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

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Julia Matevosyan, Chief Engineer, Energy Systems Integration Group

Synopsis

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

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

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

Stability and Inverter-Based Resources

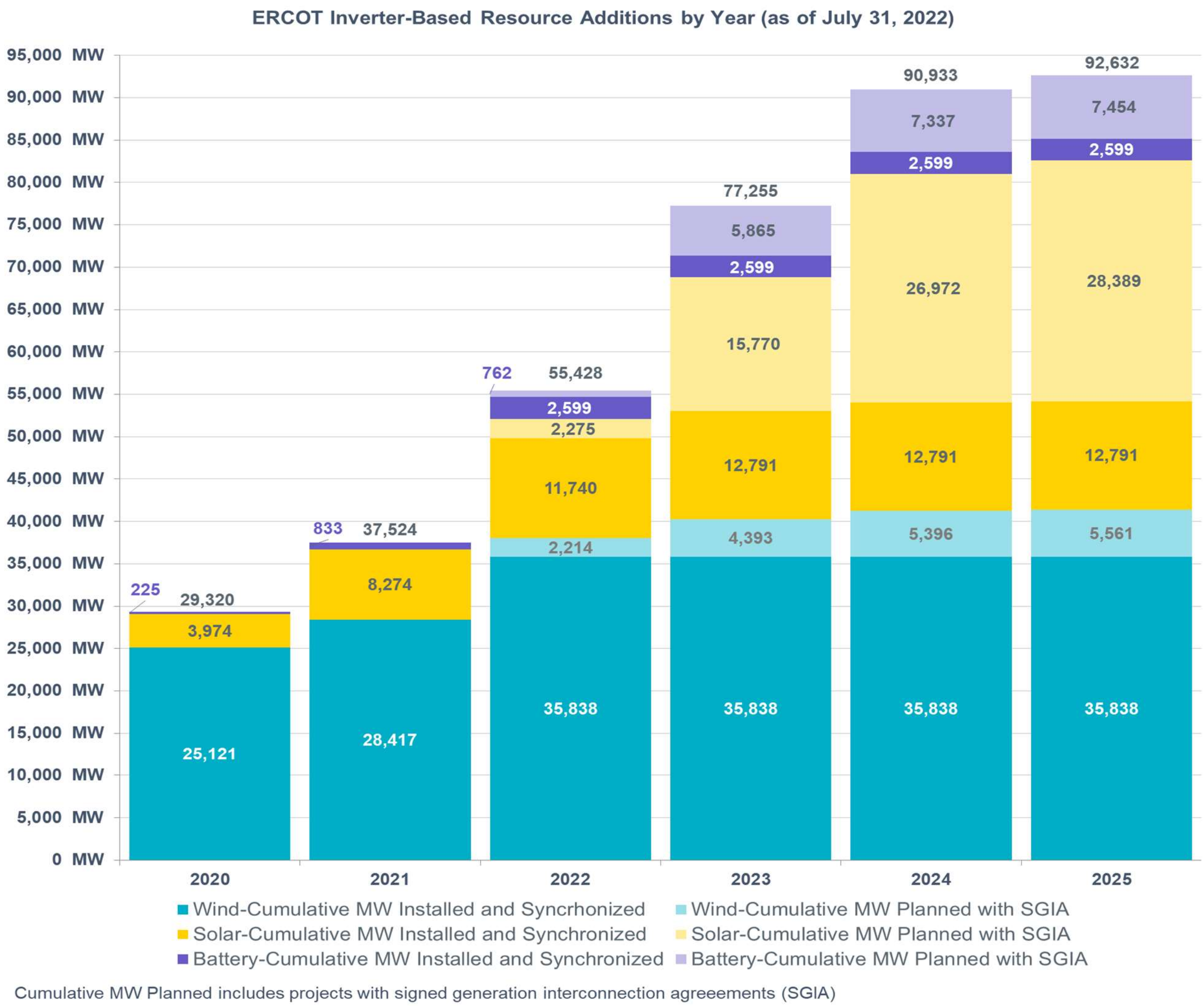
The majority of the inverters used today in wind, solar, and energy storage resources are "grid-following" (GFL). They read the voltage and frequency of the grid, lock onto it, and inject power aligned with that signal. However, instability can result in areas with high levels of GFL inverter-based resources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

Where ERCOT's IBRs Are Today

Today, more than 50 GW of GFL IBRs are installed or synchronized in ERCOT (Figure 1), and most are built in remote areas with high wind, high solar intensity, and good land availability on the edges of the grid.[1]

FIGURE 1

Combined Wind, Solar, and Battery Capacity in ERCOT



The darker shades of each color indicate installed and synchronized generation capacity, while lighter shades indicate planned generation capacity of each type with signed generation interconnection agreements (SGIA).

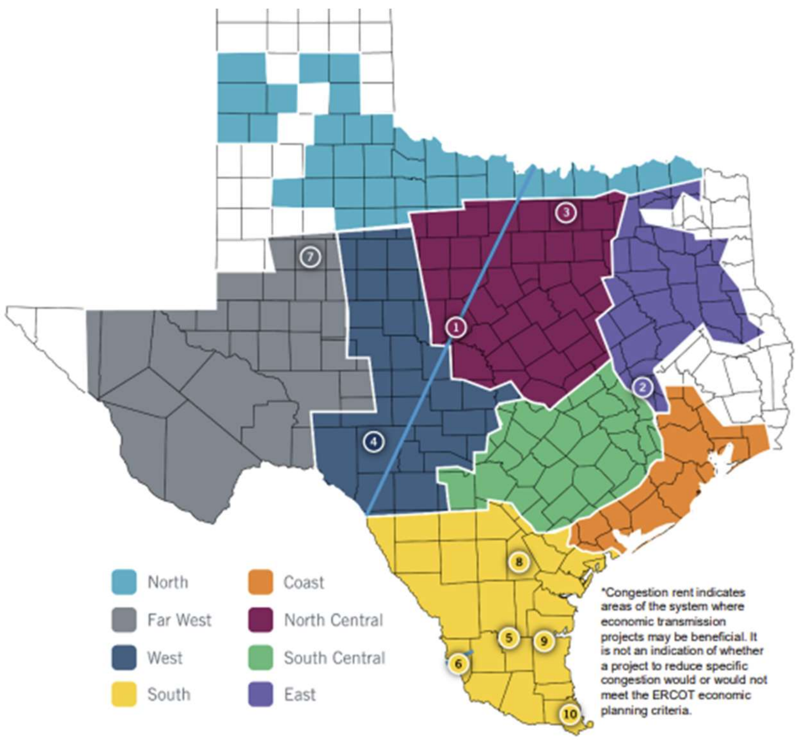
Source: Energy Systems Integration Group. Data from [ERCOT Resource Adequacy https://www.ercot.com/gridinfo/resource].

[1] Synchronized capacity refers to projects that ERCOT has approved to generate energy for the grid but that have not passed all qualification testing necessary to be approved for participation in ERCOT market operations.

An increasing number of regions within the ERCOT grid with high IBR concentrations are facing weak grid–related stability issues. To mitigate these issues, ERCOT is using Generic Transmission Constraints (GTCs) to monitor power flows on one or more transmission elements near weak grid regions and limit those flows in order to maintain grid stability using market-based generation dispatch. If a transmission limit on a given GTC is reached, generation on the sending end of the GTC is re-dispatched to keep power flow over the GTC at or below the limit. The number of GTCs is growing over time as more IBRs, using today's common, GFL technology are being added to remote parts of the grid. Figure 2 shows the locations of the top 10 transmission constraints, while Figure 3 illustrates how the number of GTCs has grown over time.

FIGURE 2

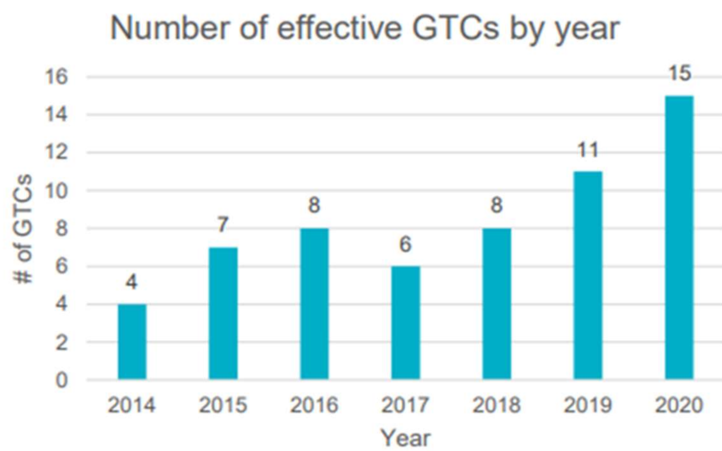
Top 10 Projected Constraints on ERCOT System for 2023 and 2026



Source: ERCOT, *Report on Existing and Potential Electric System Constraints and Needs*, December 2021, https://www.ercot.com/files/docs/2021/12/23/2021_Report_Existing_Potential_Electric_System_Constraints_Needs.pdf.

Generation redispatch due to stability limits increases energy prices in and around regions with high customer demand. It results in the curtailment of low-marginal-cost wind and solar generation in pockets of the grid with high shares of IBRs. This, in turn, causes an equivalent increase of more expensive thermal generation on the receiving end of the GTCs. Figure 4 illustrates growth of solar and wind energy curtailment in ERCOT.

FIGURE 3
Number of Stability-Related Constraints in ERCOT by Year, 2014-2020



Source: ERCOT, *Report on Existing and Potential Electric System Constraints*, December 2020, https://www.ercot.com/files/docs/2020/12/23/2020_Report_on_Existing_and_Potential_Electric_System_Constraints_and_Needs.pdf.

Current Strategies for Alleviating the GTCs

Strategies for alleviating the GTCs include synchronous condensers or new transmission lines (reducing electrical distance from IBR pockets to the load centers); however, these solutions are only implemented if they show reliability or economic benefits in the planning studies.[2] In general, transmission improvements that have a significant impact on existing GTCs are sufficiently expensive that most do not meet existing economic criteria. Those projects that do meet the criteria will still take five to seven years to be completed. Additionally, these transmission projects typically do not completely eliminate the stability issue that cause the creation of the GTC, meaning that the new lines provide an incremental increase in the identified stability limit but cannot be utilized to their full thermal rating.

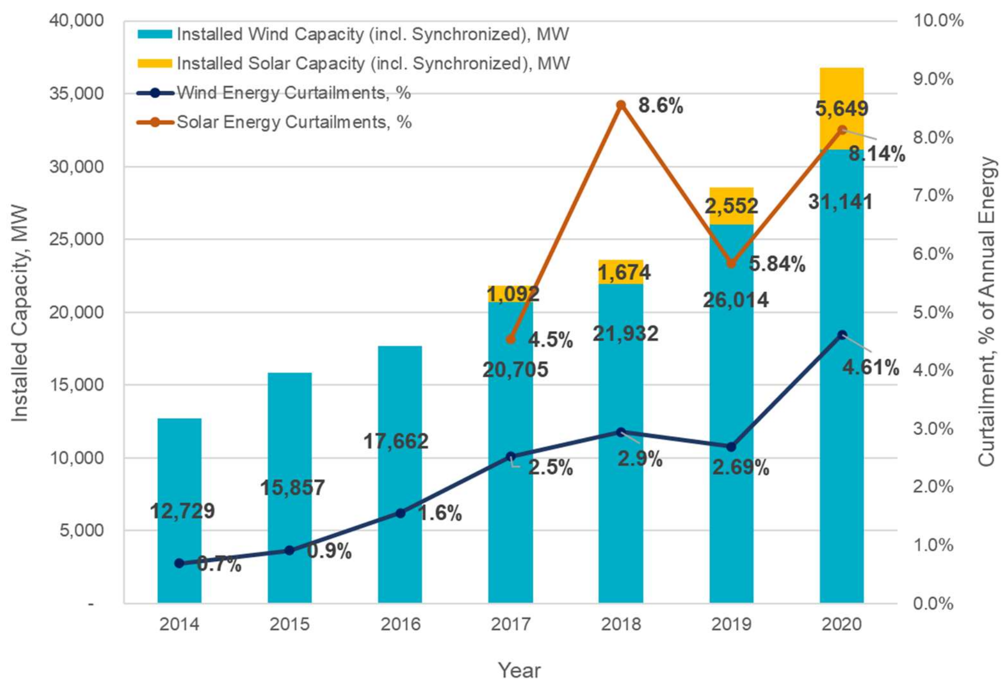
Placing synchronous condensers in remote parts of the grid may result in undesirable inter-area power oscillations between the condensers and synchronous generators in the load centers, as was demonstrated by ERCOT in a detailed 2018 dynamic stability assessment.[3]

[2] A synchronous condenser is a synchronous generator without a prime mover. Synchronous condensers are used to provide dynamic voltage support, boost system strength, and, in more recent applications, increase overall system inertia.

[3] 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.

FIGURE 4

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



The bars of the chart show installed and synchronized wind (blue) and solar (yellow) generation capacity in ERCOT. The blue trace shows wind energy curtailments and the orange trace shows solar energy curtailments. Curtailment is expressed as a percentage of annual energy production by that generation type. Due to growing installed wind and solar generation capacity, an increasing number of GTCs, and declining transfer limits on existing GTCs, wind and solar energy curtailments are steadily rising.

Source: Julia Matevosyan, "ERCOT's Experience Integrating High Shares of IBR," presentation in the Energy Systems Integration Group's virtual training sessions for the National Association of Regulatory Utility Commissioners,https://www.esig.energy/naruc-virtual-training-sessions/.

Grid-Forming Controls as an Alternative

What is needed is a solution to the growing curtailment of IBRs that: (1) is not expensive, (2) can be implemented reasonably quickly, and (3) does not result in new complications for grid stability.

A new class of inverters with advanced controls—called grid-forming (GFM) inverters—is receiving a great deal of interest in the industry. These advanced inverter controls can be designed to have a stabilizing effect[4] in weak grid areas and improve stability for existing GFL IBRs. This technology has been used for decades in microgrids and on small islands, and recent advances are allowing for the parallel operation of

[4] Note that, as with any equipment, to harness the stabilizing benefits of GFM IBRs, a location-specific tuning of control parameters may be needed. For example, without control parameter tuning, similar inter-area oscillations, as mentioned above for Synchronous Condensers, may result from GFM IBRs with virtual synchronous machine type of control. On the other hand, with control tuning may be done to optimize performance during stressful operating conditions to help damp out oscillations.

multiple GFM IBRs in larger grids to support reliable system operation with higher shares of IBRs and the retirement of synchronous generation.

GFM IBRs can provide stabilizing services that are inherently provided by conventional synchronous generators today. The advantage of this is that the stabilization is provided by the generation resources themselves as they are added to the system and, thus, stability can be achieved more efficiently and at lower cost than through the addition of transmission assets, such as synchronous condensers or new transmission lines.

GFM controls can be implemented on any type of IBR, including new solar and wind plants. However, batteries are particularly low-hanging fruit for the implementation of these controls. Batteries require only software changes (modifications to their controls), while wind[5] and solar resources would need to have a small energy buffer added in order to exhibit GFM behavior. In addition, batteries would typically remain connected to the grid at all times, whereas wind and solar resources could be disconnected during periods of little or no energy production and thus be unavailable to provide GFM functionality at certain times.

A number of GFM projects have been deployed around the world (see a selected list in the appendix), and further development is happening at the unprecedented speed. Large inverter manufacturers such as SMA, Tesla, and Hitachi have commercial offerings of GFM inverters.

With 8.3 GW of batteries with interconnection agreements currently in ERCOT's interconnection queue, there is a unique window of opportunity that needs to be seized in order to harvest the benefits of GFM capability from these new resources. Incentivizing or requiring them to be built with GFM controls will provide additional stabilization in weak grid areas, reduce curtailment of low-cost energy, and avoid the need for additional stabilizing equipment that would be required if these storage resources were built as GFL IBRs.

The Benefits of Equipping Battery Storage Projects with Grid-Forming Controls

As of September 1, 2022, there are 8.3 GW of battery storage with signed interconnection agreements in ERCOT's interconnection queue, the majority of which are being planned behind existing stability constraints (see Figure 5 for their locations and Figure 2 for the transmission constraints). If these battery storage projects are built with conventional GFL controls, these resources will face the same limitations as existing wind and solar resources in these areas. This could lead to even lower transfer limits on the existing GTCs and/or cause a need for new GTCs.[6]

However, if ERCOT were to require all new batteries to be built with GFM controls, this would facilitate higher limits on the existing GTCs or even completely alleviate some of the existing stability constraints,

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[5] Implementation of grid forming capability in wind IBRs is further complicated by additional stress on mechanical parts of a wind turbine.

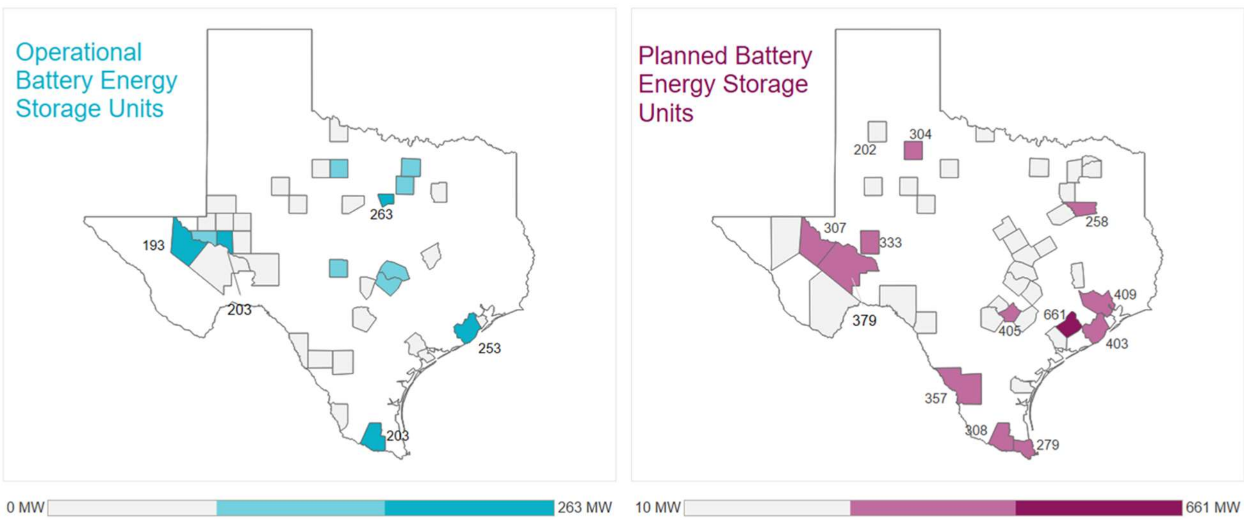
[6] Note that that while the batteries may reduce curtailment by charging during curtailment hours, the limited duration of the planned batteries means that they will not have a significant impact on overall levels of wind and solar curtailment.

thus reducing wind and solar curtailments and avoiding the additional cost to consumers for supplemental transmission assets.

ERCOT and stakeholders can draw from interconnection requirements already proposed or approved around the world to draft the requirements for GFM capability in new ESRs on the ERCOT system. For example, National Grid Electricity System Operator (NGESO) in Great Britain has already included requirements for grid-forming capability into its grid code,[7] while the European Union–funded project OSMOSE recommended the inclusion of GFM capability requirements for all new transmission-connected batteries into European grid codes.[8]

FIGURE 5

Location of Operational and Planned Batteries in ERCOT, as of August 31, 2022



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

The majority of new battery capacity is planned in areas that are subject to stability-related transmission constraints today.

Source: ERCOT Resource Adequacy Department, *Capacity Charts Report*, August 2022.

Even in the absence of requirements for GFM capability, developers can be proactive and install GFM capability on ESRs now, given that only modifications to the battery's controls are needed. The developer (as well as owners of other resources in the area, and ERCOT overall) would benefit from the resulting increase in transfer limits on existing GTCs and experience less (or no) curtailment of the ESR.

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[7] National Grid ESO, *GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability,* https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required. NGESO's grid-forming capability requirements are non-mandatory, and the capability will be procured through a market product (see appendix).

[8] Optimal System-Mix of Flexibility Solutions for European Electricity (OSMOSE) project deliverable D3.3, Analysis of the Synchronisation Capabilities of BESS Power Converters (2022), https://www.osmose-h2020.eu/wp-content/uploads/2022/03/OSMOSE-D3.3-Analysis-of-the-synchronisation-capabilities-of-BESS-power-converters.pdf.

Testing and Demonstration of Services Ahead of Requirements

There have been prior examples in which IBRs' capabilities to provide grid services were tested on existing plants prior to implementation through interconnection requirements. For example, in 2017-2018, First Solar and the National Renewable Energy Laboratory tested several existing projects in the United States and Puerto Rico, including Barilla Solar in Pecos County, Texas, to demonstrate that solar resources can provide essential reliability services (such as regulation, primary and fast frequency response, and voltage support) with similar or superior performance compared to conventional thermal generators. Following the successful demonstration, some of these plants are currently providing the services in their respective areas.

Similarly, GFM capability can be deployed in ERCOT through a pilot project operating several newly built ESRs with GFM controls. A pilot involving a number of plants concentrated in one geographical area, such as the Texas Panhandle or Far West Texas, would be more informative than testing GFM capability on a single ESR, since this would allow testing of the interoperability of GFM IBRs from different inverter manufacturers with different GFM control strategies.

In parallel with the pilot and in collaboration with involved manufacturers (to obtain manufacturer-specific models of GFM IBRs), ERCOT should carry out simulation studies and explore broader benefits and grid impacts of deploying GFM capabilities on all planned ESRs in the interconnection queue.

These two initiatives would provide a solid basis for moving forward with the necessary Nodal Protocol and Operating Guide Revision Requests to include interconnection requirements, performance specifications, and modeling requirements for GFM capabilities in ESRs.

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

While GFM capability in ESRs can be delivered at relatively low (or even zero) cost, there still may 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 can be considered to incentivize GFM capability rather than implementing it through an interconnection requirement.

The Cost of Inaction

This is a moment in the industry when a need is becoming fully understood and an effective, low-cost solution has emerged. GFM capability in batteries is the clear solution to the weak grid issues[9] that

[9] This is not to be confused with increased short circuit current contribution and increased short circuit ratio (SCR). While SCR is used today as a simple proxy for system strength, the concern here is impedance (or electrical distance) between a network node and a strong voltage source rather than with short circuit current sufficiency. The larger the impedance the more sensitive is the voltage to current injection at that node. SCR served well as a system strength metric in power systems dominated by synchronous generators, however in IBR-dominated systems it fails to recognize contribution from GFM IBRs. New system strength metrics is an active area of research. In the absence of these metrics, detailed transient stability studies can identify weak grid issues; however, developing new system strength metrics will allow simpler analysis of system conditions in real time.

increasingly are the cause of wind and solar curtailments in ERCOT and elsewhere. But ERCOT's opportunity to utilize this low-cost solution may soon pass; while there are only 2.3 GW of ESRs on ERCOT grid today, a significant amount of ESR 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 *not* have GFM capability. If this capability is not incentivized or required very soon, the result will be continued transfer limits and solar and wind curtailment, and higher costs of supplemental stabilizing equipment in the future.

ERCOT should work with stakeholders to carry out studies of the implementation of GFM technology in its weak grid areas and act quickly to implement pilot projects (similar to how the provision of ancillary services from GFL IBRs has been tested in the past). Experience from installations around the world, particularly Great Britain and Australia (see the list of projects in the appendix), can be used as a guide.

Unrelated to system strength issues, a certain amount of fault current is needed to make existing protective relays detect and clear faults in timely manner. To understand this need In IBR-dominated systems a systems-specific protection coordination studies will be needed.

Appendix: Grid-Forming Initiatives Around the World

- GFM batteries are used to enable black start capability of simple-cycle gas turbines have been installed in several locations in the United States in 2019-2020 (by GE)
- GFM batteries were installed to support 100% renewable operation on the island of St. Eustatius in 2017 (by SMA) https://www.smainverted.com/st-eustatius-100-solar-power-in-the-caribbean/
- The Dersalloch wind farm in Scotland converted an existing GFL wind farm inverter to GFM and tested it for several months in 2019 and tested islanded operation as well as black start capability of the plant in 2020 (by Siemens Gamesa).
- The Dalrymple battery was installed in South Australia in 2018 (by Hitachi) https://go.hitachi-powergrids.com/grid-forming-webinar-2020
- Conversion of the Hornsdale battery in South Australia from grid following to grid forming is currently compete and synchronized and is undergoing final model validation process (by Tesla). Measurements during grid disturbances already provide evidence of stabilizing behavior of the Hornsdale battery.
- 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.
- National Grid Electricity System Operator (independent system operator in Great Britain) has established non-mandatory interconnection requirements 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 in the future to procure it through one or more new market products. The five GFM batteries mentioned above will have to comply with the new GFM interconnection requirements. https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required
- Hawaii 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 grid-forming batteries are currently in operation in Kauai, Hawai'i, in different parts of the grid, from different manufacturers, one of the plants is a grid forming solar and battery hybrid (by Tesla and AES) https://pv-magazine-usa.com/2019/07/25/solar-batteries-help-the-grid-recover-in-kauai/
- At ESIG'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) all came to a consensus that the implementation of GFM capabilities in a battery only involves software/control modifications, is a low-cost solution, and all that is needed for widespread adoption is a clear technical specification from a system operator and demand from project developers. https://www.esig.energy/event/2022-special-topic-workshop-grid-forming-ibrs/