1.4
Support Grid Interconnection Codes and Fault Current Injection	Section 2.2.1 and Section 2.2.2
Power Quality	Section 3.2

1.2 Scope

The UNIFI Specifications for GFM IBRs establish functional requirements and performance criteria for integrating GFM IBRs in electric power systems at any scale. This may include devices used at the local customer, microgrid, distribution, and transmission scale. These specifications cover all grid-forming technologies applications including, but not limited to: battery storage, solar Photovoltaics (PV), wind turbines, high voltage direct current (HVDC), static synchronous compensator (STATCOM), uninterruptible power supply (UPS), supercapacitors, fuel cells, or other yet to be invented technologies. While each may have different dc side and energy limitations, this specification focuses on the AC side performance requirements as they relate to interoperability between GFM IBRs and the power system.

1.3 Purpose

The purpose of the UNIFI Specifications for Grid-forming Inverter-based Resources is to provide uniform technical requirements for the interconnection, integration, and interoperability of GFM IBRs of any size in electric power systems of any scale.

UNIFI Specifications for GFM IBR – Version 1

Operations under Normal Grid Conditions

UNIFI Specifications for GFM IBR – Version 1

Operations under Normal Conditions

2.1.1 Autonomously Support the Grid

Both GFL and GFM IBRs are expected to autonomously respond to changes (both transient and steady state) in their locally measured signals (e.g., terminals of IBR or point of interconnection (POI) voltage, current, and frequency) to support the local power system.

2.1.12 Dispatchability of Power Output

When operating as part of an interconnected grid, a GFM IBR plant's steady state power output, within the normal range of voltage magnitude and frequency, should be dispatchable either through a grid operator command or by a locally determined goal, based upon a market clearing solution, like a GFL IBR.

UNIFI Specifications for GFM IBR – Version 1

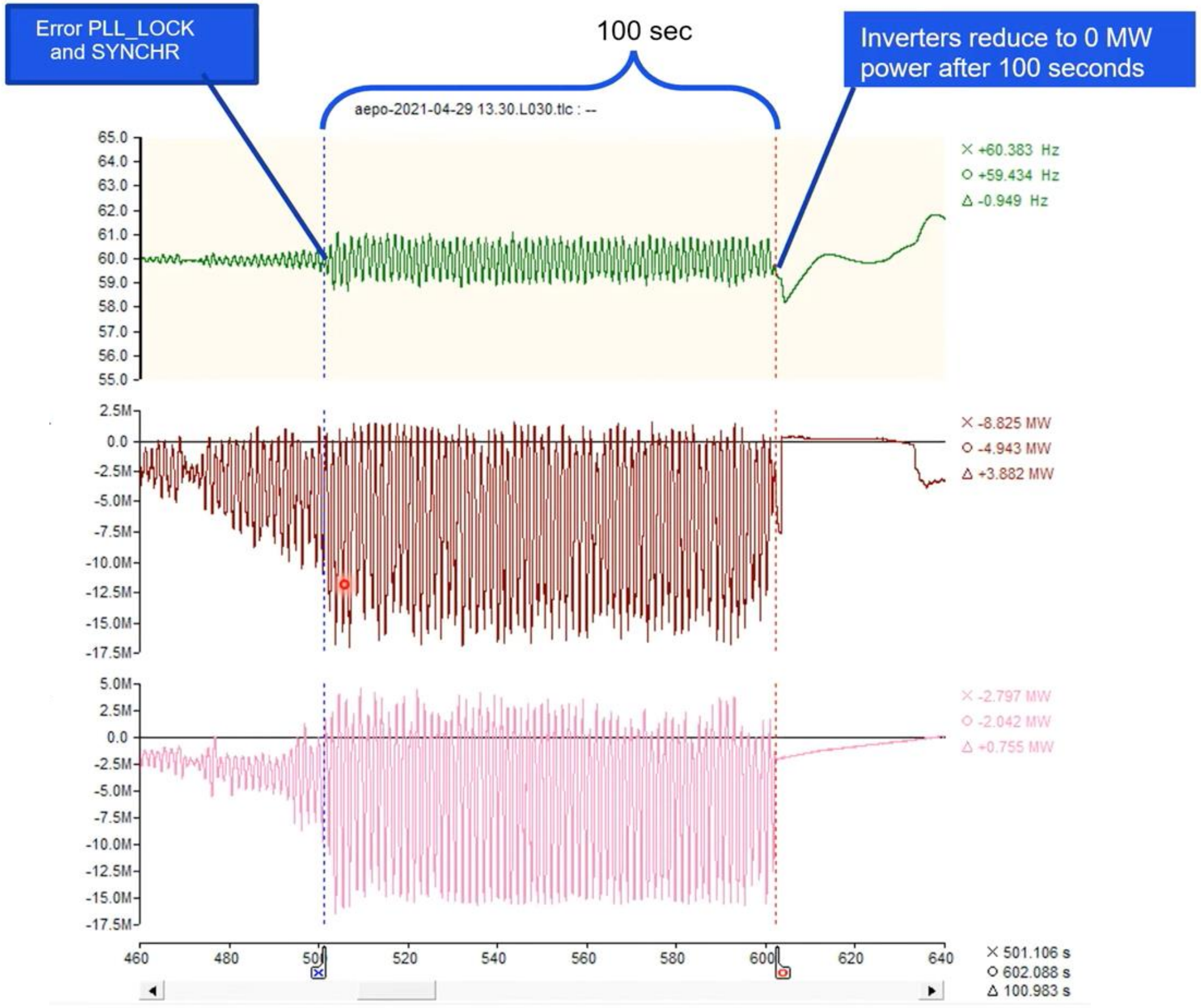
Operations under Normal Conditions

2.1.3 Provide Positive Damping of Voltage and Frequency Oscillations

It is expected that a GFM IBR will present a non-negative resistance or damping to the grid within a frequency range of common grid electrical resonances to prevent the initiation of any adverse interactions or oscillations.

2.1.4 Active and Reactive Power Sharing across Generation Resources

A GFM IBR is expected to share (e.g. incrementally increase power burden) with other generation resources using the principles of droop akin to the operation of conventional synchronous generators or GFL IBRs.



Source: Lessons Learned from Inverter-Based Grid Forming Operations, C. Krause KIUC and A. Dcosta AES Clean Energy – UNIFI Seminar Fall 2022

Operations under Normal Conditions

2.1.5 Robust Operation in Grids with Low System Strength

A GFM IBR is expected to operate stably when connected to a power system with low system strength and to improve the strength of the network in the region of connection during normal operations via a reduction in the sensitivity of voltage to current injection and a reduction in the rate of change of frequency during an event.

2.1.6 Voltage Balancing

A GFM IBR should not actively oppose or prevent the flow of negative sequence current for small levels of voltage unbalance.

Characteristics of low system strength
A power system with low system strength will exhibit one or more of the following:

- Wider area undamped voltage and power oscillations. Generator fault ride-through degradation.
- Mal-operation or failure of protection equipment to operate.
- Prolonged voltage recovery after a disturbance.
- Larger voltage step changes after switching capacitor or reactor banks.
- Instability of generator / dynamic plant voltage control systems.
- Increased harmonic distortion (a by-product of low system strength and higher system impedances).
- Deeper voltage dips and higher over-voltages (e.g. transients).

"System Strength" – AEMO March 2020

Operations Outside Normal Grid Conditions

UNIFI Specifications for GFM IBR – Version 1

Operation Outside Normal Conditions

2.2.1 Ride-through Behavior

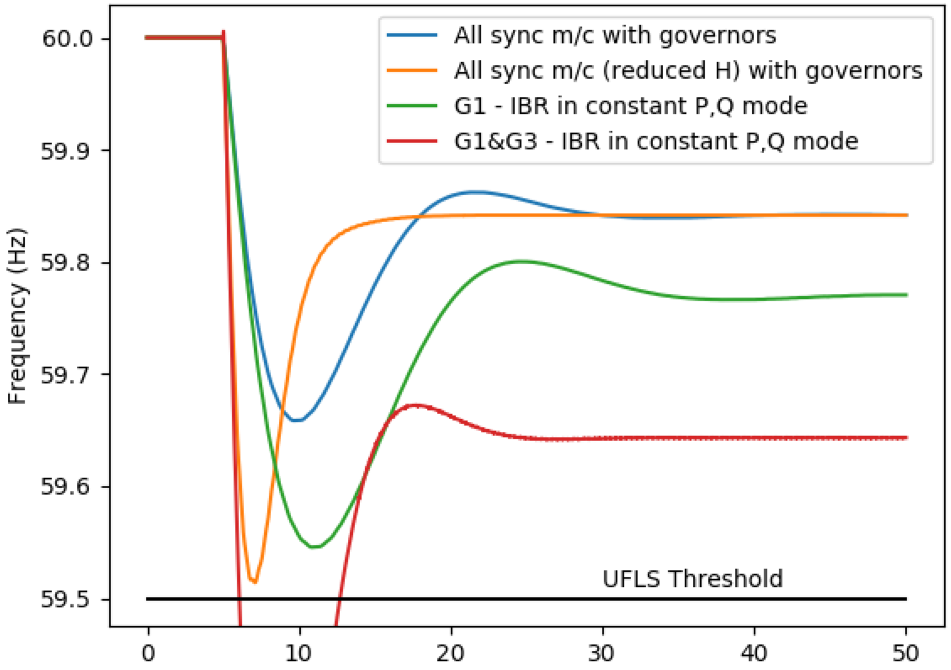
A GFM IBR is expected to inject current during and after a voltage sag to aid in voltage recovery.

2.2.2 Response to Asymmetrical Faults

During asymmetrical faults, a GFM IBR is expected to maintain a balanced internal voltage to the extent possible within its physical limits.

2.2.3 Response to Abnormal Frequency

A GFM IBR is expected to modulate active power as required during and after a frequency excursion event to aid in frequency recovery and stability.



EPRI Grid Forming Inverter Tutorial
https://www.epri.com/research/products/000000003002025483

UNIFI Specifications for GFM IBR – Version 1

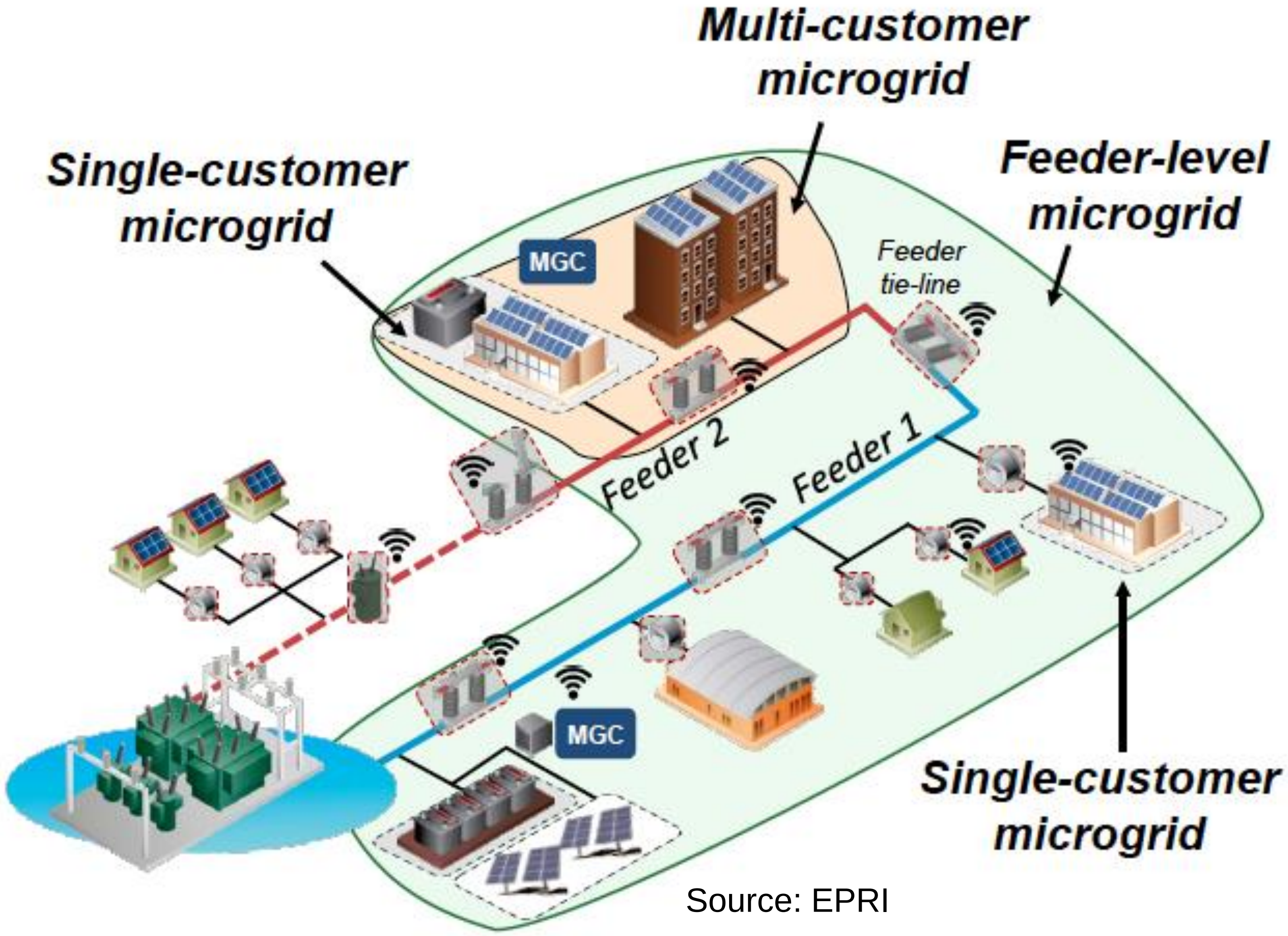
Operation Outside Normal Conditions

2.2.4 Response to Phase Jumps and Voltage Steps

A GFM IBR is expected to absorb or inject active and/or reactive power to resist changes in positive sequence voltage phase angle and is expected to do so without exceeding equipment limits.

2.2.5 Intentional Islanding

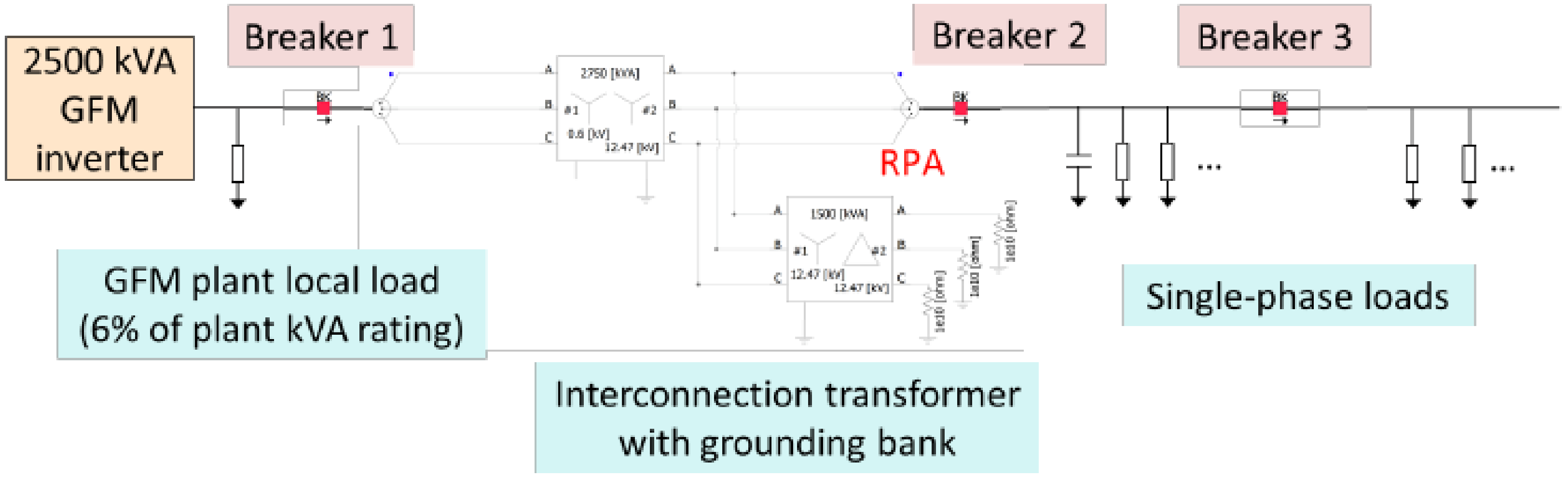
A GFM IBR (designed to maintain an intentional island) is expected to be capable of continuing to support the evolution of a stable voltage and frequency of the island/microgrid.



Source: EPRI

UNIFI Specifications for GFM IBR – Version 1

Blackstart – a GFM+ Service



Black start sequence:

- t=0 GFM inverter black start
- t=1s close breaker 1
- t=2s close breaker 2&3

- Utilizing the GFM plant to black start the microgrid is investigated with different percentage of motor load and different short-term overcurrent capability of the GFM inverter
- Transformer saturation is modeled for all the transformers in the system (interconnection transformer, grounding bank, and load service transformers)

EPRI Grid Forming Inverter Tutorial
https://www.epri.com/research/products/000000003002025483

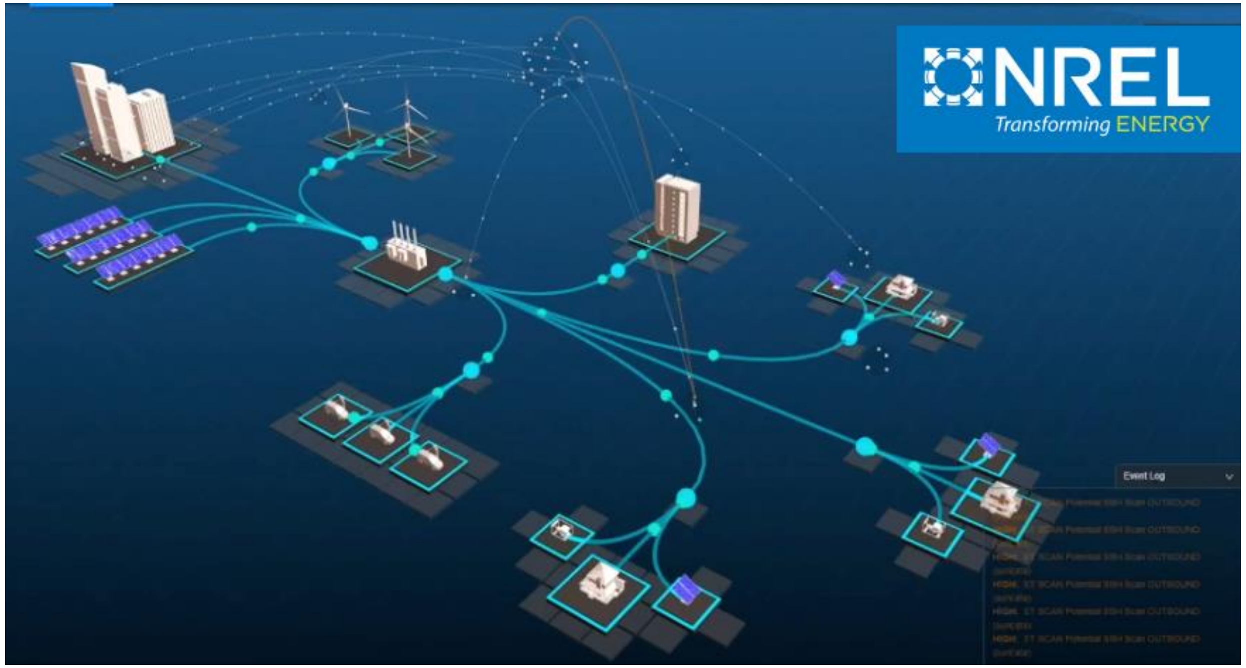
UNIFI Specifications for GFM IBR – Version 1

Communications and Secondary Response

- When communications are required between the GFM IBR units or plant and the system operator, a cyber-secure communications method should be used.

- The power system and the GFM IBR should continue to operate when communications are delayed or interrupted.

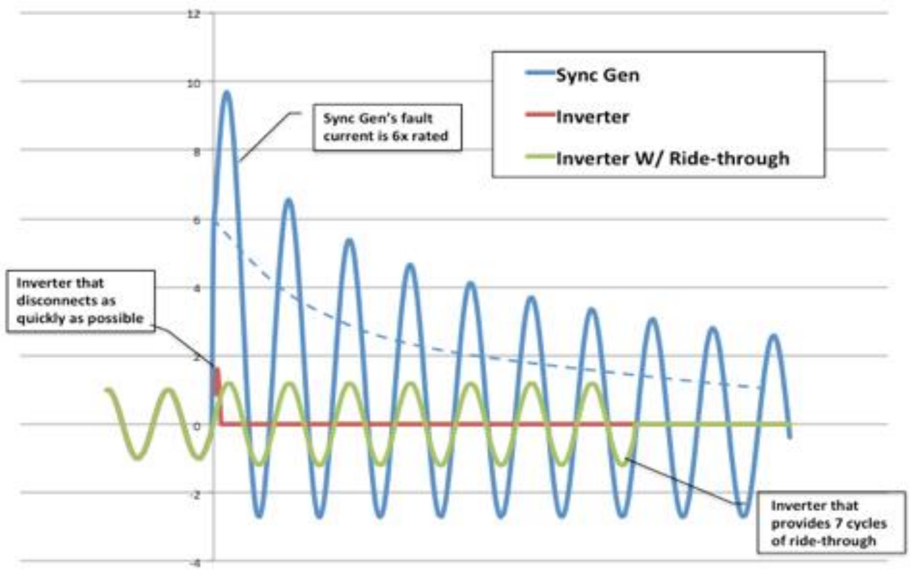
- It is expected that signals from the power system operator or an aggregator would have an update rate on the order of seconds and represent a **secondary control signal** (primary control being autonomous controls inside the IBR unit) for providing power flow set points or other commands.



UNIFI Specifications for GFM IBR – Version 1

IBR Short-term Rated Current

- The IBR short-term rated current (ISRC) is the output of current in excess of the continuous rated current for a time-limited period, but without exceeding the IBR's absolute maximum current capability, so that the IBR remains able to regulate voltage and frequency.
- The GFM IBR data sheet should provide a magnitude and duration for ISRC that enables the GFM inverter to support protection operations or events like transformer inrush and motor starting. This capability might also impact the response of unbalanced faults wherein the current on one phase exceeds that of the others.
- An example IRSC specification would be "1.5 times full-rated current for 2 seconds".
- If the ISRC capability is not provided by the GFM IBR and it is used to support transformer inrush and motor starting, then the inverter should be sized properly such that its continuous current capability is sufficient in supplying the inrush current.



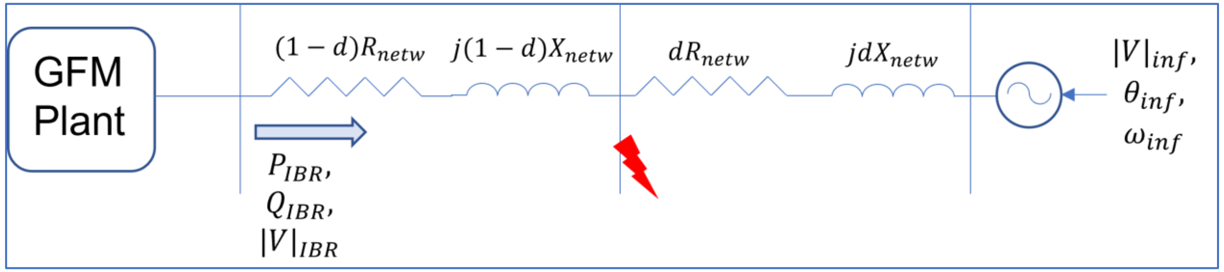
UNIFI Specifications for GFM IBR – Version 1

Constraints due to Input Source

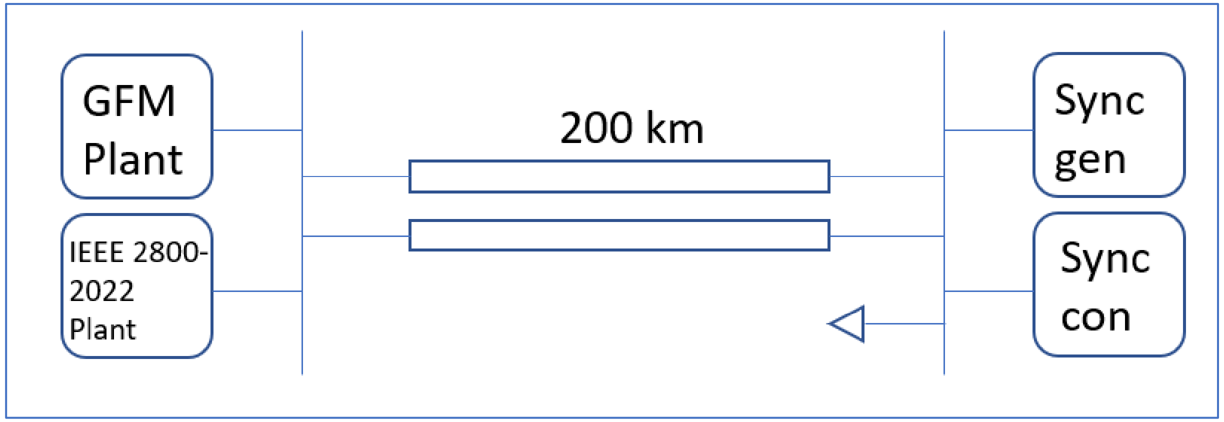
The speed of response may be constrained by the basic limitations of the DC source behind the GFM inverter.

Developing Models for GFM to Verify Specifications

UNIFI Modeling and Simulation Area Working Group is evaluating how simulation can verify various specifications



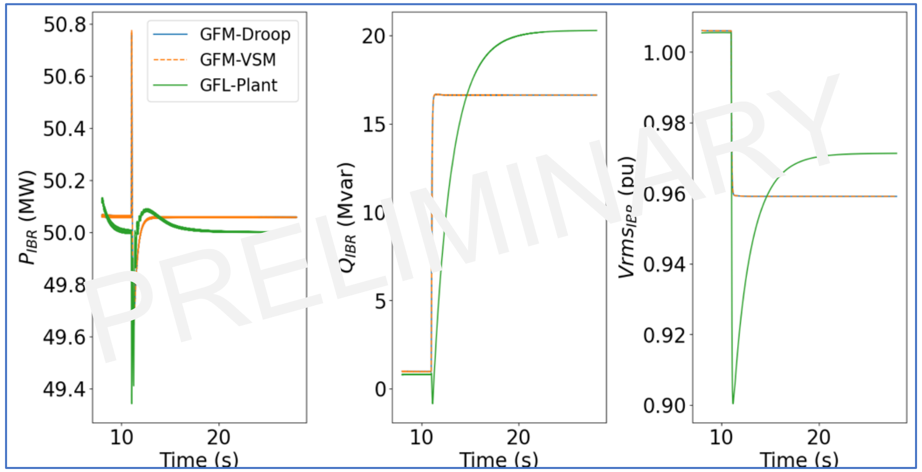
Test network A



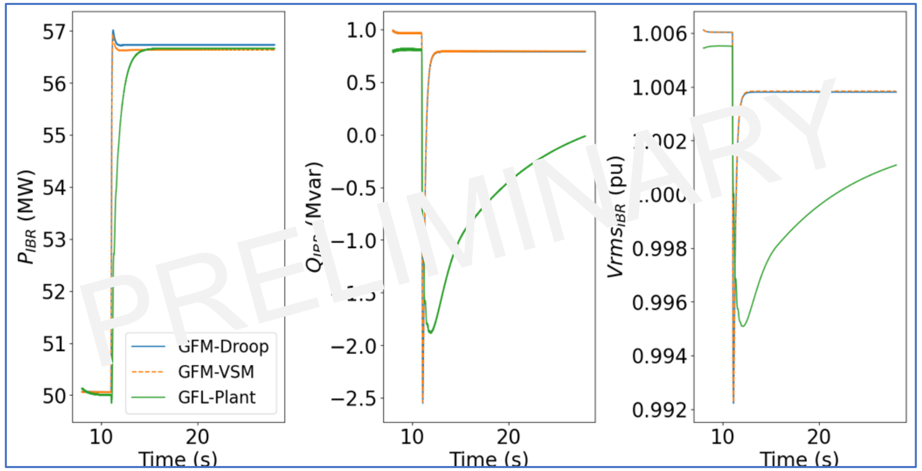
Test network B

Test	Test network	Specifications sections that can be verified
$\lvert V_{inf} \rvert$ step change	A	2.1.1, 2.1.4, 2.1.5, 2.2.4
ω_{inf} step change	A	2.1.1, 2.1.4
θ_{inf} step change	A	2.2.4
Double line to ground fault	A or B	2.2.1, 2.2.2, 3.5
Trip of synchronous sources	B	2.1.1, 2.1.4, 2.1.5, 2.2.5

Preliminary time domain results from UNIFI Modeling and Simulation Area Working Group



Step change in Voltage



Step change in Frequency

Preliminary results showcase the speed and robustness of GFM response when compared to GFL devices.

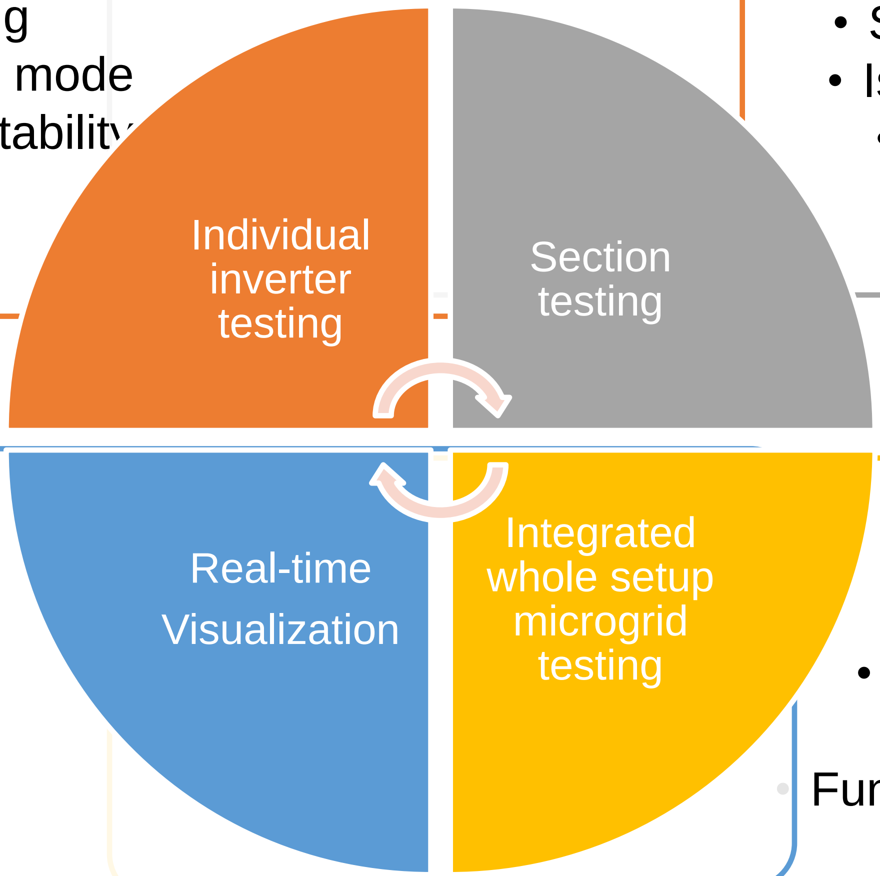
They also provide an expectation that it is possible to meet UNIFI Specifications

UNIFI 1MW Multi-Vendor Experiment – Integration & Validation Working Group

Will help evaluate UNIFI Specifications

- Black-box testing
- Programmable inverter testing
- Grid-connected and islanded mode
- Evaluate individual inverter stability performance

- Mix of GFM, GFL and SG
- Single-phase residential homes
- Islanding and resynchronization
- Preliminary interactions study
- Evaluate nano-grid system



- RMS values (V, I, P, Q, f)
- Sinusoidal waveforms
- Coordination signals
- Operation modes and settings

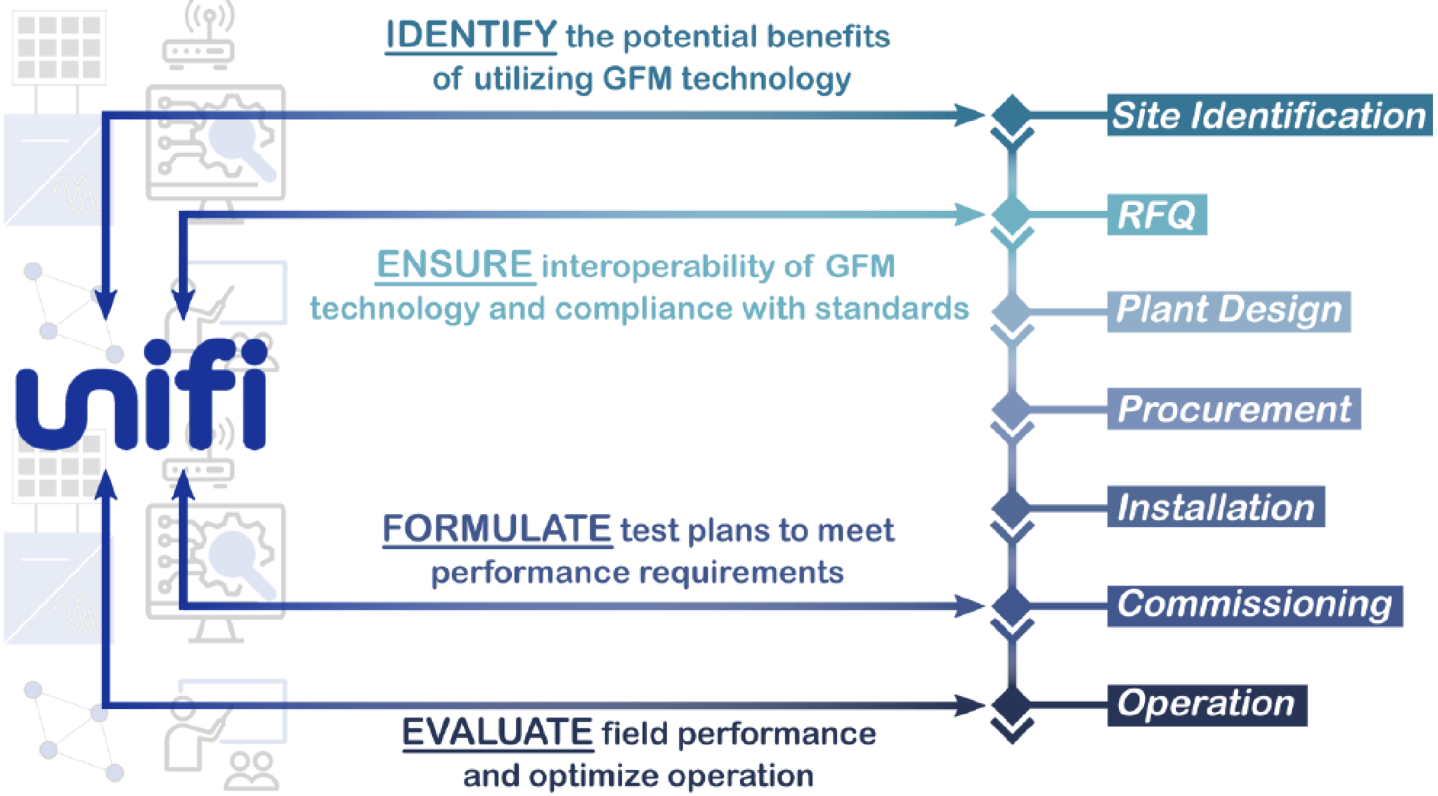
- Multi-vendor GFM inverters
- Various GFM penetration level
- Emulate a realistic microgrid
- Functionalities and interoperability

Grid-forming Inverter Capability Demonstration

are you planning a 20+ MW plant with inverter-based resources and considering grid-forming technology?
…we have you covered from site identification to operation…

why grid forming?

- **Dispatchable active/reactive power**
  in response to system-operator needs
- **Frequency and voltage droop**
  to comply with grid codes
- **Power sharing in proportion to capacity**
  with no external communication
- **Black-start functionality**
  to maximize system resilience
- **Improved stability**
  even in low system-strength conditions



Summary

- Wind, Solar PV, and Batteries have favorable economics and are being deployed at a high rate
- Wind, Solar PV, Batteries are all inverter-based resources
- IBRs will soon be a dominant part of the power grid during many hours of the day
- IBR and synchronous generator operation needs to be unified to ensure stable and reliable operation of the grid
- GFM IBR are needed to provide grid support and stable operations above 60-70% instantaneous levels
- GFM specifications, models, testing procedures, and integration processes are needed
- UNIFI Consortium is actively working on these items (and more!)

Google: **UNIFI Consortium** or go to https://sites.google.com/view/unifi-consortium

Thank you

Special Thanks to the UNIFI Consortium Area Leads:

- Wei Du, PNNL
- Deepak Ramasubramanian, EPRI
- Duncan Callaway, Univ. of California – Berkeley
- Dominic Gross, Univ. of Wisconsin – Madison
- Yashen Lin, NREL
- Brian Johnson, Univ. of Texas - Austin
- Iqbal Husain, NC State
- Jack Flicker, Sandia
- Alejandro Dominguez-Garcia, Univ of Illinois - UC
- Deepak Divan, Georgia Tech
- Vijay Vittal, Arizona State Univ.
- Sairaj Dhople, Univ. of Minnesota
- Aidan Tuohy, EPRI