Advancing Grid Resilience: Grid-Forming Inverter-Based Resources and Emerging Standards

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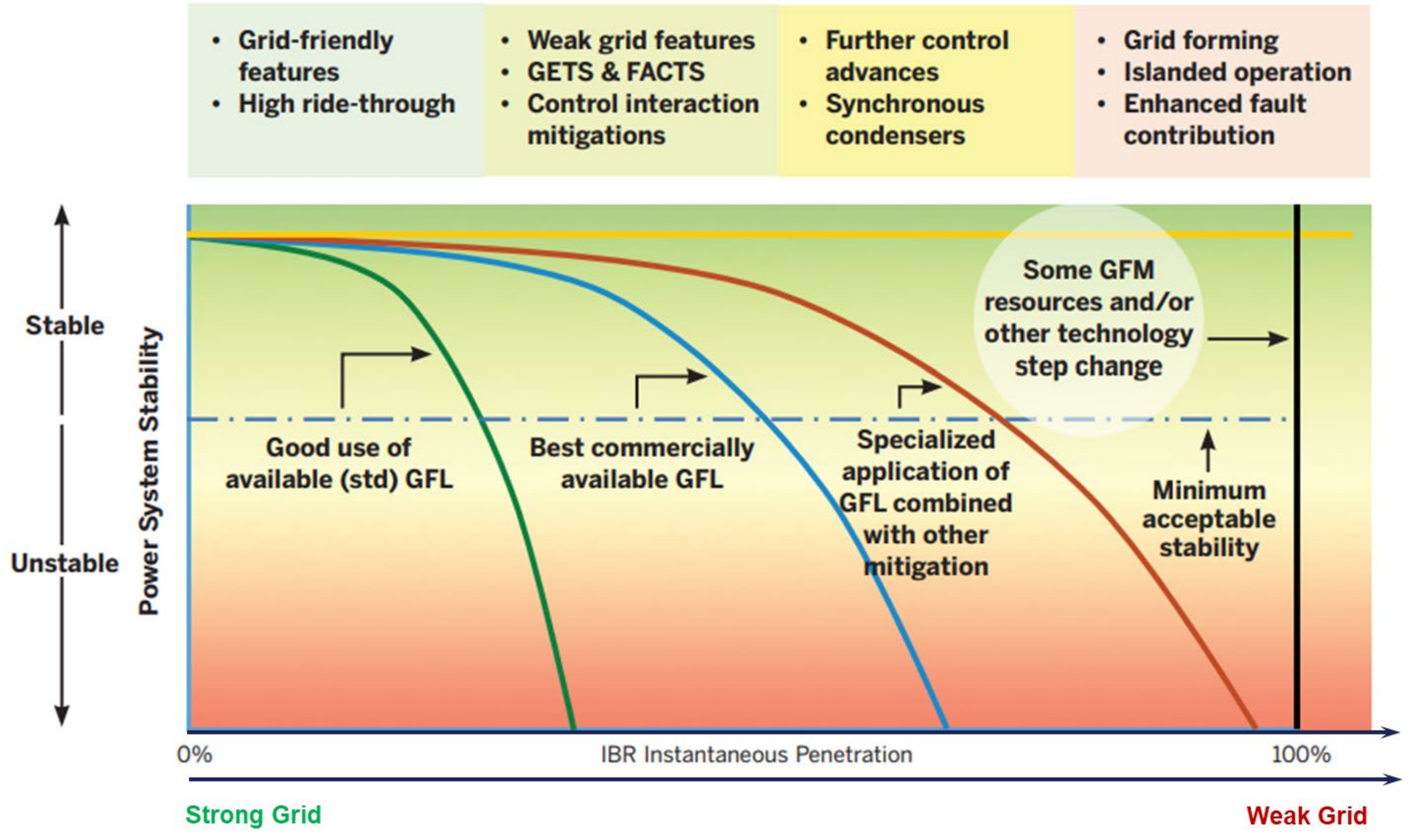
Need for Essential Reliability Services from IBRs



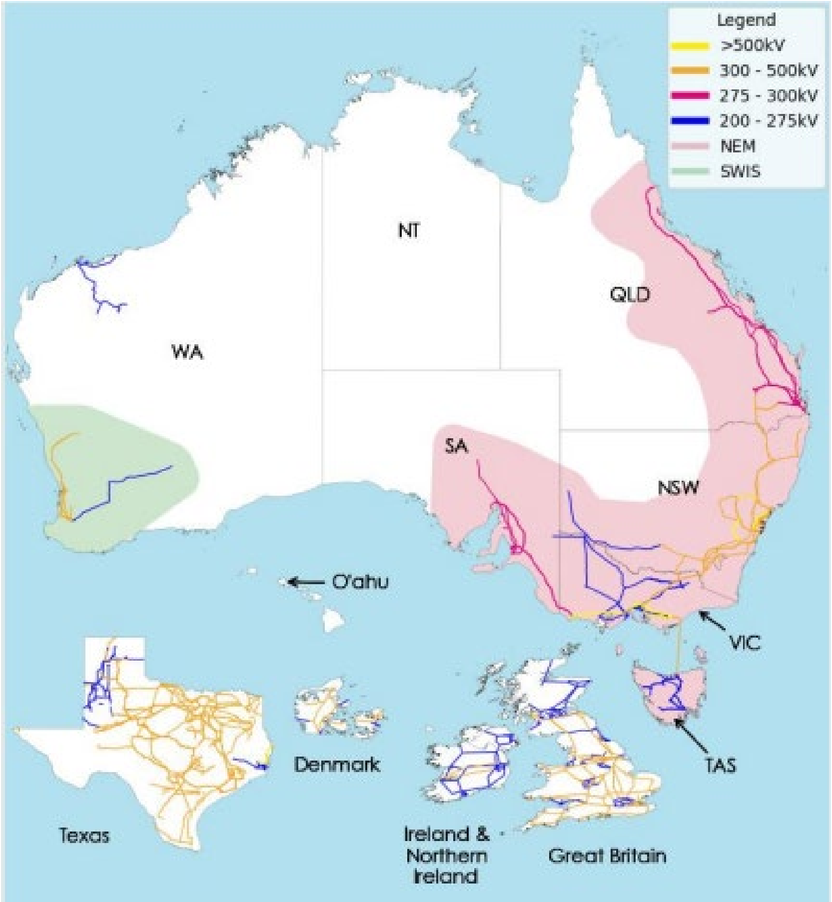
- Majority of the inverters today are "grid-following"
- They read the voltage and frequency of the grid, lock onto that, and inject power aligned with that signal.
- That signal comes from synchronous generators.
- The further wind and solar generation pockets are from synchronous generation, the "weaker" the grid.
- The signal is then easily perturbed by power injection from wind and solar resources, making it hard for inverters to lock onto it correctly.
- This may lead to local instability issues.

https://www.esig.energy/grid-forming-technology-in-energy-systems-integration/

What are the issues?

- System services inherently provided by synchronous machines are becoming scarce and need to be provided by inverter-based resources (IBRs) such as wind, solar, battery storage
- **Frequency Stability**
  - Low inertia leading to fast rate of change of frequency after contingencies (e.g. generator trip)
  - Too fast frequency control may introduce oscillations in lower inertia systems
  - Common mode events resulting in loss of multiple IBRs
- **Voltage and Angular Stability**
  - Long distance high power transfer (wind and solar IBR often far from load)
  - Convergence of voltage stability limits on normal voltage range, brittleness of the system
  - Low system strength, voltage oscillations
- **Control Stability**
  - Control interactions

Will all power systems get see same issues at the same time?

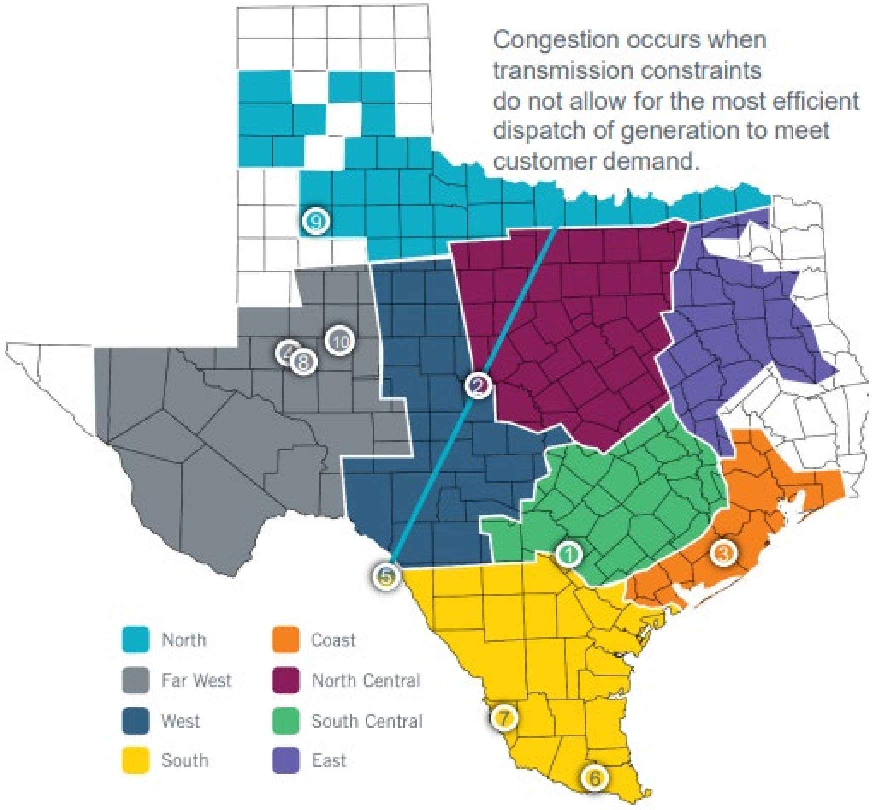


- Small electrical islands, e.g. Hawaii, are the first to experience a number of issues at once, but are more meshed, coordination is easier, solutions are not necessarily scalable for larger systems;
- Medium electrical islands, e.g. Ireland, more meshed, frequency is an issues before other challenges;
- Large electrical islands, e.g. Great Britain, ERCOT and mainland Australia, further challenges due to IBRs being far from load centers, in weak grid locations.
- Geographically Large Interconnected Systems, e.g. Central Europe, Eastern Interconnection and Western Interconnection in the U.S., no issues with IBRs for intact system, but high concerns during system splits.

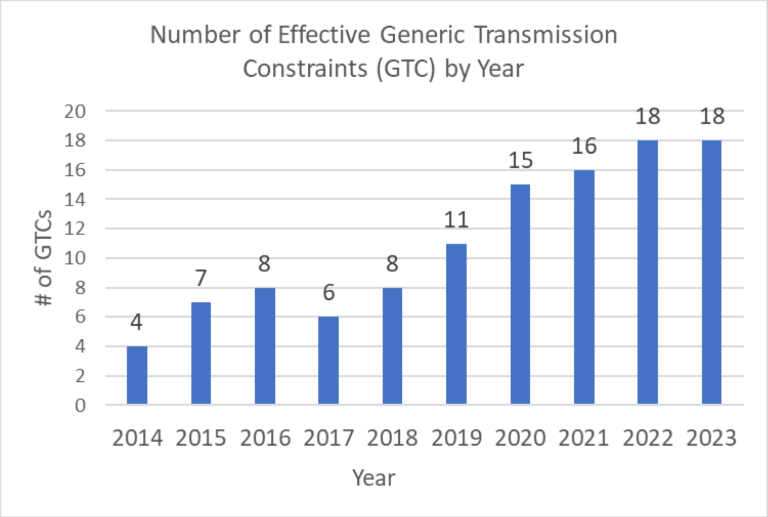
Source: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf

Stability-Related Constraints & Renewable Curtailments, with Example of ERCOT

Top 10 Constraints on ERCOT System
(based on real time data)



Source: ERCOT, Report on Existing and Potential Electric System Constraints and Needs, December 2023



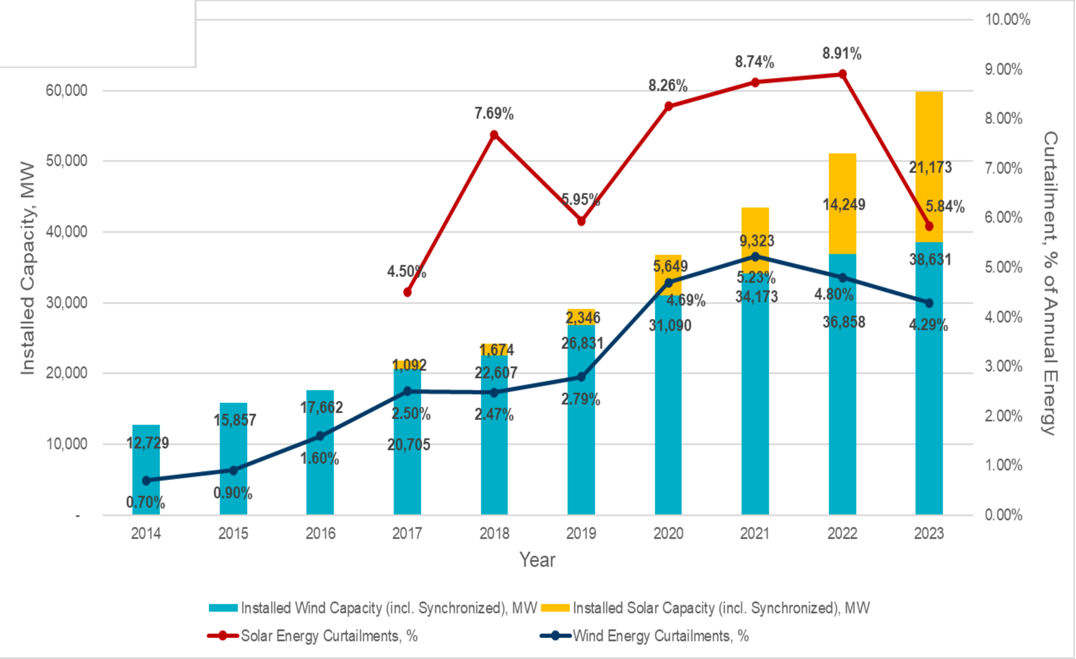
Peak Load – 85.5 GW

75.67% instantaneous wind and solar penetration record (03/29/24)

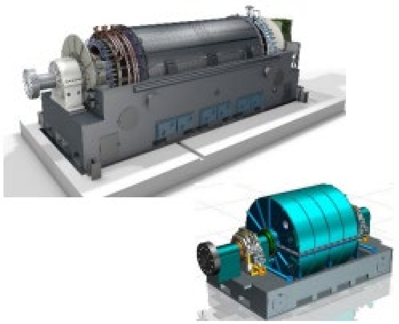
IBRs already providing some system services

Wind - 39.5 GW
Solar – 29 GW
Battery – 9.9 GW (1-2 h duration)

Growth of Wind and Solar Curtailments as More Capacity is Added to the ERCOT Grid, 2014-2023

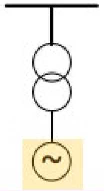


Current Strategies for Relief the Stability Constraints – Adding Transmission Assets



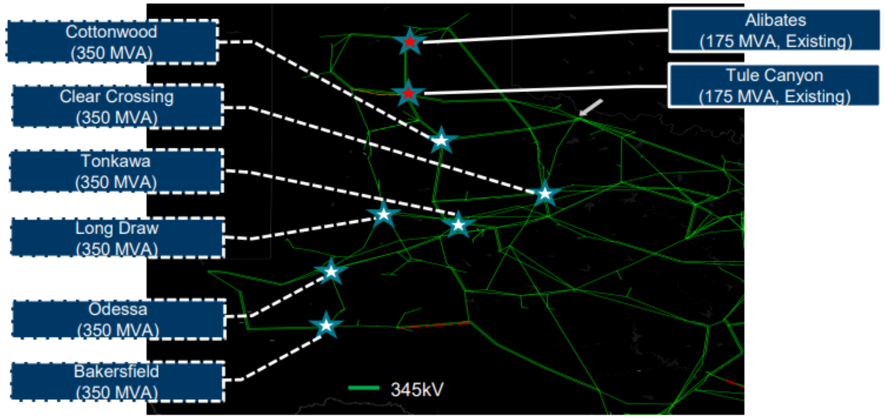
Synchronous Condenser – (w/wo Flywheel)

- Short circuit power and inertia support
- Rotating equipment



Source: Siemens Energy, Ian Ramsay, EIPC Workshop, June 2022

Additional six synchronous condensers with total of 2,100 MVA were identified that will provide effective improvement to WTX.



Source: ERCOT, *Strengthening the West Texas Grid to Mitigate Widespread Inverter-Based Events – Operation Assessment Results*, Regional Planning Group meeting, Feb 2023

New transmission lines to reduce electric distance between high IBR areas with low system strength and strong grid areas

Source: iStockphoto/Yelantsevv

Can something be done on IBR Side to Relieve Stability Constraints?

What is Grid Forming ?

NERC definition:

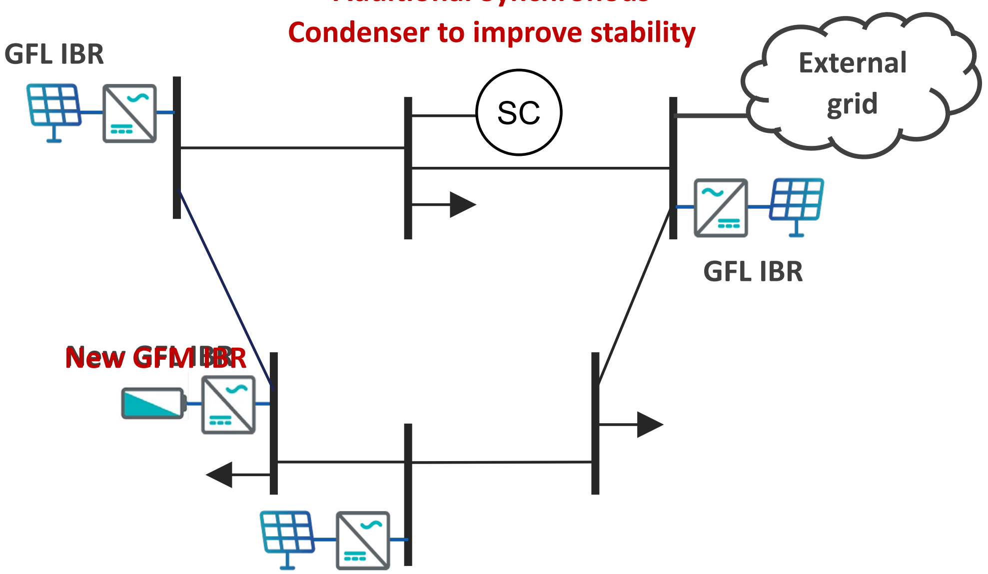
- Grid Forming IBR controls **maintain an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame.** This allows the IBR to immediately respond to changes in the external system and maintain IBR control stability during challenging network conditions. The voltage phasor must be controlled to maintain synchronism with other devices in the grid and must also regulate active and reactive power appropriately to support the grid
- There are many variations of both grid-forming and grid-following controls. Both are subject to physical equipment constraints including voltage, current and energy limits, mechanical equipment constraints (on WTGs) as well as external power system limits.
- Further, performance requirements for GFL plants, will also apply to GFM inverters unless explicitly identified as inapplicable.

Sources: NERC, Grid Forming Technology Bulk Power System Reliability Considerations , December 2021
ESIG, Grid Forming Technology in Energy Systems Integration, March 2022

Grid Forming Controls as an Alternative for Grid Strength Support

- Grid Forming (GFM) IBRs can be designed to provide, within equipment limits, most of the services that are currently inherently provided by synchronous machines
- GFM IBRs have a stabilizing effect in weak grid areas and improve stability for IBRs with conventional grid-following (GFL) controls
- If GFM controls are implemented on planned IBRs, they may provide more cost-effective alternative to improve stability.

  This is because the improvement is provided by the new IBRs themselves as they are added to the system and addition of supplemental transmission assets may not be needed.



Source: [ESIG Report Grid-Forming Technology in Energy Systems Integration]

Potential Use-Cases for Grid Forming Controls

- Weak grid operation
- Damping of voltage and frequency oscillations
- Resist voltage phase angle change (phase jump response)
- Resist frequency change / limit RoCoF (substitute/supplement for inertial response of synchronous generation)
- Fast fault current injection (balanced and unbalanced)
- Mitigation of sub-synchronous control interactions
- Support of islanded operation (when required)
- Black start (when required)

Source: Adopted from Y. Cheng, Preliminary assessment of Grid Forming Inverter-based Energy Storage Resources in the ERCOT Grid ERCOT IBRWG, August 2023

Grid Forming Testing and Specs Landscape At Glance

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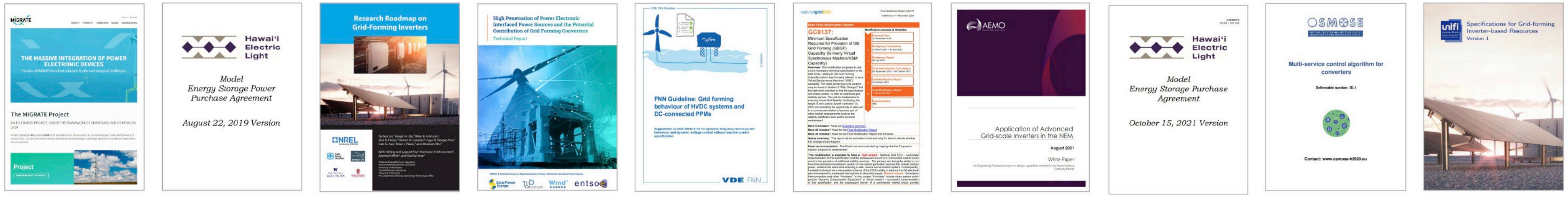
Links to all these specification documents can be found here

MIGRATE | HECO | NREL | ENSTO-E | VDE FNN | NGESO | AEMO | HECO | OSMOSE | UNIFI



2019 | 2020 | 2021 | 2022

NGESO | AEMO | FINGRID | NERC | AEMO | VDE FNN | UNIFI | FINGRID | MISO | ACER/ENTSO-E | ERCOT | CEN

2023 | 2024

This presentation contains presenter's interpretation of the requirements, please refer to original documents for exact specifications

Grid Forming Testing and Specs Landscape, cont.

	System Operator or Regulatory Body	Research Orgs or Industry WGs
Published	• NG ESO GC & Guide • FNN VDE • HECO • AEMO • Fingrid	• MIGRATE / OSMOSE • UNIFI V.2 • NERC IRPS
Draft	• ACER/ ENSTO-E RfG 2.0 • ERCOT • MISO (almost published) • CEN	
Planned	• AESO • IESO • BPA • Florida Power & Light	• CIGRE JWGB4/C4.93 • IEEE SA

The table is not exhaustive but provides some examples

- High level vs slightly more detailed
- Functional specifications vs test-based vs both
- Split into “core” & advanced capabilities vs not split
- Voluntary vs mandatory
- In addition to existing GFL req., unless conflicts
- For all types of resources vs all IBRs vs just BESS

For more information on GFM Specification and Testing see ESIG Webinar: A Global Update on GFM Projects and Specifications

GFM Batteries are a Low-Hanging Fruit

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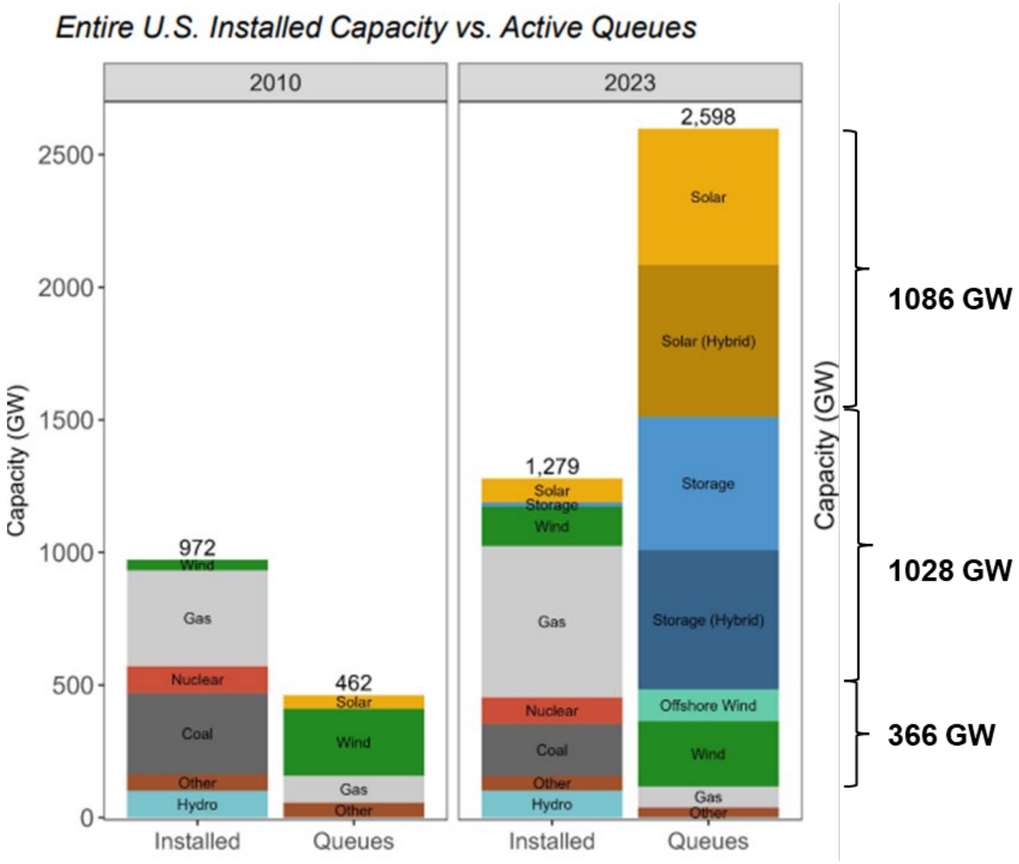
- GFM controls can potentially be implemented on any type of IBR including new solar and wind
- GFM behavior requires a certain amount of energy buffer, which for wind and solar resources means continuous operation below their maximum available power production.
- In addition, GFM control in wind turbines may result in greater and more frequent mechanical stress.
- The battery is the energy buffer, and only software modifications to a battery's controls are needed to make the battery a GFM resource – **batteries are the low-hanging fruit for GFM application**.
- Note, retrofitting existing GFL batteries to GFM may potentially bring additional costs and delays (model updates, re-studies, changes to various contractual agreements)

Source: Neoen Australia

A number of batteries with GFM controls have already been deployed around the world, and further development is happening at unprecedented speed

GFM Batteries are a Low-Hanging Fruit

Source: E. Quitmann, [ESIG Spring Technical Workshop, 2020]



Source: LBNL, Queued Up [https://emp.lbl.gov/queues]

Specifications for All IBRs vs Just for BESS

All IBR	Just Battery Energy Storage
NESO (Great Britain), but specifications call for availability of energy buffer.	HECO (U.S., Hawaii)
ENTSO-E (Europe)	MISO (U.S., Eastern Interconnection)
AEMO (Australia), but specifies that for GFM capability storage is needed	ERCOT (U.S., Texas)
VDE FNN (Germany)	NERC (U.S.)
	Fingrid (Finland)
	CEN (Chile)

GFM Progress Globally

Operator Specifications

- HECO – Hawaii, U.S.
- NESO – Great Britain
- AEMO – Australia
- Fingrid – Finland
- MISO – U.S.
- ERCOT (drat) – U.S.
- ENTSO-E (draft) - Europe

OEMs

- SMA
- Tesla
- Sungrow
- Power Electronics
- Hitachi Energy
- Siemens (e-STATCOM)
- EPC Power
- GP Tech
- GE

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

Common Functionalities

- Response to voltage phase angle step
- Response to voltage magnitude step
- Limiting of RoCoF
- Active Power Sharing
- Behavior at the current limit
- Counter Unbalances
- Counter Harmonics
- Provide Damping
- No Control Interactions/ Interoperability
- Low system strength operation
- Islanded Operation & Re-synch
- Surviving Loss of Last Synch Machine
- Black Start

GFM Requirements vs Incentives for at Glance

Voluntary (no market)	Incentive: Market , Tender for Stability Products, Other Forms of Payment	Requirement
NESO (Great Britain) =>	NESO (Great Britain) =>	Fingrid (Finland)
AEMO (Australia)	VDE FNN (Germany) =>	MISO (U.S., EI)
		ERCOT (U.S., TX)
		ENTSO-E draft (Europe)
		HECO (Hawaii)
		CEN (Chile)

GFM Requirements v.s. Incentives: HECO

- From recent studies, it was found that GFM BESS is the most effective resource to maintain our grid stability (this is not a general conclusion necessarily applicable to other grids)
- GFM requirement for BESS in HECO’s service territories (Oahu, Maui, Hawaii island, Molokai and Lanai) transmission and sub-transmission grid is a mandatory requirement for all future BESS <u>until HECO’s study shows that they have enough GFM resources.</u>
- HECO’s Request For Proposals (RFPs) have a MWh target (but not necessarily has a MW target) for GFM BESS, and also asks for firm capacity, wind, wind/BESS and PV/BESS.

GFM Requirements v.s. Incentives: NESO

- Great Britain – Stability Pathfinder, Phase 2 in 2022 awarded five GFM BESS, Grid Forming Requirements apply to these projects.
- NESO followed up with development of Stability Market Design, developing eligibility rules, contract structures, procurement strategies for the future stability market. Mid-term stability market launched in 2023.
- As of September 2024, NESO is proposing from 12/31/25, to mandate GFM capability on:
  - Type D Power Generating Modules (50 MW and above and/or connected at 110 kV or above) and:
  - HVDC Systems (including Interconnectors)

  with compliance required by the end of 2028. This **will not be** retrospective on pre 12/31/25 plants

GFM Requirements v.s. Incentives: AEMO

- AEMO has minimum system strength requirements in certain areas:
  - Transmission owner determines minimum required system strength and obliged to maintain it
  - GFL IBRs connecting in these areas are assessed for their impact on system strength and have to pay to bring the system strength level back to the minimum required
  - TO builds system strengthening assets of procures from third party providers, GFM **is not** valued for provision of system strength.
  - New GFL IBRs may chose to co-locate GFM BESS to offset their impact on system strength and avoid payments.
- In December 2022, Australian Renewable Energy Agency announced $176 million in conditional funding for eight grid-scale GFM BESS to promote deployment (a total project value of $2.7 billion and a capacity of 2.0 GW / 4.2 GWh)

MISO GFM BESS Requirements Moving Forward

- MISO presented the latest draft of the proposed performance requirements for GFM BESS at October Planning Advisory Committee (PAC) meeting.
- The proposal was **to require GFM control capabilities from all BESS, starting with the DPP 2023 Cycle*** (i.e. next gen interconnection cycle).
- The requirements and process are outlined in Business Practice Manual (BPM-015) redlines (Section 5.3.7 on Page 52).
- PAC stakeholders were invited to review and submit feedback to MISO's proposal
- MISO responded to stakeholder feedback submitted by 2 parties and shared requested clarifications in the responses and November PAC meeting materials.
- **Next Steps: Finalize BPM-015 redlines to implement proposed requirements**

* DPP – Definitive Planning Phase

GFM Requirements v.s. Incentives: Fingrid, ENTSO-E, Germany

- Fingrid currently allows **only GFM** BESS to build in weak grid areas, ERCOT proposed a similar idea in their Dynamic Stability Assessment of High Penetration of Renewable Generation in 2018.
- Fingrid grid code update is looking to require all future BESS to be GFM.
- ENTSO-E RfG 2.0 aims to require from all future Type B-D power park modules
- German Inertia Market, payment for “new” inertia to all resources fulfilling VDE FNN specs. This initiative still under development and will be implemented in 2025.

Limits for Thresholds for Power Generating Modules of Type B, C and D in ENTSO-E RfG

Synchronous areas	Limit for maximum capacity threshold from which a power-generating module is of Type B (<110 kV)	Limit for maximum capacity threshold from which a power-generating module is of Type C (<110 kV)	Limit for maximum capacity threshold from which a power-generating module is of Type D (≥ 110 kV)
Continental Europe	1 MW	50 MW	75 MW
Great Britain	1 MW	50 MW	75 MW
Nordic	1,5 MW	10 MW	30 MW
Ireland and Northern Ireland	0,1 MW	5 MW	10 MW
Baltic	0,5 MW	10 MW	15 MW

Connection point below 110 kV and maximum capacity of 0,8 kW or more – Type A;

Grid-Connected GFM BESS Projects

Project Name	Location	Operator/Utility	Size (MW)	OEM	Technology	Year*	Operational?
Kriegers Flak	Denmark/Germany	Energinet/50Hertz	410	Hitachi Energy	HVDC back-to-back system	2018	Y
Wallgrove	Australia	AEMO	50	Tesla	BESS	2022	Y
Maritime Link	Canada, Nova Scotia	NSP Maritime Link Inc.	500		HVDC bipolar system	2018	Y
Riverina and Darlington Point	Australia	AEMO	150	Tesla	BESS	2023	Y
Provincetown BESS	USA, Massachusetts	Eversource Energy	25	SMA	BESS	2022	Y
Project #1	USA, Hawaii	KIUC	13	Tesla	BESS	2018	Y
New England BESS	Australia	AEMO	50		BESS	2023	Y
Mackinac	USA, Michigan	ATC	200	Hitachi Energy	HVDC back-to-back system	2014	Y
Kupono Solar	USA, Hawaii	HECO	42	Tesla	BESS	2024	Y
Kauai PMRF	USA, Hawaii	KIUC	14		BESS	2022	Y
Kapolei Energy Storage	USA, Hawaii	HECO	185	Tesla	BESS	2023	Y
Hornsdale Power Reserve	Australia	AEMO	150	Tesla	BESS	2022	Y
Dalrymple	Australia	AEMO	30	Hitachi Energy	BESS	2018	Y
Broken Hill BESS	Australia	AEMO	50	SMA	BESS	2023	Y
Bordesholm	Germany	Versorg. Betrb. Bordesholm	15	SMA	BESS	2019	Y
South Fork Wind	USA, New York	Eversource Energy	75		GFM STATCOM	2024	Y
Wheatridge RE Facility	USA, Oregon	Pacific Gas & Electric	380		Wind, PV, BESS		N
Hams Hall	Great Britain	NESO	350	Sungrow	BESS	2026	N
Mountain View Solar	USA, Hawaii	HECO	7		BESS	2024	N
Eccles	Great Britain	NESO	400	SMA	BESS	2026	N
Western Downs Battery	Australia	AEMO	200	Tesla	BESS	2025	N
Blackhillock, Phase I	Great Britain	NESO	200	SMA	BESS	2024	N
Victorian Big Battery	Australia	AEMO	300	Tesla	BESS	2024	N
Terang BESS	Australia	AEMO	100	Tesla	BESS	2026	N
TagEnergy BESS	Australia	AEMO	300	Tesla	BESS	2026	N
Mortlake BESS	Australia	AEMO	300	SMA	BESS	2026	N
Liddell Battery	Australia	AEMO	500	Power Electronics	BESS	2025	N
Kilmarnock South	Great Britain	NESO	300	SMA	BESS	2026	N
Bungama BESS	Australia	AEMO	200		BESS	2025	N
Blyth Battery	Australia	AEMO	200		BESS	2025	N
Blackhillock, Phase II	Great Britain	NESO	100	SMA	BESS	2025	N
Waiawa Phase 2 Solar	USA, Hawaii	HECO	30		BESS+PV		N

Links to the table and additional details on these project is here

Conclusions

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- If IBRs are built with grid-forming controls, stability can be provided by the resource itself, the need for additional mitigation can be greatly reduced, and higher share of IBRs (up to 100%) achieved.
- Grid code requirements and/or market products are needed for grid-forming IBRs to be deployed in an efficient and timely manner.
- It took 20 years in Europe to develop grid codes for present-day IBR technology, while the U.S. still does not have harmonized grid codes. **We do not have another 20 years to develop and harmonize the requirements of GFM IBRs!**
- Recently published GFM requirements and specifications agree on high level functionalities needed but detailed requirements and level of specificity still differ widely.
- There have been a number of activities in the U.S., Europe, and Australia in the past three years to accelerate the deployment of grid-forming IBRs.
- However, the challenge is broad and global. Much more work is needed — and quickly — to seize this window of opportunity and deploy GFM controls at least on new BESSs.

THANK YOU

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