# Grid-Forming Technologies in North America and Beyond

## Current Status and Future Outlook

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# Real-World Examples of GFM Inverter and Its Applications

# Example commercial 3ph energy storage GFM inverters

## — as advertised/marketed by vender to date



### SMA Sunny Central Storage

- Frequency Control
- Stability services (inertia, system strength, short-circuit level)
- System restoration




### Tesla Megapack

- Virtual synchronous machine control
- Provides grid strength and inertia
- Black-start capable




### EPC Power Drawer PD250/500, CAB1000, M system

- Fast frequency response
- Synthetic inertia
- Black-start capable




### Hitachi Power Conversion System

- Virtual synchronous machine control approach (provides synthetic inertia)
- Black-start capable




### Dynapower CPS-1250/2500

- Supports islanded operation
- Black-start capable



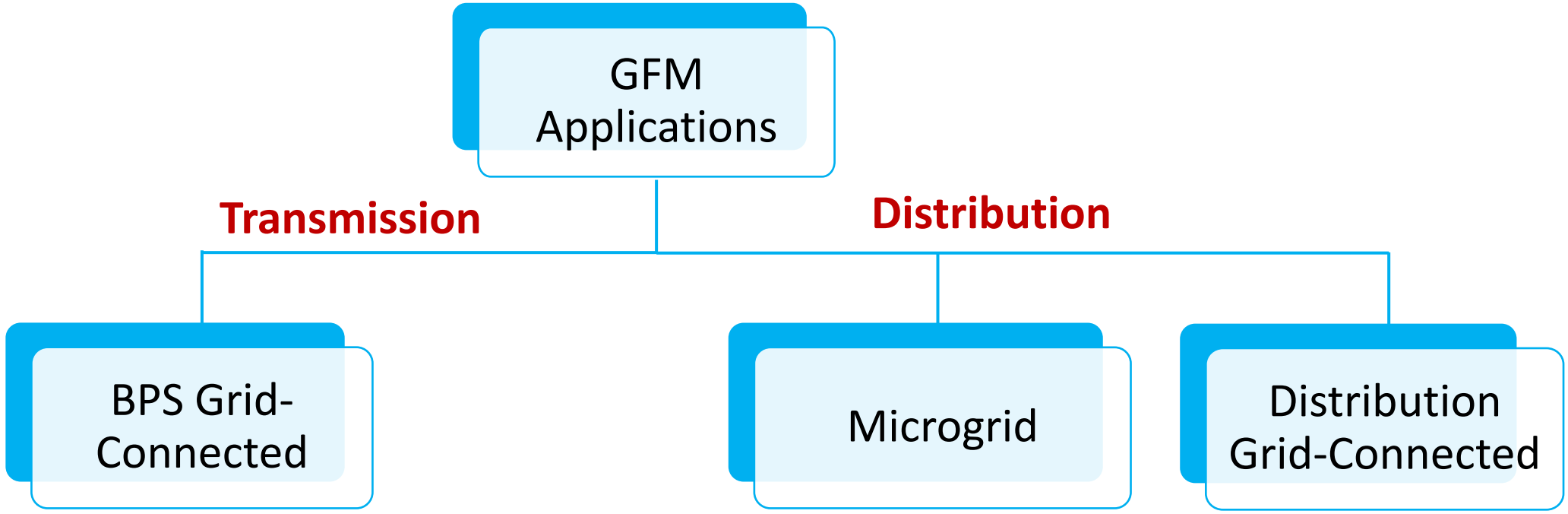
### Power Electronics PCSM and PCSK

- Different operation modes available depending on the application: grid forming or grid following

*Few examples, non-exhaustive; GFM inverters for wind and solar are in their nascent phase (example commercial GFM PV inverter from Ingeteam)*


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# GFM inverter applications




- So far, GFM inverters are primarily considered in
  - Transmission systems with low fault current and rotational inertia
  - Inverter-based microgrid
- Moving forward, GFM inverters may be deployed in both transmission and distribution grids to support reliable grid operation with high IBR penetration


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# Examples of GFM installations in utility-level microgrids

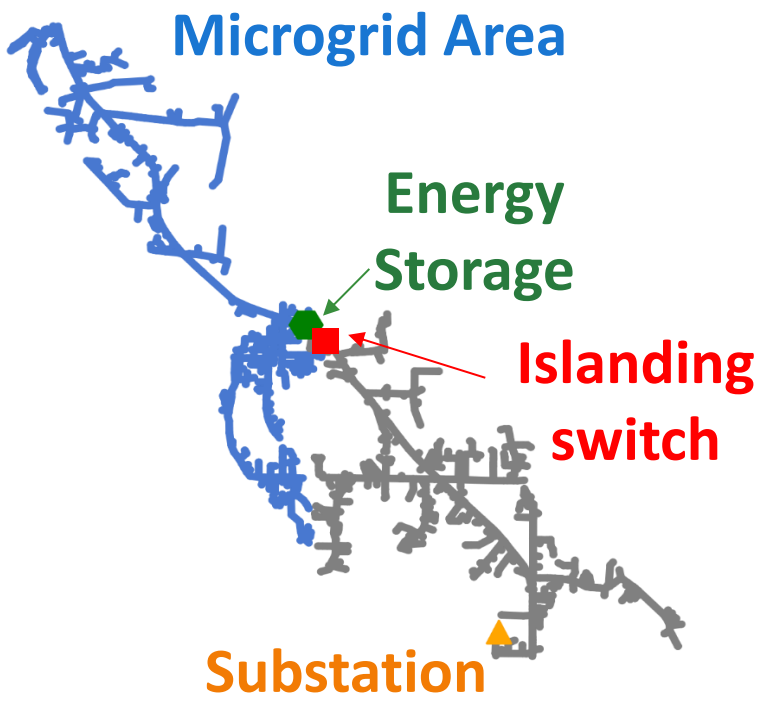



Illustration of a utility-level microgrid containing a section of a distribution feeder

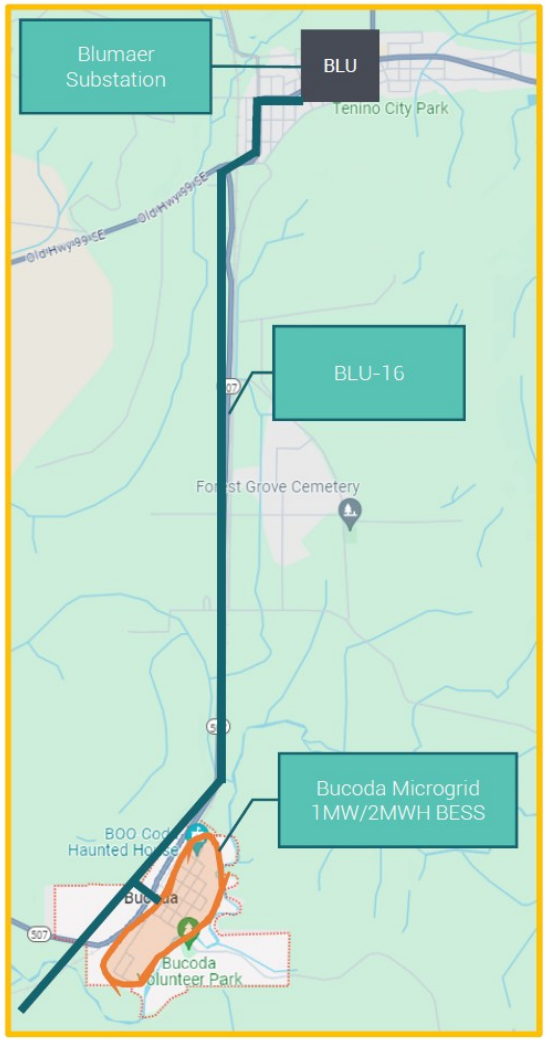
- BESS with GFM capability is increasingly deployed in North American inverter-based microgrids, typically switching between GFL and GFM modes; few operate exclusively in GFM mode

| Utility | Location | BESS size | Operating mode |
|---|---|---|---|
| Duke | Hot springs, NC | 4.4 MW<br>4.4 MWh | Grid-connected: GFL<br>Islanded: GFM |
| Duke | Micanopy, FL | 8.25 MW | |
| Hydro One | Aroland First Nation, ON | 1.2 MW<br>3 MWh | |
| Fortis Alberta | Waterton, AB | 1.6 MW<br>5.2 MWh | |
| PG&E | Redwood Coast Airport, CA | 2.2 MW<br>9 MWh | |
| Eversource | Provincetown, MA | 25 MW<br>38 MWh | **Always GFM** |
| Puget Sound | Bucoda, WA | 1 MW<br>2 MWh | |

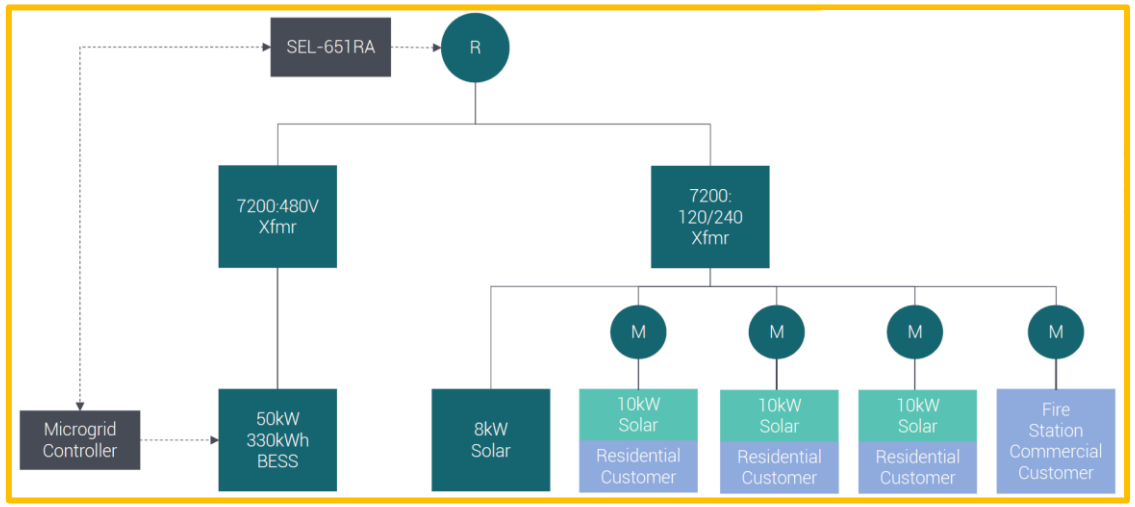
*Few examples in North America, non-exhaustive*


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# PSE example of BESS in GFM mode under blue-sky scenarios — in distribution system




Bucoda Microgrid



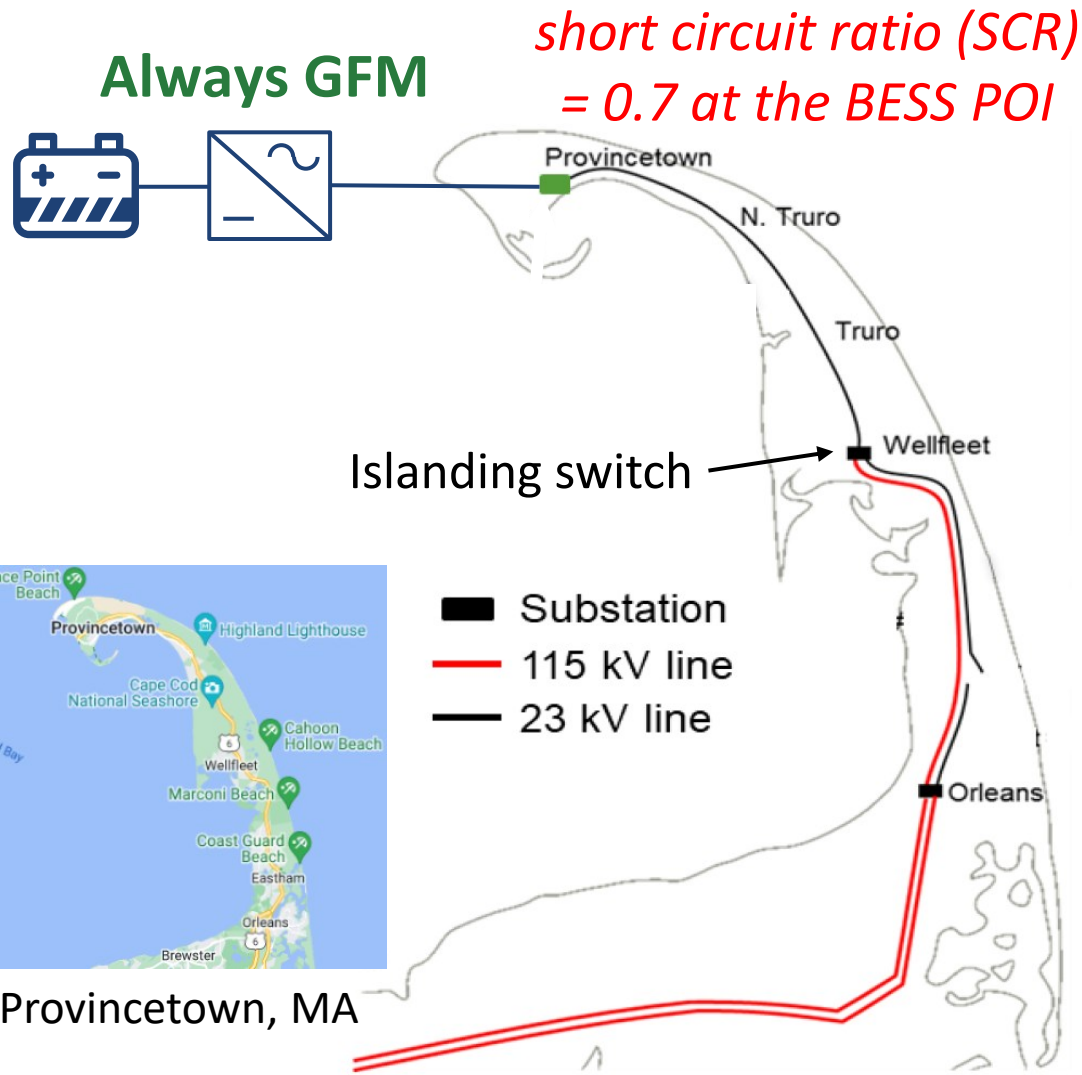

Samish Island Microgrid

Ref: *Distribution Grid-Forming Inverter Working Group (DiGFI) - Scaling Microgrids for a Sustainable Future*, Puget Sound Energy presentation, June 6, 2024 (Link)

- The BESS inverters (50kW in Samish island microgrid and 1MW in Bucoda microgrid) are **held in grid-forming mode all the time**
- The main driver is to **enable seamless transition** between grid-connected and microgrid operation


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# Eversource example of BESS in GFM mode under blue-sky scenarios — in distribution system




- 25 MW/38MWh/57.6MVA BESS connected to the 23 kV system
- The BESS inverter operates in GFM mode under both grid-connected and islanded conditions
- GFM inverters can **operate stably under ultra-weak grid conditions** unlike GFL inverters


Ref: [1] "*Analysis and Application of Grid-Forming Battery Energy Storage System for Reliability Improvement on the Eversource Distribution System in Cape Cod Massachusetts*," 2022 Grid of the Future Symposium
[2] *Distribution Grid-Forming Inverter Working Group (DiGFI) - Eversource Provincetown BESS Project*, Eversource presentation, March 2, 2023 (Link)



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# Challenges in Operating an Inverter-Dominated Power System — HECO example

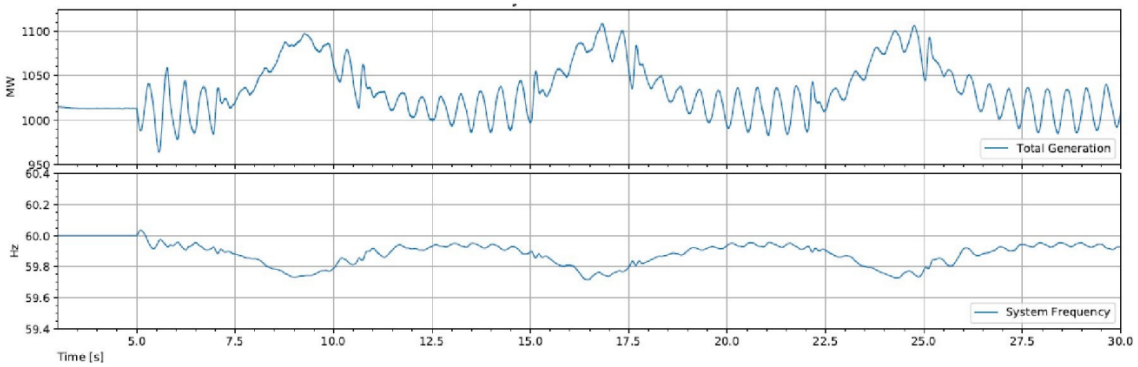



*Figure 3.1: Sustained oscillation in the Oahu Severe Dispatch N-0 grid-following case.*

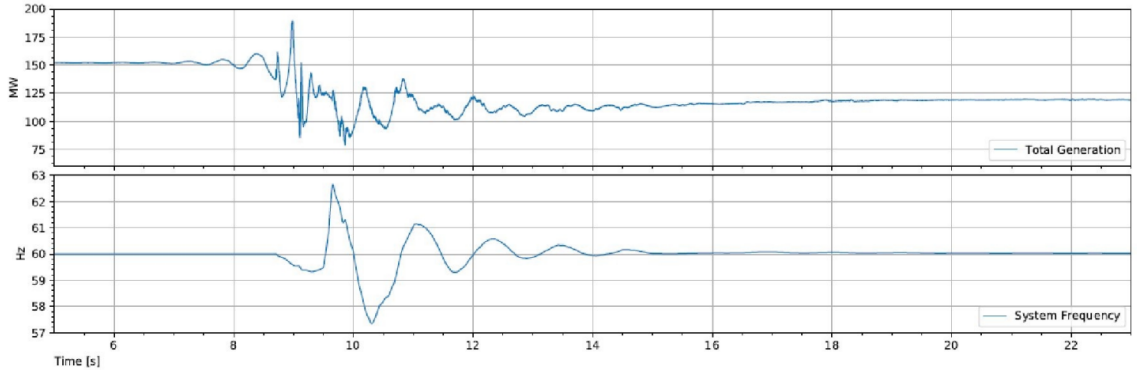


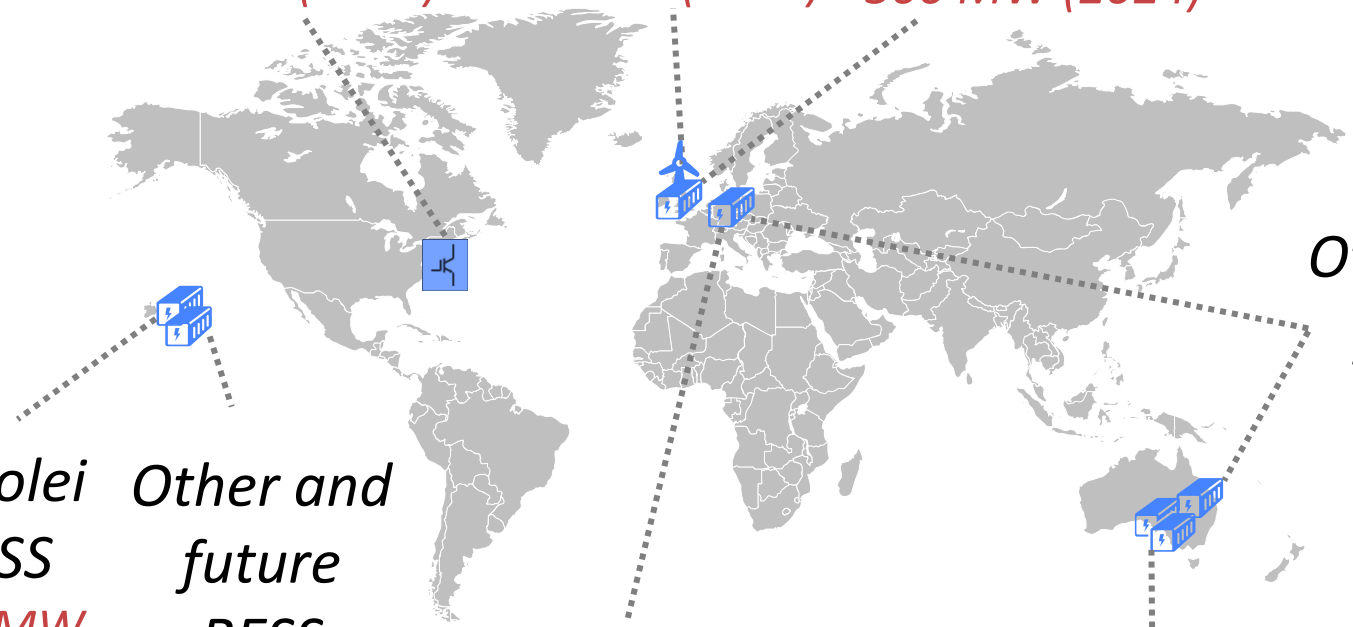

*Figure 3.8: Growing oscillation leading to load shedding for Maui N-0 grid-following case.*

*Figure source: Hawaiian Electric Island-Wide PSCAD Studies (Stage 2 System Impact Study)

- In 2021, HECO conducted island-wide PSCAD studies comparing GFL (constant power operation) and GFM control for its stage 2 transmission-connected projects (9 utility-scale PV plus storage projects and 3 standalone storage projects)
- It is shown that with IBR with constant power control, the system can become unstable during steady state operation when renewable generation is higher than 90%
- It also shows properly tuned GFM control can stabilize the system in most cases
- HECO has required GFM control for all new BESS connected to transmission since 2022


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# Select real-world Examples of GFM Inverter Applications — in bulk power system



*South Fork STATCOM, 75 MVA (2024)*

*Dersalloch Wind Farm 69 MW (2016)*

*Blackhillock BESS 300 MW (2024)*

*Other and future BESS*

*Kapolei BESS 185 MW (2023)*

*Other and future BESS*

*Bordesholm BESS 15 MW (2019)*

*Dalrymple BESS 30 MW (2018)*

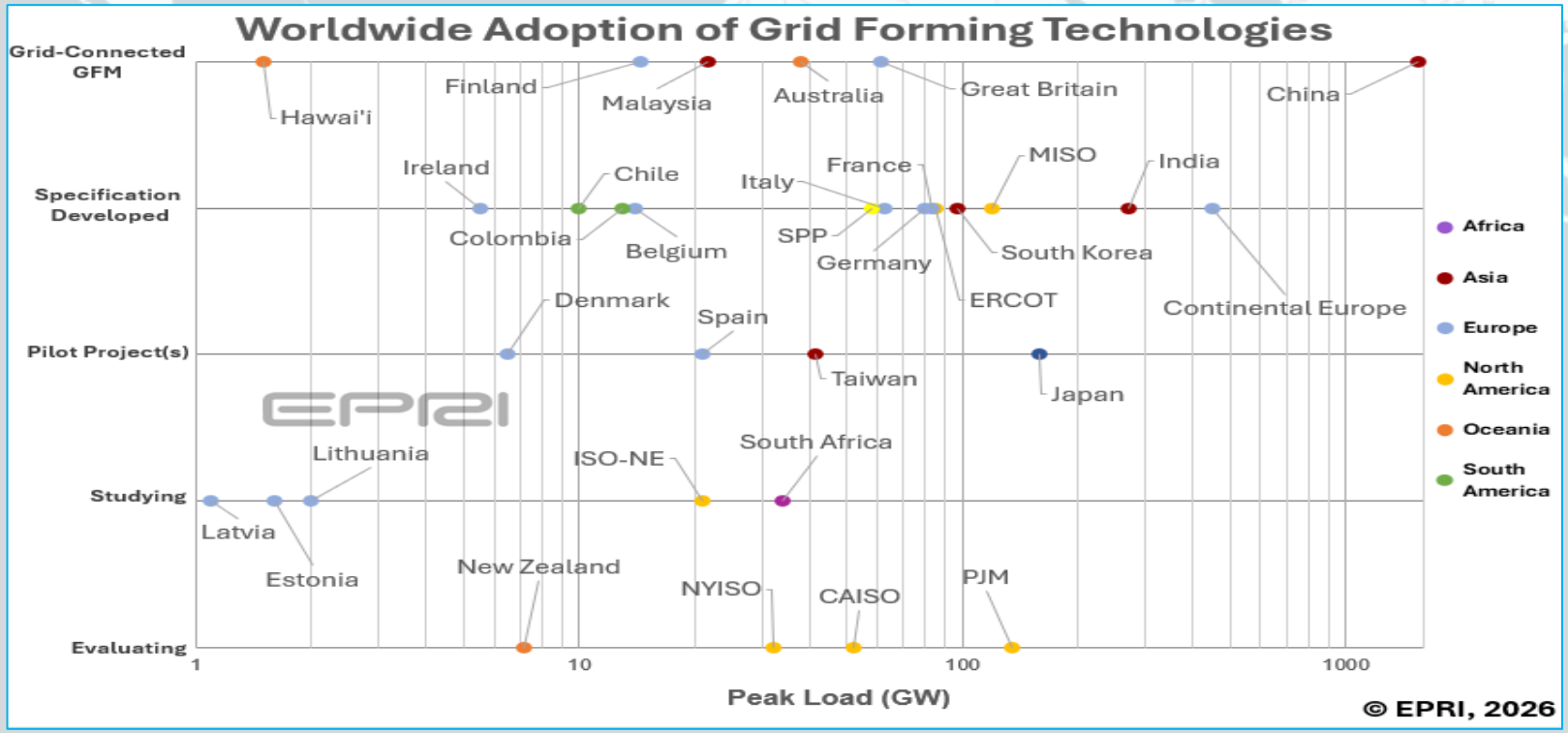
*Hornsdale BESS 150 MW (2022)*

- **Benefits**
  - Provide grid strength and facilitate connection of IBR in weak grid areas
  - Provision of fast frequency and voltage response
  - System restart
  - Island operation

Ref: GFM around the world on UNIFI website


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# GFM/AGS: Now a global phenomenon…




As of September 2026

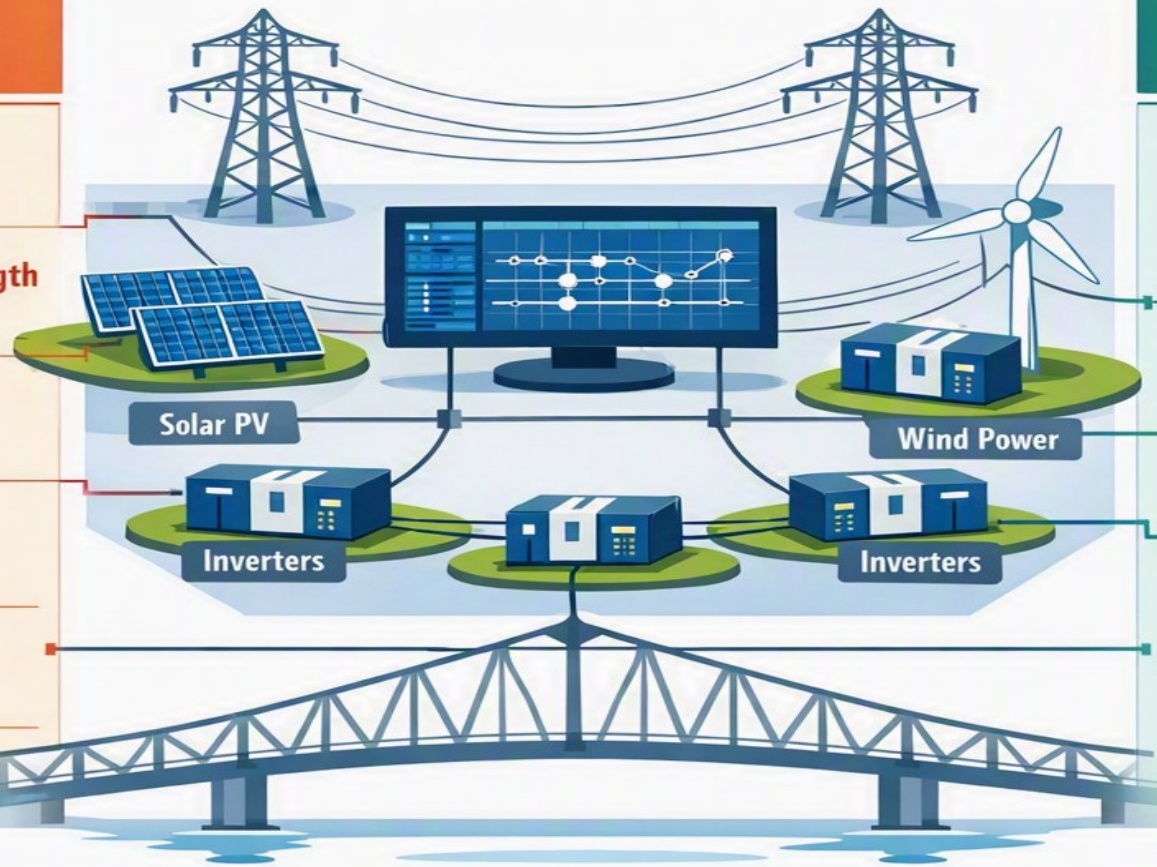

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# Outlook for Future GFM Inverter Applications in Transmission and Distribution Systems

# Inverter-Based Resources: Grid Challenge + Grid Support

## Potential Challenges
*if poorly integrated*

- **Less physical inertia**
  → Faster frequency changes
- **Weak grid / Low system strength**
  → Voltage can swing
- **Fault behavior differs**
  → Protection may need updates
- **Control interactions**
  → Oscillations or trips
- **Models / settings matter**
  → Surprises if not validated




## Potential Grid Support Benefits
*when planned and controlled well*

- **Fast frequency response**
- **Voltage + reactive power support**
- **Ride-through during faults**
- **Grid-forming controls create a voltage/frequency reference**
- **Black-start / Island support** when designed for it
- **Operational flexibility from storage**

***Outcome depends on planning, standards, controls, validated models, commissioning, monitoring, and location.***


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# Distribution-Connected GFM DERs

*Value of Grid-Forming DER in Grid-Connected Operation: Second Edition.* EPRI, Palo Alto, CA: 2024. 3002030961. (free to public)
*Distribution System Impacts of Grid-Forming DERs in Grid-Connected Operation: First Edition*. EPRI, Palo Alto, CA: 2025. 3002034020. (free to public)


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# What Are the Potential Issues in Weak Distribution Grids?

- Higher chance of instability of GFL inverter-based DERs
  - Inverter/PPC volt-var control instability
  - Active islanding detection (AID) induced instability
  - Phase locked loop (PLL) tracking instability

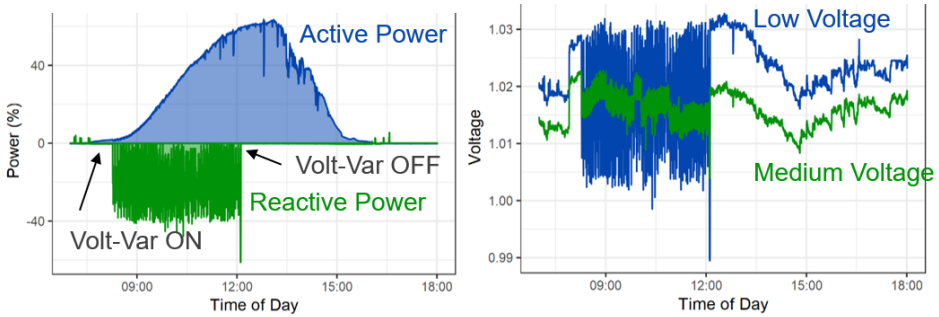
  … …
- Weak grid may amplify power quality issues
  - Voltage violation
  - Voltage unbalance

  *Well-understood steady-state issues*
  - Voltage harmonics
  - Rapid voltage change
  - Flicker

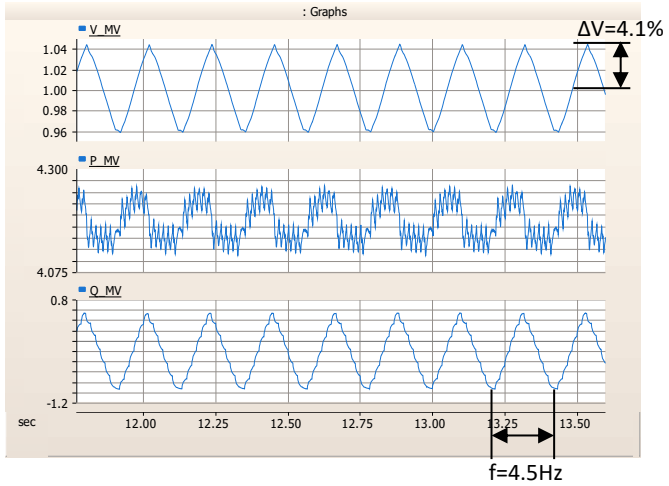
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  *Can be consequences of inverter/DER instability or harmonic injection*

*Power Plant Controller (PPC) Volt-Var Control Instability*

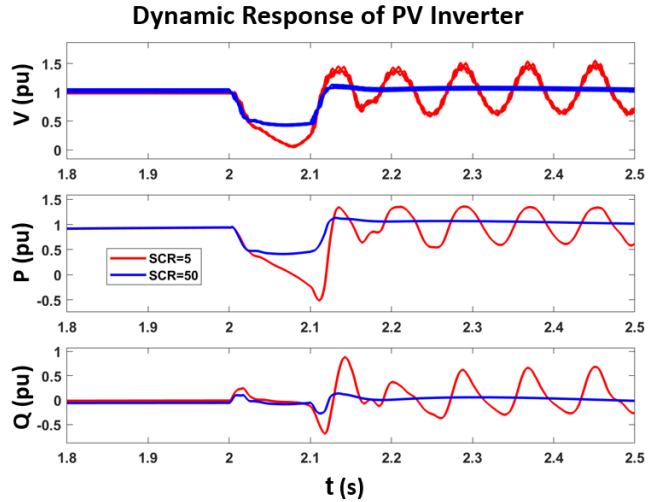



*Ref: National Grid presentation at EPRI webcast on power plant controller (PPC) Stability Analysis and Volt-Watt and Volt-Var Control Setting Guideline for DERs. EPRI, Palo Alto, CA: 2021 3002021716*




*Inverter AID-Induced Instability*

*When Normal PV Operation Causes Visible Light Flicker, EPRI PQ Hotline, April 2026*



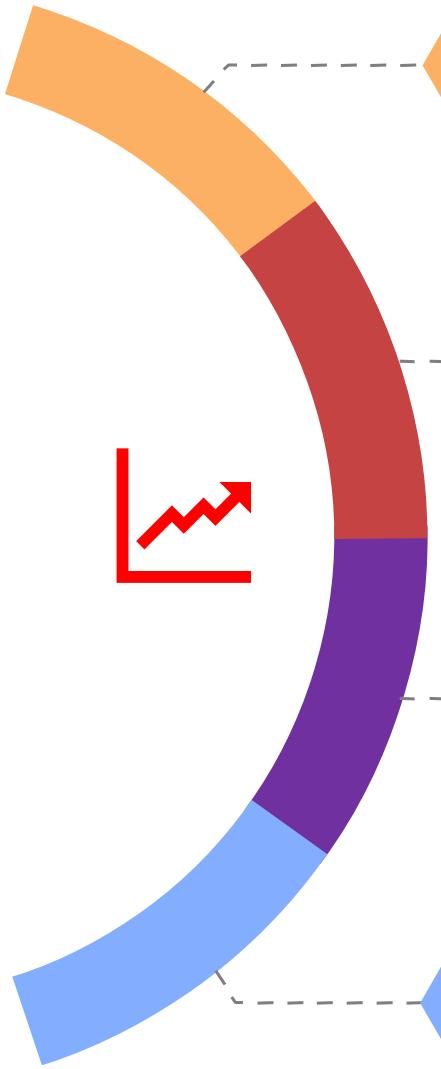

*Inverter PLL Tracking Instability*

*Benefit of Fast Reactive Power Response from Inverters in Supporting Stability of Weak Dx Systems. EPRI, Palo Alto, CA: 2020. 3002020197*


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# 13+ weak grid related power quality issues recently reported by 6+ utilities in North America

***SCR/WSCR/CSCR ranges from 1.3 to 9 at problematic DER locations (multi-MVA scale)***



## Light Flickering

Caused by
- *Aggressive active islanding detection*
- *Inverter instability/misbehaving*
- *Power plant controller instability*

## GFCI Tripping

Caused by
- *Harmonic injection*

## Equipment Damage

Caused by
- *Inverter instability/misbehaving*
- *Harmonic injection*

## Load Tripping

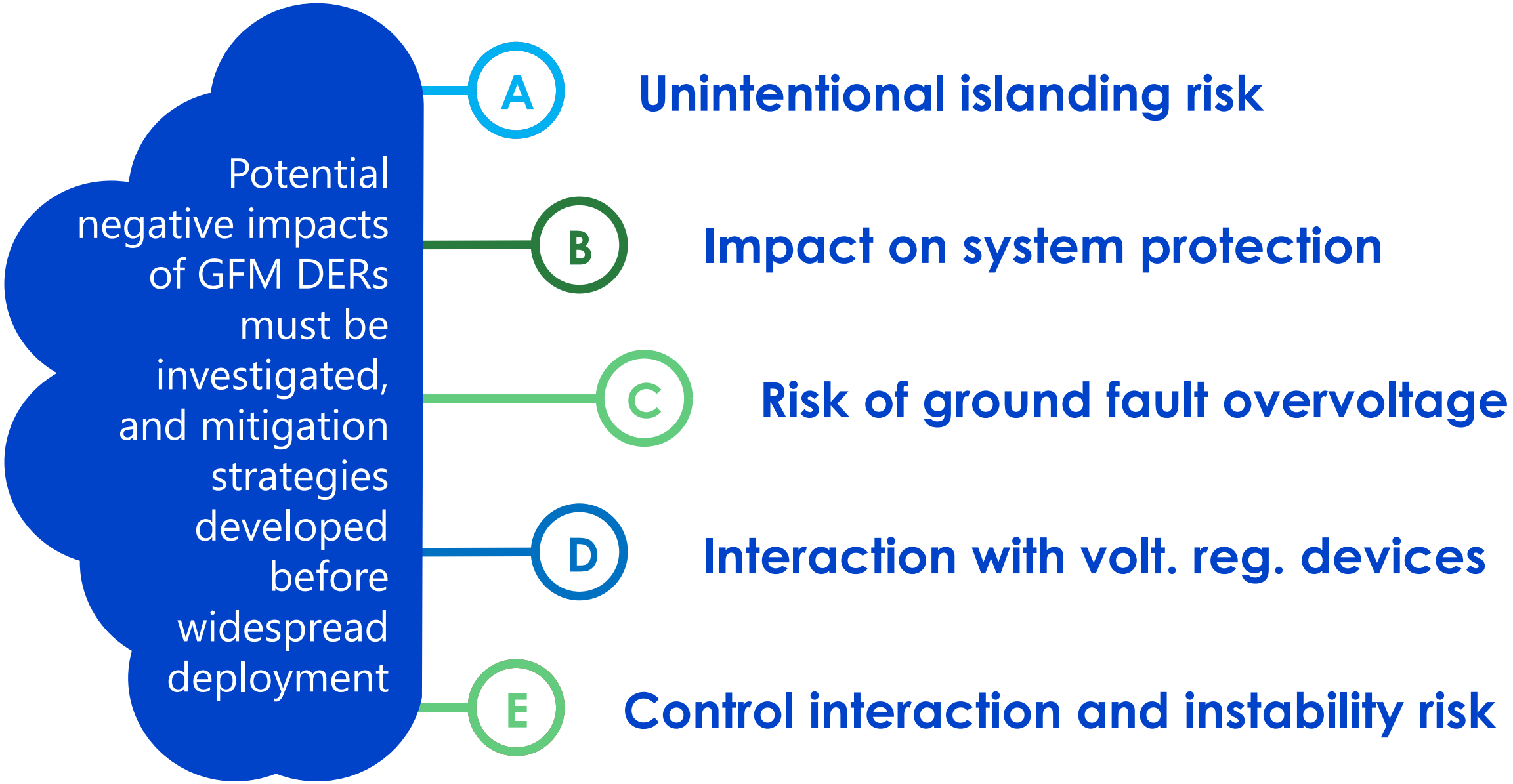
Caused by
- *Voltage sag during transformer energization*

*Ref: EPRI DER Field Experience Interest Group #65 - Feeder Voltage Quality with Inverter-based DER (Link); DER forum thread: Stability Considerations Relative to Feeder Strength (Link)

**Do Emerging Weak-Grid Challenges Call for GFM Control in Distribution?**


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# List of Potential Implementation Challenges





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