

March 16, 2026 (Hybrid event at ESIG Spring Workshop)

Grid Forming IBR Specifications, Testing Requirements, and Lessons Learned (~50 in-person attendees and ~100 virtual attendees)

Presentation recording and slides are available to download [here](#). (Breakdown of attendee by sector was not available for this event.)

The eleventh and final meeting of Season 2 of the DOE i2X FIRST initiative involved a hybrid (in-person and online) workshop in conjunction with the ESIG Spring Workshop. This session focused on grid forming (GFM) inverter technology including basics of the technology, system needs that drive GFM utilization, evolving grid code requirements, and global landscape and trends.

Introduction, Julia Matevosyan, ESIG; Cynthia Bothwell, DOE (Contractor)

Julia welcomed in-person and online participants to the workshop, provided a recap of the i2X FIRST Season 2 efforts, and gave an overview of the workshop agenda for the day. Julia also highlighted some new updates regarding DOE i2X and related topics, including the following:

- **i2X FIRST Season 3**, which will include four meetings from June 2026 to January 2027 covering emerging topics including NERC PRC-029 implementation process updates, NERC Milestone 4 projects and the NERC Project 2022-04 EMT Modeling drafting efforts, IEEE P2800.2 deep dive and adoption pathways, and updates on new IEEE 2800 series efforts (including GFM requirements).
- **i2X STITCH** “Studies, Tools, and InTerconnection Consistency & Harmonization,” which will include nine meetings from May 2026 to March 2027 and summarize current interconnection studies approaches across ISOs, strive for opportunities to standardize and harmonize interconnection study methods, identify industry recommended practices, and discuss possible gaps and ways to overcome these challenges.
- **Interconnection Technical Assistance Office Hours** where industry stakeholders can meet with ESIG and the Elevate Energy Consulting team to discuss specific technical issues related to understanding, implementation, adoption of harmonized and/or comprehensive interconnection requirements or standards for generators, as well as conformity assessment approaches for new standards.
- An encore round of upcoming in-person and online trainings being planned for 2026 focused on interconnection and EMT modeling/studies based on successes from both trainings in 2025.

Cynthia provided an overview of the i2X initiative, its mission, and some of its recent successes. The i2X effort is focused on enabling a simple, fast, and affordable generator interconnection

process while enhancing reliability and security of the electric grid. It is focused on strategic solutions, stakeholder engagement, data and analytics, and research and development efforts. Some recent 2026 highlights are listed in Figure 1.

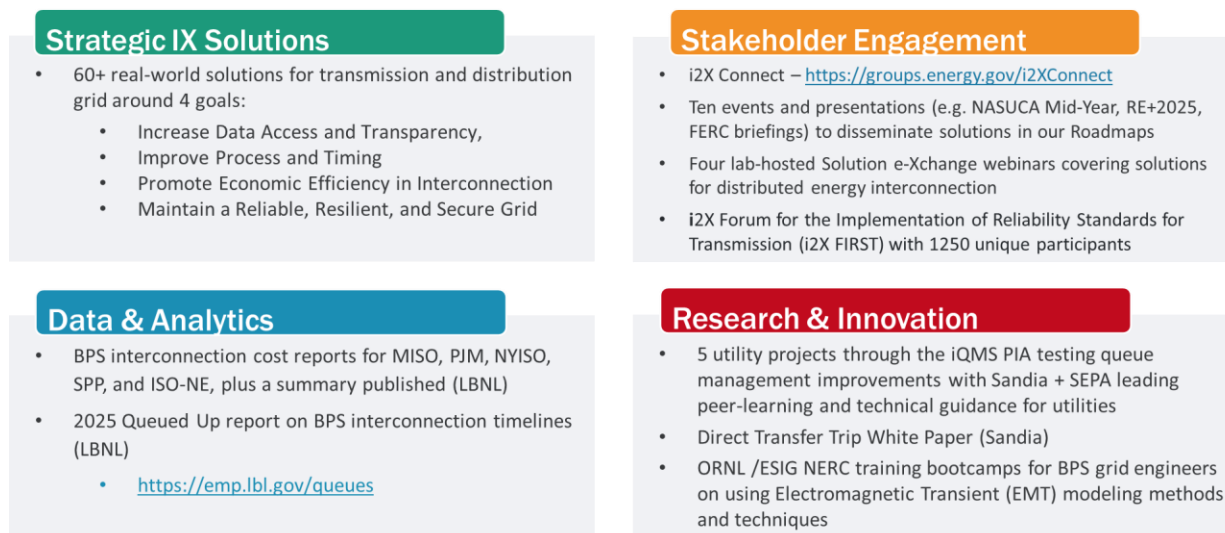


Figure 1: i2X Focus Areas and 2025 Activity Highlights

Cynthia also shared details regarding the upcoming [Interconnection Cost Reduction Solutions \(iCRS\) Program](#) opportunities for transmission ([iCRS-T](#)) and distribution ([iCRS-D](#)). The iCRS-D effort will be funding local, state, or regional partnerships to execute a “Lighthouse Project” to develop and demonstrate new technologies and effective solutions to increase data access and transparency, streamline and expedite interconnection services, and maximize economic efficiency. The iCRS-T effort will facilitate matchmaking between US transmission providers and organizations with specialized expertise in advanced grid modeling and interconnection studies in an effort to pursue cost-reducing technologies in interconnection studies.

Session 1, Part I – Basics of Grid Forming IBRs, Andrew Isaacs, Electranix

Andrew provided a brief tutorial about the fundamentals of GFM technology, controls, and applications. GFM has evolved and matured significantly as a technology over the past decade and today the engineering community generally agrees on fundamental principles, definitions, and integration techniques of the technology. It has been proven and tested extensively in the field in many applications around the world and industry continues to develop and enhance requirements that have led to grid reliability improvements and effective utilization of the technology.

There are numerous definitions of GFM proposed by [NERC](#), [UNIFI](#), [MISO](#), [AEMO](#), [NESO](#), and others. Many of these definitions align on the core principle that GFM technology seeks to “maintain an internal voltage phasor (magnitude and angle) that is constant or nearly constant in the subtransient to transient timeframe.” There are minor terminology differences among the

definitions, but nearly all of them align on this fundamental concept. Some entities have chosen to use alternative definitions to GFM that focus more on the performance and services provided, such as ERCOT’s Advanced Grid Support ([AGS](#)) concept. **Ultimately, one can think about GFM as simply another type of converter control that has inherent grid-stabilizing properties. These general properties seek to resist changes occurring in the system rather than quickly try to follow those changes.** This core concept is fundamental to differentiating GFM and GFL IBR technologies and how they get defined and applied on the BPS.

The high-level concept of GFM versus GFL can be illustrated with a simple test system as shown in Figure 2. A change in system bus/node phase angle (θ_2) occurs. The GFL BESS seeks to hold its active power constant and thus rapidly changes its internal phase angle (θ_1) to “follow” the system phase angle θ_2 (some variations in active power will occur due to physical properties, measurement delays, and other factors). On the other hand, the GFM BESS seeks to keep its internal phase angle θ_1 constant and thus a change in active power occurs within the “inertial” timeframe. These same concepts also apply to the voltage (V) change / reactive power (Q) response, which is useful and applicable to GFM resources with little or no active power availability such as GFM STATCOM and VSC-HVDC systems.

What does it look like when you disconnect the generator G1? (Island system)

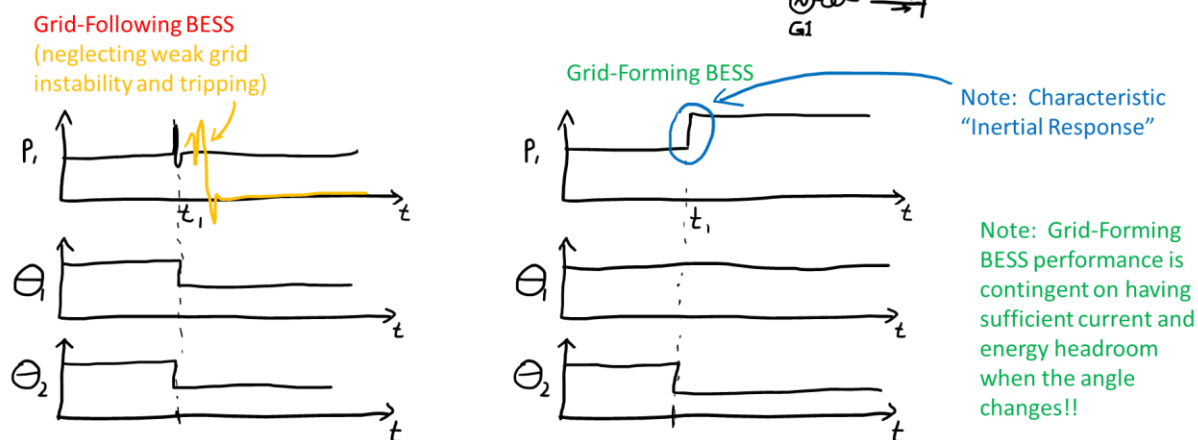


Figure 2: Conceptual Core Response of GFM and GFL in Simple Test System [Source: Electranix]

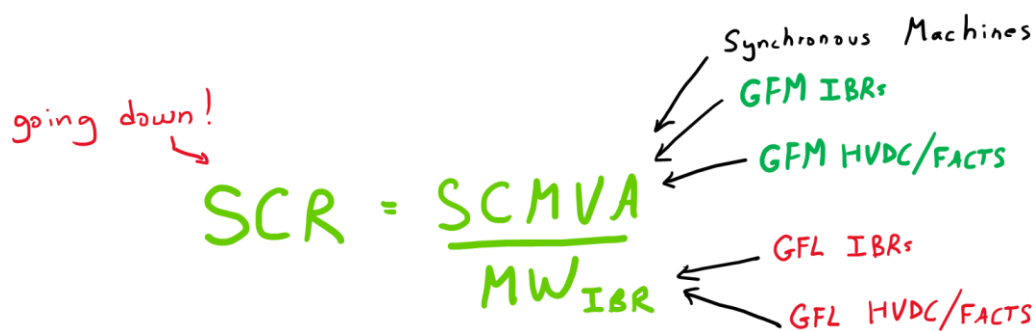
The reaction of the GFM versus GFL inverter controls are defined within the inner controls of the IBR units and are dependent on many factors such as available headroom,¹ equipment ratings, etc. Additionally, more conventional IBR controls that do not occur within the

¹ For GFM resources with energy and current headroom (like batteries) the hardware between GFM and GFL are generally quite similar; there are unique challenges that limit commercial viability for applying GFM to other IBR technologies such as wind and solar, although those are also under development by some vendors.

subtransient to transient timeframe can also be layered on to the GFM controls. For example, a GFM IBR can also provide steady-state reactive power-voltage control or active power-frequency control similar to a GFL IBR. **Generally, all the control features and benefits a GFL inverter can provide should also be expected from a typical GFM inverter.**

Furthermore, there are multiple GFM control strategies such as virtual synchronous machine or droop-based GFM controls; these various control topologies are analogous to the variations of synchronous generator excitation system and turbine-governor controls that have evolved over time and each have unique benefits, drawbacks, and operational considerations for tuning and utilization.

GFM can also fundamentally be described in terms of how GFM (versus GFL) resources affect system strength and stability. Conventional SCR-based system strength metrics are no longer relevant with the introduction of GFM IBRs. Conventional GFL IBRs reduce SCR whereas adding a GFM IBR improves SCR; therefore, one can consider GFM as increasing the numerator rather than increasing the denominator of the conventional SCR equation, as shown in Figure 3.



$$SCR = \frac{SCMVA}{MW_{IBR}}$$

Handwritten annotations in the diagram:

- Red text: "going down!" with an arrow pointing to the denominator.
- Green text: "Synchronous Machines" with an arrow pointing to the numerator.
- Green text: "GFM IBRs" with an arrow pointing to the numerator.
- Green text: "GFM HVDC/FACTS" with an arrow pointing to the numerator.
- Red text: "GFL IBRs" with an arrow pointing to the denominator.
- Red text: "GFL HVDC/FACTS" with an arrow pointing to the denominator.

Figure 3: Conventional SCR Calculation and the Impacts of GFM versus GFL on the Calculation [Source: Electranix]

Briefly put, there are multiple key applications where GFM can provide a cost-effective solution to known reliability challenges including:

- **Strengthening** weak local IBR interconnections
- **Adding inertial response** to large interconnections
- **Increasing passive damping** at sub-synchronous frequencies, unlocking renewables in series-compensated networks
- Automatic **injection of negative sequence currents** to help balance the system
- Providing **very fast frequency response**
- **Transferring system strength** from one region to another, particularly with respect to GFM HVDC applications
- **Improving response times** and stability for reactive power devices such as GFM STATCOMs

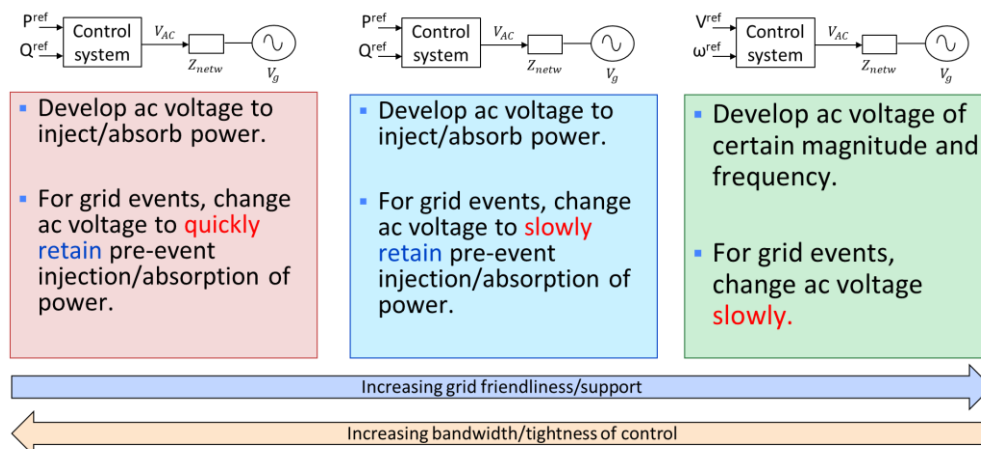
- Reducing active power fluctuation impacts, **enabling data center load growth**

GFM technology in newly connecting BESS is commercially available across multiple vendors and has been deployed around the world. GFM technology in wind and solar is not yet commercially available but is under exploration and development by some manufacturers. Existing GFL BESS may or may not be able to be upgraded to GFM at a future date, depending on vendor-specific details; there are increased costs associated with retrofits in some cases that should not be overlooked.

Session 1, Part II – Basics of Grid Forming IBRs, Deepak Ramasubramanian, EPRI

Deepak provided a complementary view of GFM technology to explain the fundamentals and basics of GFM control. Industry often describes GFM as “acting like a voltage source” and GFL as “acting like a current source”; however, this should not be conflated with *ideal* voltage and current sources. All inverters used in power generation are inherently voltage source converters as they generate a dc voltage that is converted into an AC voltage waveform using power electronic switches. The control objectives of the inverter, however, then decide how that AC voltage waveform is created including the magnitude, phase angle, frequency, and response to grid events.

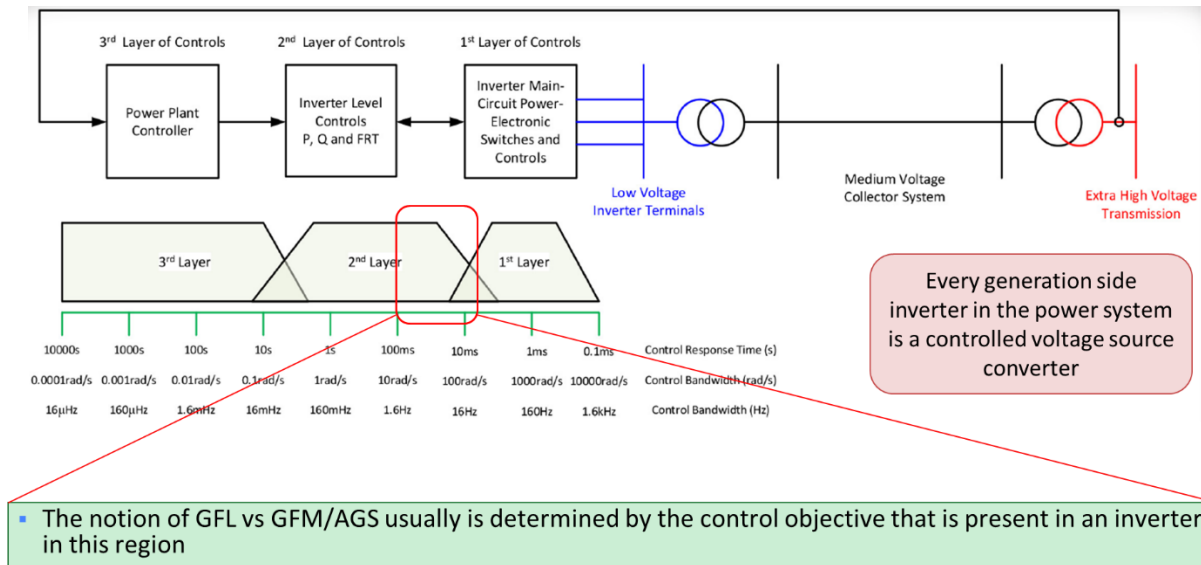
In power systems, AC voltage is an independent quantity whereas AC current and AC power are dependent quantities. The flow of AC current is dependent on the voltage (magnitude and phase) difference between two nodes; power is calculated as the multiplication of current and voltage. Inverter control objectives that use dependent quantities as their references can be less grid-friendly. Figure 4 illustrates broad families of inverter control objectives. The left two examples try to maintain active and reactive power by (quickly or slowly) changing AC voltage. The right example tries to maintain voltage and frequency (angle) and therefore responds to grid events slowly. The left-hand examples are illustrative of GFL controls whereas the right-hand example is illustrative of GFM controls.



We are only discussing a single inverter here, not an entire plant.

Figure 4: Broad Families of Inverter Control Objectives [Source: EPRI]

Deepak also described how the concepts of GFM and GFL are mainly applicable to a relatively tight bandwidth of controls that affect response times from around a few milliseconds to around 100 ms (see Figure 5).



An Overview of Grid-Forming Inverter Technologies and the Readiness of Power Systems Worldwide to Deploy the Technology. EPRI, Palo Alto, CA: 2024. 3002031346.

Figure 5: Hierarchy of Controls within an IBR Plant [Source: EPRI]

Figure 6 shows a summary of the key attributes of GFM and non-GFM (i.e., GFL) controls in the various timeframes, which provides a good summary of the key differences between technology options.

Time scale	Non-Grid Forming (non-GFM)	Grid Forming (GFM)
Sub-transient	Prioritizes current to meet fixed P/Q	Prioritizes current to meet fixed V/f control
Transient	Prioritizes P/Q control	Prioritizes V/f control
Steady – State	May have droop characteristics for controlled V/f response	

Figure 6: Summary of Attributes for GFM and non-GFM (i.e., GFL) [Source: EPRI]

Deepak also shared research on the topic of frequency domain characterization of GFM controls. Frequency scanning approaches can characterize and explain GFM as compared with GFL controls that capture key attributes differently than typical time domain tests. Figure 7 illustrates the key checks used as part of frequency domain analysis, which will be covered in more detail in other sessions.

(i) an increase in grid voltage magnitude should result in decrease in Q injection from device and vice versa (ii) this behavior should occur even for fast voltage changes (< 1 cycle)

(i) an increase in reactive power injection should result in decrease in V generated from device and vice versa (ii) the feedback loop should remain passive and a sink for oscillations

(i) an increase in active power injection should result in decrease in ω generated from device and vice versa (ii) the feedback loop should remain passive and a sink for oscillations

Figure 7: Key Checks in for Frequency Domain Characterization of GFM [Source: EPRI]

There are additional considerations for GFM (and GFL) IBRs that deserve careful attention and additional research. Some of these areas include blackstart capability utilizing GFM capabilities, transformer energization, motor pickup, benefits of GFM providing subsynchronous damping, and BPS protection system impacts with high IBR penetration levels that include GFM technology.

Deepak closed the discussion reiterating that as long as an IBR can prove to deliver interconnection requirement performance expectations in a stable, reliable manner, it is less important whether than OEM defines the specific control as GFM or some other designation. **The concept of GFM may just be “a fancy suit” on what is already a stabilizing control architecture that provides grid benefits and should not be discouraged because of terminology alone. Interconnection requirements should be focused on specific performance needs rather than designation of GFM or not.**

Session 1 Q&A

It was noted that SCR-based metrics may not be useful in the future; some new tools include injection factor metrics. Are these useful for screening?

Unit interaction factor metrics are overall a good metric and similar to SCR-based metrics should be carefully leveraged to screen for potential IBR reliability risks in the future.

With an HVDC tie line connecting two transmission systems, can you use both converters as GFM?

HVDC systems can be operated with one converter in GFM and one in GFL and this takes advantage of the strong side for the benefit of the weaker side that has GFM implemented. One can also use GFM on both sides but must be careful with active power balancing. If both ends

are GFM and HVDC connects two separate systems, then it may not be sufficient for one end to have a requirement; both systems should be considered.

When can industry apply GFM to hybrid systems or other types of IBRs?

BESS can be GFM today and this is widely commercially available. However, other portions of IBR plants may not have commercially available technology. The BESS side of a hybrid plant can be GFM with technology today. Other aspects need to be addressed for hybrid systems such as requirements, operating procedures, etc.

SPP adopted IEEE 2800, and in the ride-through requirements it talks about reactive current priority during ride-through. With GFM, this is less applicable, so how do we handle this?

A subgroup of IEEE 2800 is now looking at GFM and non-GFM technology and what language needs to be adjusted. Requirements language will evolve at the IEEE level and then can be adopted by entities who have integrated the IEEE 2800 language into their requirements.

We collectively need to simplify all these technical details down to executives and decisionmakers. What is missing here?

That sentiment is well understood by many in the GFM community, and those practitioners continue to share messages that appeal to less technical audiences that GFM is simply an evolution of IBR controls and nothing entirely new. It has been proven effective around the world and is widely commercially available. For policy people and people thinking about GFM as this new complicated thing, experience recommend “stop panicking” and try out the new technology as it is not a significant deviation from GFL controls in most ways. Start early before problems arise rather than wait until serious issues show up on the system. Add more testing to make sure it is robust and that performance is validated.

Can you articulate system versus local requirements and needs for GFM?

When thinking of regional requirements or system requirements, it is important to recognize holistically that synchronous generation levels are declining rapidly and IBRs are replacing those resources under operating conditions throughout the day and year. GFM is part of a solution to that problem that can *add* system strength rather than drain it.

Regional requirements are seeking a base level response of GFM to avoid the larger system-wide problem, and the specific rules are applicable to those assets (e.g., BESS) related to models, tests, performance, commissioning, etc. Local grid issues can then leverage GFM as a solution to specific needs, if required, for stability and controls tuning.

Any good examples doing model validation of IBRs for real world events?

There are many good examples of GFM specifically performing well to grid events as well as highly accurate models that reflect those GFM responses. The concept of validation using real world event model validation applies to both GFL and GFM equally. Hawaiian Electric, for example, has put DFRs at all IBRs and an event occurs they conduct model validation. They take recordings and compare against PSCAD models to gain experience and do model comparisons.

Session 2 – System Needs for Grid Forming Capabilities

Session 2 included a facilitator-led, interactive discussion among the following panelists:

- Alex Shattuck, ESIG (moderator)
- Weiqing Jiang, MISO
- Mostafa Sedighizadeh, SPP
- Scott Anderson, SRP
- Bin Wang, ISO-NE

Question: In your region, do you have a need or foresee a need for GFM capabilities and facilities?

SRP: Looking to the future, SRP is seeing a rapid growth of instantaneous IBR penetration and sees GFM as a cost-effective solution option worth pursuing. There are no glaring reliability issues or risks that SRP has identified, but does see a very different BPS in the years ahead than what it has experienced in the past. SRP is focused mainly on GFM BESS given its commercial maturity and availability, particularly for new resources. Some differences of opinion exist within the organization but overall SRP is pursuing GFM as one of multiple solutions to grid stability issues in the future.

SPP: SPP is facing a 110 GW queue and 75% of that queue is IBR technology. Thus, SPP expects very high penetration of IBRs in the years ahead and has already hit operating conditions

upwards of 90% instantaneous penetration back in 2022. This raised concerns about what if a fault occurred during that time and whether the grid would remain stable under those conditions. SPP believes that more grid-stabilizing options are needed to assure reliability and minimize risk.

MISO: MISO conducted a [comprehensive engineering study](#) and identified an inflection point around 30-40% penetration level, which is nearing very rapidly. Issues included weak grids, voltage issues, etc. At 50-60% penetration levels, frequency issues also arose. In 2024, MISO implemented GFM requirements focused on “core” GFM capabilities and attributes, applicable to all BESS entering the 2023 interconnection queue and ahead. Looking forward, MISO wants to observe operational performance and explore additional GFM benefits.

ISO-NE: At the moment, ISO-NE has not identified a specific need for GFM and has not developed any requirements related to GFM technology. In the future, they are looking at multiple solution options but need more information to make these decisions. They are undertaking research endeavors with universities to explore this topic further, and developing a “systematic approach” with those partners.

Question: Are there other additional drivers your organization is tracking or wishes to track beyond IBR penetration levels?

SRP: SRP is expecting rapid instantaneous penetration growth in the next few years, upwards of 60-70%. SRP is also seeking to leverage the full capabilities of GFL IBRs today and into the future and monitoring their performance, but do lack dashboards and reporting at a granular level. SRP is also focused on variable large loads and sees GFM as an effective, multi-value solution to support these efforts as well. They are looking at cost-effectiveness across multiple solutions, and see GFM as one of the least-cost options, particularly for new projects.

SPP: SPP is focused on the very high IBR penetrations expected in the years ahead, but is also monitoring the NERC guidance, MISO efforts, other ISO and industry efforts, etc. SPP made the decision to take action to minimize risk, added language to their tariff regarding modeling, but is mainly looking at broad industry indicators and consensus from key trade organizations and regulatory bodies.

MISO: MISO has [observed](#) trends in resource adequacy studies and the growth of IBRs that have presented risks to MISO system reliability. MISO does see locational impacts, system strength issues, and other challenges beyond just broad IBR penetration levels. The MISO strategic approach is to observe trends, identify needs, and determine cost-effective solutions. GFM is one solution that can be provided by IBRs that provide a missing grid-stabilizing need.

ISO-NE: Main driver of identifying risk is the ISO-NE [Needs Assessment](#) for its various portions of the system. These studies focus on violations of voltage, frequency, thermal, etc. Then the assessments explore solutions to those needs in the planning horizon, of which GFM may be considered among other solutions. ISO-NE aims to deploy whichever solution is most effective

and economic rather than pursuing one specific technology. Some recent research has illustrated that inertia and ROCOF are not issues for ISO-NE so long as FFR/PFR with sufficient droop is enabled in the region. ISO-NE also recognizes that they need to ensure that conventional GFL IBRs are parameterized and performing to meet system needs, in addition to potential additional technologies like GFM, synchronous condensers, and other solutions.

Question: For those that have formally determined a need for GFM integration (3 out of 4 panelist organizations), what decision-making process was undertaken to accomplish this?

SRP: SRP has been tracking the multiple industry and regulatory papers and recommendations that strongly advocate for leveraging GFM technology, particularly for new IBRs. SRP underwent a cross-departmental decision-making process to pursue GFM enhancements to an existing site and to business practices. No specific studies were run identifying a need for GFM solely, but general operational readiness trends point toward leveraging the solution as a viable solution among others. SRP sees GFM as a low-cost solution that provides value to its stakeholders and customers. SRP has taken the approach of requiring capability of GFM for new BESS, which may or may not be enabled operationally at specific sites depending on SRP needs in the future.

SPP: SPP recognized a need to have requirements for GFM for energy storage resources (ESR) to ensure technology readiness. This process started in 2024, and SPP presented background, learnings, industry efforts, and proposed new requirements for modeling and testing of GFM ESR to its members. SPP received significant pushback from its generator owner/developer members, which slowed the process overall. Roughly 80% of the language presented was similar or identical to that used by MISO, and still resistance was rather extensive. The requirements focus on four model-based tests: loss of last synchronous generator, phase angle jump, changing SCR, etc. The final language is pending approval by FERC, but is generally expected sometime in 2026. Due to pushback from generator owner/developers, SPP had to focus only on new interconnection requests and not pursue any retroactivity of existing BESS.

MISO: MISO requires standalone BESS starting in the MISO 2023 interconnection queue to be operationally in GFM mode. MISO conducted its comprehensive engineering study to identify the inflection point where stability risks are identified and worked backward to realize they need to take action quickly. MISO conducted an extensive stakeholder outreach effort to ensure minimized costs, no oversizing obligations, and other key factors. MISO focused specifically on “core” GFM capabilities and a limited number of modeling tests to prove capability. Other tests were included (ROCOF, phase jump, system strength) to demonstrate normal performance expectations and that GFM was not harming performance expectations in any way. The goal was to utilize low hanging fruit capabilities of GFM to support system reliability as soon as possible.

Question: ISO-NE has not identified a need for GFM and has not adopted any requirements for GFM thus far. How was that determined?

The ISO-NE Needs Assessments study various system conditions against a range of contingencies and identify system performance violations (voltage, frequency, thermal, etc.). Voltage violations have been observed but frequency violations do not widely show up. So, as IBR penetration rises, some additional voltage-related issues may arise locally. ISO-NE is exploring solutions broadly and not focused specifically on GFM adoption.

Question: In the ISO-NE Needs Assessments, GFM may be a possible solution; however, GFM is mainly focused on supporting stability-related risks such as system strength, controller stability, etc. How is this explored in the Needs Assessment?

ISO-NE is focused on screening metrics to help scope the work needed on these specific topics. More advancements in this area are needed, but based on the studies being performed today, ISO-NE does not observe these issues in the planning horizon.

Question: Do you believe that GFM technology is mature enough to trust, implement, and utilize on the BPS today?

SRP: Yes, especially for BESS. The hardware is basically the same and the controls have been proven in many parts of the world. Lots of room for continuous improvement, but no notable drawbacks.

SPP: Yes, especially for ESR.

MISO: Yes, GFM BESS technology is commercially ready and has been proven and should be utilized. MISO plans to work closely with OEMs to stay updated on trends and evolving GFM technology for future adoption.

ISO-NE: From a device-level perspective, GFM technology readiness is high; there have been lots of improvements and advancements recently. Focus also needs to include identifying what the system needs, to develop good quantification of system needs metrics, to determine how GFM can contribute to these needs, and then to how GFM can be compared side-by-side along with other solution options.

Question: NERC recommends that new IBRs come with test and verification reports (i.e., model validation reports) from OEMs. In your experience, have OEMs supplied such documentation for GFM projects? Or what other information or data are you seeing for GFM projects?

MISO: The MISO GIA and [Business Practice Manuals](#) require IBR modeling requirements and milestones throughout the interconnection process; however, OEM test and verification (model

validation) reports are not included. PMUs are also required at specified sampling rates, which may help provide data for model validation against actual grid events.

Question: For the entities that have determined a need for GFM, what is next in terms of implementation?

SRP: SRP has developed a [Business Practice](#) on [OASIS](#), which is referenced in the recent [2025 All-Source RFP](#) for new resources being procured by SRP. SRP then evaluated the different sites, developed a comprehensive scoring matrix, and has identified a couple sites where GFM is being pursued operationally. All sites are required to have GFM capability in case it is ever needed in the future. SRP is still fairly early in this process since these sites are not expected until around 2030. SRP is also pursuing a retrofit of an existing GFL BESS to convert it to GFM; this work is collaboratively underway with the IBR owner presently. SRP noted that some IBR developers are quite familiar with GFM and welcome its adoption and utilization while other are less familiar and are trying to get up to speed on new requirements.

SPP: SPP's proposed requirements are pending FERC approval, and SPP is expecting a determination around May 2026 timeframe. GFM ESR would be part of SPP's Business Practice, and mandated for new applicable interconnection customers starting in the 2027 cluster queue.

MISO: Requirement based on high-level studies, and driving system-wide operational requirement. Not focused on determining specific "availability" numbers. See broad need to move on this to maintain grid stability. For new resources, very minimal cost. Thus, requirement put in place based on trend and very minimal or no incremental costs for new assets. Very difficult to quantify "how much do we need" and thus want to see reliability assurance rather than get lost in research endeavors/studies.

Question: All panelists highlighted that your respective entities have put GFM requirements into Business Practice documents. Why was this approach used rather than in the tariff?

SRP: This is a common question explored within SRP, as they have evolved requirements from power purchase agreements to facility connection requirements, business practices, and some tariff revisions. Generally, the level of specificity and detail combined with the need to continuously adapt and update drive these types of requirements more toward the facility connection requirements and business practices. Regardless of tariff, business practice, or other requirements, relatively the same level of internal review and scrutiny occurs.

SPP: High-level requirements fall into the tariff generally but this is very challenging and lengthy to get updated. More detailed specifications fall into business practices.

MISO: High-level revisions to tariff have occurred, but generally all the details remain in business practices and go through a rigorous stakeholder process for approval. Business practices can be changed quicker and more effectively, which is needed for topics that are evolving such as GFM.

All: Generally, the tariff is not the optimal place for detailed requirements. Additionally, much more extensive regulatory requirements are required for tariff revisions, which slow down flexibility and speed to adopt requirements as they evolve, which have been recognized for IBR-specific topics. Business practices are binding and must be met by applicable entities and also require thorough approval processes. It is good practice to ensure that the tariff revisions align with the other requirements so they have ample “hooks” such that they are adequately enforceable.

Question: How did you engage stakeholders and inform them about the direction taken related to GFM, particularly in terms of articulating needs, determining specific details of adoption, and developing requirements?

SRP: SRP teams shared key messages and findings coming out of NERC, ESIG, EPRI, and other efforts to help build momentum and explain the benefits and needs broadly. Additionally, SRP Operational Readiness efforts followed their established governance processes to educate senior leadership and get their buy-in.

SPP: SPP initiated its typical stakeholder process for rule changes. This started with an introduction to GFM and its benefits in 2024. Every month, the SPP team presented fundamentals, learnings, industry reports (NERC, ESIG, AEMO, MISO, etc.) across four SPP working groups. This resulted in over 60 industry engagements through the stakeholder groups, and SPP received more than 100 unique comments throughout the process. All comments were resolved and then stakeholder committees approved the rule modifications before the updated tariff was sent to FERC.

MISO: Overall, MISO had a similar experience to SPP following its stakeholder process. OEMs were engaged as well as generation developers and policymakers to ensure the technology was commercially available and feedback was received.

Question: For ISO-NE, in addition to tracking the needs assessments, were any other sensitivities, studies, or efforts off-cycle pursued to inform possible needs?

Nothing specifically was, or is currently, planned off-cycle, and the main direction is periodic needs assessments. There is some discussion regarding whether GFM BESS would be a generation asset or more of a transmission asset.

Question: What other solutions beyond GFM has your organization evaluated in support of grid-stabilizing system needs?

SRP: SRP is focused on ensuring that all its generators (including GFL IBRs) are providing essential reliability services such as voltage and frequency control. SRP does not have any STATCOMs and does have a large HVDC connecting into their system soon. They are considering a re-evaluation of their voltage control strategy. There are many options on the table and being explored in terms of system reliability and costs and value to customers.

SPP: Some areas of focus include HVDC with dynamic performance studies, SSO screening studies, etc. Lots of studies focused on HVDC growth as well as large load requirements.

MISO: MISO continues to explore model validation to ensure models are accurate and conduct event analysis on any abnormal performance events for continuous improvement.

ISO-NE: ISO-NE is also looking at technologies such as synchronous condensers, STATCOMs, grid-enhancing technologies like dynamic line rating, HVDC, and others.

Question: During the GFM evaluation process, how useful have IEEE 2800-2022 and IEEE P2800.2 been either as a starting point or a framework for IBR capabilities and performance? How were they used?

SRP: They have been useful and were adopted by SRP; however, they are not specifically focused on GFM.

SPP: SPP has adopted clauses of IEEE 2800-2022 clauses with careful consideration but focused on how to adopt test/modeling requirements, which is challenging to implement for developers. Some exceptions with IEEE 2800-2022 requirements were considered and adopted, enabling some flexibility in implementation which has been positive.

MISO: IEEE 2800-2022 was adopted to redefine IBR performance requirements, and MISO focused on ride-through, frequency and voltage support, etc. Regarding GFM, MISO included GFM exceptions to IEEE 2800-2022 implementation with the goal of maintaining the core characteristic of GFM as acceptable.

ISO-NE: ISO-NE adopted IEEE 2800-2022 using the “detailed reference” approach for specific clauses. They have recognized exemptions to IEEE 2800-2022 for GFM and are actively participating in IEEE P2800.1 efforts.

Question: What type and extent of model verification and model validation testing do you believe is required for a GFM BESS going into commercial operation and during commercial operation?

SRP: Both PSLF and PSCAD models need to be validated to build trust in the installed equipment and its performance. SRP is exploring ways to do this better with data available to it.

SPP: The new Business Practice defines specific tests for GFM performance testing in PSCAD, but nothing is established regarding commissioning.

MISO: MISO included measurement requirements in its IBR requirements enhancements, which can be used for model validation.

Session 3: Grid Forming Requirements

This session focused on the development and adherence to GFM requirements around the world.

“GFM Requirements at HECO, AEMO, ERCOT, MISO, etc.” – Andrew Isaacs, Electranix

Andrew shared an overview of various GFM requirements across multiple regions and described some of the history and reasoning for those requirements. Figure 8 shows how GFM requirements can be developed for different assets (or groups of asset types) and then can either be descriptive or test-based in nature. Then one must determine if these requirements are broad or if they are intended to be implemented within a specific region or area. One must also then determine if they are implemented at the equipment level or IBR plant level. It is also important to determine if these requirements will be comprehensive of all IBR performance or if they are intended to work in tandem with existing IBR requirements. Lastly, there are time domain testing techniques that have generally been well established and there are novel frequency domain testing techniques being explored (discussed in more detail below). *Many of the existing requirements, specifically in the United States have focused on time domain testing of performance characteristics for GFM BESS assets.*

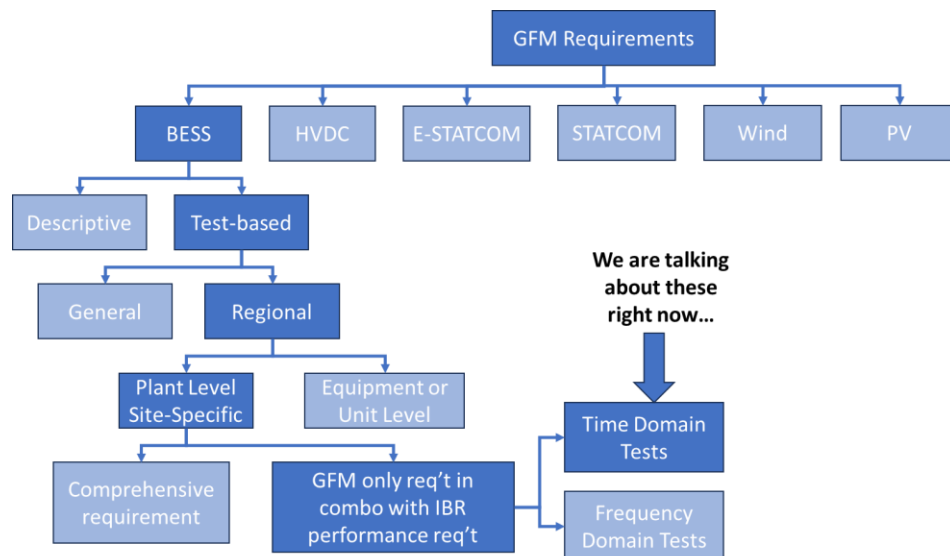
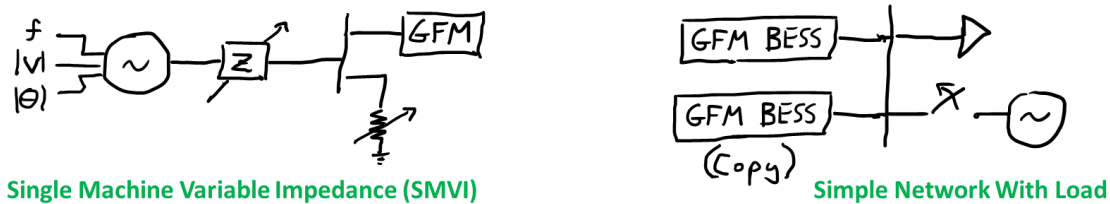


Figure 8: Categorization of GFM Requirements [Source: Electranix]

Time domain, regional, plant-level requirements have been utilized to-date because they are directly written for a specific TO/ISO and can be tailored to specific system needs. They can also

be written relatively quickly and can be rather explicit in terms of acceptable and unacceptable performance criteria. Broader OEM-based equipment standards for GFM can be valuable but require a much broader stakeholder process and take significantly longer. Thus, transmission providers in some areas have adopted time domain plant-level requirements to move much quicker and leverage the technology for newly connecting resources where possible.

A common set of tests have been adopted by multiple entities, as shown in Figure 9, that stem from a couple test bench system configurations. A simple network with load involving GFM BESS assets is used to test GFM core functionality. A single machine variable impedance system is also used to test response to grid events to ensure overall stability and favorable response. A few tests have been defined as informational whereas most of the tests have a clear pass/fail criteria associated with them.



Test #	Test Name	Testing for:	Test Type	Testbench System	AEMO	ERCOT	Fingrid	HECO	MISO	NERC	UNIFI
1	Loss of synchronous machine - discharging	GFM core functions (BESS only)	Pass / Fail	2 - SNWL							
2	Loss of synchronous machine - charging	GFM core functions (BESS only)	Pass / Fail	2 - SNWL							
3	Loss of synchronous machine - limit test	GFM core functions, limits (BESS only)	Pass / Fail	2 - SNWL							
4	Loss of synchronous machine - power balance	GFM core functions	Pass / Fail	2 - SNWL							
5	Large ROCOF up and down	Control stability	Pass / Fail	1 - SMVI							
6	SCR step-down with fault	Control stability	Pass / Fail	1 - SMVI							
7	Angle step change	GFM core functions	Pass / Fail	1 - SMVI							
8	Special severe fault scenarios	Extreme disturbance stability	Pass / Fail	1 - SMVI							
9	Voltage step up and down	GFM core functions	Pass / Fail	1 - SMVI							
10	Energy response test	Transient energy response	Informational	1 - SMVI							
11	Frequency scan	Damping, impedance trend	Informational	4 - PVS							

Figure 9: Categorization of GFM Requirements [Source: Electranix]

Andrew warned that each test must be intentionally created, have a defined purpose, and have a clear set of success criteria for ease of implementation by all stakeholders involved. Time domain tests are vulnerable to “gaming” where a set of arbitrary controls parameters may be able to pass the tests but have other adverse consequences. For example, a ROCOF stability test may offset an incentive to use very high inertia for an energy response test. The creation of simulation tests should always be extensively tested against multiple varieties of equipment, where possible.

Andrew briefly shared additional details to the various tests listed above, including:

- Loss of Last Synchronous Machine:** These are the tests proposed in the [NERC GFM specification white paper](#), which focus on the core GFM functions under different operating conditions.

- **SCR Step Down with Fault:** Decrease in system strength occurs after a fault, and GFM response should generally be better as compared with GFL, down to an SCR of about 1.25.
- **Angle Step Change:** Phase angle step changes are applied to ensure GFM response is provided quickly enough and sustained for a sufficient duration.
- **Voltage Magnitude Step Response:** Voltage magnitude step changes are applied to ensure GFM response is provided quickly enough and sustained for a sufficient duration.
- **Energy Response Test:** Quantifies short-term (first 0.5 seconds) energy provided by GFM for frequency events. System frequency ramps up and down at 1 Hz/second, and the IBR plant is configured with headroom. The energy constant can be calculated by the area under the active power curve within the defined time period.

“UNIFI GFM Requirements” – Shahil Shah, National Laboratory of the Rockies & Dominic Groß, University of Madison–Wisconsin

Shahil presented on frequency domain specifications for GFM resources and perspectives and insights from testing experience. Unlike time domain testing, frequency-domain specifications can be defined relatively independently of the operating conditions (power output and grid strength). They directly and quantitatively show system strength contribution provided by GFM resources and are strongly correlated to time domain tests but provide greater insights regarding GFM performance. The main drawback is that frequency domain specifications focus only on the small signal behavior. Large disturbance behavior is also important to verify, particularly important during operation of GFM near their ratings.

Shahil shared two practical considerations for frequency domain specifications. Firstly, avoid duplication; limited new information is obtained from defining frequency-domain specifications for a performance characteristic of a GFM resource that is effectively captured by time domain specifications. Secondly, avoid complication; keep frequency domain specifications as simple as possible.

An ESIG [report](#) (see webinar [here](#)) was recently released related to testing performance of GFM resources and included details on frequency domain specifications. Tests and performance metrics for quantifying voltage source behavior are included, with frequency domain tests defined and pass/fail criteria specified. The frequency domain tests include:

- Impedance or V/I scan (equivalent Thevenin impedance)
- Q/V scan (related to voltage magnitude step test)
- P/θ scan (related to phase angle step test)

The tests are specifically analyzing the voltage source behavior of the resources. Figure 10 illustrates the characteristics of a voltage source behind a reactor up to the POI in time domain

and frequency domain. In the frequency domain, for example, you can develop a transfer function relationship from voltage to reactive power (or from angle and to active power). The gain (in pu/pu) gives the equivalent SCR, which establishes a path to define the dynamic SCR (*dSCR*).

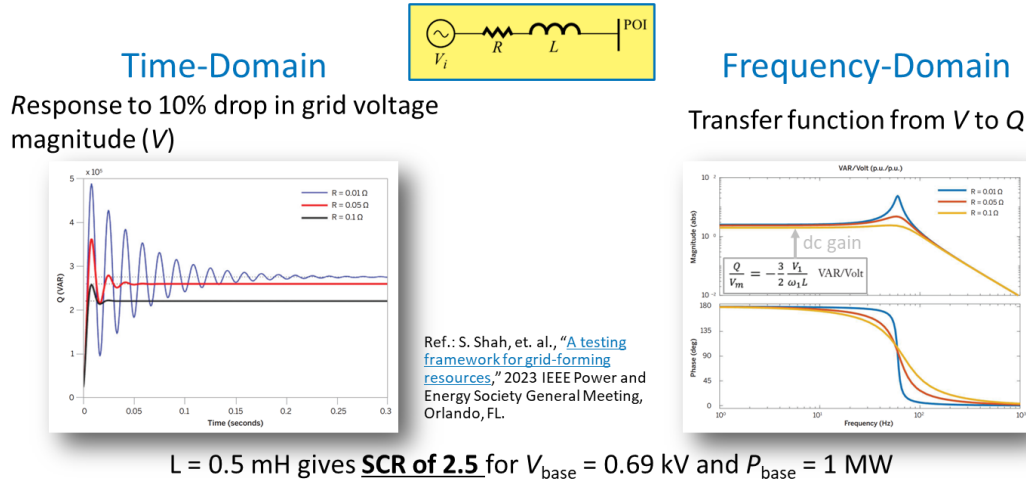


Figure 10: Characteristics of a Voltage Source Behind a Reactor [Source: NLR]

NLR has tested OEM-supplied models for a synchronous condenser and three GFM BESS to estimate their *dSCR* and impedance ($Z = 1/dSCR$) – results are provided in Figure 11. The black trace shows the synchronous condenser and the other plots are the GFM BESS. The results show the voltage source behavior for all resources, and the gains show the contribution to system strength (higher means more contribution).

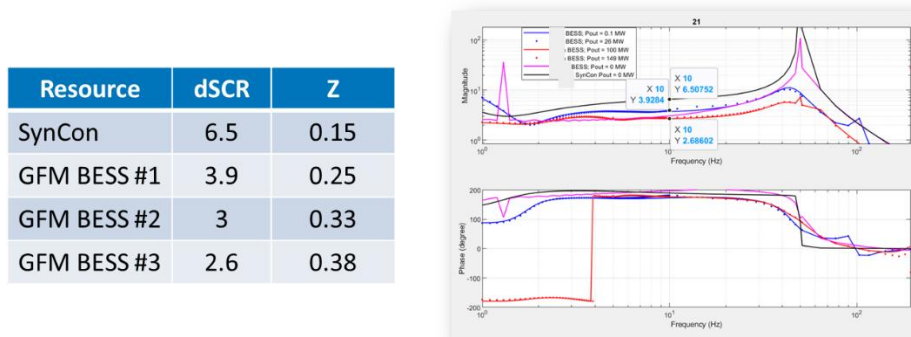


Figure 11: Frequency Domain Characterization of Synchronous Condenser and Three GF BESS [Source: NLR]

Performance metrics for each test can be developed. For example, for the Q/V frequency scan test, the magnitude of Q/V frequency scan should be higher than 2 p.u./p.u. within the frequency range of 4 to 40 Hz. The phase of the Q/V frequency scan should be $\pm 180^\circ$ within the frequency range 4 to 40 Hz. The error between the actual phase and $\pm 180^\circ$ should be smaller than 20° . Note that the specific frequency ranges and gains should be changed based on system needs.

Resonance or mechanical considerations might require deviation from this specification around certain narrow frequency ranges. The performance metrics for P/θ frequency scan are similar to that of Q/V frequency scan test.

Shahil also highlighted that frequency domain tests can also be helpful in sizing necessary amount of GFM. Once the amount of system strength contribution needed is defined, then the deficit can be provided by adequately sized GFM resources.

Dominic shared updates on dynamic droop specifications for GFM IBRs, which is being pursued by the [UNIFI Consortium](#). UNIFI recently released [Version 3](#) of its Specifications for GFM IBRs, which includes an approach to dynamic response specifications with the goal of quantitative and verifiable specifications of key grid support functions and quantitative specifications for two “flavors” of GFM control.

Dominic shared some examples of GFM and GFL resources responding to a frequency perturbation across frequency ranges (both with frequency droop configured). Figure 12 shows results from testing. The figure on the left shows time domain response at a 0.1 Hz and a 30 Hz frequency deviation from nominal. At lower frequency (0.1 Hz), both the GFL and GFM respond following the droop curve. As frequency increases (figure at 30 Hz), phase shift results in portions of the waveform where droop response is in the opposite direction than desired, thus destabilizing the response at that frequency. The figure on the right shows the gain and phase shift drifting away between the GFL and GFM resource.

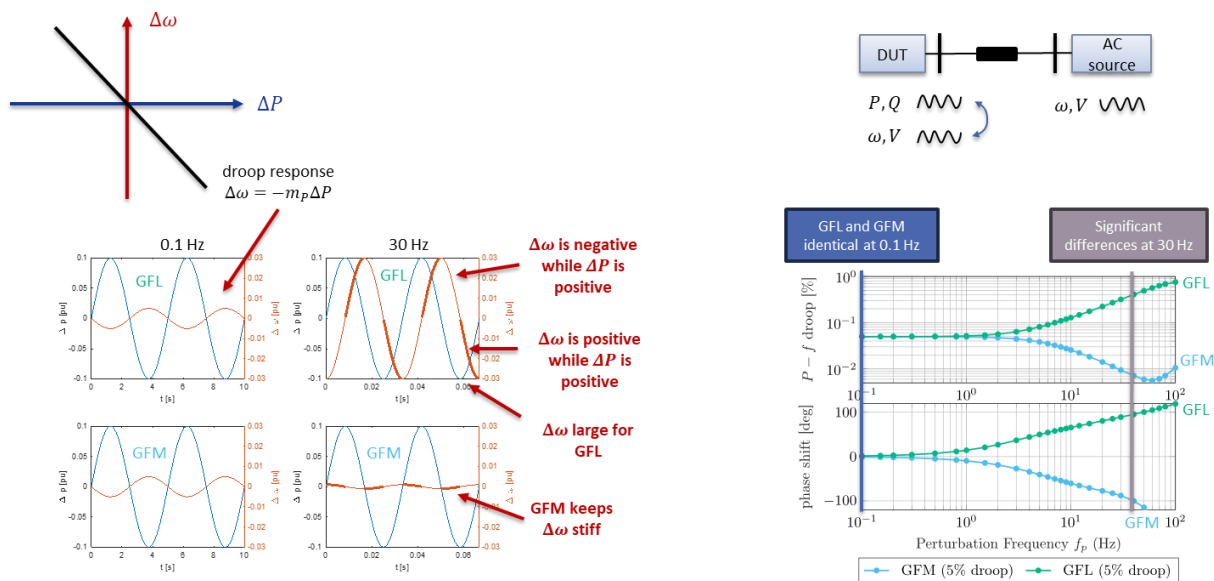


Figure 12: Dynamic Droop Results over Frequency Ranges [Source: UNIFI]

From the work conducted, Dominic described two GFM IBR “flavors”. Figure 13 includes 1) power synchronization and passive high-frequency voltage phasor stiffness (left), and 2) power synchronization and low-gain high-frequency voltage phasor stiffness. Power synchronization

encodes requirement for GFM IBR to synchronize through power, which allows for frequency synchronization without steady-state droop. Passive “high-frequency” response includes a requirement to remain in phase with droop specifications for at least half a cycle. Low-gain “high-frequency” response refers to negligible droop (thus frequency stiff). Bounds can be placed on these characteristics related to core GFM functions. Virtual synchronous machine (VSM)-type GFM may have increasing gain at higher frequency but phase remains within tighter bounds. On the other hand, if you have a lower gain, then phase limits can be relaxed. The UNIFI specifications include both types and do not show preference to one or the other.

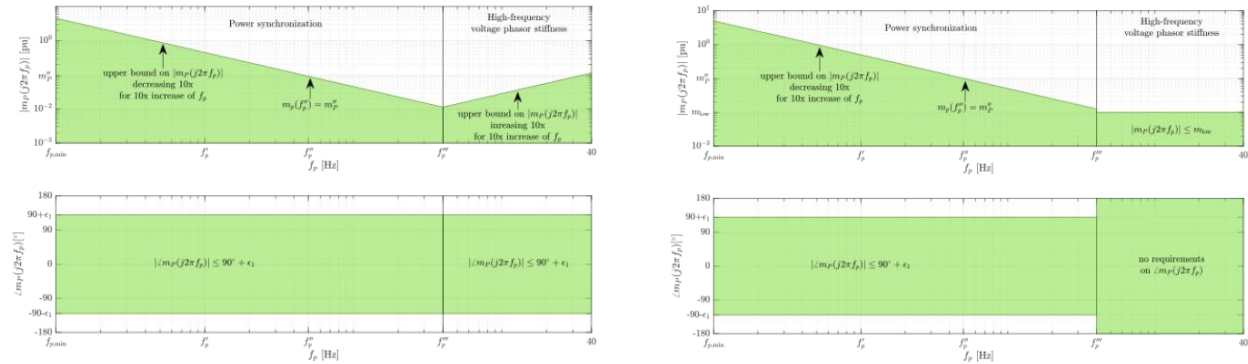


Figure 13: GFM IBR Flavors. (Left: Power synchronization and passive high-frequency voltage phasor stiffness. Right: Power synchronization and low-gain high-frequency voltage phasor stiffness) [Source: UNIFI]

Future work for UNIFI and IEEE P2800.1 will focus on P–V and Q–f cross coupling and how a GFM IBR should respond when limits are reached. UNIFI v3 specifications are being considered as a starting point for IEEE P2800.1 efforts.

“IEEE/IEC New GFM Requirements Efforts” – Alex Shattuck, ESIG

Alex shared an update on the IEC and IEEE GFM standardization efforts underway. He shared an update on the joint effort between IEC PWI 8A-26 and IEEE P2800.1, which are working collaboratively to create a framework for GFM requirements at the equipment-level. There are strengths, weaknesses, opportunities, and threats with this approach, as listed in Figure 14.



Figure 14: SWOT of IEEE/IEC Effort for GFM Standardization [Source: IEEE/IEC]

The IEC and IEEE frameworks are well aligned and a joint standard would have to adequately balance specificity with flexibility and align on terminology. The contributors to this effort are international members from both IEC and IEEE drafting teams, who are meeting regularly to coordinate their work. Figure 15 shows the joint standardization effort among IEC and IEEE committee structures.

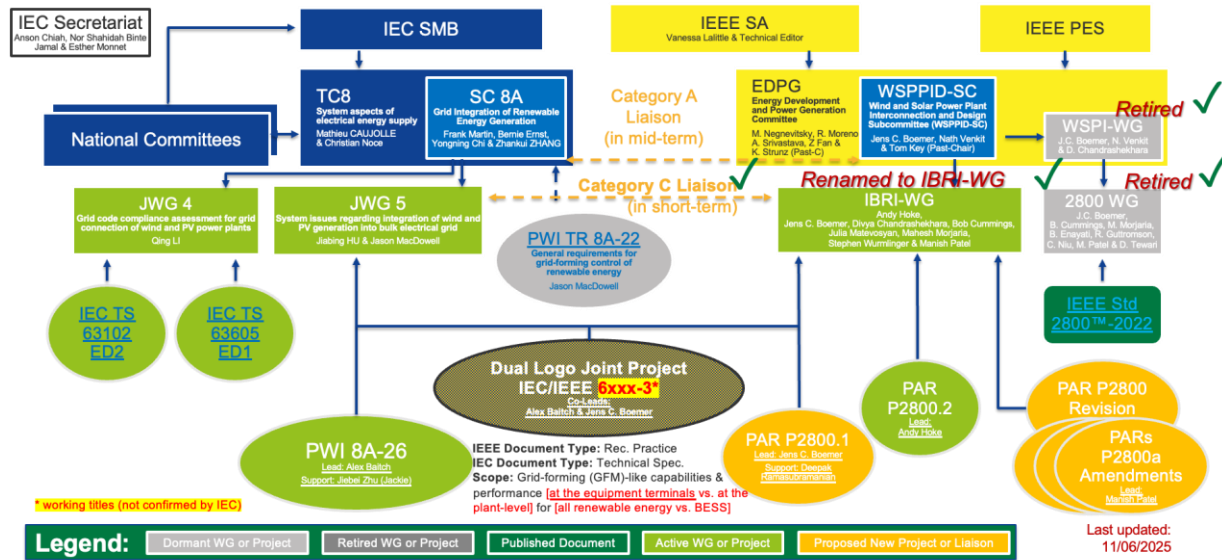


Figure 15: Visual Organizational Mapping of IEEE/IEC GFM Effort [Source: IEEE/IEC]

“VDE FNN GFM Requirements” – Roland Singer, Fraunhofer

Roland provided an update on the VDE-FNN GFM technical requirements for GFM capabilities including the provision of inertia, which have been adopted in Germany. In 2023, the German government approved the “Roadmap System Stability,” defining milestones and processes toward a path to 100% renewable energy. German Transmission System Operators (TSOs) must show the needs and ways to fulfill them in their development plans. The needs are based on: TSO assets (HVDC, STATCOM, etc.), market-based procurement, and minimum requirements.

The German regulatory authority published the regulatory framework for procurement of local inertia in the middle of 2025, and procurement started in January 2026. The VDE-FNN is responsible for the definition of technical requirements, defined in the FNN-guideline [“Technical requirements for grid-forming capabilities incl. provision of inertia.”](#) The third version (2.1) was published in January 2026, and is an addition to the Technical Connection Rules VDE AR-N-41XX.

The third pillar, definition of minimum requirements, is planned to be implemented via the European law via the update of the “regulation for generators” (RfG). The European energy regulator, ACER, proposed the amendment of the RfG to enable system operators to require

GFM capabilities from all generation and storage. An ENTSO-E technical group published a [report](#) proposing the technical requirements for national implementation.

The VDE-FNN requirements are applicable to synchronous generators as well as inverter-based generators (including controllable loads), and include a framework for verification of electrical properties of GFM units including principles of the verification process, prototype certificates of GFM units and systems, transferability of measurements to other units, tests and validation for synchronous units, and tests and validation for converter-based units.

The requirements for inverter-based units focus on the permanent behavior of a GFM unit as an “inertial voltage source behind a mainly inductive impedance” where a voltage amplitude change leads to a mainly reactive current change and a phase angle change leads to a mainly active current change. The following specifications are included:

- Effective impedance must be partly physical and may be controller-based. Effective impedance (without current limitation) shall be smaller than 0.27 pu without the unit transformer (low voltage side) or 0.35 pu including the unit transformer (medium voltage side). In normal operation, the negative sequence impedance must be the same as the positive sequence impedance.
- Voltages source behavior must be a general behavior, and during limitations:
 - During disturbances (step-wise changes of voltage angle or amplitude) for 40 ms, current clipping is acceptable. Current can be limited to 95% of the current that leads to current clipping
- Active current response within current capabilities to a voltage phase angle jump must be:
 - For at least 50% of the change in current in the procured direction, the power change may be limited to $\geq 45\% P_{E_{max}}$
 - For at least 5% of the change in current in the procured direction, the power change may be limited to $\geq 5\% P_{E_{max}}$
- Behavior in the sub- and super synchronous frequency range must dampen oscillations in frequency range of 3–50 Hz in the rotating reference frame
- Behavior in the harmonic frequency range must act passively in the frequency range of 100 Hz–2.5 kHz in the stationary reference frame
- Behavior must dampen power-frequency oscillations in the frequency range of 0.05–10 Hz in the rotating reference frame. Damping ratio must be $D \geq 0.5$ for SCR values of 3 and higher.
- Stable parallel operation of GFM units with synchronous, GFM non-synchronous, and GFL non-synchronous units at SCR values of 1.0, 3.0 and 25.0.

- Reactive power provision must follow control modes defined in the applicable VDE AR-N-41XX requirements, and behavior must follow a first order system defined in the requirements. Damping must be within defined tolerances for SCR between 10 to 50.
- Voltage control must be based on voltage source behavior for a controlled voltage source behind an impedance with linear proportional behavior for voltage amplitude steps (e.g., double step size of the amplitude change must lead to double the current reaction). Dynamic response time to set point change must be ≤ 1 s. For a change in grid voltage, control must have a response time (90%) ≤ 10 ms, settling time ≤ 60 ms, and damping ≥ 0.3 . Stability of the voltage source behavior must be maintained, and the R/X ratio shall not change.
- Robustness to over- and under-voltage follows the applicable VDE AR-N-41XX requirements. Current limitations must be based on an amplitude limitation, and prioritizing between active and reactive current is not allowed. Active power needs to return within 1 second.
- There are additional requirements defined for connection in medium voltage systems.

The market-based procurement allows unidirectional inertia provision to enable the participation of renewable generation and controllable loads, and products are defined for:

- Positive inertia provision (power increase during negative RoCoF)
- Negative inertia provision (power reduction during positive RoCoF)

For both directions, a “Premium” (>90% availability) and a “Basic” (>30% availability) product are defined. The inertial contribution is calculated and after the supply of inertia, the unit can recharge the internal storage. The energy for recharging must be smaller than 1.5x the supplied inertial energy. Within current limits, the GFM device needs to supply inertia over the whole operation range, and the OEM must specify the power range for which provision of inertia is possible.

Session 3 Q&A

From a verification and validation perspective, what changes between GFL and GFM?

In IEEE 2800-2022 and IEEE P2800.2, requirements exist for commissioning and post-commissioning behavior, what should be monitored and recorded, and how model validation can be conducted. This is a challenging job for any IBR, and that does not change for GFM. However, it is critically important to conduct these model validation efforts to ensure understanding of the technology and its dynamic performance and also to ensure accurate models.

How were the theories of GFM specifications derived?

There are multiple approaches to developing GFM specifications, including: 1) specifying the specific controls for GFM technology and trying to quantify them or 2) starting with performance attributes and specifying what performance is required (not focused on controls). The latter has historically been used to avoid defining specific GFM control architectures.

This is not necessarily a GFM-specific question or topic. Any IBR can be tuned to poorly perform on the grid or degrade stability and reliability. Rather we should be focusing on how to configure a GFM so that it is tuned to provide the right functions for a specific system.

Once the grid needs and desired attributes are defined, you can build tests against those, which is mostly what we have today in terms of specifications.

What is your experience of mandatory versus market-based?

Regardless of answer, very few entities will follow recommended practices unless they are mandatory because adherence to the recommended practices costs more. This is a general issue for the industry and not specific to GFM.

There are also concerns with tuning models to pass specific tests and then failing to implement controls aligned with those models. This again is not a GFM-specific issue and should be addressed with model verification and validation checks at IBR plant commissioning.

Session 4 – Global Landscape of Grid Forming Projects

This session focused on the global landscape of GFM requirements, developments, and commercial projects. Julia started the session by sharing relevant links to ESIG literature and webpages that provide details regarding the landscape of GFM projects around the world, including:

Julia shared the GFM webpage:

- GFM Landscape: <https://www.esig.energy/working-groups/reliability/grid-forming-landscape/>
- Installed and Planned GFM Projects: <https://www.esig.energy/working-groups/reliability/grid-forming-landscape/installed-and-planned-gfm-projects/>
- GFM Specifications and Interconnection Requirements: <https://www.esig.energy/working-groups/reliability/grid-forming-landscape/specifications-and-interconnection-requirements/>
- GFM Modeling and Model Verification Efforts: <https://www.esig.energy/working-groups/reliability/grid-forming-landscape/modeling-and-model-verification-efforts/>

- GFM Performance in Real-Time: <https://www.esig.energy/working-groups/reliability/grid-forming-landscape/grid-forming-performance-in-real-time/>
- GFM Studies Evaluating Benefits of GFM: <https://www.esig.energy/working-groups/reliability/grid-forming-landscape/studies-evaluating-benefits-of-gfm/>

The session continued with short introductory presentations from each panelist followed by a facilitator-led Q&A.

Sarah Walinga, Tesla

Sarah shared experience with GFM deployments and operational experience globally. One of the key challenges of integration is translating IBR plant-level requirements down to GFM inverter specifications and management of reference and command signals and such. Generally, Tesla has lots of operational GFM experience with 3.21 GW and 7.52 GWh of operational assets as of March 2026, including some recent projects in the US.

All projects generally followed a similar pattern. The sites were designed in GFL mode and eventually ran into stability-related issues (e.g., low SCR/controls instability) and conversion to GFM was pursued. This has included some quite large BESS installations with lots of solar PV nearby or co-located facilities as well. In some cases, issues with oscillations were uncovered during commissioning and then the site was converted to GFM to achieve commercial operation. In one case, the facility is undergoing official approval since studies were not conducted in GFM mode.

The key message articulated by Sarah was that multiple utility-scale GFM projects are already operational in the continental US and around the world, and have been successfully integrated to address grid stability issues.

Jayanth Ranganathan Ramamurthy, AEMO

AEMO has numerous GFM Projects in service today in the AEMO NEM and WEM regions, and these have been highlighted in AEMO's [Transition Plan for System Security](#). Refer to this document for numerous publications and references pertaining to GFM technology, integration, requirements, and utilization. The pipeline for GFM projects in Australia is very aggressive. [ARENA](#) has funded eight GFM projects constituting 100s of MWs of GFM. Jay highlighted that from an operational perspective, the best use case today is GFM used to enable IBR integration and support reliable operation in low system strength grids. GFM BESS has proved very efficient and reliable, and there are lots of studies supporting GFM providing FFR in AEMO.

Laurence Copson, Zenobe

Laurence shared a case study in the UK of the 200 MW Blackhillock GFM BESS, one of the world's first and largest GFM BESS installations, which provides stability services (inertia and system strength contribution) to the UK grid. Multiple large grid events involving generator

tripping, pumped storage units tripping, HVDC circuits tripping, and other events have been used to test the performance operationally, and overall, the response is very positive. Figure 16 shows the expected versus actual response of the BESS over a time window, with very close match.

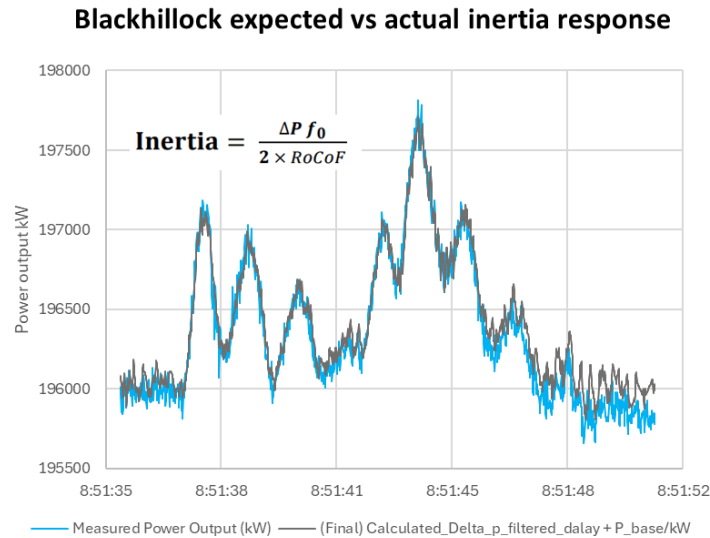


Figure 16. Blackhillock Expected vs. Actual Inertia Response [Source: Zenobe]

Overall, Laurence highlighted that GFM is a proven technology able to provide grid-stabilizing services. Grid planners need to model the capabilities of these resources and identify where GFM can benefit the grid, and either incentives or requirements can be put in place to drive the performance.

Ken Aramaki (for Li Yu), Hawaiian Electric Company (HECO)

Ken described GFM resources that have successfully been integrated in the HECO system across Hawaii. HECO is on a pathway to achieving net zero carbon emissions by 2045 and thus requires innovative solutions to ensure grid stability. Multiple existing projects have provided valuable grid-stabilizing benefits such as Kapolei Energy Storage (135 MW/540 MWh with 50 MW/25 MWh FFR) and Kupo Solar + BESS project. Multiple projects will be commissioned in the near future including Mountain View and Waiawa Phase 2 DC-coupled PV/BESS projects. On the Maui island, Waena BESS will also be coming online. The Stage 3 RFP awarded GFM projects of 126 MW, 60 MW, and 86 MW on Oahu, Maui, and Hawaii Island, respectively.

Benjamin Braun, Fluence

Benjamin shared international experience integrating over 3000 MVA of GFM projects worldwide, highlighting three key drivers for GFM BESS as shown in Figure 17 – physical and operating risk posed by grid conditions, regulatory response and standards evolutions, and economic value. However, disparate requirements around the world have led to challenges effectively deploying solutions for different sets of standards and specifications. For example,

short-term overcurrent capability, inertia constant versus ROCOF and time duration, phase angle response, and damping across frequency ranges all pose technical challenges designing an optimal product across all markets. Battery system design, power conversion system (PCS) and PPC design and tuning, hardware in the loop testing, factory testing, and careful project execution – all are key to successful project and technology deployment. It was also noted that short-term overload capability is essentially mandatory for stable GFM controls, regardless of whether it is specified in grid codes.



Figure 17. Key Drivers for GFM BESS [Source: Fluence]

Session 4 Q&A:

What has motivated GFM projects that are in commercial operation today?

Key drivers often include system strength or low SCR conditions, addressing controls instability issues, existing GFM requirements, or incentives/market opportunities. As requirements are developed around the world for key markets, the OEMs play a significant role in trying to ensure those requirements are developed in a suitable way that enables product integration. It has become rather challenging for OEMs when an authority developing requirements picks and chooses stringent sub-requirements from different regions and pieces them together without much consideration for the impacts and costs this may have. Realizing these complications after requirements have been solidified can create serious obstacles during modeling, studies, and commissioning. Additionally, some GFM projects came to existence due to challenges observed and identified during commissioning that required GFM capabilities to improve stability. Situations where the transmission provider does not allow for GFM are withholding valuable grid-stabilizing features and contribution of system strength for the grid.

In HECO, system studies showed a significantly weakening grid strength that warranted improved inverter stability beyond conventional GFL controls and the need for grid strength

contributions from GFM, particularly from BESS. This has allowed HECO to minimize the need for other large-scale transmission infrastructure on the islands.

In AEMO, GFM is not mandatory but there are GFM specifications being developed. AEMO currently has voluntary specifications but strong incentives for adoption due to system strength “do no harm” requirements for IBRs that have driven aggressive growth of GFM across the system. AEMO has also been studying the need, for example, of overcurrent for certain durations to support specific network providers and their primary fault current needs for relaying. These topics are not yet part of the basic GFM requirements.

The only equipment-level requirements for GFM are being developed by IEEE P2800.1. All other GFM specifications are plant-level requirements. How do OEMs translate plant-level requirements to equipment and how do you make sure the equipment is able to support the plant-level obligations? How do system operators and developers also handle/manage this?

Tesla described that a significant amount of time and effort goes into product design, site design, controls design and tuning, testing, modeling, etc. There are lots of stages of development for GFM projects. Once into commissioning, hold point testing occurs in phases to ensure product performance meets expectations. Julia noted that these perspectives sound very similar to a developer rather than an OEM. Sarah highlighted that as more IBRs come online, there is not enough verification and validation work going on throughout the project lifecycle to ensure models and performance match, which leaves significant risk on the table. More entities should be raising the alarms about these topics, “especially when an OEM is requesting more verification and more validation.” Tesla in particular is very concerned with the lack of checks by developers and transmission providers, and thus takes it upon themselves to ensure performance of the site, to the extent possible.

Fluence described that they are developing their own converter with their own controls in-house. Past experience proved extremely costly trying to work with multiple vendors, which was not sustainable nor supportable. They are trying to streamline everything between the PCS up to the POI for successful controls performance. Developers then have one point of contact to engage across the entire stack from a controls perspective, which has led to greater success.

Zenobe highlighted that just 5 years ago, GFM was a much less mature space. Contracts have also matured significantly, with penalties for suppliers and OEM-backed products and delivery expectations.

What are the checkpoints that system operators require during design and development stage during an IBR project development and lifecycle to make sure GFM requirements are met? What is desired?

HECO does not have a formal process for testing IBR plants during ride-through/fault events. Once in service, they check performance against model. This has led to post-commissioning

changes working with OEMs to address discrepancies between performance and model. Some issues are harder to get addressed but overall it has been a positive experience.

AEMO noted that their hold point tests (i.e., commissioning checkpoints) and registration process are working well and result in adequate checks that need to be completed ahead of commercial operation. Models, site information, test data, etc., particularly from the developer and OEM, have been adequate. Anyone registering in the AEMO NEM must meet all stages in this process, which has become very streamlined. AEMO also has conducted model validation for severe real-world events and seen very accurate models of GFM sites.

What are you seeing in terms of measurements and model validation for GFM compared with GFL projects?

There is not much difference between technologies regarding model validation using measurements for real-world events. In AEMO, plants come online and are waiting for a grid event. If possible, within 90-days, they need to demonstrate plant behavior matches the model. For example, Figure 18 shows a very good match of performance between model and actual equipment for a large event. Tesla stated that “intense enforcement of requirements is what results in this type of match.”

Tesla Controls: Expected (PSCAD) vs. Actual Plant Behavior During Grid Frequency Event in Australia

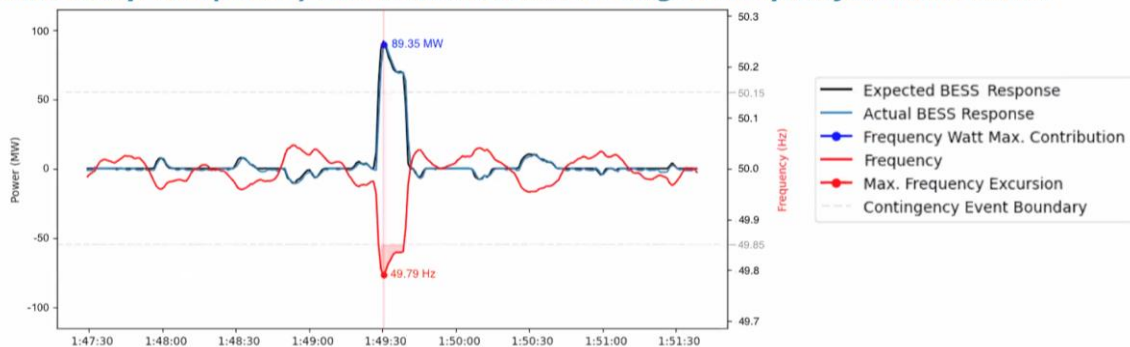


Figure 18. Example of Model Validation Experience for Real Event [Source: Tesla]

In the US, it is rather common to have a site-level PPC overlaid on top of an OEM-specific PPC, particularly for co-located and hybrid sites. These controls have a higher likelihood of not being modeled correctly as they are often configured and tuned during commissioning and never tried up. These issues are typically underenforced by the transmission provider and therefore go unnoticed until a performance issue occurs.

In some areas, however, these types of modeling issues are tested onerously both in the modeling phase and during site commissioning. In those cases, models generally have much higher quality and accuracy (i.e., match the as-left site settings). Some dynamic performance issues depend on field events and thus post-commissioning model validation based on real events is extremely valuable and should be conducted using on-site disturbance monitoring data.

What lessons can you share based on GFM experience thus far?

There are numerous older BESS projects that would ideally like to be converted to GFM such as sites with PPC issues, controls instability issues, weak grid problems, etc. However, the level of complexity for conversion of some of those sites is significant and creates financial strains.

As requirements change over time, new products must adapt to those new requirements and this must be done carefully and with attention to implementation timelines. If requirements are not developed carefully, complications can arise during implementation between IBR plant developers/owners and transmission providers. Situations have arisen where the IBR plant developer believes the site passes based on OEM-supplied documentation but the transmission provider states that the site fails performance tests. This leaves the IBR developer “stuck in the middle” in many ways, and they need guidance as to how to get out of this situation.

OEMs are testing and improving their controls all the time, including HIL testing and real world event validation. GFM products are already highly reliable and continue improving robustness to all sorts of grid events. However, GFM is not a “magic solution” that solves all problems – it is a complement to other types of grid solutions and can provide enhanced grid stability in situations with high IBR penetrations. Continued review and evaluation of models, performance, studies, etc., will all help the system overall become more reliable.

What are future issues we should be thinking about in terms of GFM deployment?

Speed of response, aggressiveness of controls, stiffness of GFM controls, and other issues beyond “inertia” all need to be considered and explored further. Post-fault overvoltage is another challenging area for GFM controls that OEMs are paying close attention to. Minimum and maximum current at various SOC points and temperature points are other areas of focus for OEMs. Energy and DC current limits can also trip the PCS if not carefully managed so these are a focus for OEMs and must be built into the controls. Lastly, OEMs need to ensure GFM controls are not overly degrading BESS battery lifespans. All these issues are OEM-centric challenges currently being explored and should be considered by all applicable parties.

How are you thinking about sizing GFM solutions in the future?

Entities are considering future scenarios and identifying worst case conditions under those scenarios. This may require an iterative process to review response of the grid and IBR plants and identify issues, then seek solutions to address those issues. This can help inform how much GFM (or other solutions) may be needed to solve those reliability issues. AEMO has used similar approaches to determine synchronous condenser sizing based on EMT simulations and results, looking at the contribution of stability benefits.

Sizing of GFM depends somewhat on the amount of GFL plants nearby, particularly from a system strength perspective. A simple ratio of how much GFM is needed for a specific level of GFL is not always straightforward and is site- and location-specific.

What part of revenue would you ideally see come from stability services/GFM aspects?

In the UK experience, one specific project contract for stability services is 1 million pounds per year for a 200 MW project, so this equates to about 5-10% of revenues and that was deemed “enough” by the developer to pursue it. Developers expect more monetization of these services in the future. If a developer is building a battery, for example, and there is no impact on how that BESS is trading energy or granted a certain capacity, then it is a matter of how much more cost burden occurs to procure GFM and developers want to see about 10% of the revenue stack from these additional services.

For a “premium” product and availability (in Germany) for a 500 MW BESS, you’re looking at \$5-10 million in fixed revenue for about 5-10 years. Having that fixed revenue and not volatile is very attractive for developers and financiers.

Key Themes

- GFM has matured from an emerging concept to a deployable, field-proven IBR technology. Over the past decade, GFM controls have matured to the point where fundamental principles are broadly agreed upon and validated through real-world deployments across multiple regions globally. Operational experience from large-scale BESS installations demonstrates that GFM is actively resolving stability challenges today. The industry is increasingly treating GFM as a practical extension of IBR control philosophy rather than a novel or experimental solution.
- The primary driver for GFM adoption is the rapid erosion of traditional system strength. High instantaneous penetrations of IBRs are exposing limits in conventional GFL IBR behavior, particularly under weak grid and disturbance conditions. System operators are observing inflection points (often in the 30–60% IBR penetration range) where stability, frequency response, and control interactions become more difficult to manage. GFM is a scalable, cost-effective mechanism to restore stabilizing characteristics historically provided by synchronous machines.
- Industry implementation is proceeding pragmatically, often ahead of complete analytical certainty. Several ISOs and utilities are adopting GFM requirements based on system-level trends and low incremental cost for new assets rather than waiting for perfect quantification of need. This reflects a shift toward risk-informed engineering judgment, where early deployment is viewed as preferable to delayed action in the face of evolving

system conditions and rapid deployment of BESS.² In practice, requirements are focusing on “core capabilities” with iterative refinement based on operational experience.

- Performance-based specifications are generally the preferred framework over prescriptive control definitions. Rather than mandating specific GFM control architectures, the leading approaches define measurable system behaviors through time-domain (and possibly frequency-domain in the future) tests that GFM resources must meet. This allows flexibility for OEM innovation while ensuring grid needs are met in a verifiable manner. Care must be taken to avoid poorly constructed tests that can be “gamed” or that fail to capture broader system interactions.
- Modeling, validation, and commissioning remain critical (and currently underdeveloped, even for GFL IBRs) risk areas. Across multiple stakeholders, there is consistent concern that model fidelity and as-built performance are not sufficiently aligned, particularly at the IBR plant and IBR controls integration level. While GFM itself is not uniquely problematic, the complexity of layered controls (e.g., PPCs, hybrid systems) increases the likelihood of discrepancies. Stronger enforcement of model validation, including use of PMU/DFR data and post-event performance evaluation and model validation, is essential to realizing the full reliability benefits of GFM.
- GFM is best understood as an IBR controls technology advancement, not a completely different solution, with broad grid-stabilizing attributes. System operators consistently emphasize that GFM complements, not replaces, other technologies such as synchronous condensers, STATCOMs, HVDC, and improved GFL performance. The optimal solution set remains highly location-specific, driven by system topology, resource mix, and operational objectives. As such, planning frameworks are evolving toward comparative, multi-technology evaluations rather than single-solution mandates.
- Standardization is accelerating but remains fragmented across regions and organizations. Parallel efforts across IEEE, IEC, UNIFI, and ISOs are converging on common principles yet differences in terminology, testing methods, and performance thresholds persist. Lack of harmonization introduces complexity for OEMs and developers attempting to design globally deployable solutions. The next phase of industry progress will depend heavily on aligning these frameworks into coherent, interoperable standards.
- Economic signals and policy structures are beginning to reinforce technical adoption. Market-based mechanisms for inertia and stability services, along with requirements embedded in business practices and interconnection processes, are creating revenue streams and compliance drivers for GFM deployment. Developers are increasingly willing to incorporate GFM when it represents a modest cost increment paired with

² It was noted that ERCOT may be a prime example of this delayed action where they expect upwards of 50 GW of BESS that are *not* required to be GFM due to delays in deploying requirements.

predictable value. This alignment of engineering need with economic incentive is likely to be a decisive factor in scaling adoption across the bulk power system.