WIRAB Webinar Series:
Inverter Based Resources and Grid Reliability

Webinar #3:

Grid Forming Inverter Based Resources and Supporting Reliability

November 30, 2023

WIRAB
Western Interconnection Regional Advisory Body

WIRAB Webinar Series

Western Interconnection Regional Advisory Body

Webinar #1: Overview of Inverter Based Resources and Grid Reliability

- Thursday, October 19 at 2:30 PM MT (4:30 PM ET)
- Speakers:
  - Nick Miller, HickoryLedge;
  - Debbie Lew, ESIG

Webinar #2: Inverter Based Resource Standards and Rules to Maintain Reliability

- Thursday, Nov 16 at 2:30 PM MT (4:30 PM ET)
- Speakers:
  - Julia Matevosyan, ESIG;
  - Ryan Quint, NERC;
  - Debbie Lew, ESIG

Webinar #3: Grid Forming Inverter Based Resources and Supporting Reliability

- Thursday, November 30 at 2:30 PM MT (4:30 PM ET)
- Speakers:
  - Julia Matevosyan, ESIG;
  - Debbie Lew, ESIG

For more information, please visit https://www.westernenergyboard.org/category/webinars/

Grid-forming Inverter-based Resources: Supporting Reliability

WIRAB Webinar #3

Debbie Lew

Associate Director, ESIG

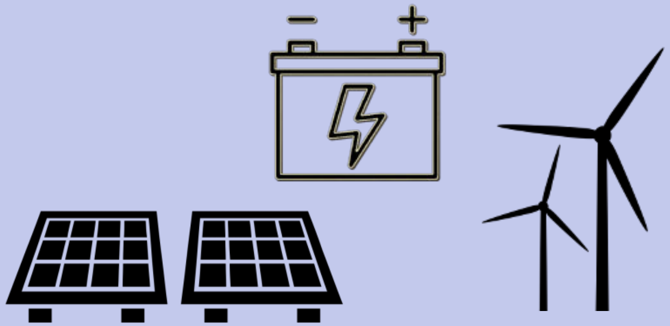
ESIG
ENERGY SYSTEMS INTEGRATION GROUP

Nov 30, 2023

The grid must be reliable

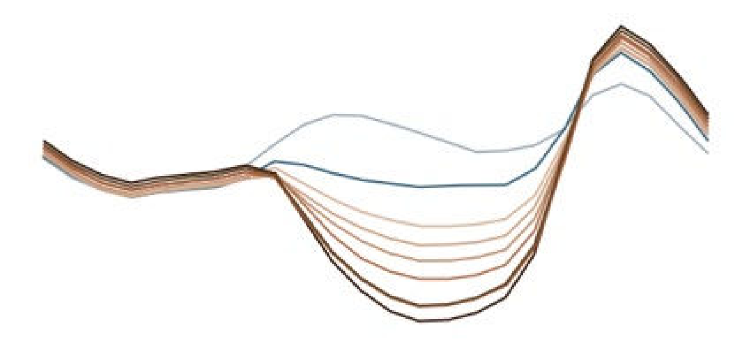
Disturbance response
System Stability

- High penetrations of inverter-based resources (IBR)
    - Frequency response
    - Transient stability
    - Small-signal stability



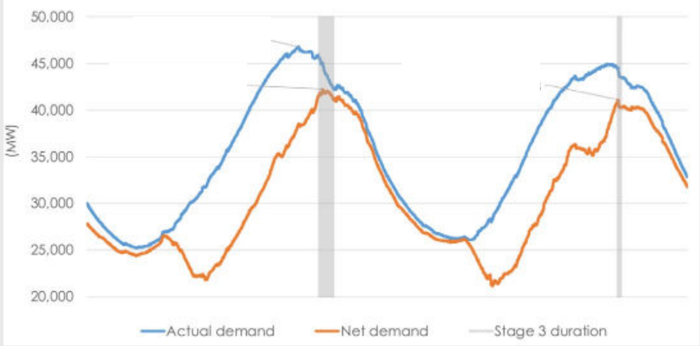
Operations
System Balancing

- Wind and solar variability and uncertainty
- Diurnal mismatch of supply and demand
- Reducing curtailment
- Flexibility needs



Planning
Resource Adequacy

- Seasonal mismatch of supply and demand
- Periods of low wind/solar/hydro
- 1 day in 10 years Loss of Load Expectation

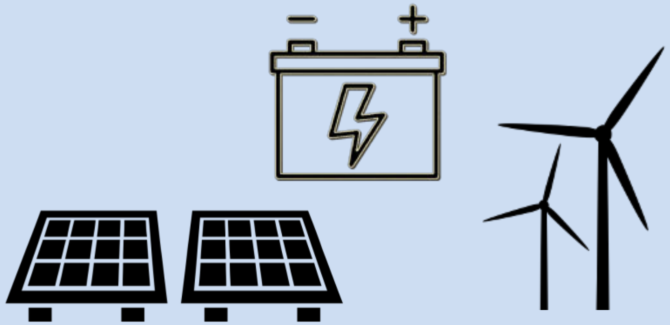


Seconds → Hours/Days → Years

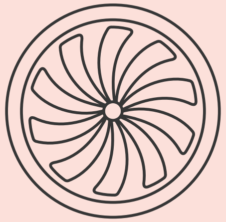
Graphics: CAISO, https://www.caiso.com/documents/flexibleresourceshelprenewables_fastfacts.pdf; http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf

What's an inverter-based resource (IBR)?

Wind, PV, batteries, fuel cells, and some other resources connect to the grid through an inverter. Inverters have advantages because we can program them; however we did not originally design the grid around them.



This is different from conventional synchronous steam, gas, and hydro generators that directly couple to the grid. We designed the grid around both the good and bad characteristics of these generators.



NOT talking about the duck curve, intermittency, resource adequacy during extreme weather. Those issues have to do with wind and solar resources being variable and forecasts being uncertain.

Grid-following vs Grid-forming Inverters

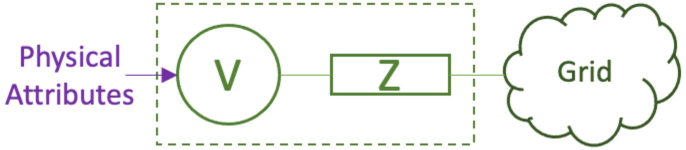
- Grid following (Inverter follows): Inverters measure the grid voltage and frequency, and then try to inject the correct real and reactive power.
- Grid forming (Inverter leads): Inverters create a local voltage and frequency, and then try to move that voltage to cause the correct real and reactive power to flow into the system

A bit oversimplified, but close enough - the point is this behavior is fundamentally different.

Brief Technology Overview

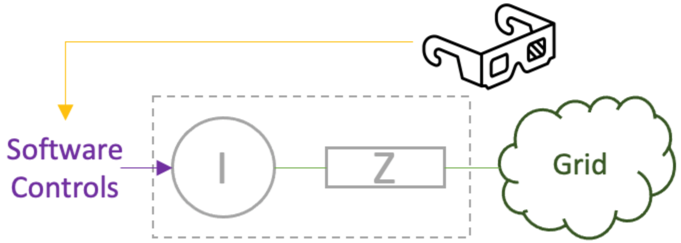
Synchronous Machines (SM)

- Behaves like a voltage source (inherent, physics-defined response)
- Stored energy in rotating mass and magnetic field (relatively small amount – seconds at rated)
- Ability to release energy quickly (3-5x current rating)



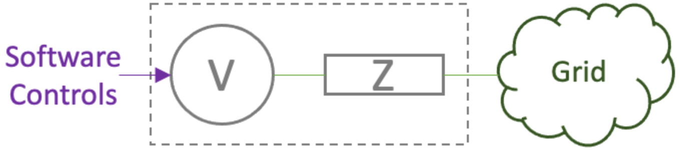
Grid-Following Inverters (GFL)

- Behaves like a current source (sense-then-respond, software-defined response)
- Stored energy varies (cycles at rated for PV, more with wind, hours with battery)
- Limited ability to release energy (1 – 1.5x current rating)

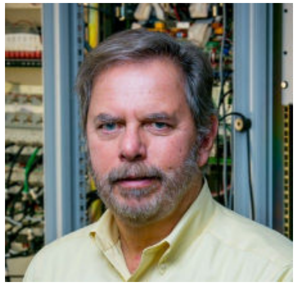


Grid-Forming Inverters (GFM)

- Behaves like a voltage source (inherent-like, software-defined response)
- Stored energy varies (cycles at rated for PV, more with wind, hours with battery)
- Limited ability to release energy (1 – 1.5x current rating)



Reliability Webinar series



Overview of Inverter-based resources and Grid Reliability

- What issues do we see today and how are they evolving?
- When does WECC need to worry about different issues?
- IBRs and essential reliability services

Oct 19 at 2:30pm MT

NERC and IEEE Activities on IBRs

- NERC Inverter-based Resources Performance Subcommittee
- NERC standards
- IEEE 2800 standard for IBRs

Nov 16 at 2:30pm MT

Grid-Forming Inverters

- What is a grid-forming inverter and how does it differ from today's inverters?
- Current experience with grid-forming inverters
- Grid-forming batteries for future proofing the system

Nov 30 at 2:30pm MT

Dr. Julia Matevosyan, ESIG

Julia is ESIG’s Chief Engineer and has more than 20 years of experience in the power industry. She was formerly the Lead Planning Engineer at ERCOT. Julia received her BSc from Riga Technical University in Latvia, and her MSc and PhD from the Royal Institute of Technology (KTH) in Sweden.

Grid Forming Battery Storage

Julia Matevosyan

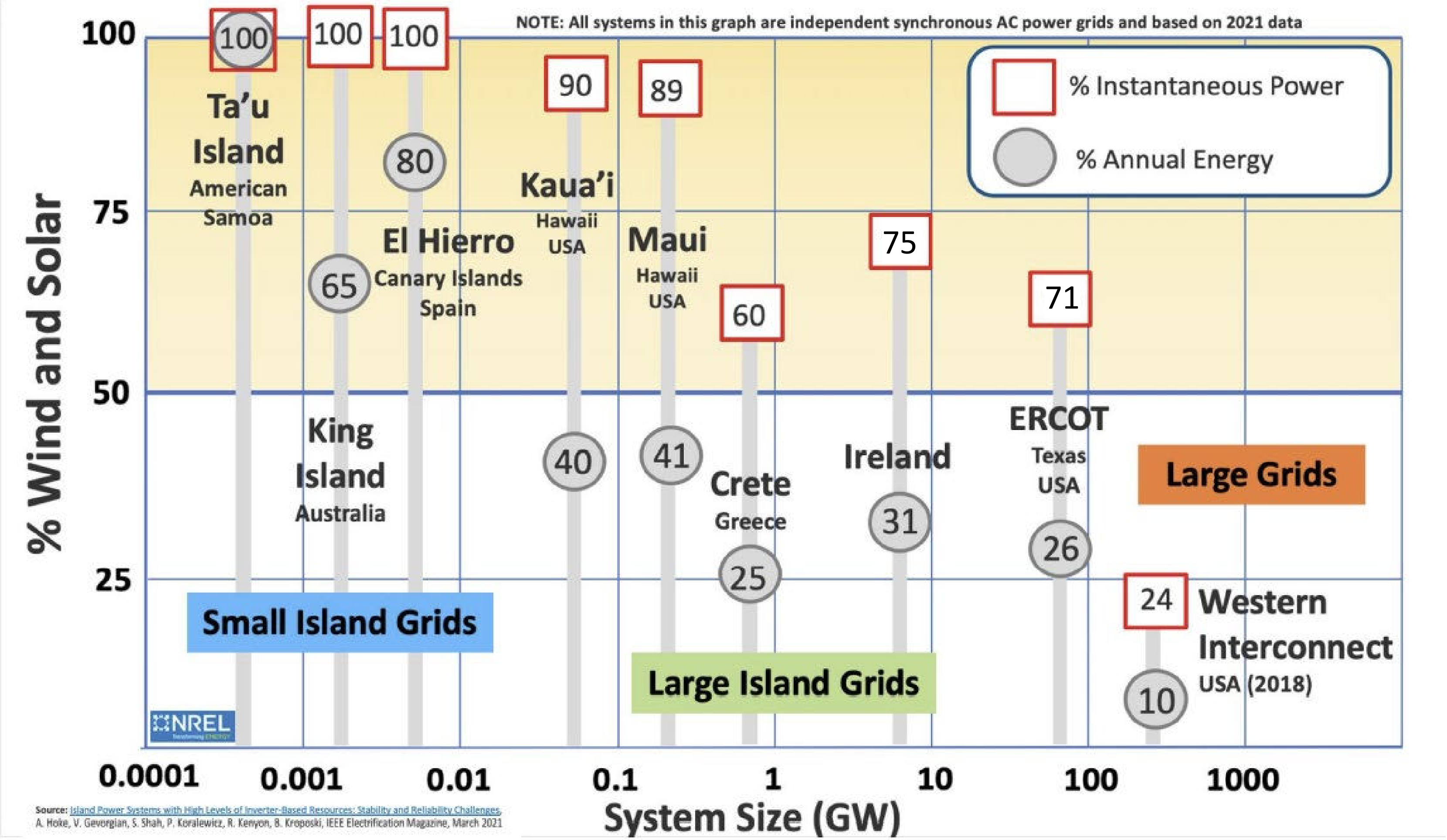
Chief Engineer

ESIG

11/30/2023

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

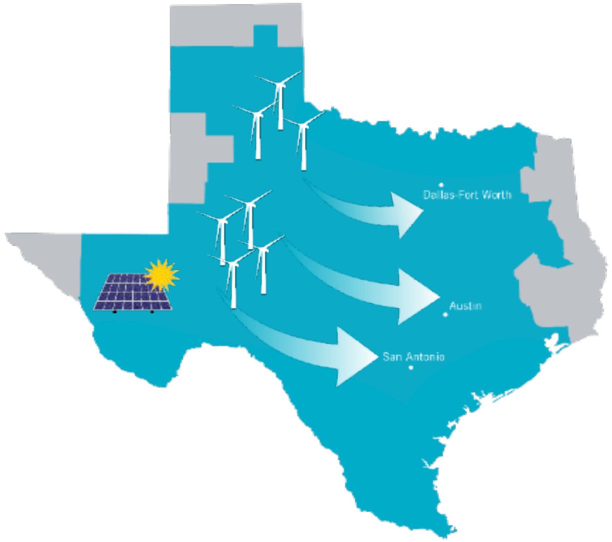
Where Are We Today with Inverter-Based Resources?



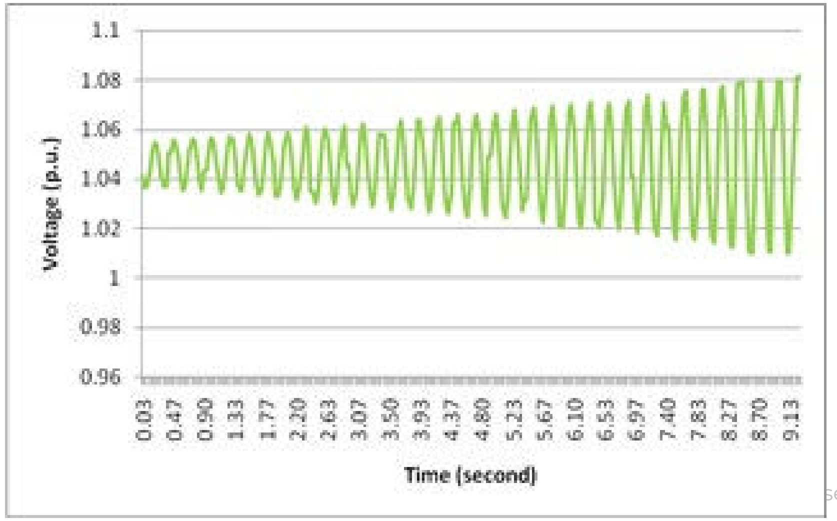
Source: NREL adjusted with latest changes in Irelands and ERCOT

Weak Grid Issues

- Majority of the inverters today are “grid-following” (GFL)
- They read the voltage and frequency of the grid, lock onto that, and inject power aligned with that signal.
- That signal comes from large 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.

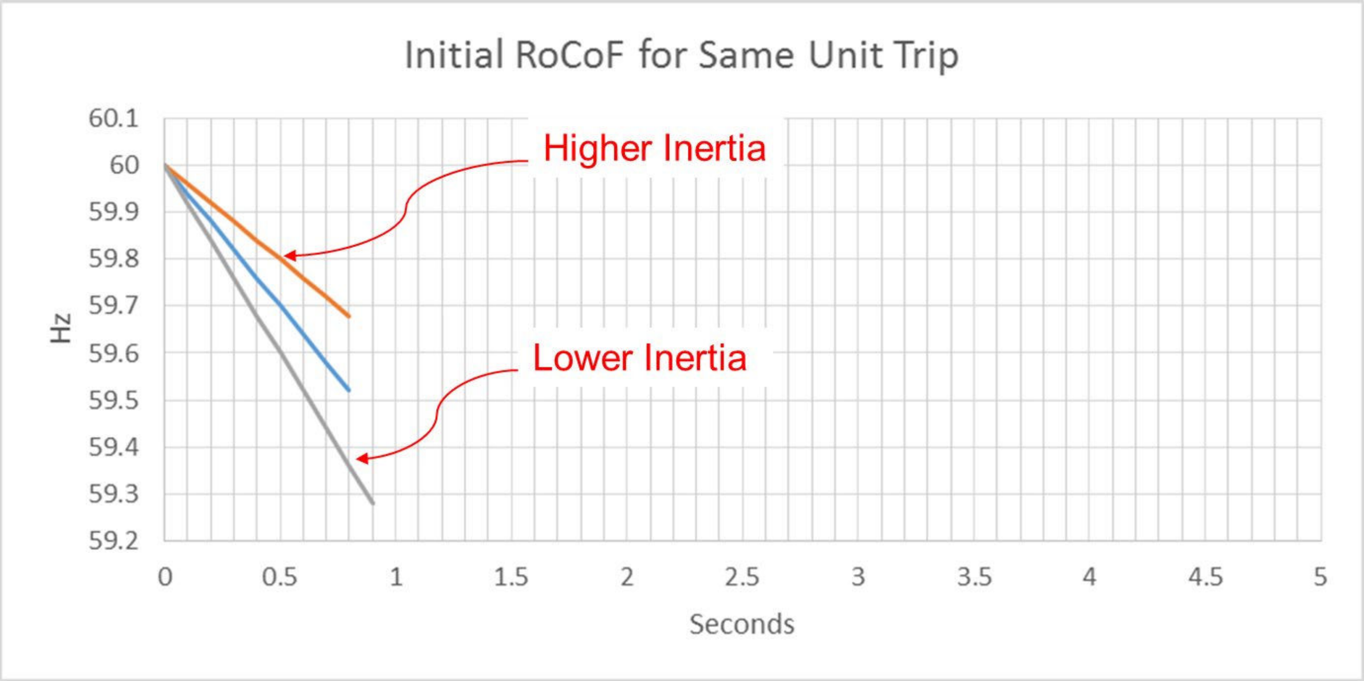


Example of Weak Grid in ERCOT



Inertia Issues

- Following a generator trip, the initial rate of change of frequency (prior to any resource response) is solely a function of inertia and size of tripped generator. To date, primarily synchronous machines provide inertia to the system
- With increasing integration of inverter-base resources (IBR), there could be periods when total inertia of the system could be low, as less synchronous machines will be dispatched to be online.



Summary of Issues with High Shares of GFL IBRs

- GFL IBRs do not contribute to system inertia or system strength
- IBRs displace synch. gen. exacerbating weak grid and inertia issues
- GFL IBRs require sufficient system strength to operate and sufficient inertia (if providing frequency response)
- Possible operating issues at high shares of GFL IBR:
  - Deeper frequency deviations after contingencies due to diminishing inertia
  - Inverter control interactions, due to low system strength
  - Failure to ride through disturbances in reduced system strength conditions
  - Protection issues
  - Diminishing black start capability

System Strength and Inertia Solutions

- There is a limit of how many GFL IBRs that can be accommodated (due to system strength and inertia issues)
- System operators may limit the output of IBRs and supply the remaining load with synchronous generators to ensure sufficient system strength and/or inertia (e.g. Australia, Ireland, Texas)
  - Such operational constraints in the long run may impact further development of IBRs
- Alternatively, other supplemental equipment is added to the grid, costs and benefits need to be carefully assessed
- Grid forming (GFM) inverter technology is also being considered in recent years. GFM IBRs can create their own voltage and frequency signal (islanded operation) or operate in coordination with other GFM resources supporting stability of an interconnected grid.

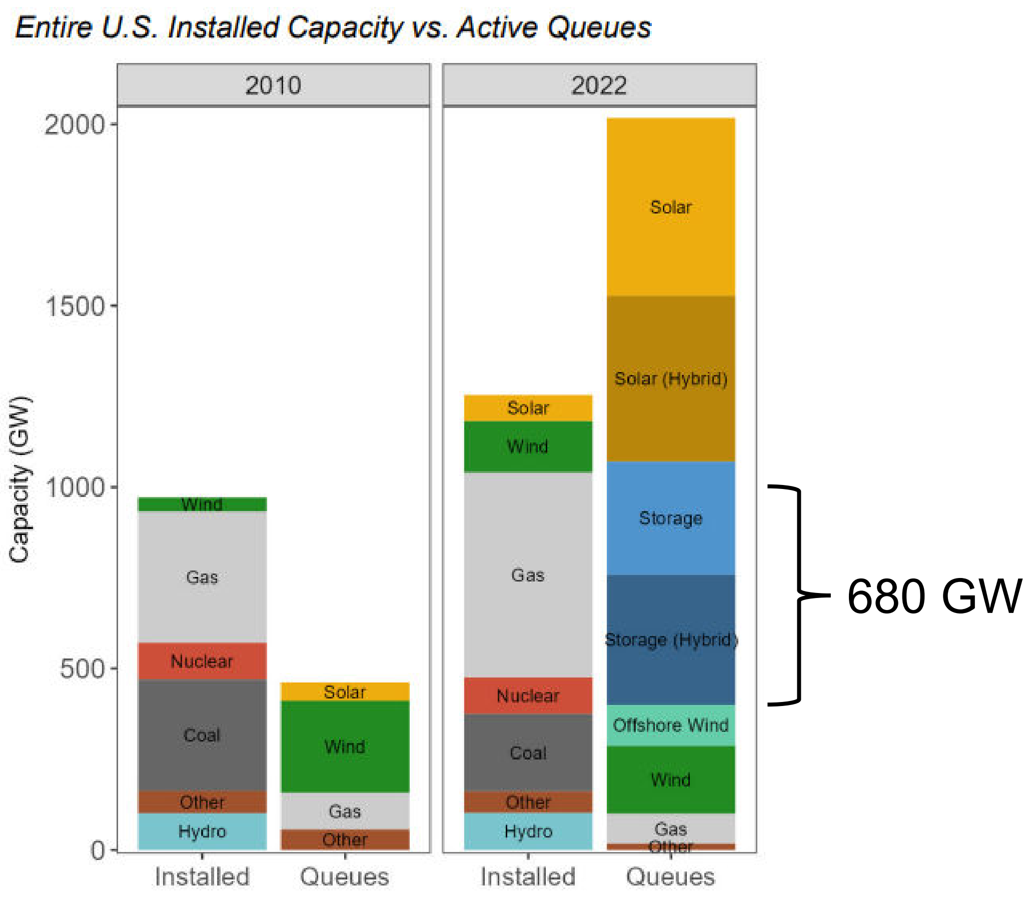
GFM Batteries are a Low-Hanging Fruit

- 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)

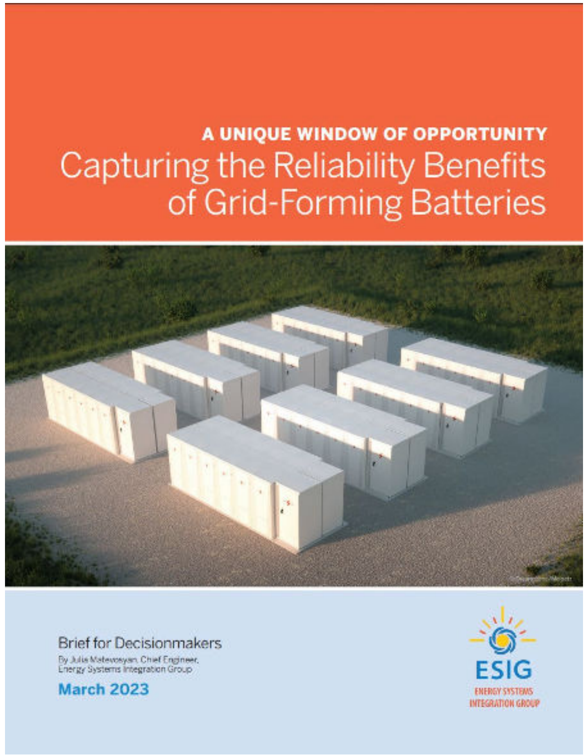
Source: E. Quitmann, ESIG Spring Technical Workshop, 2020

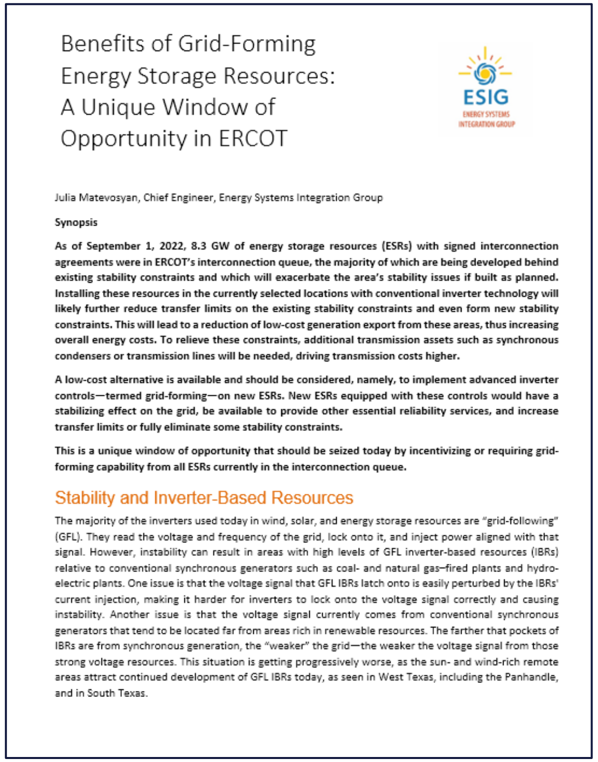
A number of batteries with GFM controls have already been deployed around the world, and further development is happening at unprecedented speed

Grid Forming Batteries a Unique Window of Opportunity



Source: LBNL, Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection, https://emp.lbl.gov/queues





Benefits of Grid-Forming Energy Storage Resources: A Unique Window of Opportunity in ERCOT

Julia Matevosyan, Chief Engineer, Energy Systems Integration Group

Synopsis

As of September 1, 2022, 8.3 GW of energy storage resources (ESRs) with signed interconnection agreements were in ERCOT's interconnection queue, the majority of which are being developed behind existing stability constraints and which will exacerbate the area's stability issues if built as planned. Installing these resources in the currently selected locations with conventional inverter technology will likely further reduce transfer limits on the existing stability constraints and even form new stability constraints. This will lead to a reduction of low-cost generation export from these areas, thus increasing overall energy costs. To relieve these constraints, additional transmission assets such as synchronous condensers or transmission lines will be needed, driving transmission costs higher.

A low-cost alternative is available and should be considered, namely, to implement advanced inverter controls—termed grid-forming—on new ESRs. New ESRs equipped with these controls would have a stabilizing effect on the grid, be available to provide other essential reliability services, and increase transfer limits or fully eliminate some stability constraints.

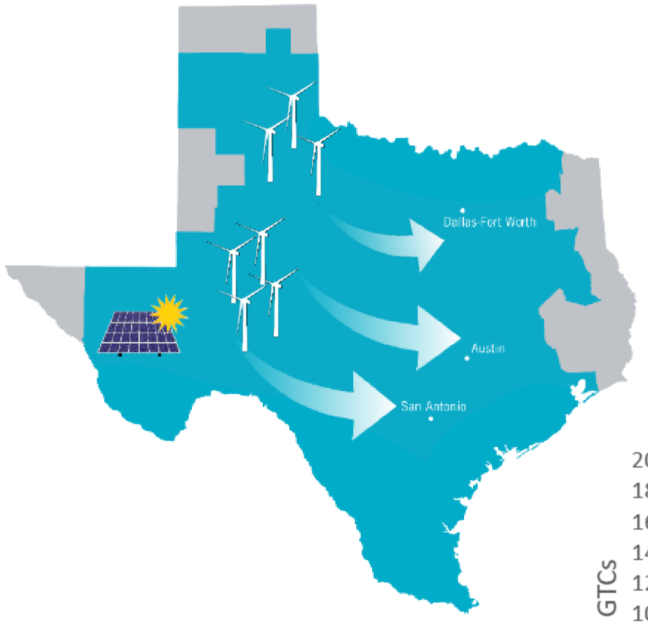
This is a unique window of opportunity that should be seized today by incentivizing or requiring grid-forming capability from all ESRs currently in the interconnection queue.

Stability and Inverter-Based Resources

The majority of the inverters used today in wind, solar, and energy storage resources are "grid-following" (GFL). They read the voltage and frequency of the grid, lock onto it, and inject power aligned with that signal. However, instability can result in areas with high levels of GFL inverter-based resources (IBRs) relative to conventional synchronous generators such as coal- and natural gas–fired plants and hydro-electric plants. One issue is that the voltage signal that GFL IBRs latch onto is easily perturbed by the IBRs' current injection, making it harder for inverters to lock onto the voltage signal correctly and causing instability. Another issue is that the voltage signal currently comes from conventional synchronous generators that tend to be located far from areas rich in renewable resources. The farther that pockets of IBRs are from synchronous generation, the "weaker" the grid—the weaker the voltage signal from those strong voltage resources. This situation is getting progressively worse, as the sun- and wind-rich remote areas attract continued development of GFL IBRs today, as seen in West Texas, including the Panhandle, and in South Texas.

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

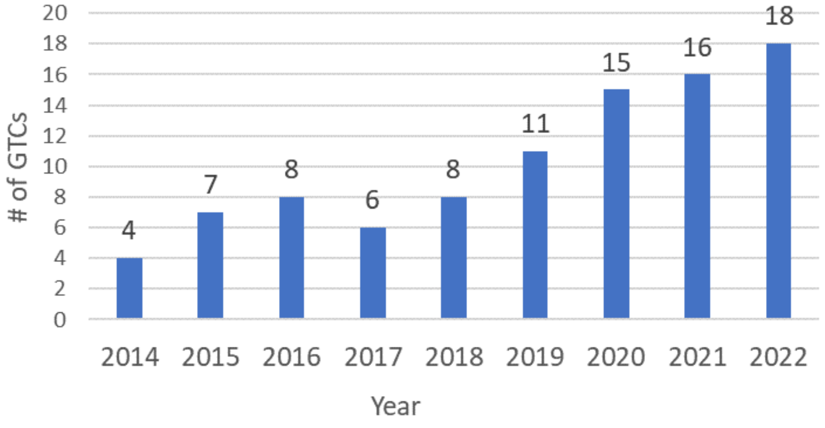
Stability-Related Constraints & Renewable Curtailments, with Example of ERCOT



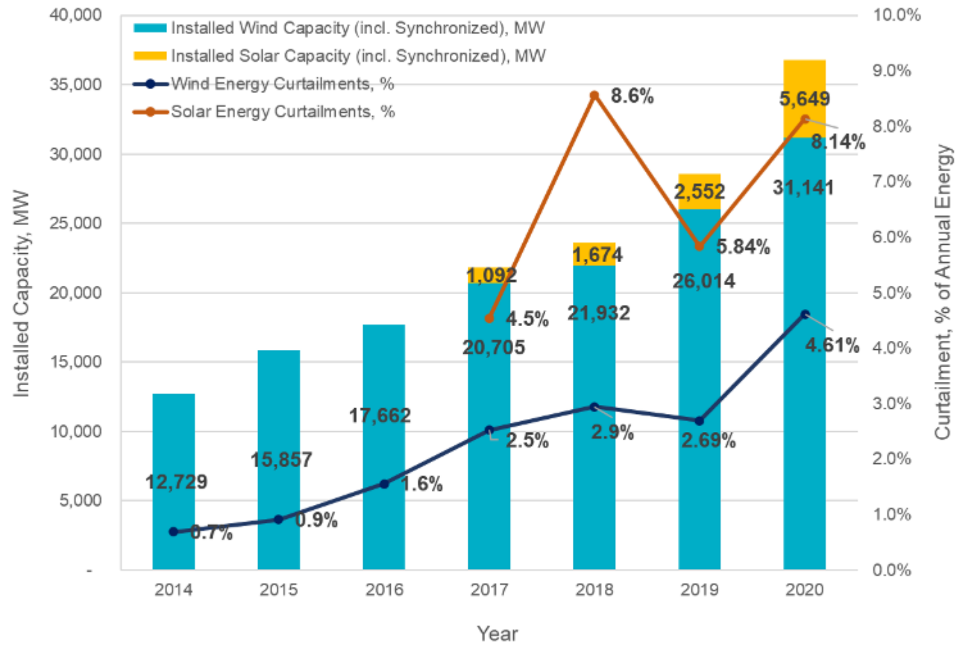
Peak Load – 85 GW
Wind - 37.7 GW
Solar – 19.6 GW
Battery – 4 GW

71% instantaneous IBR penetration in April 2022

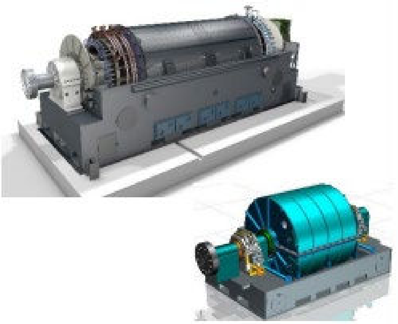
Number of Effective Generic Transmission Constraints (GTC) by Year



Growth of Wind and Solar Curtailments as More Capacity is Added to the ERCOT Grid, 2014-2020

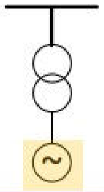


Current Strategies to Relieve Stability Constraints due to Weak Grids– Adding Transmission Assets



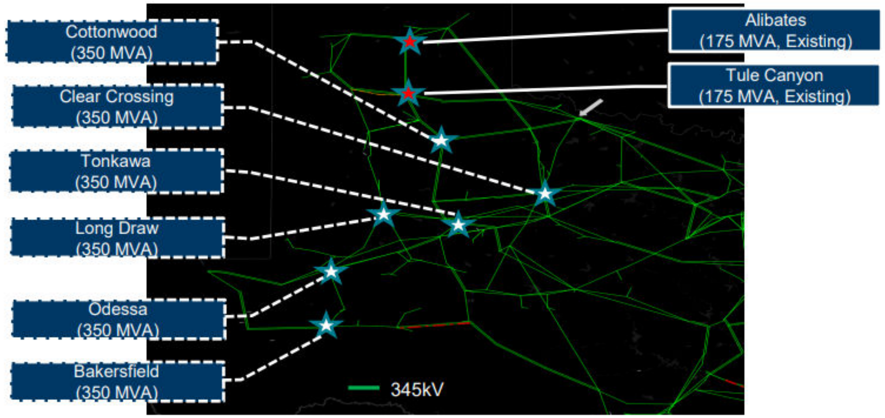
Synchronous Condenser – (w/wo Flywheel)

- 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.



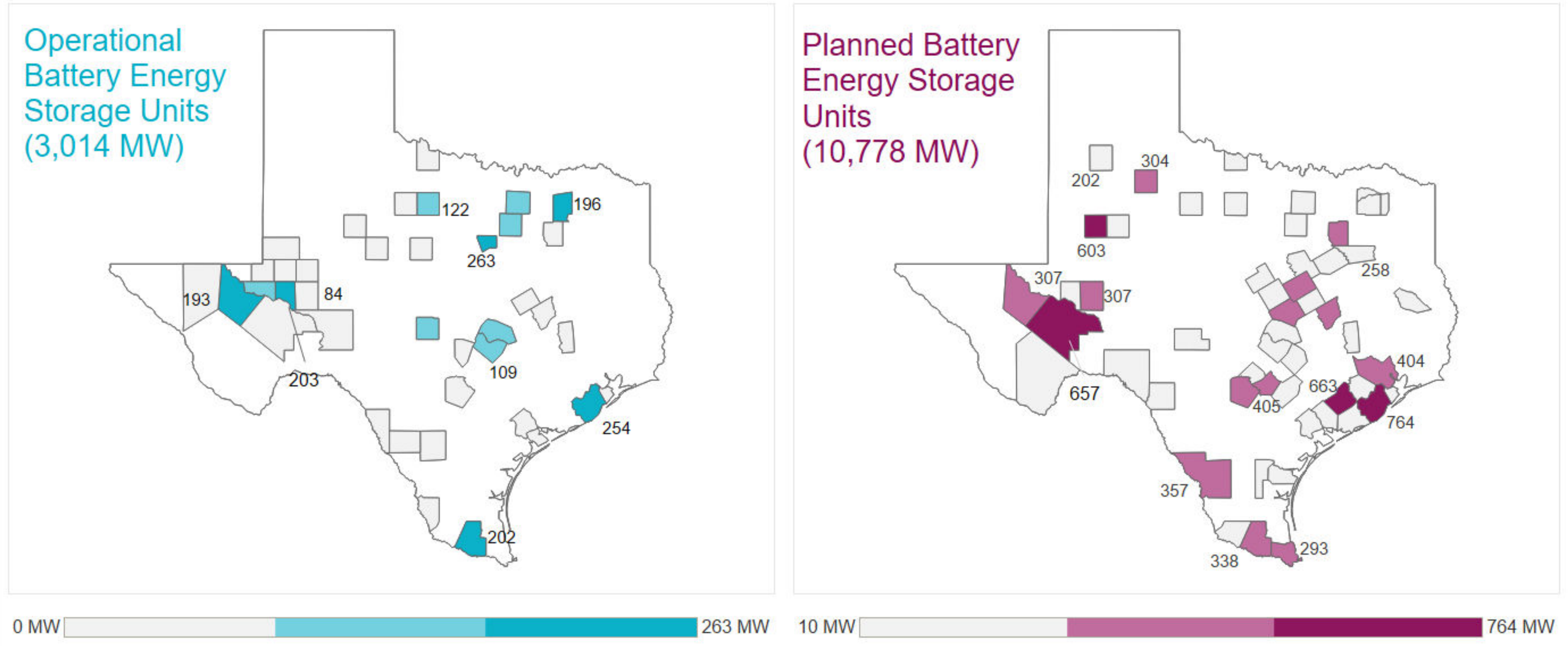
Source: ERCOT, *Strengthening the West Texas Grid to Mitigate Widespread Inverter-Based Events – Operation Assessment Results*, Regional Planning Group meeting, Feb 2023

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

Source: iStockphoto/Yelantsevv

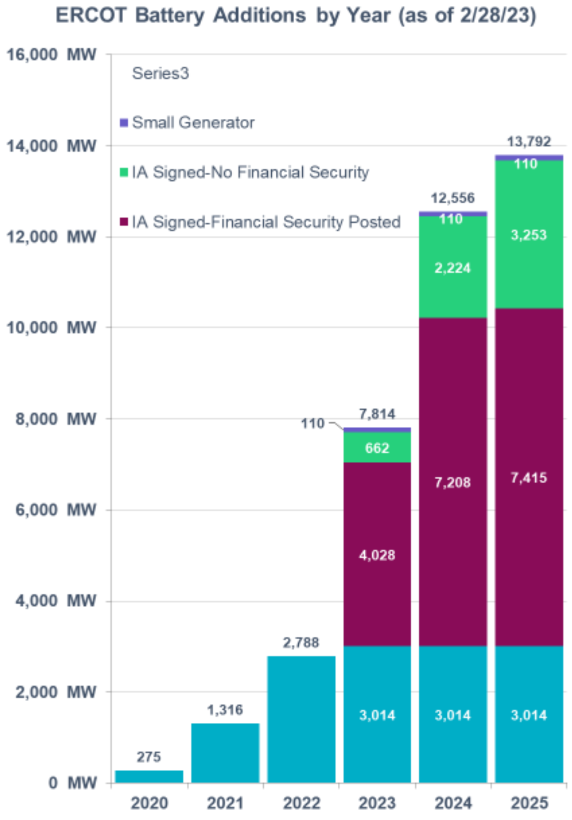
Existing and New Batteries Behind Constraints

In the absence of clear requirements and market incentives for GFM control capabilities, all planned batteries will be built using GFL controls. This may increase systems' needs for additional supplemental devices to improve stability, which will drive-up overall system costs.



Footnotes: Operational category includes units approved to be Synchronized but not Approved for Commercial Operations. Planned category includes incudes DGRs and planned projects with signed interconnection agreements (IA Signed) thare have not been Synchronized to the ERCOT Grid.

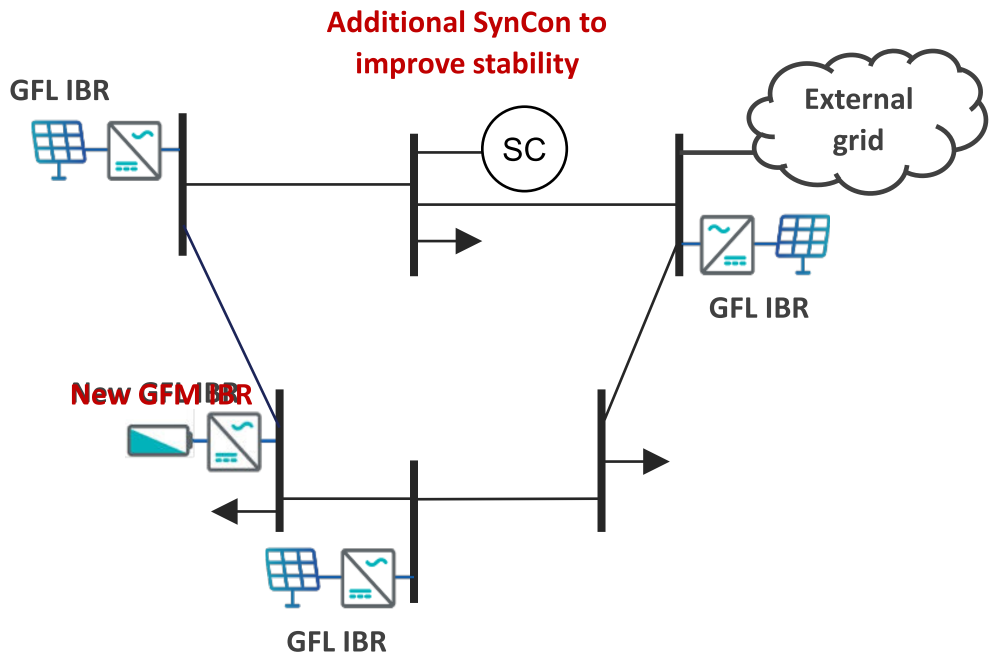
Data from ERCOT Resource Adequacy Department - February 2023 Resource Capacity Trend Charts



Grid Forming Controls as an Alternative for Grid Strength Support

- GFM IBRs can be designed to provide, within equipment limits, most of the services that are currently inherently provided by synchronous generators
- GFM IBRs have a stabilizing effect in weak grid areas and improve stability for IBRs with 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.



GFM Battery Projects Deployed and Under Construction

Table I.1: GFM BESS Projects Deployed or under Construction			
Project Name	Location	Size (MW)	Time
Project #1	Kauai,USA	13	2018
Kauai PMRF	Kauai,USA	14	2022
Kapolei Energy Storage	Hawaii, USA	185	2023
Hornsdale Power Reserve	Australia	150	2022
Wallgrove	Australia	50	2022
Broken Hill BESS	Australia	50	2023
Riverina and Darlington Point	Australia	150	2023
New England BESS	Australia	50	2023
Dalrymple	Australia	30	2018
Blackhillock	Great Britain	300	2024
Bordesholm	Germany	15	2019

Additionally, in Dec 2022, the Australian Renewable Energy Agency (ARENA) announced co-funding of additional eight large scale GFM batteries across Australia with total project capacity of 2 GW/4.2 GWh, to be operational by 2025

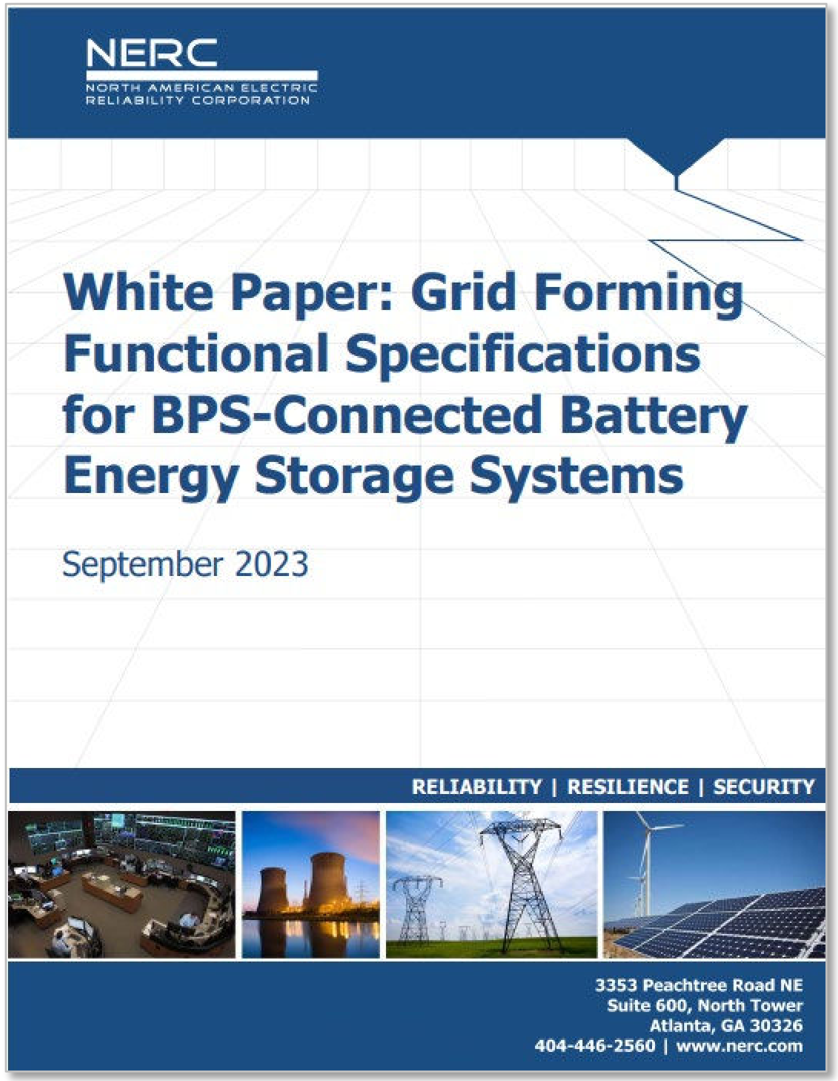
Source: NERC IRPS White Paper, Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems

Grid Forming Specs Landscape At Glance

- **MIGRATE:** EU-funded project on the Massive Integration of Power Electronic Devices (2019)
- **HECO:** Model Energy Storage Power Purchase Agreement (2019)
- **NREL:** Research Roadmap for Grid Forming Inverters (2020)
- **ENTSO-E:** High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters (2020)
- **VDE FNN:** Guideline Grid forming behavior of HVDC systems and DC-connected PPMs (2020)
- **NGESO:** GC0137 Minimum Specification Required for Provision of GB Grid Forming Capability (2021)
- **AEMO:** Application of Advanced Grid-Scale Inverters in the National Electricity Market (2021)
- **HECO:** Model Energy Storage Power Purchase Agreement (2021)
- **OSMOSE:** EU-funded project (continuation of MIGRATE) that defined grid forming capability and new services (2022)
- **UNIFI:** Specifications for Grid-Forming Inverter-Based Resources – Version 1 (2022)
- **NGESO:** Great Britain Grid Forming Best Practice Guide (2023)
- **AEMO:** Voluntary Specification for Grid-Forming Inverters (2023)
- **FINGRID:** Specific Study Requirements for Grid Energy Storage Systems (focuses on grid forming requirements) (2023)
- **NERC:** Grid Forming Functional Specifications for BPS-Connected Battery Energy Systems (2023)

Source: Adopted by ESIG based on UNIFI, [GFM Inverter Technology Specifications: Review of Research Reports and Roadmaps]

Updates on Grid Forming Inverter Technology


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems

September 2023

RELIABILITY | RESILIENCE | SECURITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

- GFM is commercially available for BPS-connected BESS
  - Standalone and hybrid element
  - Very small incremental project cost
- All new BESS should be designed, commissioned, and operated in GFM mode
  - Additional grid-stabilizing characteristics
- Requires studies, like any plant
- Also requires testing against a GFM functional spec
- Requires EMT studies

Source: WIRAB Webinar Series, Ryan Quint, Webinar #2: Inverter Based Resource Standards and Rules to Maintain Reliability

Common Functionalities

- Response to voltage phase angle step
- Response to voltage magnitude step
- Active/Reactive Power Sharing
- Provide Damping
- Counter Harmonics
- Response to RoCoF event (MW loss)
- Response to Faults (balanced and unbalanced)
- Low SCR Operation
- Island Operation
- Black Start

ERCOT: Preliminary assessment of GFM BESSs

- ERCOT: 4 GW of BESS installed, 10 GW with SGIA and Financial Security, 3 GW with signed IA by 2025
- ERCOT GFM BESS evaluation in 3 scenarios
  1. A weak grid condition (a simple test case in phasor-domain to prove the concept)
  2. West Texas grid (tested in phasor-domain)
  3. ERCOT local area, 138 kV, with identified stability constraints (tested in both phasor-domain and EMT)
- GFM BESS generic dynamic models used from PNNL and EPRI
- Results show that a GFM BESS could be a viable option to improve system dynamic responses, but:
  - cannot solve all the issues with GFM only
  - require headroom to provide adequate GFM support
  - still require proper control settings and coordination
- ERCOT is working on the GFM BESS requirements including but not limited to performance, models, studies, and verification.

Y. Cheng, ERCOT, *Preliminary assessment of Grid Forming Inverter-Based Energy Storage Resources in the ERCOT Grid*, ESIG Fall Technical Workshop, 2023

AEP/EPRI: Case Studies of the Stability Benefit of GFM Inverters on Energy Storage Facilities

Studies in phasor domain with EPRI's generic GFM BESS model (allows to test three different GFM control modes):

- Case 1: 230 kV station in Oklahoma
- Case 2: 345/138 kV station in ERCOT
- Case 3: 138 kV Generic Transmission Constraint area in ERCOT

Results:

- A BESS equipped with GFM control is effective in stabilizing GFL IBRs under various "weak" grid conditions.
- Different forms of instability: partial voltage collapse, poorly damped oscillations, and rapid unstable GFL IBRs can all be resolved.
- GFM BESS brings a system to stable operating points by short-term dynamic active and reactive power injection.

Future Work:

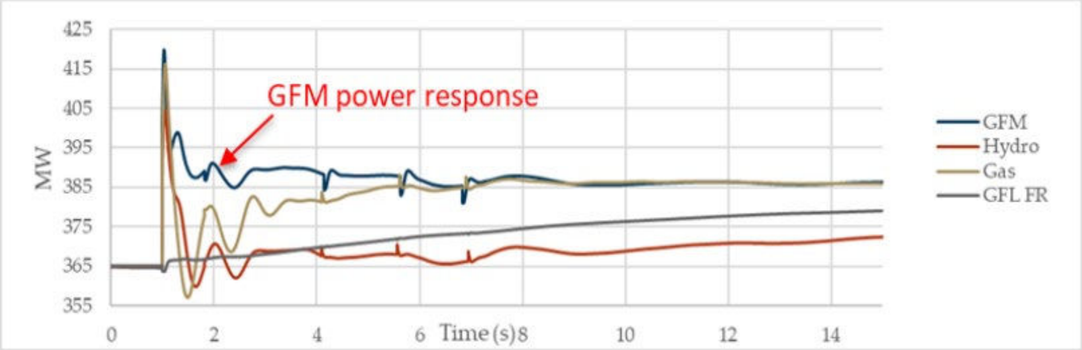
- Test other GFM control modes and study of GFM behavior in other unstable events
- Determine of optimal GFM sizing, appropriate number and placement of GFMs
- GFM device control tuning is very important; particular settings may not always be effective in all scenarios.

N. Ekneligoda, R. O'Keefe (AEP), D. Ramasubramanian (EPRI), Case Study of the Stability Benefit of Grid Forming Inverters on Energy Storage Facilities, ERCOT IBRWG, September 2023

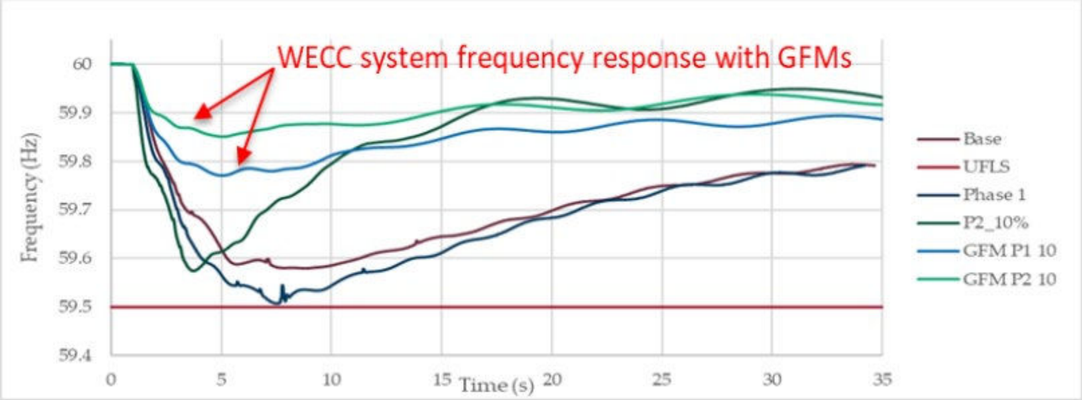
WECC Study, Grid Forming Inverters

- 37 GW of synchronous generation was replaced by IBRs (GFMs and GFLs)
- Two levels of headroom were studied: 10% and 6%
- The response of the GFM in the study is faster than the gas generator, hydro generator, and GFL, which would be beneficial for the system frequency stability
- The system primary frequency response is significantly improved by GFMs with headroom

WECC Recommendation: *Planning Coordinators should strongly consider GFM technology when replacing synchronous generators with IBRs. They should be designed to provide reliable and robust performance that supports high IBR penetration in the Western Interconnection.*



Response of gas generators, hydro generators, GFMs and GFLs near the outage



Note: The purpose of the study was to demonstrate capabilities of GFM BESS, not to evaluate capabilities of existing GFL IBRs. If GFL IBR provide fast frequency response, less GFM BESS is needed.

WECC, Grid Forming Inverters, November 2023

Conclusions on Specifications

- GFM specifications is still a new topic and is developing together with GFM controls
- All specifications are similar in terms of functionalities, with main differences being around level of specificity and if a requirement is explicit or implicit in a certain specified behavior
- Some of the requirements are more specific while others are high level, in some cases accompanied with performance expectations during testing
- Balance is needed between incentivizing desired behavior (as synchronous machines are being displaced) and allowing freedom in control implementation by OEMs
- High level requirements accompanied with more detailed performance guidelines seems to be a preferred approach today
- Some functionalities can be implemented in grid following inverters as well; these shouldn't be included as a part of GFM specifications.

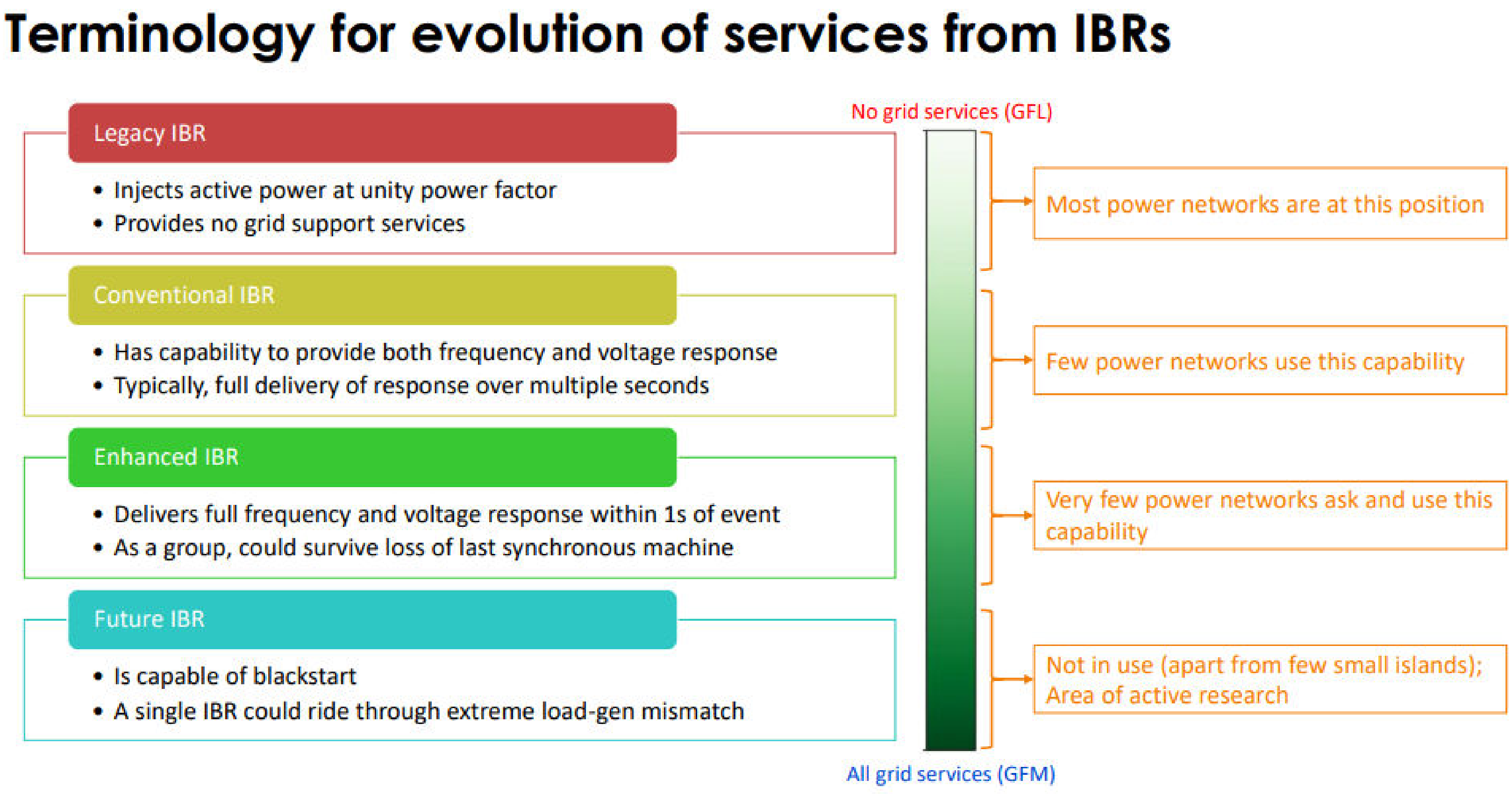
Opportunity to Future-proof Today's Installations

- Deploying GFM control capability in batteries is a low-hanging fruit solution to weak grid issues that increasingly are the cause of stability-related transmission constraints, and renewable curtailments.
- But the opportunity for ISOs/RTOs/utilities to utilize this resource-based solution may soon pass.
- While only a relatively small number of utility-scale batteries are installed in the U.S. today, a significant amount of battery capacity will likely be developed in the next few years.
- Without specifications and/or incentives for GFM, new batteries will be built with GFL controls, exacerbating stability challenges and the need for additional stabilizing equipment such as synchronous condensers or new transmission.
- With specifications and incentives, new batteries will be installed with GFM capability and help to improve grid stability, reduce curtailment, and reduce the need for additional stabilizing equipment.
- ISOs/RTOs/utilities can work with stakeholders to carry out studies of the benefits of deploying GFM technology and initiate pilot projects
- Experience from installations around the world, particularly in Hawaii, Australia, and Great Britain, can be used as a guide.

THANK YOU

Julia Matevosyan

julia@esig.energy



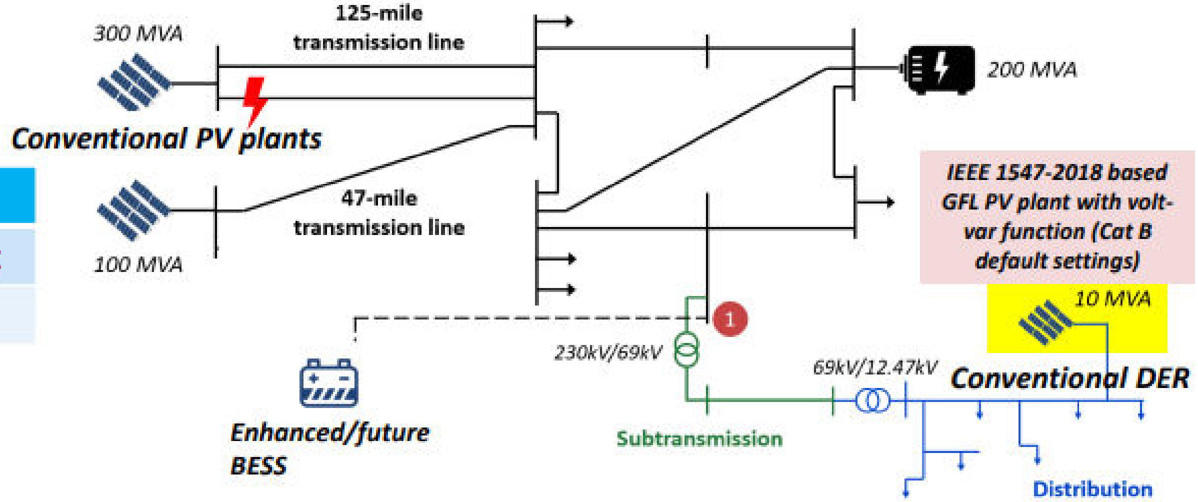
The presentation focused on:

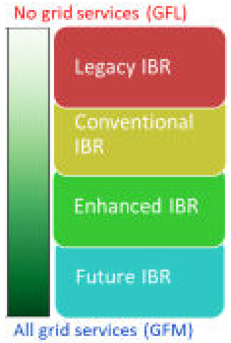
- How does transmission stability is impacted be DER
- What role does load dynamics play
- If DERs are facing stability challenges, can these be effectively resolved by transmission connected enhanced/future IBRs alone?
- Will increased robustness of DERs become necessary in power systems with high renewable penetration?

Deepak Ramasubramanian, EPRI, *Value of GFM DER in High Penetration Scenarios*

Will the same BESS solutions work when additional large DER is connected in Dx?

Location	Minimum future BESS Capacity	
	Stabilize Tx	Stabilize Tx & Dx
1	45 MVA	90 MVA



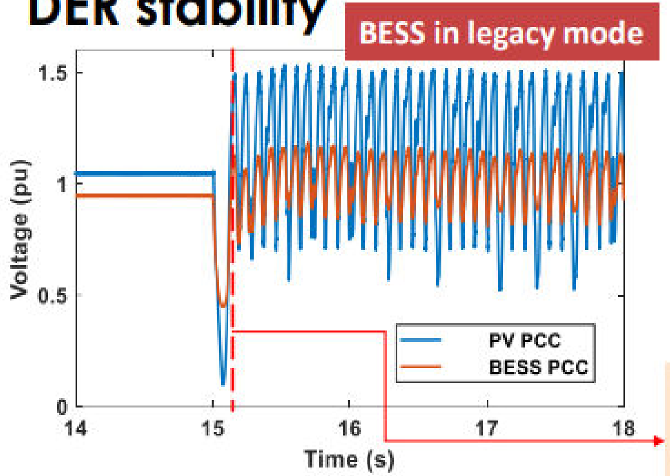


- The Tx-connected BESS capacity required to stabilize both Tx and Dx is much greater than the capacity required to stabilize Tx itself
- Increasing hosting capacity of renewable DERs is critical to reach net-zero emissions but relying solely on Tx-connected resources may not be an efficient solution

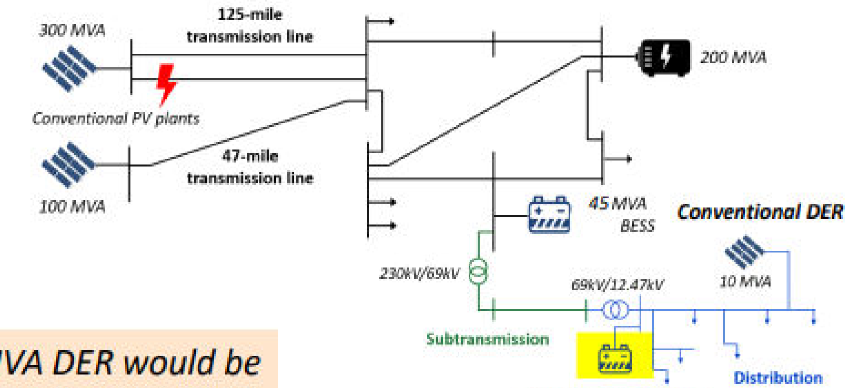
Deepak Ramasubramanian, EPRI, *Value of GFM DER in High Penetration Scenarios*

ESIG Fall Workshop 2023 Session 6: GFM Developments

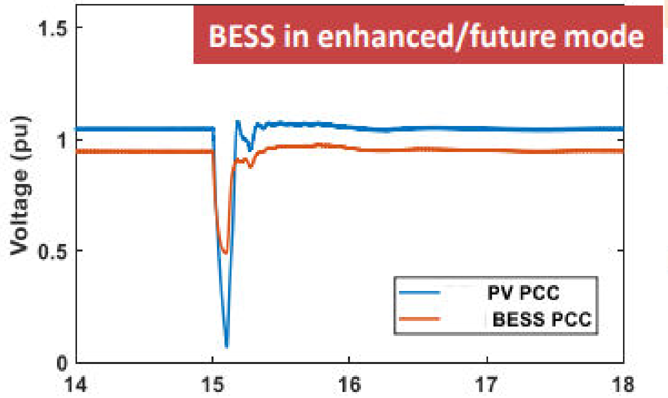
Example results – beneficial impact of enhanced/future BESS on DER stability



The 10MVA DER would be tripped if IEEE 1547-2018 trip settings are activated



5 MVA BESS mode?



- Operating the BESS in enhanced/future mode can stabilize the conventional PV for the 0.1s fault event considered
- Compared to Tx-connected BESS, ***less BESS capacity*** is needed in the Dx to stabilize the conventional DER

Conclusion:

- High penetration of DERs/IBRs and retirement of SGs can cause instability in distribution and transmission networks
- Load dynamics are important to be considered
- Transmission connected enhanced/future IBRs can help increase distribution hosting
- capacity of DERs but high capacity might be required
- Enhanced/future DER may be an effective to increase hosting capacity and improve power quality of the distribution system

Deepak Ramasubramanian, EPRI, *Value of GFM DER in High Penetration Scenarios*

THANK YOU

Western Interconnection Regional Advisory Body