A UNIQUE WINDOW OF OPPORTUNITY

Capturing the Reliability Benefits of Grid-Forming Batteries

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Brief for Decisionmakers

By Julia Matevosyan, Chief Engineer,
Energy Systems Integration Group

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Synopsis

Implementing grid-forming (GFM) controls on new battery storage systems has the potential to increase grid reliability at low cost. As of 2021, interconnection queues in the United States contained an estimated 427 GW of battery storage capacity that, in the absence of incentives or requirements for GFM controls, will be built with conventional grid-following (GFL) controls. Some of these batteries will be deployed in weak grid areas already dominated by GFL inverter-based resources (IBRs) (wind, solar, and battery storage). Power export capability from these areas may already be limited due to stability concerns, and the integration of additional GFL IBRs in such areas is likely to further reduce stability margins (i.e., lower the power export limits) and could create additional transmission constraints. Reductions in the export of low-cost generation from these areas will drive up overall energy costs. To relieve these stability-related power export constraints, additional transmission assets such as synchronous condensers or transmission lines will be needed, thus also driving transmission costs higher.

As levels of IBRs continue to rise and stability issues become a concern for more and more regions, areas that have taken advantage of this opportunity will be able to maintain reliability through the less expensive, more efficient means of having the GFM IBRs provide stability advantages themselves.

However, when batteries are equipped with GFM controls, rather than exacerbate weak grid issues, they can provide stability services. The advantage of implementing GFM controls in newly planned batteries is that stability can be provided by resources themselves as they are added to the system. Thus, improved stability margins can be achieved at lower cost, as these GFM resources can help avoid the need for supplemental stabilizing equipment.

While some areas—for example, the Hawaiian Islands—already have an acute need to install GFM batteries to maintain grid stability and prevent blackouts, in much of the United States and globally, IBR levels are moderate, and existing conventional power plants are still providing reliability services. This presents a unique window of opportunity to procure, test, and gain experience with GFM technology now, before the need for wind, solar, and battery storage to contribute to grid stability becomes acute. As levels of IBRs continue to rise and stability issues become a concern for more and more regions, areas that have taken advantage of this opportunity will be able to maintain reliability through the less expensive, more efficient means of having the GFM IBRs provide stability advantages themselves.

Stability Challenges in Areas with High Levels of Inverter-Based Resources

Emergence of Stability-Related Transmission Constraints

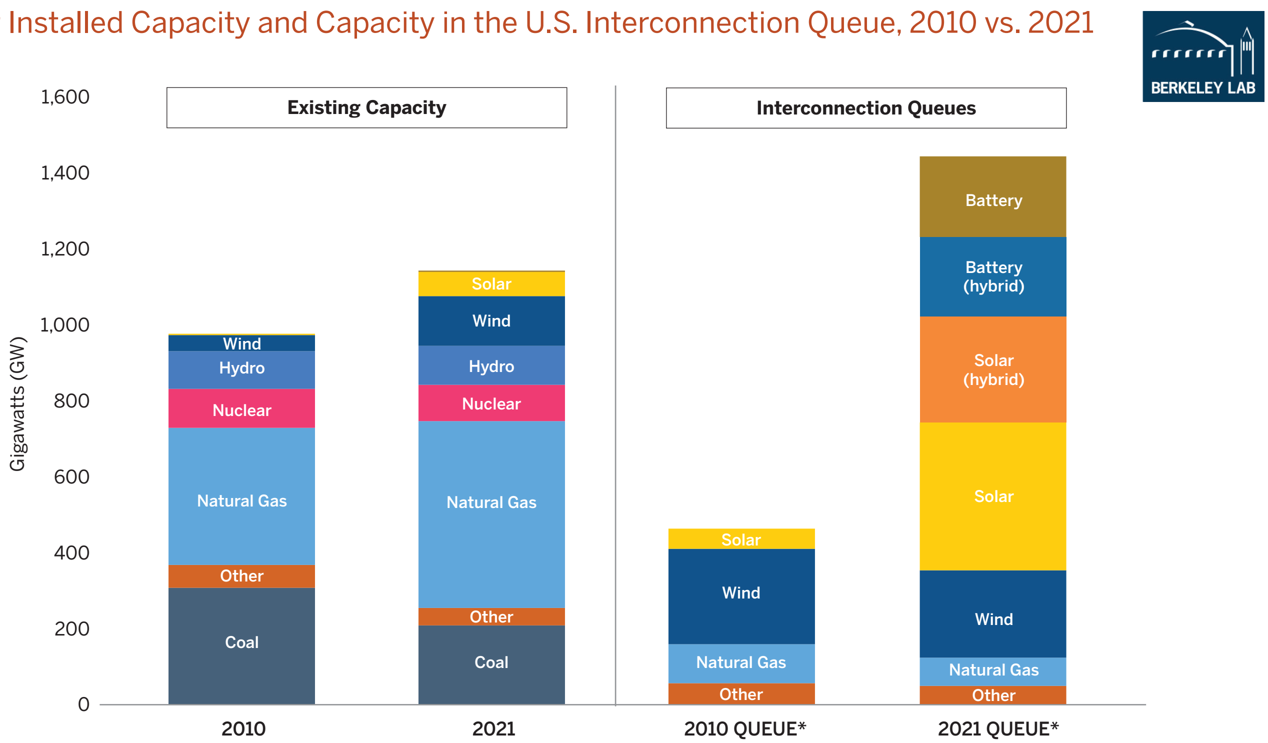
The majority of the inverters used today in wind, solar, and energy storage resources are grid-following. They read the voltage and frequency of the grid, lock onto it, and inject power aligned with that signal. However, instability can result in areas with high levels of GFL inverter-based resources relative to conventional synchronous generators such as coal- and natural gas–fired plants and hydroelectric plants. The reason for this instability is that the voltage signal is easily perturbed as GFL IBRs are injecting power into the grid, making it harder for them to lock onto the grid voltage signal correctly. Additionally, the conventional synchronous generators that provide the strong voltage signal tend to be located far from areas rich in renewable resources. The greater the distance between pockets of renewables and conventional synchronous generation, the "weaker" the grid—the weaker the voltage signal from those strong voltage sources.

This situation is getting progressively worse as remote sun- and wind-rich areas attract continued development of GFL IBRs, as seen, for example, in West Texas and New England in the United States, in South Australia, and in many other regions. Interconnection queues in the United States contain more capacity than the total currently installed generation capacity, with the vast majority of projects being wind, solar, and battery storage (Figure 1). In the absence of incentives or requirements for control improvements, all of the IBRs built (likely 20 to 30 percent of those in the queue) will have conventional GFL controls, thus exacerbating stability concerns.

To mitigate the instability of weak grid areas, system operators monitor power flows on one or more transmission lines exporting power out of the weak grid regions and limit the power export on those lines in order to

FIGURE 1

Existing Installed Capacity and Capacity in the U.S. Interconnection Queue, 2010 vs. 2021



* Queue data represents about 85% of U.S. electric load; AK and HI and some non-RTO utilities not included.

Source: Based on visualizations from Lawrence Berkeley National Laboratory's analysis "Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection" (https://emp.lbl.gov/queues). © The Regents of the University of California, Lawrence Berkeley National Laboratory.

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maintain grid stability. If a limit on a given transmission corridor is reached, wind or solar generation on the sending end of the corridor is reduced to keep power flow over the exporting lines at or below the stability limit. This requires an equivalent increase of usually more expensive conventional generation closer to the load centers, and results in higher energy prices. The number of such transmission constraints is growing as more wind, solar, and battery storage plants equipped with today's common GFL technology are being added to remote parts of the grid, with renewable curtailment increasing accordingly.

Current Strategies for Alleviating the Stability Constraints

Currently, alleviating the stability constraints includes strategies that are often expensive and slow. One strategy is to build new transmission lines to areas with high shares of wind and solar. However, these new lines are only approved if they show reliability or economic (production cost savings) benefits in planning studies. In general, transmission improvements that have a significant impact on existing stability constraints are sufficiently expensive that most do not meet existing economic criteria. Projects that do meet the criteria will take five to ten years to be completed. In addition, these transmission projects typically do not completely eliminate the stability issue—the new lines provide an incremental increase in a stability limit but cannot be used to their full thermal rating.

A second strategy for alleviating stability constraints involves placing synchronous condensers—synchronous machines without a prime mover, which are installed to provide reliability services—in remote parts of the grid. However, this may result in undesirable inter-area power oscillations between this equipment and coal, natural gas, or nuclear generators in the load centers, as was demonstrated, for example, by the Electric Reliability Council of Texas (ERCOT) in a detailed 2018 dynamic stability assessment.[1] Adding synchronous condensers also increases transmission costs.

Grid-Forming Controls as a Better Alternative

Fortunately, there exists a solution to the growing curtailment of renewables that: (1) is inexpensive, (2) can be implemented reasonably quickly, and (3) improves grid stability.

Grid-forming inverters—a new class of inverters with advanced controls—are receiving a great deal of interest in the industry. In the first moments after a disturbance (for example, a large generator going offline or a transmission line disconnecting), GFM IBRs help to stabilize the grid by keeping their internal voltage constant. They can thus provide stabilizing services that are inherently provided by conventional synchronous generators today. These advanced inverter controls can be designed to

GFM technology has been used for decades in microgrids and on small islands, and recent advances are making possible the use of multiple GFM IBRs in larger grids to support reliable system operation where there are high shares of IBRs and retirements of conventional generation.

1 ERCOT, *Dynamic Stability Assessment of High Penetration of Renewable Generation in the ERCOT Grid*, April 2018, https://www.ercot.com/files/docs/2018/04/19/Dynamic_Stability_Assessment_of_High_Penetration_of_Renewable_Generation_in_the_ERCOT_Grid.pdf.

have a stabilizing effect in weak grid areas and improve stability for existing GFL IBRs.[2] GFM technology has been used for decades in microgrids and on small islands, and recent advances are making possible the use of multiple GFM IBRs in larger grids to support reliable system operation where there are high shares of IBRs and retirements of conventional generation.

Increasing the stability of the grid through the use of GFM IBRs has important advantages over strategies involving the addition of transmission assets such as synchronous condensers or new transmission lines. When GFM IBRs are used, the stabilization is provided by the generation resources themselves as they are added to the system, relieving stability-related transmission constraints more quickly and at lower cost.

GFM Batteries, the Low-Hanging Fruit

While GFM controls can potentially be implemented on any type of IBR including new solar and wind plants, batteries are the low-hanging fruit. GFM behavior requires a certain amount of energy buffer, which for wind and solar resources means they must continuously operate below their maximum available power production. In addition, GFM control in wind turbines may result in greater and more frequent mechanical stress. But utility-scale batteries have none of those drawbacks. The battery *is* the energy buffer, and only software modifications to a battery's controls are needed to make the battery a GFM resource. While it could sound reasonable to continue deploying GFL batteries and simply retrofit them with GFM controls when needed, such retrofitting would bring substantial costs and delays. Once a battery has been designed, studied, and built as GFL, retrofitting it with GFM controls would constitute material changes in the battery's controls. The resource would then have to undergo most of the interconnection studies again and update its models and maintenance agreements, all of which take time, result in lost revenue, and burden the generator owner with additional costs.

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Several grid-connected GFM projects have been deployed around the world, and further development is happening at unprecedented speed. Australia leads the way with three large-scale GFM batteries already in operation and three large projects under construction. In late 2022, the Australian Renewable Energy Agency announced co-funding of eight large-scale GFM batteries across Australia with a total capacity of 2 GW/4.2 GWh, to be operational by 2025.[3] In Great Britain five new large grid-connected GFM batteries will be deployed between 2024 and 2026.[4] Large equipment manufacturers such as SMA, Tesla, and Hitachi already have commercial offerings of GFM controls in battery storage.

One issue faced by manufacturers and developers today is the lack of detailed technical specifications for GFM capabilities required by independent system operators (ISOs), regional transmission organizations (RTOs), and utilities, as well as a lack of incentives for battery storage developers and owners to include GFM functionality. At the Energy Systems Integration Group's Special Topic Grid-Forming Workshop in June 2022 and the IEEE Power and Energy Society General Meeting in July 2022, large battery inverter manufacturers (SMA, Tesla, Hitachi) came to a consensus that the implementation of GFM capabilities in a battery involves only software/control modifications and is a low-cost solution; what is needed for widespread adoption is a clear technical specification from a system operator and demand from project developers.[5]

2 Note that, as with any equipment, to harness the stabilizing benefits of GFM IBRs, a location-specific tuning of control parameters will be needed. For example, without control parameter tuning, inter-area oscillations could result from GFM IBRs with virtual synchronous machine–type of controls. But control tuning can optimize GFM IBRs' performance during stressful operating conditions to help damp out oscillations.

3 Australian Renewable Energy Agency, "ARENA Backs Eight Grid Scale Batteries Worth $2.7 Billion," December 17, 2022, https://arena.gov.au/news/arena-backs-eight-grid-scale-batteries-worth-2-7-billion/.

4 National Grid ESO, "Scotland's Wind Success Story Bolstered by £323m Stability Investment," April 6, 2022, https://www.nationalgrideso.com/news/scotlands-wind-success-story.

5 See https://www.esig.energy/event/2022-special-topic-workshop-grid-forming-ibrs/.

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To address this, ISOs, RTOs, utilities, and their stakeholders can draw from interconnection requirements already proposed or approved around the world to draft the specifications for GFM capability for new batteries in their systems.

For example, the National Grid Electricity System Operator in Great Britain includes non-mandatory specifications for GFM capability in its grid code,[6] while the European Union–funded project OSMOSE recommended the inclusion of GFM capability requirements for all new transmission-connected batteries in European grid codes.[7] The association of European Transmission System Operators is currently in the process of developing relevant grid code changes to add GFM capability requirements.[8]

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Even in the absence of requirements for GFM capability, developers can be proactive and procure new batteries with GFM capability today, given that only software modifications to the battery's controls are needed, with negligible addition to the overall project cost. Due to the additional services provided by the GFM batteries, these new batteries (as well as other existing resources in the area, and the region overall) will benefit from increased stability margins.

Testing and Demonstration of Grid Services Can Be Done Ahead of Requirements

We do not need to wait for GFM functionality to be specified in the interconnection requirements. In the past, IBRs' capability to provide new grid services was tested on existing solar plants and battery storage in the absence of requirements, and the same can be done for testing GFM capabilities now. In 2017–2018, the developer First Solar and the National Renewable Energy Laboratory tested the ability of several existing solar projects in California, Arizona, Texas, and Puerto Rico to provide essential reliability services (such as regulation, primary and fast frequency response, and voltage support) and found that they had similar or superior performance compared to conventional

6 National Grid ESO, "GC0137: Minimum Specification Required for Provision of GB Grid Forming Capability (formerly Virtual Synchronous Machine/VSM Capability)," 2023, https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required.

7 OSMOSE (Optimal System Mix of Flexibility Solutions for European Electricity), "Leveraging Flexibilities for the European Power System," https://www.osmose-h2020.eu/.

8 ENTSO-E (European Network of Transmission System Operators for Electricity), "ENTSO-E Webinars on Connection Network Code Amendments (Grid Forming and Rate of Change of Frequency Withstand Capability) and Stability Management," https://www.entsoe.eu/events/2022/11/23/save-the-date-entso-e-webinars-on-connection-network-code-amendments-grid-forming-and-rate-of-change-of-frequency-with-stand-capability-stability-management.

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synchronous generators. Following the successful demonstration, some of these plants are now providing reliability services in their areas.

Similarly, RTOs, ISOs, and utilities can deploy GFM capability in pilot projects involving newly built batteries with GFM controls. A pilot involving several plants concentrated in one geographical area would allow testing of the interoperability of GFM IBRs from different inverter manufacturers with different GFM control strategies. In parallel with the pilots and in collaboration with the manufacturers involved (to obtain manufacturer-specific models of GFM IBRs), ISOs, RTOs, and utilities can carry out simulation studies and explore the broader benefits and grid impacts of GFM batteries. These two initiatives, a pilot and a benefits study, would provide a solid basis for moving forward with the necessary interconnection requirements, performance specifications, and modeling requirements for GFM capability in batteries.

The Energy Systems Integration Group, through its Reliability Working Group, can support this work by providing its members' subject matter expertise regarding stressful grid conditions that it would be beneficial to study, GFM battery storage models to use, interpretation of results, and recommendations for interconnection requirements.

While GFM capability in batteries can be delivered at relatively low (or even zero) cost, there may still be some cost burden associated with the development of a project with this relatively new technology. Depending on the outcomes of the benefits study, some market-based mechanisms could be considered to incentivize GFM capability rather than implementing it through an interconnection requirement.

The Cost of Inaction: Continued Curtailment, Instability, and Higher Costs

This is a moment in the industry when a need is becoming fully understood and an effective, low-cost solution has emerged. Deploying GFM capability in batteries is the clear solution to the weak grid issues that increasingly are the cause of wind and solar curtailments. But the opportunity for ISOs, RTOs, and utilities to utilize this low-cost solution may soon pass. While only a relatively small number of utility-scale batteries are installed in the U.S. today, a significant amount of battery capacity will likely be developed in the next few years. Without specifications and the appropriate incentives or requirements, much or all of this capacity will likely lack GFM capability, which would result in continued stability challenges, continued solar and wind curtailment, and the need for costly supplemental stabilizing equipment such as synchronous condensers or new transmission build-out. In contrast, with specifications and the appropriate incentives or requirements, this battery storage capacity can be installed with GFM capability and lead to improved grid stability, less curtailment, and little or no need for additional costly stabilizing equipment.

With specifications and the appropriate incentives or requirements, battery storage installed in the next few years can have GFM capability, leading to improved grid stability, less curtailment, and little or no need for additional costly stabilizing equipment.

ISOs, RTOs, and utilities can work with stakeholders to carry out studies of the benefits of deploying GFM technology in weak grid areas and then act quickly to implement pilot projects, proceeding in a fashion similar to how the provision of grid services from GFL solar and wind IBRs was tested and implemented in the past. Experience from installations around the world, particularly in Hawaii, Australia, and Great Britain, can be used as a guide.

Appendix: Grid-Forming Projects and Interconnection Requirement Initiatives Around the World

GFM batteries used to enable blackstart capability of simple-cycle gas turbines were installed in several locations in the United States during 2019-2020 (by GE) (https://ieeexplore.ieee.org/document/9583125).

GFM batteries were installed to support 100 percent renewable operation on the island of St. Eustatius in 2017 (by SMA) (https://www.smainverted.com/st-eustatius-100-solar-power-in-the-caribbean/).

At the Dersalloch wind farm in Scotland, an existing GFL inverter was converted to GFM and tested for several months in 2019 (https://ietresearch.onlinelibrary.wiley.com/doi/full/10.1049/iet-rpg.2020.0638). In 2020 they tested islanded operation as well as blackstart capability of the plant (by Siemens Gamesa) (https://www.scottishpowerrenewables.com/pages/innovation.aspx).

The GFM Dalrymple battery was installed in South Australia in 2018 (by Hitachi) (https://go.hitachi-powergrids.com/grid-forming-webinar-2020).

The Hornsdale battery in South Australia was converted from GFL to GFM by 2022 (by Tesla), and measurements during grid disturbances already provide evidence of the stabilizing behavior of this battery (https://reneweconomy.com.au/world-first-hornsdale-battery-gets-approval-to-deliver-critical-inertia-services-to-grid/, https://reneweconomy.com.au/virtual-machine-hornsdale-battery-steps-in-to-protect-grid-after-callide-explosion/).

The Wallgrove GFM battery (by Tesla) began commercial operation in Australia in December 2022 (https://reneweconomy.com.au/world-first-hornsdale-battery-gets-approval-to-deliver-critical-inertia-services-to-grid/).

Three additional GFM projects in Australia—Broken Hill, Riverina, and Darlington Point Energy Storage System—are under construction, with expected commercial operation dates in mid-2023 (https://www.agl.com.au/about-agl/how-we-source-energy/broken-hill-battery-energy-storage-system, https://edifyenergy.com/project/riverina-darlington-point/).

As noted above, on December 17, 2022, the Australian Renewable Energy Agency (ARENA) announced co-funding of an additional eight large-scale GFM batteries with a total project capacity of 2 GW/4.2 GWh, to be operational by 2025 (https://arena.gov.au/news/arena-backs-eight-grid-scale-batteries-worth-2-7-billion/).

In April 2022, the Stability Pathfinder project in Great Britain awarded provision of stability services such as inertia and system strength to five GFM batteries with commercial operation dates between 2024 and 2026 (https://www.nationalgrideso.com/news/scotlands-wind-success-story).

National Grid Electricity System Operator (the independent system operator in Great Britain) has established non-mandatory interconnection specifications for GFM IBRs, approved and included in their grid code in February 2022. The intent is to tender for this capability through Stability Pathfinder initially and to procure it in the future through one or more new market products. The five GFM batteries mentioned in the previous point will have to comply with the new GFM specifications (https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required).

Hawaiian Electric Company (HECO) currently requires all newly built batteries to have GFM capabilities. Interconnection requirements for these resources are specified in HECO's codes (https://www.hawaiianelectric.com/documents/clean_energy_hawaii/selling_power_to_the_utility/competitive_bidding/20220531_exh_5.pdf).

Two GFM batteries are currently in operation in Kaua'i, Hawaii, in different parts of the grid, from different manufacturers. One of the plants is a GFM solar and battery hybrid (by Tesla and AES) (https://pv-magazine-usa.com/2019/07/25/solar-batteries-help-the-grid-recover-in-kauai/).

This brief for decisionmakers is available at https://www.esig.energy/reports-briefs.

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