Grid-Forming Battery Energy Storage Systems

ESIG GFM BESS Benefits Project Team Meeting

October 3, 2024

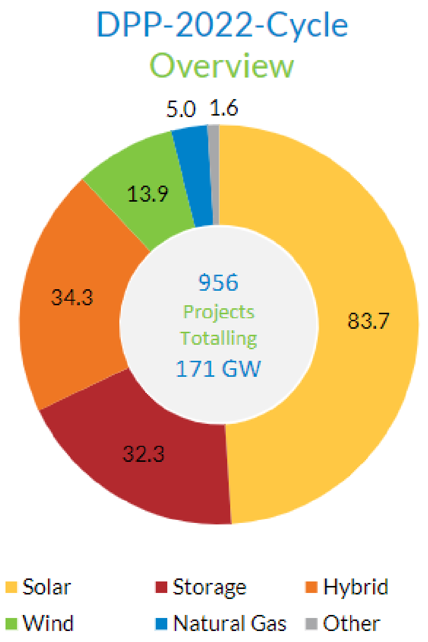
Purpose & Key Takeaways

Purpose: Share MISO's path to adopt advanced inverter-based resource performance standards

Key Takeaways:

- An influx of inverter-based resources in MISO's area coupled with identified risks is driving action
- MISO is taking a stepped approach to implementing IEEE 2800-2022, with the first phase approved by FERC
- Grid-forming control requirements for battery energy storage systems are proposed for future resources

MISO's 2022 generator interconnection queue submissions set new records, with IBR making up the vast majority of proposed resources



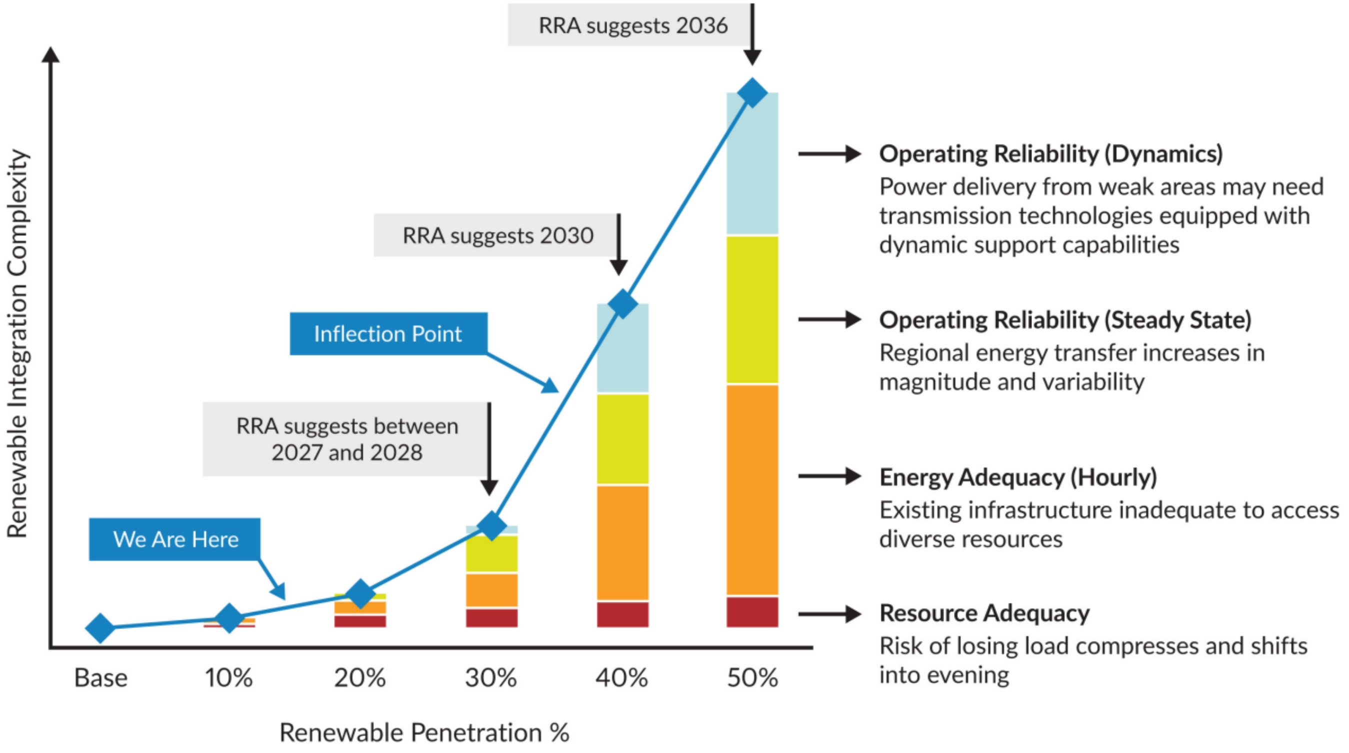
Fuel	# of Requests	GW
Solar	469	83.7
Storage	231	32.3
Hybrid	163	34.3
Wind	66	13.9
Natural Gas	21	5.0
Other	6	1.6
Grand Total	**956**	**170.8**

Around 96% of capacity is likely inverter-based

The next round of requests in 2023 had roughly 124 GW of submissions with 93% consisting of IBR

MISO, 2022 Generator Interconnection Queue Submissions. Available at: https://cdn.misoenergy.org/2022%20GIQ%20Submission%20Statistics626443.pdf

MISO's Regional Resource Assessment indicates a renewable integration inflection point may be approached in coming years



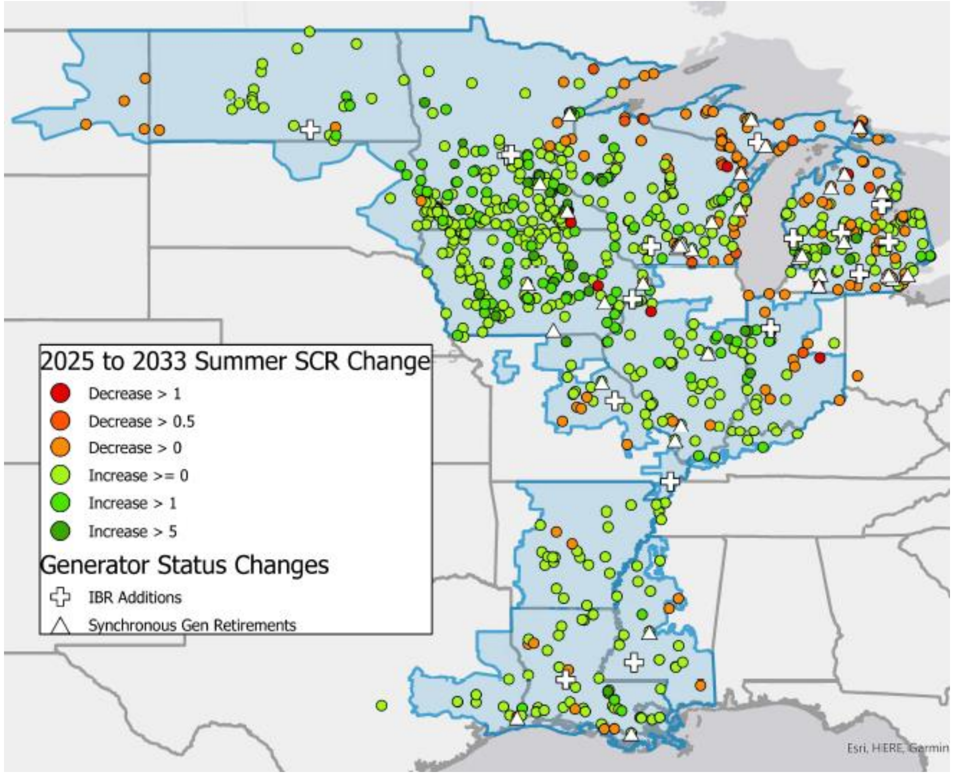
Dynamic voltage stability impacts are anticipated to be first stability issue that will need to be addressed (30% milestone).

Renewable penetration % is the portion of energy served in that milestone. Peak instantaneous penetration can be roughly double this value.

Resource fleet transition is a major driver of decreasing system strength within localized pockets of MISO

- − Resource retirements lower system strength and "grid-following" capabilities
- − IBR deployments do not offset drops in system strength from retirements
- + Transmission build-out can help boost system strength

MISO is still investigating the role of MTEP Report Appendix A projects in offsetting fleet transition system strength impacts.



Change in SCR between MTEP23 2025 Summer peak and MTEP23 2028 Summer peak cases with resources retirement and IBR additions mapped

In 2023, MISO supported Telos Energy and Hickory Ledge development of a screening method that was applied to the large MISO system to evaluate effectiveness at scale

- The scaled analysis started with the Illinois interface transfer, which has been discussed in other stakeholder forums.[1]
  - Transfer scaled up for limited portion of the system to accentuate the results.
  - Dynamic impedance applied to all large resources, amounting to 1100 generators.
- However, an extraordinary contingency (i.e., beyond TPL) was used to accentuate difference in static and dynamic limits.
  - Two 345 kV lines were taken out simultaneously to stress the system, which is considered "N-1" for this demonstration.

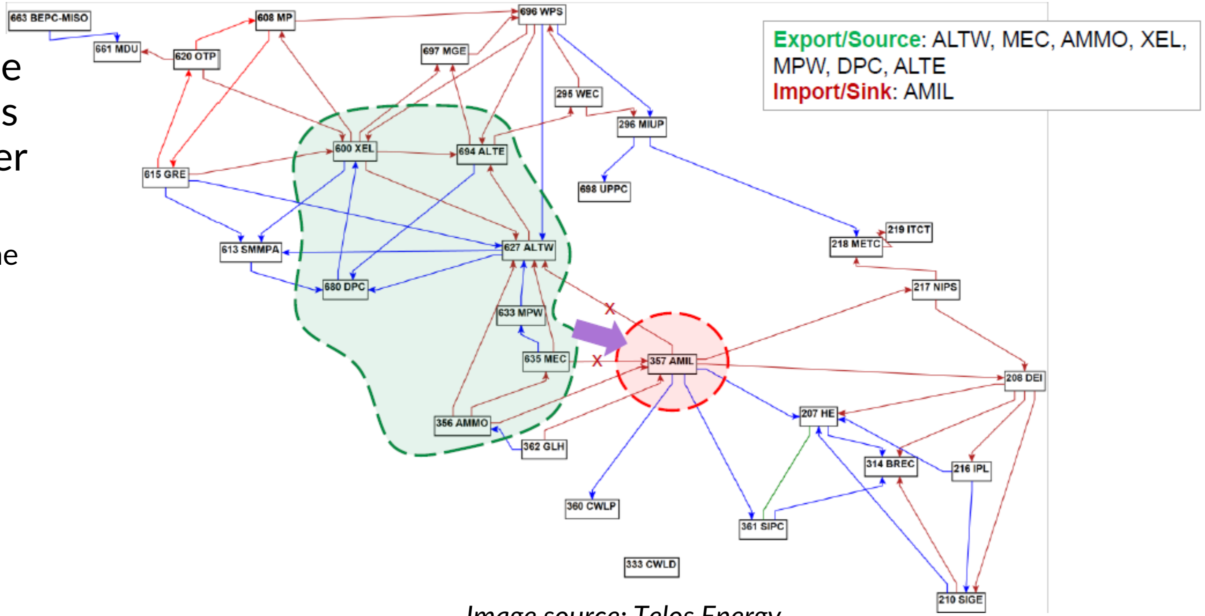
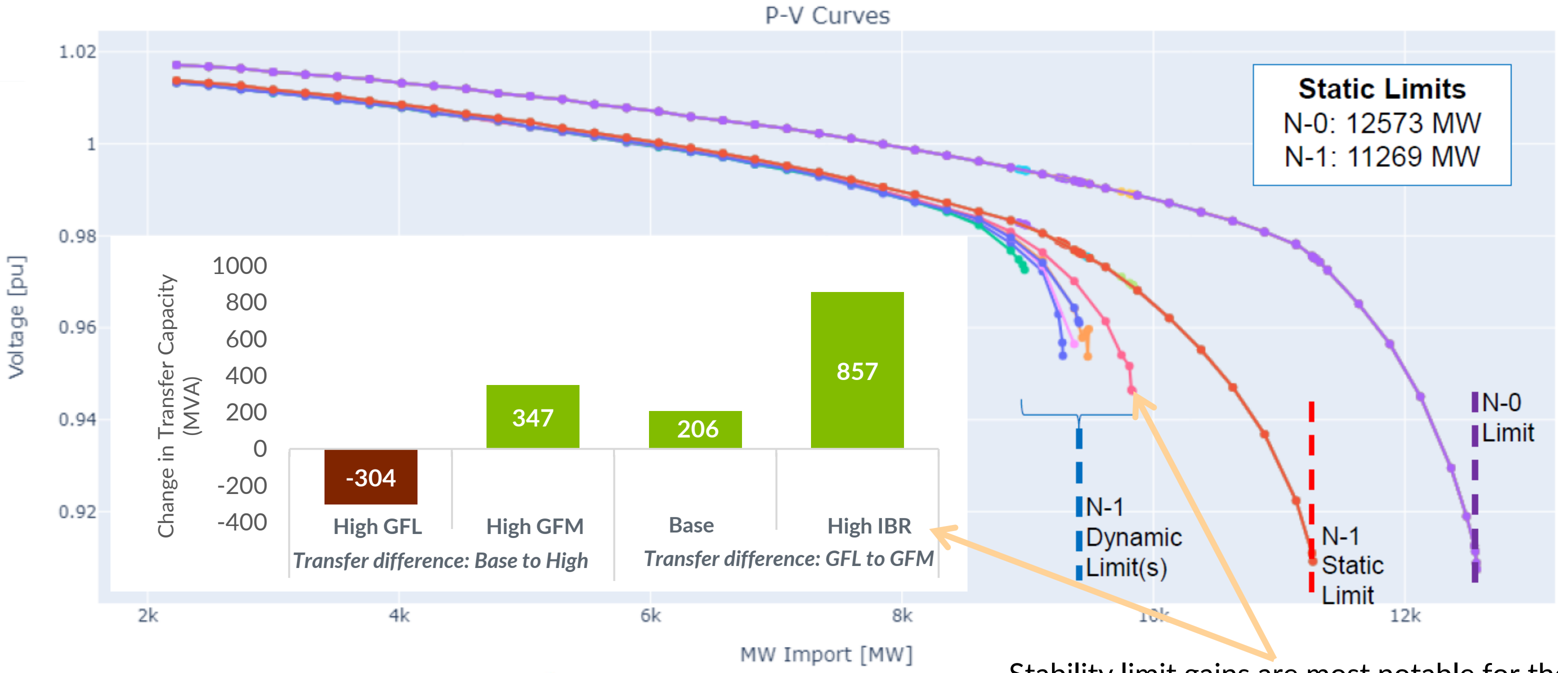


Image source: Telos Energy

[1] The Illinois transfer is analyzed as part of the MTEP process and has been presented at Planning Subcommittee meetings. Materials for the September 27th PSC are available at: https://cdn.misoenergy.org/20230927%20PSC%20Item%2005b%20MTEP23%20Voltage%20Stability%20Analysis%20Results630304.pdf

Analysis suggests grid forming technologies meaningfully increase dynamic stability limits when compared to grid following technology

For high IBR penetrations, the **high GFM case limit is about 10% higher than the high GFL case**

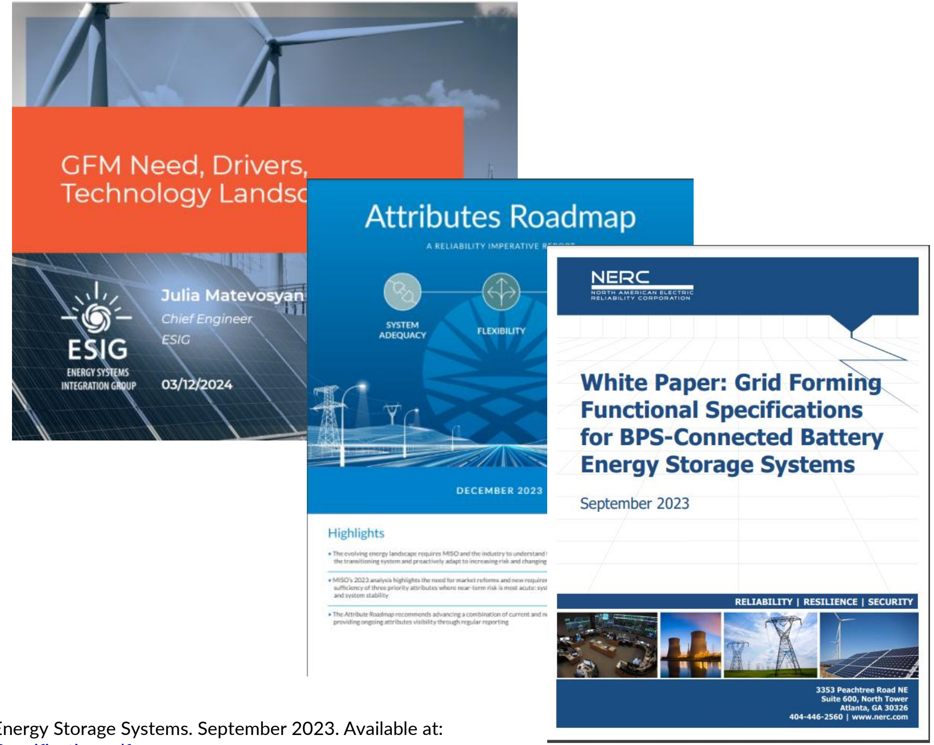


Stability limit gains are most notable for the case of GFM compared to GFL in the High IBR case

Source: Telos Energy

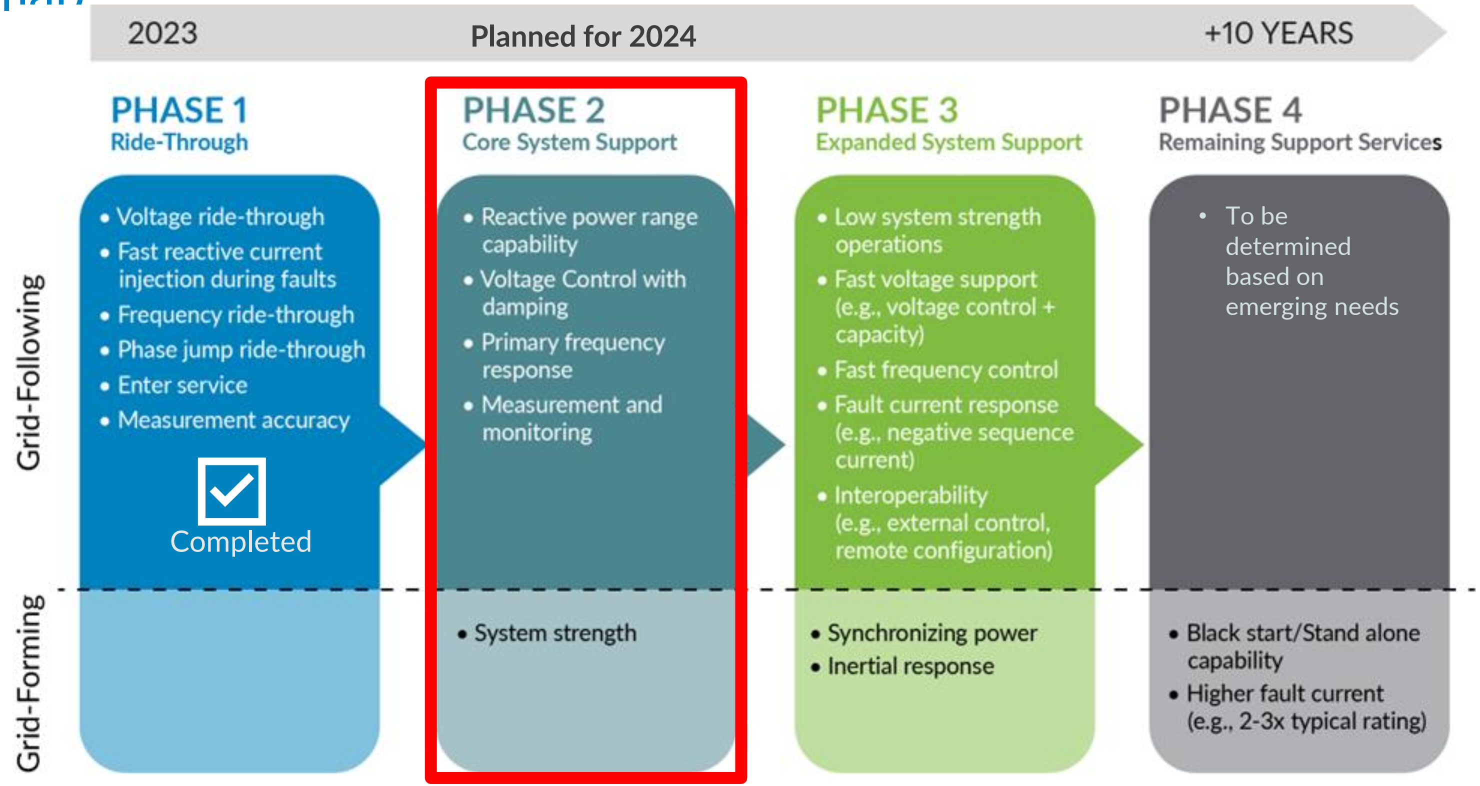
MISO is proposing GFM BESS requirements based on NERC recommendations and to support system attribute needs

- NERC's whitepaper indicated GFM BESS should be considered, and technology is available today.[1]
- MISO's 2023 Attributes Roadmap built on industry information showing the benefits of GFM controls to support voltage stability, especially under weak grid conditions which are likely to increase in prevalence.[2]
- At a March MISO stakeholder meeting, ESIG shared that other ISOs are also implementing GFM requirements.[3]



[1] NERC, White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems. September 2023. Available at: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf
[2] MISO, Attributes Roadmap. December 2023. Available at: https://cdn.misoenergy.org/2023%20Attributes%20Roadmap631174.pdf
[3] ESIG, GFM Need, Drivers, and Technology Landscape. Presented to MISO IPWG 3/12/24. Available at: https://cdn.misoenergy.org/20240312%20IPWG%20Item%2004a%20GFM%20Need%20Drivers%20Technology%20Landscape%20(PAC-2024-2)_ESIG632108.pdf

IBR performance requirements were identified as a key solution to ensuring system stability, and four main phases were proposed in the Attributes roadmap



Attributes technical screening analysis found grid-forming controls to support voltage stability

Attributes Roadmap Publication: https://cdn.misoenergy.org/2023%20Attributes%20Roadmap631174.pdf
Renewable Integration Impact Assessment (RIIA): https://cdn.misoenergy.org/RIIA%20Summary%20Report520051.pdf

GFM controls will naturally provide both system strength and frequency strength

Given the natural GFM control response, and potential implications of current limiting, MISO suggests evaluating all "core" capabilities.

In suggesting an exploration of frequency strength, MISO is not proposing storage "overhead / energy buffer" requirements.

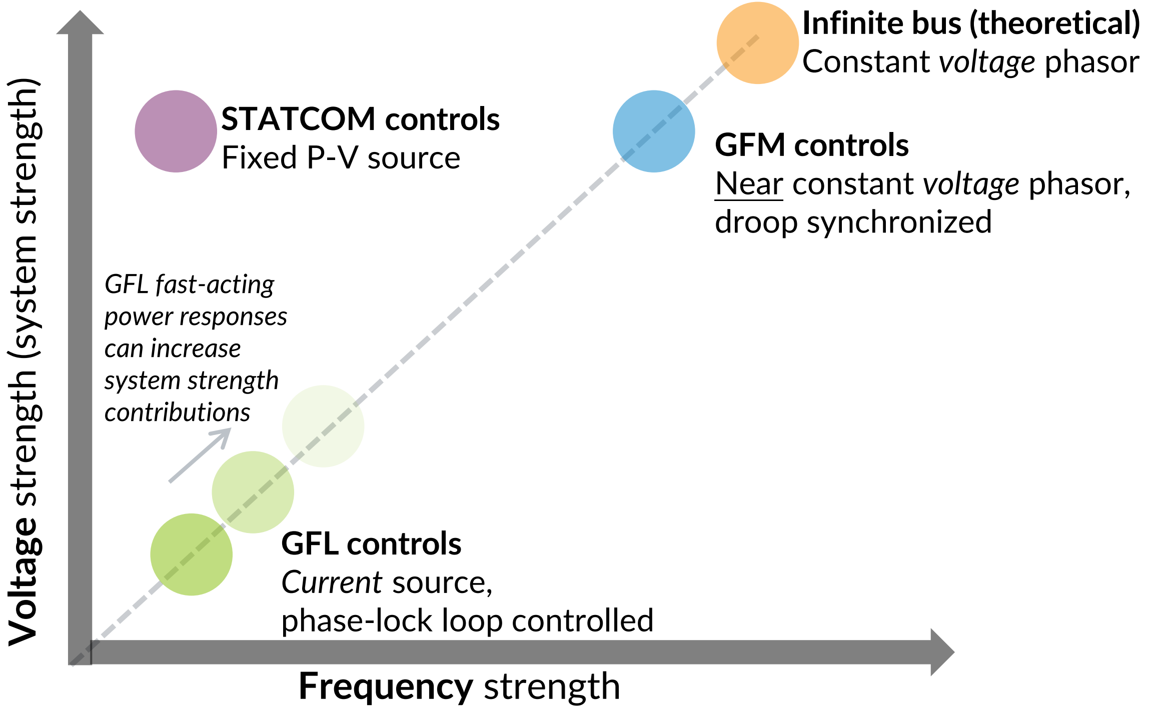


Image is adaptation from work at the Imperial College of London, presented to G-PST.

MISO

MISO posted a whitepaper outlining the need, industry readiness, and technical details of MISO's GFM proposal

- In addition to stakeholders, MISO engaged a wider range of industry experts for a detailed review of the whitepaper approach
  - Experts included staff from National Labs, research institutes, original equipment manufacturers, non-profit industry groups, ISOs/RTOs, and consultants
- MISO is using the whitepaper concepts to propose business practice changes
- MISO will propose generator interconnection tariff language is only to address IEEE 2800 exemptions


MISO Grid-Forming Battery Energy Storage Capabilities, Performance, and Simulation Test Requirements Proposal

DRAFT Whitepaper
July 2024 (Version 1.0)

Highlights

- The evolving energy landscape requires MISO and the industry to adopt available grid-forming control technologies to support MISO's Reliability Imperative and grid stability as the fleet transitions.
- MISO proposes an initial draft framework of capability and performance requirements with supporting simulations tests to determine conformity.
- MISO's current effort aligns with the general direction of industry to anticipate advancements in grid-forming inverter technology capabilities and standard maturity.

MISO
misoenergy.org

Whitepaper posted with September IPWG Meeting Materials

Stakeholder feedback and MISO responses available at: https://www.misoenergy.org/engage/stakeholder-feedback/2024/ipwg-recommended-gfm-bess-requirements-pac-2024-2-20240723/

MISO

MISO is proposing BESS GFM “core” requirements that do not require holding capacity or energy in reserve

- MISO proposes only to adopt “core” requirements in 2024.
- Core capabilities do <u>not</u> require hardware oversizing (e.g., larger inverter or battery).
- These capabilities are enacted through available software settings supported by all state-of-the-art battery energy storage systems.

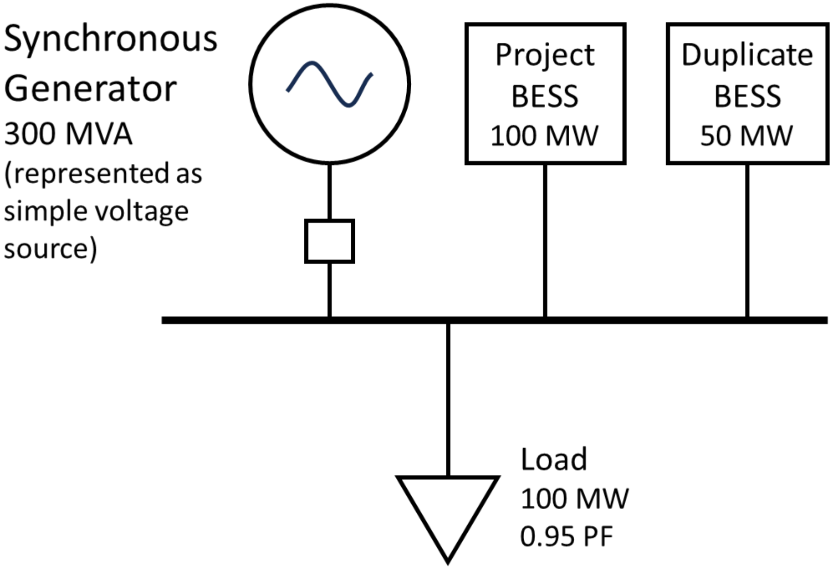
Core capabilities:

- Voltage source behavior
- Frequency domain response
- Inertial response
- Surviving the last synchronous connection
- Weak grid operation and system strength support
- Oscillation damping

Additional capabilities:

- Headroom and energy buffer
- Current capacity above continuous rating
- Black start capability
- Power quality improvement

NERC's loss of last synchronous machine (LLSM) simulation broadly tests grid forming performance and current responses

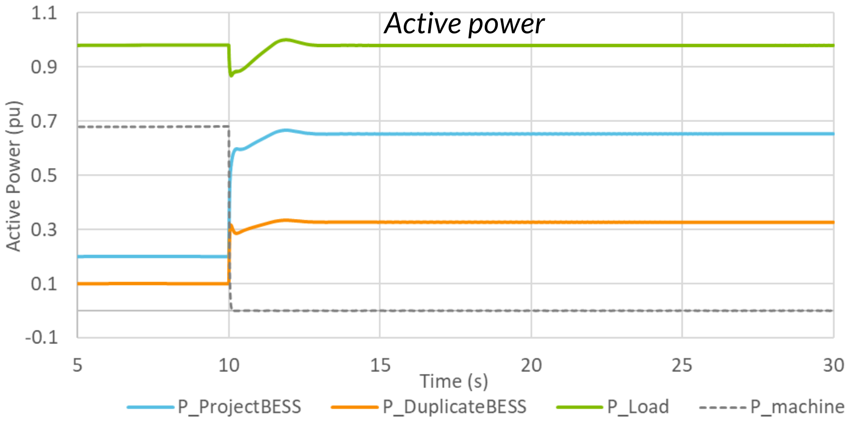


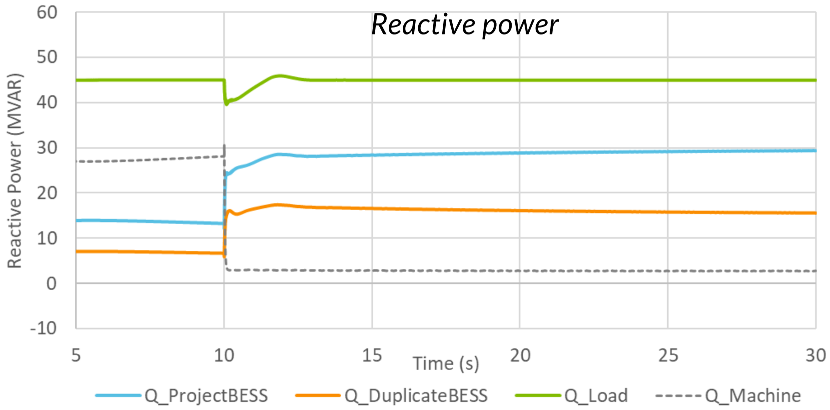
Three cases proposed, varying the initial conditions prior to SM disconnection

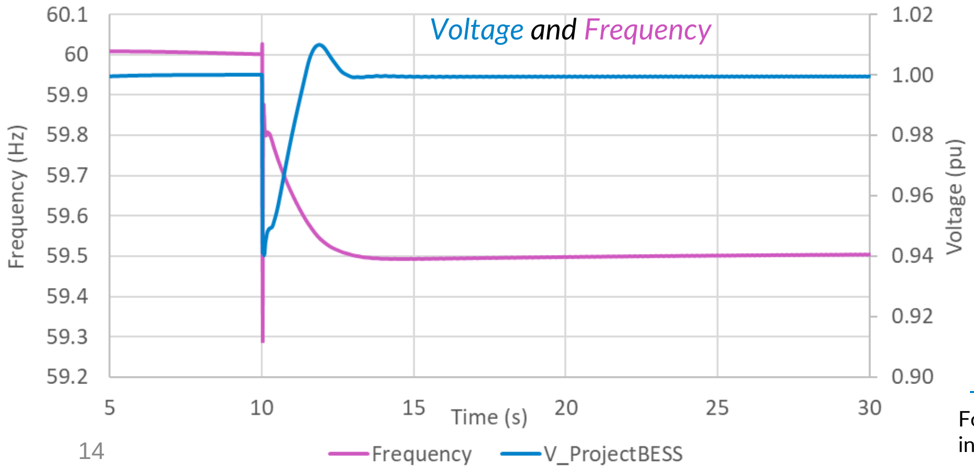
Case	Description	Project Plant[1]	Duplicate Plant[1]	Load[2] (% of project plant rating)
1	BESS Charging	50% charge	50% charge	50%
2	Limit Test	0% exchange	100% discharge	100%
3	Power Balance	50% discharge	50% discharge	75%

[1] "total load" refers to the combined storage and load apparent power in this context

Test results show GFM technologies meet proposed requirements while non-GFM cannot (LLSM Case 1 results for GFM)







Post-trip:

a. ☑ Plant output is well controlled with no significant frequency/voltage oscillations.

b. ☑ Voltage settles to a stable operating point.

c. ☑ Final voltage is expected based on droop and deadband settings.

d. ☑ Frequency settles to a stable operating point.

e. ☑ Final frequency is expected based on droop and deadband settings.

f. ☑ Oscillations is adequately damped.

g. ☑ Distortion observed in phase quantities dissipates over time.

h. ☑ Active power immediately moves to meet load requirement and settle according to its frequency droop setting.

Footnotes on the post-trip criteria and examples of all simulation tests, including non-GFM, are show in in the whitepaper

Three additional AEMO tests can supplement verification of GFM controls' active and reactive current responses

Low short circuit ratio (SCR) with fault

*Objective**: verify stable reactive current response to support voltage in weak grid areas.

MISO aligned with AEMO test steps of SCR 10, 3, 2, 1.5, and 1.25 with a fault applied after each step.

Phase jump

Objective: verify fast and stable active power response.

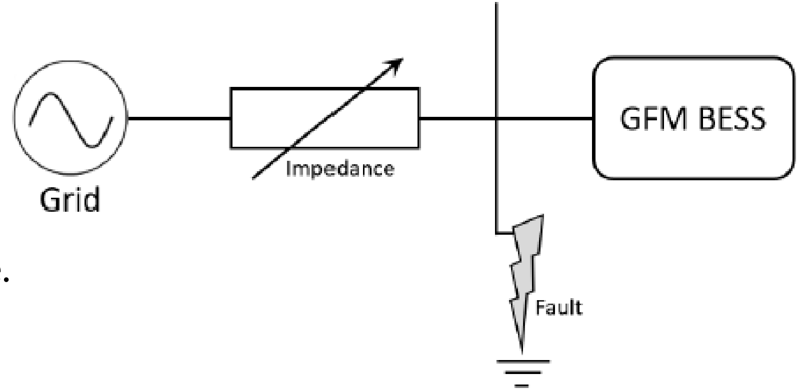
MISO test has phase jumps of 10 and 25 degrees.
AEMO test has phase jumps of 10, 30, and 60 degrees while the NGESO uses 10 and 30 degrees.

Rate of change of frequency (RoCoF)

Objective: verify stable active power response.

MISO aligned with AEMO version of test uses 4 Hz/sec while the NGESO and Fingrid tests use 2 Hz/sec

Simulation test set-up (EMT domain)



Source: AMEO

*Primary objective is listed here. The simulations test a range of performance, capability, and control stability features.

An initial proposal for integration of GFM requirements with IEEE 2800-2022 is introduced in the whitepaper

- MISO shares a list of IEEE 2800 requirements adopted by MISO that may need to be exempted or modified to achieve desired GFM response.
- MISO offers draft requirements that could enact these changes.

IEEE 2800	Subclause name	Potential issue	Recommended action
4.7	Prioritization of IBR responses	Incompatibility with GFM fundamental operation (e.g., prioritization between ridethrough and current responses).	GFM exemption
7.2.2.1	Voltage ride-through – General	Definition of permissive operation region in Table 11 and Table 12	Only allow current blocking or tripping for self-protection in permissive operation region.
7.2.2.3.2	Low and high voltage ride-through capability	Refers to performance in Table 13. Defaults to reactive current priority mode.	Exempt Table 13. Exempt reactive current priority, if affecting GFM operation
7.2.2.3.3	Low and high voltage ride-through performance	Permissive operation region allows current blocking	Only allow current blocking or tripping for self-protection in permissive operation region.
7.2.2.3.4	Current injection during voltage ride-through	Specifies type and amount of current injection. References 7.2.2.3.5 performance. Mentions "automatic voltage control"	GFM exemption
7.2.2.3.5	Performance specification [during voltage ridethrough]	Specific step response time	GFM exemption
7.2.2.6	Restore output after ride-through	Specific active power recovery time and rate	GFM clarification that rate should not constrain natural response
7.3.2.1	Frequency disturbance ride-through requirements – general	References 7.3.2.3.2 and 7.3.2.3.4	Only allow current blocking or tripping for self-protection in permissive operation region.

Table 2. Summary of IEEE 2800-2022 exemptions or modification for IBR GFM

MISO's initial GFM implementation is intended to be pragmatic step towards fuller adoption, with many opportunities remaining

Several next steps are being considered:

- Refine integration with IEEE 2800-2022
- Apply requirements to BESS portion of hybrids and co-located facilities
- Expand utilization of reactive power capability (IEEE 2800 versus FERC Order 827)
- Explore potential benefits of non-GFM, inverter-level fast responses
- Explore value of GFM hardware reserves

Questions?

Patrick Dalton
Principal Engineer, Strategic Assessments
pdalton@misoenergy.org

Appendix

Resources on Grid Forming Specifications

Entity	Document	Link	Year
FINGRID	Grid Code Specifications for Grid Energy Storage Systems SJV2019	https://www.fingrid.fi/globalassets/dokumentit/en/customers/grid-connection/grid-energy-storage-systems-sjv2019.pdf	2021
FINGRID	Specific Study Requirements for Grid Energy Storage Systems	https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/specific-study-requirements-for-grid-energy-storage-systems-en.pdf	2023
FINGRID	Modelling instruction for PSS/E and PSCAD models	https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/fingrid-modelling-instruction-for-psse-and-pscad-models-2024_01_12-002.pdf	2024
NERC	White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems	https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf	2023
AEMO	Voluntary Specification for Grid-forming Inverters	https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf	2023
AEMO	Application of Advanced Grid-scale Inverters in the NEM	https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf	2021
AEMO	Voluntary Specification for Grid-forming Inverters: Core Requirements Test Framework	https://aemo.com.au/-/media/files/initiatives/engineering-framework/2023/grid-forming-inverters-jan-2024.pdf?la=en	2024
NGESO	Great Britain Grid Forming Best Practice Guide	https://www.nationalgrideso.com/document/278491/download	2023
NGESO	GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability	https://www.nationalgrideso.com/document/159296/download	2021
UNIFI	Specifications for Grid-forming Inverter-based Resources Version 1	https://www.energy.gov/sites/default/files/2023-09/Specs%20for%20GFM%20IBRs%20Version%201.pdf	2022

Also see ESIG: Grid-Forming Technology in Energy System Integration, 2022
Comparison of Current GFM Equipment Specs, 2022

MISO

MISO has shared GFM presentations with stakeholders starting in March 2023

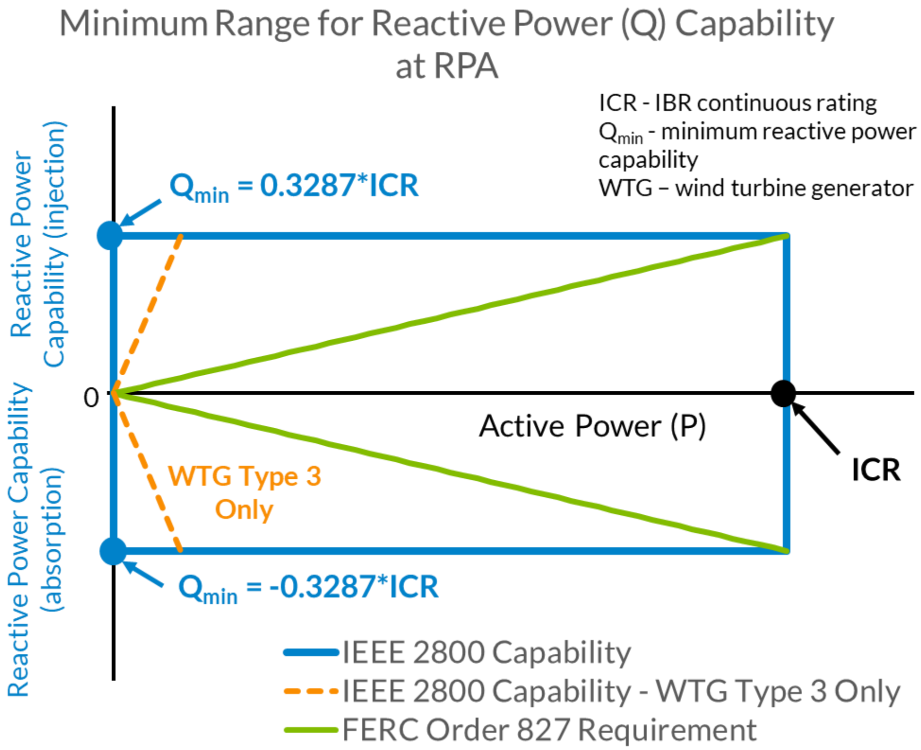
- 20240903 IPWG Item 04a DRAFT GFM BESS Performance Requirements Whitepaper CLEAN (PAC-2024-2).pdf
- 20240312 IPWG Item 04b BESS Grid Forming Controls (PAC-2024-2).pdf
- 20240312 IPWG Item 04a GFM Need Drivers Technology Landscape (PAC-2024-2)_ESIG.pdf
- 20240502 IPWG Item 04b GFM BESS Performance (PAC-2024-2).pdf
- 20240604 IPWG Item 04b GFM BESS Performance (PAC-2024-2).pdf
- 20240723 IPWG Item 04b GFM BESS Performance (PAC-2024-2).pdf
- 20240903 IPWG Item 04a GFM BESS Performance (PAC-2024-2).pdf

MISO's GFM proposal applies only to "stand alone" BESS which limits the initial applicability given recent trend towards hybrid facilities

- MISO's proposal applies to BESS plants that have a unique POI.
  - In other words, the POI is not shared with another resource type (e.g., BESS + PV hybrids or co-located facilities).
- A few potential hybrid complexities led to this approach:
  - Defining conformity at new point within plant (i.e., not the Point of Measurement as is the case for other IBR requirements).
  - Applying conformity simulation tests on partial plant model.
  - Differences in DC-coupled vs AC-coupled plant designs and resulting conformity considerations.
  - Potential need to evaulate interactions between GFM and non-GFM inverters within hybrid plants (AC-coupled) given very low impedance between controls.

MISO's adoption of reactive power requirements is currently constrained by FERC Order 827

- MISO proposes to adopt IEEE 2800 requirements for reactive power **capabilities**, including at zero active power
- MISO will not require **utilization** of the reactive power capability from IEEE 2800 beyond what is required by FERC Order 827 (0.95 leading to 0.95 lagging across the active power range) at this time
- MISO's proposed redlines also add clarity for IBR performance of voltage control

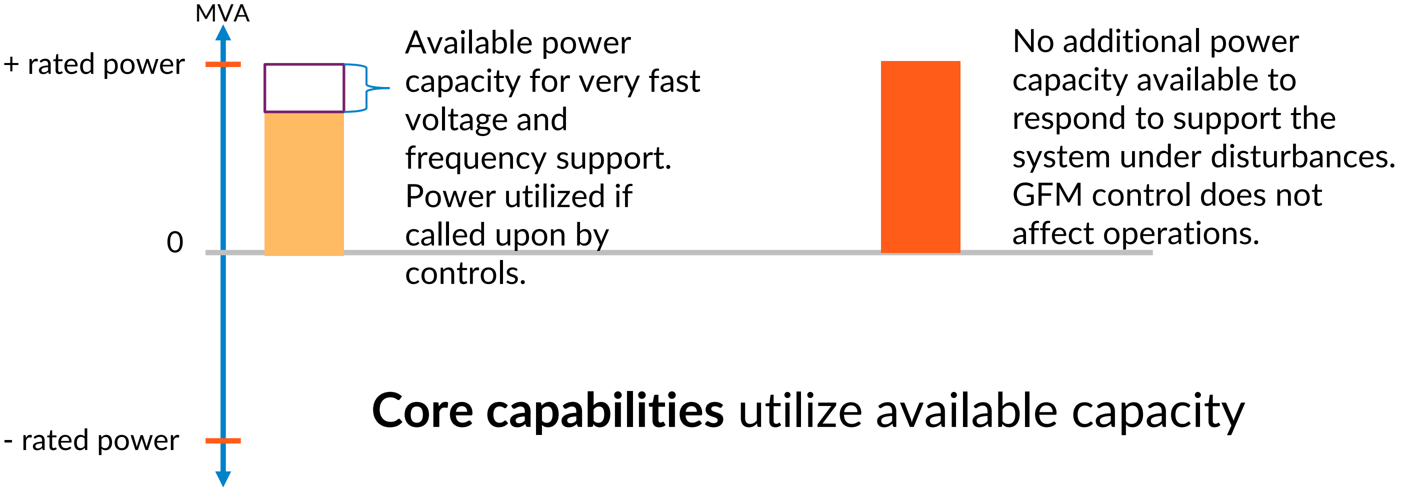


Reference Point of Applicability (RPA) shall be the Point of Measurement (POM)

MISO is proposing “core” requirements that are not expected to result in hardware oversizing

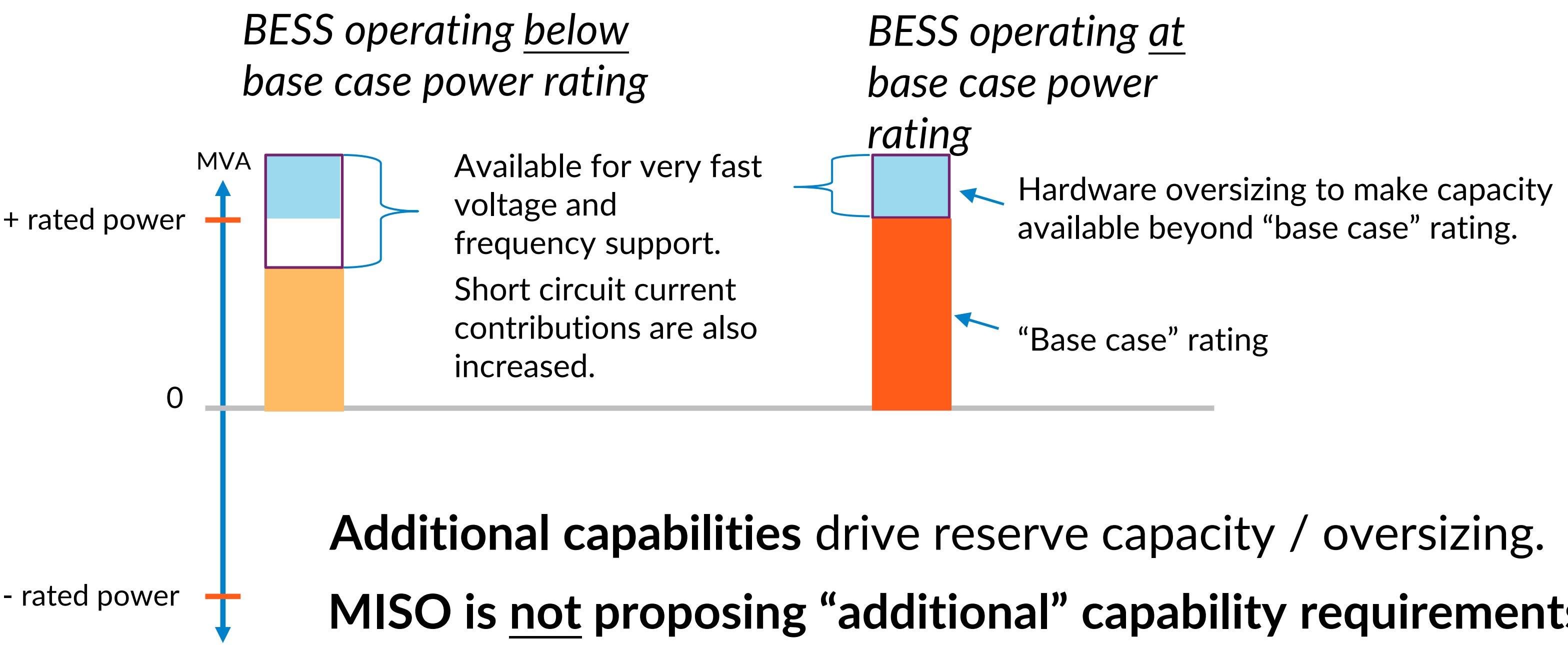
BESS operating <u>below</u> power rating

BESS operating <u>at</u> power rating



Core capabilities utilize available capacity

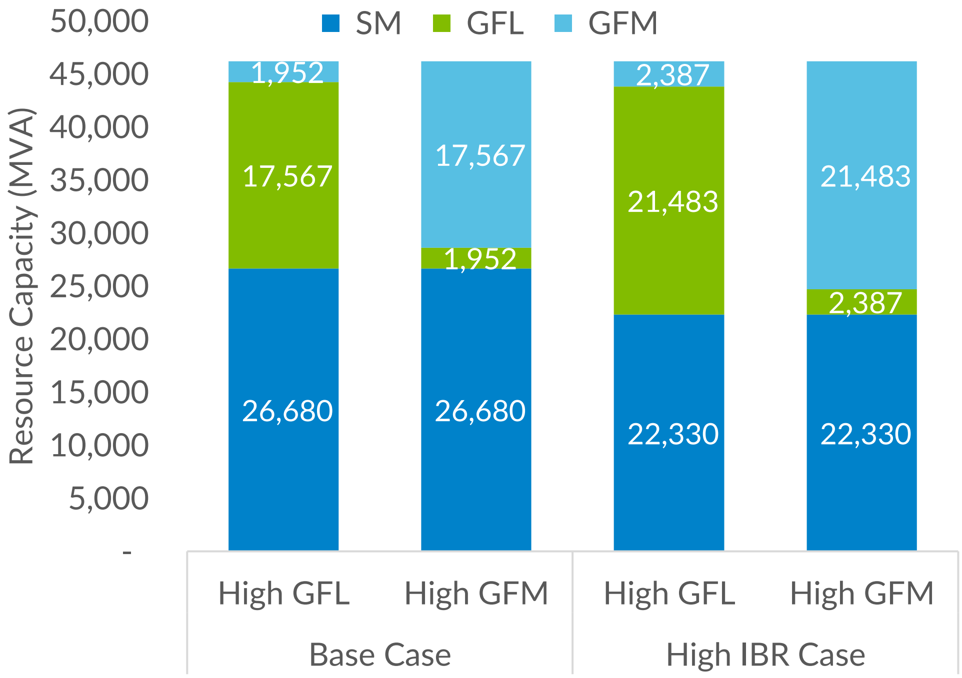
In contrast, “additional” requirements would require holding inverter capacity in reserve, resulting in hardware oversizing



Additional capabilities drive reserve capacity / oversizing.

MISO is <u>not</u> proposing “additional” capability requirements

The scaled system analysis was used to evaluate the effect of GFM and GFL inverter controls on dynamic transfer limits at a specific interface



- *Base cases* use the MISO23_2033_SUM_AA model.
    - Approximately 3:1 ratio of SM-to-GFM level of resources.
- *High IBR penetration* case converted some synchronous machines in this model to be IBR to test higher penetrations.
    - Approximately 1:1 ratio of SM-to-GFM level of resources.
- High GFM and High GFL cases assume 90% of that resource type and 10% of the other.