Defining and Deploying Advanced, Grid-Forming Controls

for Solar, Wind, and Battery Resources

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

FACT SHEET

As rising numbers of solar, wind, and battery resources are deployed in power systems around the world, their role on the grid continues to evolve. To maintain grid stability and reliability, these inverter-based resources (IBRs) need to provide some of the grid services currently (or formerly) provided by conventional power plants. IBRs are already required to have the capability to provide some of these grid services, but advanced controls will be needed to enable them to provide the full range of necessary services in a high-renewables grid (see Table 1, p. 4).

Nearly all IBRs deployed today are "grid-following"; they rely on a strong and stable voltage and frequency signal from the grid to which they can synchronize. But as levels of grid-following resources rise, and they eventually come to provide the majority of our electricity, new advanced inverter controls—termed grid-forming (GFM)—will be needed to maintain system stability.

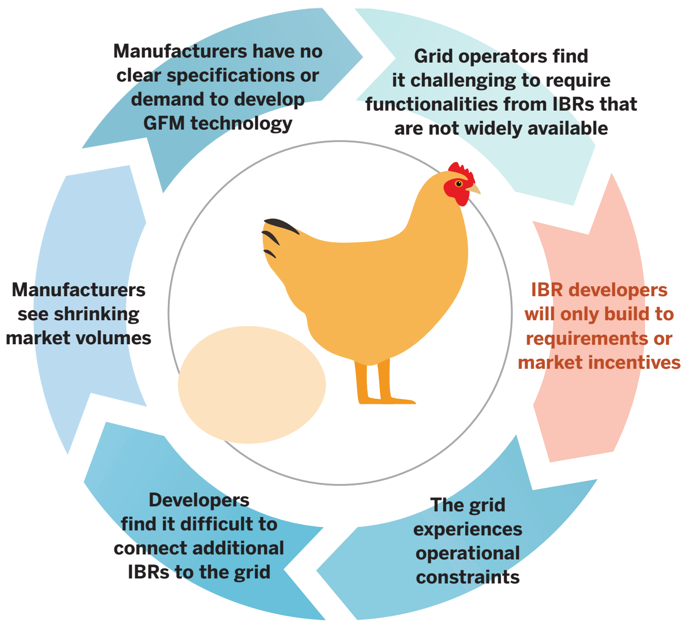
The Technological Leap

Power systems around the world have arrived at the point of needing to make this technological leap to deploy advanced IBR controls. However, system operators and planners, equipment owners, and manufacturers face a circular problem, as shown in Figure 1: Which comes first, the requirement for a capability or the capability itself? How do grid operators know what performance or capability is possible from new equipment, and therefore what they could conceivably require? How can they go about evaluating the costs and benefits of having such equipment on the grid? And what drives manufacturers to invest in new technology without it being mandated for interconnection to the grid or otherwise incentivized by the market?

The Cost of Inaction

The failure to find an exit from this circular problem may have far-reaching negative consequences, as it could hinder our ability to meet energy transition targets and increase the costs of this transition. Around the world there are thousands of solar, wind, and battery resources waiting to connect to the grid. These resources, in the absence of clear requirements and market incentives for GFM functionality, will be built using today's grid-following technology. If the IBRs currently in power systems' interconnection queues are built without advanced, GFM controls, this will increase systems' needs for additional reliability support from other sources and drive up costs.

FIGURE 1
The Circular Problem of Requirements and Deployment of Advanced IBR Controls



Source: Energy Systems Integration Group.

This fact sheet is adapted from ESIG's report Grid-Forming Technology in Energy Systems Integration.

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However, there is low-hanging fruit for the deployment of GFM capability—notably, battery storage. This commercially available technology has several key characteristics for playing a GFM role: it has dedicated energy storage (by definition), has no moving parts, and it can potentially be operated at a lower rating (leaving some "space" in the inverter to deliver extra current during disturbances) without foregoing energy, as wind or solar would have to do. With clear requirements and market incentives, a significant proportion of battery storage resources in interconnection queues could be equipped with GFM functionality today, helping power systems avoid the costs of installing much larger additional grid-supporting devices or additional grid reinforcements in the future.

Breaking the Cycle by Adopting a System Needs Perspective

Battery storage and other potentially grid-forming technologies will not be deployed in significant numbers until the chicken-and-egg cycle is resolved. The optimal approach is to begin from the perspective of evolving system needs, using the following steps as a guide (see Figure 2, p. 3).

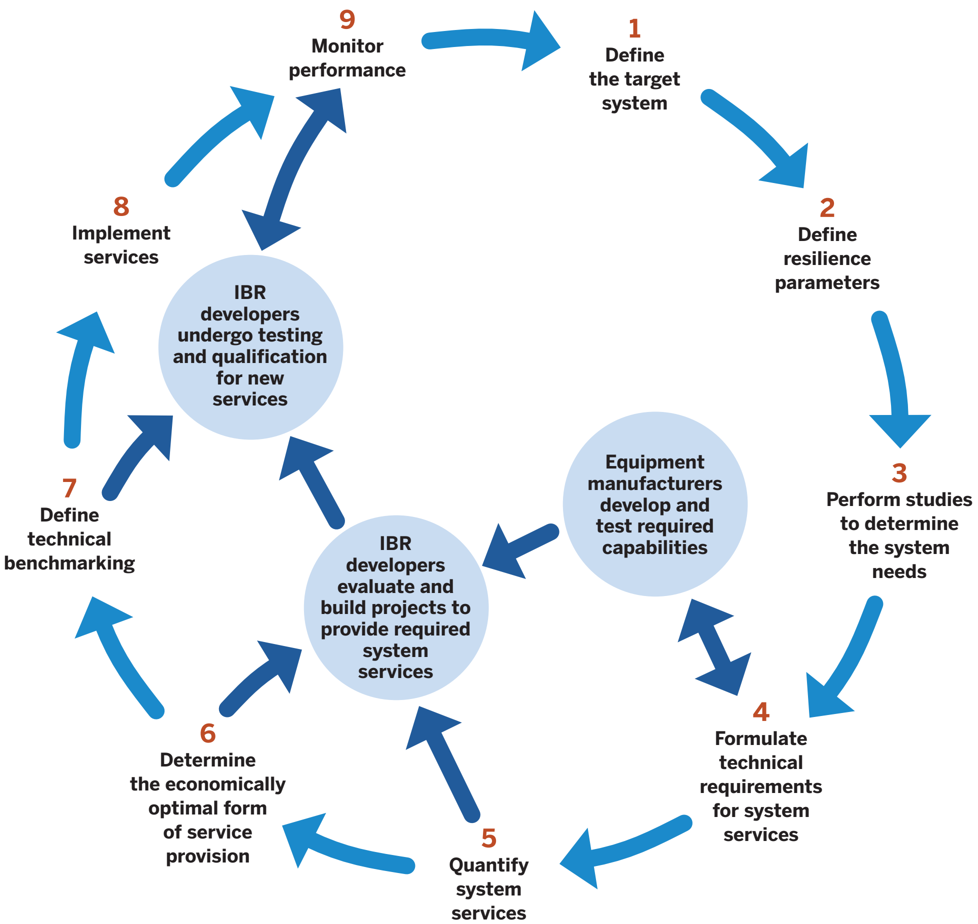
1. **Define the target system.** First, the power system is defined in terms of energy quantities, relative amounts of different power sources (including storage), and expected loads (including electrification of transportation and heating, and storage). Different scenarios may be specified based on local or national policy goals.
2. **Define resilience parameters.** The desired resilience against certain disturbances—extreme weather, generator outages, etc.—is defined, and conditions are specified with which the system should be able to cope with no (or limited) impact on serving customer load. This step is policy-driven and considers trade-offs between costs to the grid to accommodate IBRs and costs to IBRs to conform with the chosen resilience parameters.
3. **Perform studies to determine the system needs.** Studies are conducted to determine the type and scope of the minimum system needs in order for the system to be able to operate within the defined resilience parameters—for example, the speed, magnitude, and timing of active power injection into the grid following a generator trip.
4. **Formulate technical requirements for system services.** Guided by the identified system needs, technical performance requirements are defined for system services that will need to be procured. This

will inform the design and costs of the equipment providing the services. The objective is to enable as many generation resources as possible to provide grid services, because having several alternative providers tends to make the procurement of grid services more economical for grid operators.

5. **Quantify system services.** For each service, a methodology to quantify the needed amounts is developed. For greater efficiency and lower costs, varying quantities of services are procured (where practical) based on system conditions.

6. **Determine the economically optimal form of service provision.** The most efficient way to meet the demand for each of the system services is decided. The appropriate trade-off between market-based solutions and mandatory requirements established by connection rules needs to be arrived at from both technical and economic perspectives.

FIGURE 2
Proposed Process for Deploying New Grid-Forming Capabilities



In the proposed process for deploying new GFM capabilities to serve system needs, the outer circle follows steps 1 through 9 as discussed in the text, while the three inner elements show how the nine steps relate to IBR equipment manufacturers and project developers and owners. Steps 1 through 9 are not set in stone and will likely need to be an iterative loop as systems and technologies continue to evolve.

Source: Energy Systems Integration Group.

7. **Define technical benchmarking.** For both approaches above (market-based solutions and mandatory requirements established by connection rules), detailed technical benchmarking is developed and specified to verify service providers' performance, both at the time of commissioning and during operation.

8. **Implement services.** The dates of the implementation of new system services and any transitional arrangements are determined. Tender or other selected market forms for the procurement of market-based services are executed.

9. **Monitor performance.** For both market-based and connection rules–based approaches, service providers' performance is monitored during service delivery, and compliance with technical performance requirements is verified on an ongoing basis.

Tools and Models

As power systems proceed through the nine steps above to define and deploy new system services to be provided by solar, wind, batteries, and other technologies, advances are needed in modeling tools, simulation tools, and economic studies used by system planners to study grid stability in a high-renewables future. Some of these will

TABLE 1

Comparison of Grid-Following and Grid-Forming Controls

Inverter Attribute	Grid-Following Control	Grid-Forming Control
Reliance on grid voltage	Relies on well-defined grid voltage, which the control assumes to be tightly regulated by other generators (including GFM inverters and synchronous machines)	Actively maintains internal voltage magnitude and phase angle
Dynamic behavior	Controls current injected into the grid (appears to the grid as a constant current source in the transient time frame)	Sets voltage magnitude and frequency/phase (appears to the grid as a constant voltage source in the transient time frame)
Reliance on PLL for synchronization	Needs phase-locked loop (PLL) or equivalent fast control for synchronization	Does not need PLL for tight synchronization of current controls, but may use a PLL or other mechanism to synchronize overall plant response with the grid.*
Ability to provide black start	Not usually possible	Can self-start in the absence of network voltage. When designed with sufficient energy buffer and over-current capability, it can also restart the power system under blackout conditions. (Only a limited number of generators on a system need to be black start–capable.)
Ability to operate in low grid strength conditions	Stable operation range can be enhanced with advanced controls, but is still limited to a minimum level of system strength	Stable operation range can be achieved without a minimum system strength requirement, including operation in an electrical island. (GFM IBRs will not, however, help to resolve steady-state voltage stability for long-distance high-power transfer.)
Field deployment and standards	Has been widely used commercially. Existing standards and standards under development define its behavior and required functionalities well.	Has been deployed in combination with battery storage primarily for isolated applications. Very limited experience exists in interconnected power systems. Existing standards do not yet define its behavior and required functionalities well.

* A GFM inverter also needs a synchronization mechanism when it has reached its current or energy buffer limits. If it reaches these limits, it will temporarily fall back to grid-following operation and will need to track the grid voltage phasor.

Source: Energy Systems Integration Group.

model system stability under conditions of rising levels of IBRs, while others will characterize IBRs' capabilities to serve various system needs. Stability studies will also need to be more closely tied to other analytical and economic assessments, to ensure that studies' assumptions are realistic, are consistent throughout, and capture stability scenarios under all relevant grid conditions.

Learning from Early Adopters

The paradigm shift from a power system dominated by conventional power plants to one dominated by solar, wind, batteries, and other controls-driven resources requires close cooperation between system operators, equipment manufacturers, and equipment owners. This collaboration is critical to define system needs, understand equipment capabilities, and develop requirements and mechanisms to deploy new advanced-control technology in coordination with existing systems.

Some power systems, such as those in Great Britain, Germany, Hawaii, and Australia, are already on the path of reforming grid services and incentivizing their provision by IBRs with advanced controls, while other systems are just beginning. The knowledge and experience gained from successful GFM IBR pilots in Australia and Great Britain are already providing important feedback into the deployment process and serve as valuable models for other power systems around the world.

This fact sheet was adapted from *Grid-Forming Technology in Energy Systems Integration*, a report by ESIG's High Share of Inverter-Based Generation Task Force. The fact sheet and the full report are available at https://www.esig.energy/reports-briefs.

To learn more about the recommendations described here, please send an email to info@esig.energy.

The Energy Systems Integration Group is a nonprofit organization that marshals the expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation. Additional information is available at https://www.esig.energy.