Grid-Forming Inverter-Based Resource Research Landscape

Understanding the Key Assets for Renewable-Rich Power Systems

THE SHIFT TO NET ZERO ENERGY SYSTEMS HAS CHANGED THE face of our power grid. Traditional large-scale synchronous generators found inside coal and natural gas plants are being replaced with inverter-based resource (IBR) technologies. This transition to an IBR-dominant power grid introduces new characteristics, altering how our grid operates. Therefore, the role of IBRs has expanded, requiring them to provide a range of essential services to keep our grid reliable, resilient, and secure.

Currently, most of the IBRs connected to the grid operate in a mode referred to as *grid-following* (*GFL*). In this mode, GFL inverters synchronize with the existing grid and inject constant current in a steady state. However, it is widely recognized that the performance of such IBRs deteriorates in low-strength grids. Grid strength in a power system refers to its ability to withstand disturbances and maintain stable operation without significant

Digital Object Identifier 10.1109/MPE.2023.3343338
Date of current version: 22 February 2024

By Behrooz Bahrani, Mohammad Hasan Ravanji, Benjamin Kroposki, Deepak Ramasubramanian, Xavier Guillaud, Thibault Prevost, and Nicolaos-Antonio Cutululis

fluctuations in voltage and frequency. Additionally, GFL IBRs lack certain capabilities, such as operating independently or assisting in restarting the grid after a blackout.

In contrast, grid-forming (GFM) control is an alternative method that still has to synchronize with the existing grid but maintains constant internal voltage to inject power in a steady state. This control method, used in GFM inverters, allows the IBR to react nearly instantaneously to changes in the system to help stabilize the grid. GFM controls are primarily used in islanded power systems operating independently from the grid (i.e., islanded microgrids), with limited use so far in grid-connected applications. Yet, research suggests that as our grids begin to contain more and more IBRs, GFM controls will be crucial to maintaining stability.

The fast-paced transformation of our power grids highlights the need to enhance our understanding and application of GFM inverters. Yet, the research landscape on this topic is still in the early stages, with various gaps to fill and

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questions to answer. This article aims to contribute to this global effort, presenting a comprehensive, state-of-the-art review of GFM inverter-related research activities while highlighting this technology's crucial role in maintaining grid stability in an increasingly IBR-dominated world.

We will discuss various types of GFM control, delve into the ongoing efforts to devise innovative GFM control strategies, create reliable models and performance validation, and explore the challenges and shortcomings of the existing solutions and opportunities for further research. This article may serve as a guide to navigate this complex technology landscape, fostering knowledge that can stimulate further research and innovation to achieve a reliable, resilient, IBR-dominated power grid.

GFM Versus GFL Control: The Dance Floor Example

Picture a lively dance floor, with dancers moving and swaying to the beat of the music. The majority of these dancers, akin to GFL inverters, dance in response to the rhythmic cues of the disc jockey (DJ), analogous to the voltage and frequency of the grid dominantly controlled by synchronous generators today. Their dance is a carefully choreographed response to the music. Guided by synchronization elements (often a phase-locked loop) and much like a dancer's auditory senses, GFL inverters detect the rhythm and melody, electrically speaking, at the angle of the grid's voltage at the point of connection. This allows the GFL inverter to synchronize itself with the grid's "music."

Once these synchronization elements pick up the beat, they transfer the rhythm to the GFL inverter's internal controller, similar to how a dancer's body instinctively moves with the beat. The controller uses this rhythm to modulate the voltage at the inverter's terminals. This modulation allows the GFL inverter to control its current, much like a dancer using their moves to navigate the dance floor, regulating its real and reactive power exchange with the grid.

However, even a skilled dancer can falter when the music's rhythm grows complex or faint, akin to low-strength grid conditions where the grid's voltage and frequency are not as robust or predictable. Despite its attentive synchronization control, in these challenging scenarios, the GFL inverter can struggle to keep the rhythm. It is like a dancer trying to keep time with faint, erratic beats. This difficulty can cause potential instability issues and cause the GFL inverter to miss steps, which could negatively affect the grid's performance and stability.

In the crowd on the dance floor, there may be a lead dancer symbolizing a GFM inverter. Unlike the others, who move in response to the DJ's music, this lead dancer sets their rhythm for the rest of the crowd. They create their frequency and voltage reference based on the power they are supplying and not merely following the grid's voltage and frequency.

In scenarios where the grid's rhythm becomes weak, the GFM inverter, much like a masterful lead dancer, continues to perform seamlessly. They set the pace and maintain the rhythm of the dance floor despite the grid's rhythm changes. It is as if the lead dancer takes over the role of the DJ, providing the rhythm for others when the DJ's beat becomes unreliable.

Envision this dance floor evolving into a more complex performance with multiple lead dancers, each representing a GFM inverter. This troupe coordinates its movements and then communicates and adjusts the rhythm based on each other's performance. Much like the synchronization between multiple GFM inverters, this ensures the dance remains fluid, even if one dancer falters. The GFM inverters adjust their power output and are able to compensate for any faltering inverter while still maintaining the grid's voltage and frequency stability.

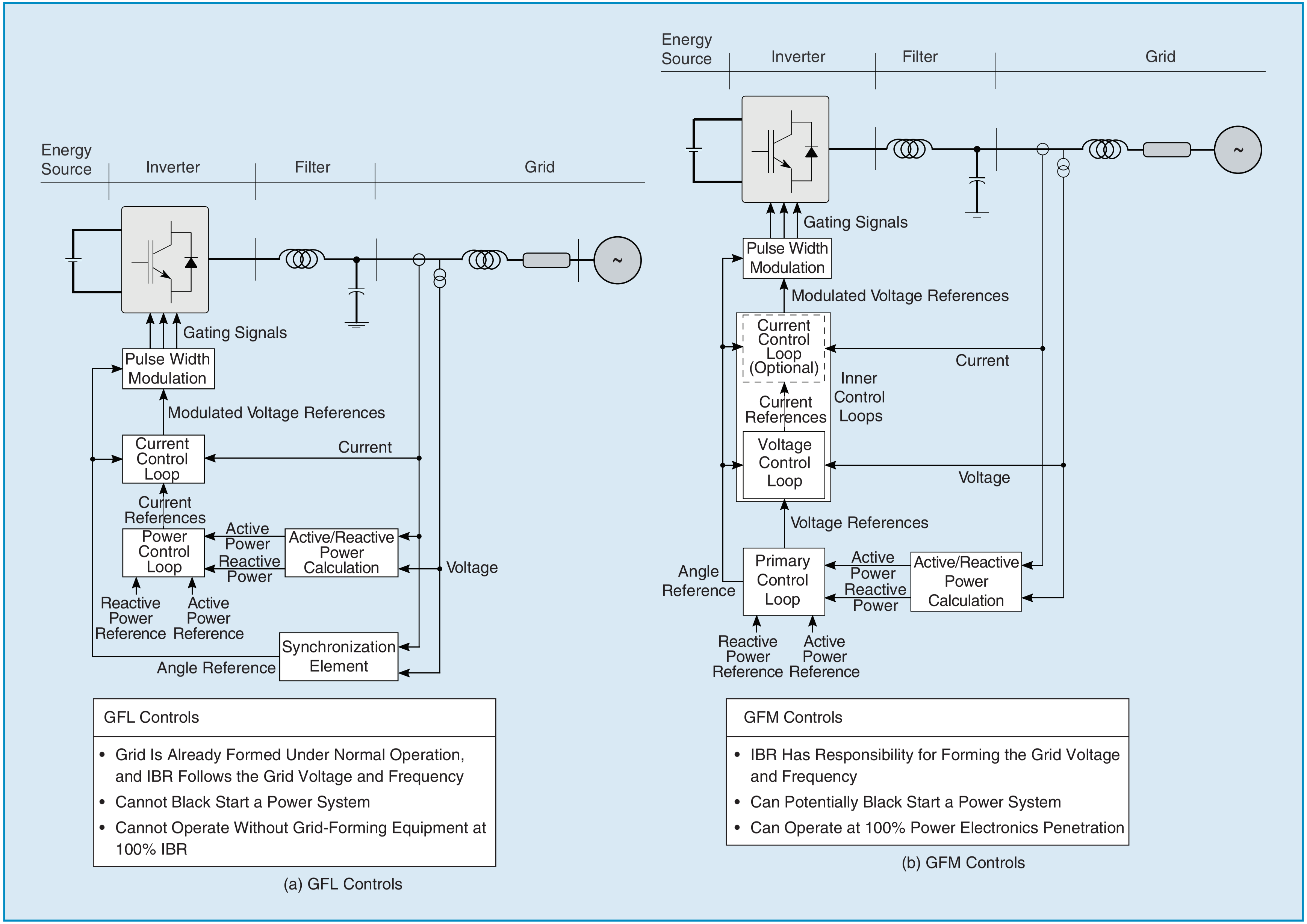
Choreographing for such a troupe requires expert fine-tuning for effective cooperation, much like the intricate configuration of multiple GFM inverters operating in tandem. Control settings must be adjusted, considering the overall system's characteristics and requirements. It is akin to an experienced choreographer ensuring every dancer's steps align with the troupe's overall performance.

The interplay between GFL inverters and GFM inverters is crucial in power systems. Like a well-choreographed dance troupe, these inverters must work harmoniously to ensure a stable and reliable power supply. This analogy underscores the importance of ongoing research to improve both GFL inverters and GFM inverters and enhance overall grid stability. It must be noted that the dance floor analogy is not meant to cover all aspects of the operation of such inverters and will eventually break down under certain circumstances.

Opportunities in GFM Inverter Control Variations

While GFM inverters can provide more services for power systems than GFL inverters, their structure is fundamentally similar to that of conventional GFL inverters in terms of their main components: the energy source, dc link, switching converter, control board, and output filter. The main difference between GFM inverters and GFL inverters lies in their synchronization and control logic. Further, both GFL inverters and GFM inverters are voltage source converters.

Figure 1(a) illustrates a conventional switching converter with an inductive–capacitive (LC) filter and its control to



GFL Controls

- Grid Is Already Formed Under Normal Operation, and IBR Follows the Grid Voltage and Frequency
- Cannot Black Start a Power System
- Cannot Operate Without Grid-Forming Equipment at 100% IBR

(a) GFL Controls

GFM Controls

- IBR Has Responsibility for Forming the Grid Voltage and Frequency
- Can Potentially Black Start a Power System
- Can Operate at 100% Power Electronics Penetration

(b) GFM Controls

figure 1. Control block diagrams and main features of grid-tied (a) GFL inverters and (b) GFM inverters.

Grid-forming control is an alternative method that still has to synchronize with the existing grid but maintains constant internal voltage to inject power in a steady state.

operate as a GFL inverter. For grid synchronization, the measured voltage is fed to an explicit synchronization element that extracts its phase angle and frequency. This phase angle is then fed into other control blocks. For power control, the measured grid voltage and current are first used to calculate the exchanged real and reactive power, which are then fed into a power control block. This block calculates the required current that the inverter needs to inject to achieve the required power set points. The calculated current set points are then fed into a current control block that determines the references for a pulse-width modulation (PWM) block that is responsible for creating the switching commands of the inverters.

On the other hand, the GFM inverter regulates its real/reactive power exchange with the grid by controlling the magnitude and frequency (and angle) of the voltage at its point of connection. This can be achieved via a cascade control structure where a primary loop determines the set points (angle and magnitude of the voltage) for an inner control loop; this loop (see "Alternatives for Inner Control Loops" subsection) dictates the references for the PWM block. Figure 1(b) depicts a typical GFM inverter system.

The role of the primary control is to determine the frequency (and angle) and voltage references of the GFM inverters as functions of active and reactive power, assuming that these components are decoupled and ensure synchronization with the grid. The primary loop determines the set point for the voltage magnitude and frequency based on the error between the calculated real/reactive power and their reference values. This primary control loop also results in carrying out the synchronization functionality. Since there is a strong correlation between real power and the frequency and reactive power and the voltage magnitude in power systems (particularly in transmission networks), the change in the reference frequency is determined as a function of real output power changes in GFM inverters. Different ways for realizing this function are implemented in various types of GFM inverters, including droop and virtual synchronous generator (VSG) controls, as seen in Figure 2. The droop method originates from the idea of power-sharing between parallel synchronous generators and determines the reference frequency changes as a proportional function of power changes. The VSG method implements the second-order characteristics oscillation equation of synchronous generators, known as the *swing equation*, which balances the kinetic energy of a rotating machine with the electrical power it produces. The VSG's swing equation mimics the behavior of synchronous generators and enables the provision of inertial response for inverters. Although droop and VSG techniques have evolved in separate contexts, it can be shown that if a low-pass filter accompanies the droop gain in the power path in the droop method, the behavior of the GFM with droop is similar to that of VSG. Thus, the two methods are functionally similar.

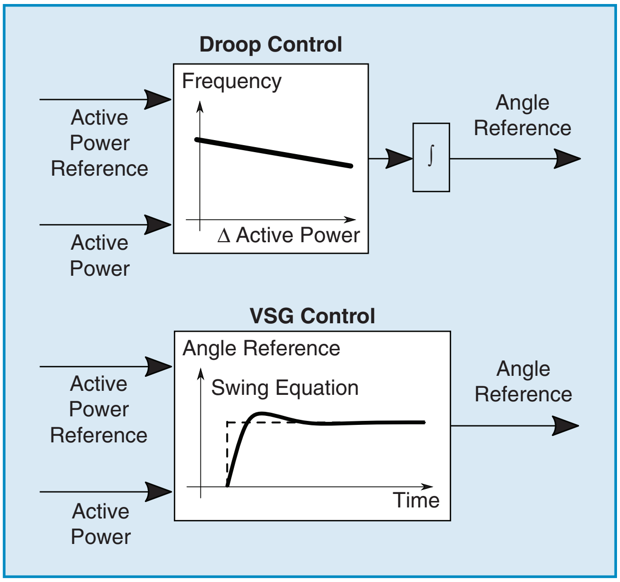


figure 2. Droop and VSG are two types of GFM control.

Additionally, the primary control loop determines the reference for the voltage magnitude as a function of reactive power. To this end, the voltage reference is determined by the difference between the reactive power's measured and reference values, similar to how the GFM inverter frequency control loop is implemented. Here again, this function can be realized by the droop characteristic, filtered droop characteristic, second-order characteristic (referred to as the *rotor-flux model* in some contexts), or other methods.

Alternatives for Inner Control Loops

The GFM inverter's internal control loops are tasked with producing converter-switching signals that shape the IBR voltage based on outputs from the primary control loop. In some approaches, voltage references derived from the primary loop are directed into an inner voltage control loop, which then generates converter current references. Following this, an inner current control loop determines the converter's PWM switching references. This methodology, termed *cascade control*, mandates that the innermost current control loop operates 10 times faster than the external voltage control loop. Such bandwidth differentiation is vital for ensuring the stable functioning of cascade loops.

> Like a well-choreographed dance troupe, these inverters must work harmoniously to ensure a stable and reliable power supply.

Moreover, the gains of the voltage control loop are adjusted so that this loop operates faster than the primary control loop. A chief advantage of the cascade control strategy is its capacity to safeguard the inverter switches. Given the vulnerability of these switches to overcurrent and potential damage, employing a cascade control system with an incorporated current control loop facilitates swift switch protection by promptly modulating the current references.

Even though a cascade voltage-current control structure is well established in the literature and is being used in certain commercial products, some recent studies aimed at increasing the bandwidth of the GFM inverter's inner control loops have examined the idea of eliminating the current/voltage control loops. In these studies, the voltage references obtained by the primary control loop are fed directly into the converter PWM generator module without incorporating current/voltage control loops; to protect the switches against overcurrent, a virtual impedance is used in the voltage reference signal path. Nonetheless, the optimal design of virtual impedance in these conditions remains an open issue and needs further studies.

Alternatives for Primary Control Loop

Due to the high switching frequency of the GFM inverters and the high bandwidth of its inner control loops, the outputs of the GFM inverters quickly follow the primary control loop references. Therefore, the dynamic behavior of the GFM inverter is mainly a function of its primary control loop. In fact, the reason for naming the VSG method is that the output behavior of the GFM inverters is similar to that of the synchronous generator, whose oscillation equation is implemented in the primary control loop. However, the key difference between synchronous generators and VSG lies in the fact that, in synchronous generators, the coefficients of the oscillation equation are not adjustable. Further, it is a function of the machine's physical properties, whereas these coefficients can be parameterized for VSG, providing a more flexible control capability. This specific feature extends the capabilities of GFM inverters beyond synchronous generators.

Recent research suggests enhancing the output of GFM inverters by adaptively tuning VSG coefficients according to grid strength variations. While it is common to adjust the primary loop coefficients, there is also potential to modify the primary control function or even expand its dynamic order. A notable approach includes introducing an optimally parameterized lead–lag term into the swing equation, thereby transitioning the VSG control to a more advanced generalized VSG control system. This results in a notably better GFM inverter dynamic performance, irrespective of whether it is operating in islanded mode or connected to grids of different strengths. Additionally, other studies have redefined the primary control loop as a multi-input (covering active and reactive power) multi-output (dealing with frequency and voltage references) system. From this perspective, a robust multivariable controller can be crafted, leading to significant improvements in the GFM inverter's reactions under diverse conditions. These advancements are just a glimpse into the GFM inverter's potential to surpass synchronous generators, achievable mainly through control loop redesigns. Indeed, the possibilities expand even further when delving deeper into their control system enhancement.

It must be noted that the flexible nature of the GFM inverter control provides unique opportunities to offer other services to the grid, such as damping subsynchronous oscillations and alleviating adverse interactions of other IBRs on each other. When designing GFM inverter's primary controllers, considering such services could be a topic of further research in this area.

Modeling and Stability Analysis

Modeling and stability analysis are essential for understanding a GFM inverter's performance and ensuring the power system's reliable operation. Many types of GFM control are interrelated and can be parameterized to represent each other. An example of this relationship is the ability to represent droop and VSG controls using a common set of equations that can subsequently be parameterized appropriately to realize a specific form of control. Simultaneously, as discussed above, common control architectures of GFM control employ either a single voltage loop or both a voltage and current control loop in cascaded form. These common structures allow for the construction of generic models in simulation software, which can have a functional representation, as shown in Figure 3. Based on the specific control that a user wants to deploy, a generic model can be appropriately

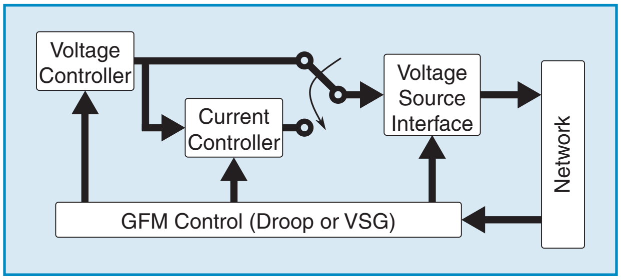


figure 3. Conceptual generic model of a GFM inverter.

configured. Since the development of generic models would usually lag behind the development of technology from manufacturers, improvements can be made to such generic models for wider use in steady-state, dynamic, and transient simulation platforms. These improvements would be driven by new performance features introduced by manufacturers.

Further, new analytical approaches need to be investigated to analyze the system stability with a mix of GFM inverters, GFL inverters, and synchronous machines. Research is being conducted to develop innovative modeling and simulation methods, and tools are being developed to improve the accuracy of GFM inverter models and computation efficiency, including model and network order aggregation tools and integrated cosimulation tools. Modeling and stability analysis help design the control strategies for GFM inverters to ensure their stability under different operating conditions. There are different categories of stability analysis that are important for GFM inverters, including small-signal stability and transient stability, which are discussed in more detail in the following sections.

Transient Stability

The *transient stability* of the system refers to its ability to recover from large disturbances, such as faults or outages, and maintain stable operation. As mentioned in the previous section, GFM inverters can provide additional capabilities for the system. Nevertheless, serious limitations still need to be tackled in GFM inverter development, with the most significant constraint being their limited overcurrent capability. This constraint limits the GFM inverters' output performance during and after severe system faults. Various studies have investigated the GFM inverter operation during faults/disturbances and subsequent to their clearance. In addition to providing insights into instability mechanisms upon such disturbances, these studies have proposed solutions, such as auxiliary loops for the primary control to modify the power reference during faults.

Various methods of current limitation during and after faults have also been proposed and studied in the recent literature. The most significant difference between current-limiting methods is their impact on the transient stability of the GFM inverters during and after a fault. Although transient stability analysis tools for synchronous generators are also applicable to GFM inverters, due to inner control loops and the impact of current limiters, the transient stability margin is different from that of synchronous generators; this might require changes to the stability analysis evaluation methods.

Moreover, control interactions between neighboring GFM inverters and GFL inverters can cause further changes in their transient stability margin. For instance, some recent studies have investigated the transient stability of a parallel set of a GFL inverter and a GFM inverter and have shown that if a VSG and a GFL inverter are analyzed as a paralleled system, there may be cases where a voltage sag accelerates the transient angle instability process, thus increasing the system's susceptibility to instability, despite the benefits of the VSG. Although the transient stability of small networks with a limited number of GFM inverters has been investigated in the literature, expanding these studies to larger networks with a combination of several GFM inverters, GFL inverters, synchronous generators, and loads is a field for further research.

Small-Signal Stability

Small-signal stability analysis is commonly used to evaluate the system's stability under small perturbations. Due to the entirely different control and dynamic structures of GFM inverters, the small-signal stability of the inverter-rich networks is also affected, making it essential to appropriately model and study their effects on the local and interarea oscillation modes. It has been shown that adding a GFM control may increase the small-signal stability of the system to which it is connected. The margin of improvement depends on the type of GFM control that is implemented. There are different methods for analyzing small-signal stability: eigenvalue analysis, frequency-domain impedance-based analysis, and state-space analysis.

One of the significant issues in small-signal stability studies of inverter-rich networks is the lack of access to detailed models of the inverters and the consequent lack of model standardization due to the proprietary nature of the inverter controls. Therefore, studying the small-signal stability of networks using traditional methods, such as eigenvalue analysis, is challenging. Other techniques, such as impedance-based stability analysis, have also been developed. In impedance-based techniques, injecting specific signals, it is possible to obtain the frequency impedance model of inverters at a specific operating point, which also enables the evaluation of their stability. However, the feasibility of studying the small-signal stability of large networks in the presence of thousands of GFL inverters and GFM inverters using these approaches is limited and requires further investigation. New analytical approaches need to be investigated to analyze the system stability with a mix of GFM inverters, GFL inverters, and synchronous machines.

Impact of GFM Inverter Placement and Penetration on Stability

The primary difference between GFM inverters and GFL inverters lies exclusively in their control systems, thereby allowing IBRs to operate in both GFM and GFL modes. In the "Standardization and Grid Codes" section we will discuss how grid codes are evolving to mandate GFM capability from all or some of the grid-connected IBRs. Depending on the grid code, this could be a basic requirement or a voluntary service. However, a persistent question is how to ensure stability during the transition from one mode to another.

As the global rate of IBR installations continues to climb, new questions are emerging for system operators. One of the

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key questions is determining the necessary minimum amount of GFM inverters and their optimal placement. Another related question is whether the minimum amount of GFM inverters changes as existing inverter technology evolves. In some countries, inverters will not always be required to operate in the GFM mode, particularly where GFM is proposed as a voluntary service. For instance, in some European grid codes, inverters can switch from one mode to another under specific circumstances. Consequently, studying the optimal placement of such GFM inverters becomes crucial to ensure they provide the most stabilizing effect.

GFM Inverters for Different Energy Sources

The functionality of GFM inverters varies based on their connected energy source. Today, commercially operational GFM inverters primarily utilize battery energy storage system (BESS)-based inverters. However, research is underway to integrate GFM inverters with non-BESS resources, like photovoltaic panels, type 3 and 4 wind turbines, high-voltage dc (HVdc) converters, and even devices like static synchronous compensators. One merit of these non-BESS resources is their ability to offer GFM capabilities using existing renewables, circumventing the substantial costs associated with energy storage systems. Yet, this advantage is influenced by the resource's operational point and surrounding conditions.

When we look at type 3 wind turbines, which employ doubly-fed induction generators, they stand out by providing enhanced fault current levels. This is mainly due to only about 30% of their generated power going through the inverter, with the majority, over 70%, coming directly from the stator circuit of the induction generator. Consequently, they exhibit a higher fault current capacity compared to a typical inverter-linked GFM component.

While BESS-based systems consistently hold the dc link voltage at a standard value, achieving this stability in non-BESS sources presents challenges. Fault conditions can lead to overvoltage, which threatens the protection system, or undervoltage, which can negatively affect performance and power quality. Furthermore, enabling GFM features for wind turbines might expose their mechanical parts to network disturbances, and the turbines' inherent limitations can also restrict GFM functionalities. Unlike BESS-based GFM inverters, which can offer substantial virtual inertial response temporarily, this ability in non-BESS sources is dictated by their operational state. Such constraints must be factored in when integrating GFM features.

Current research initiatives are also exploring the feasibility of bestowing GFM capabilities onto industrial load inverters, ranging from electrolyzers and electric vehicle charging stations to dc-connected motors and data centers. This approach can expand the GFM source spectrum and potentially stabilize areas with high loads. Moreover, the idea of a hybrid setup, where short-duration storage complements existing dc-linked devices, can transform inverters into GFMs without disrupting their primary functions. Such innovations could lessen the demand for battery-building materials, like lithium, cobalt, and silicon.

Services From GFM Inverters

Just like conventional generators, GFM inverters are essential for bolstering the power system's stability. They should be capable of providing the same services as GFL inverters do today but with improved performance. Additionally, the GFM inverter may be asked to provide new services, such as the ability to restart a power system subsequent to a blackout, commonly referred to as a *black start*. Services provided by GFM inverters are based on their capabilities and can be classified into "core" and "additional." The list of core and additional capabilities is provided in Table 1. The core capabilities can be achieved with minimal modifications to plant hardware and operational processes compared to GFL inverters, primarily requiring adjustments to the software and control algorithms. Most of these core capabilities are expected to be common across all GFM inverters. To fulfill these core capabilities, a GFM inverter

table 1. GFM inverters core and additional capabilities.

Core Capabilities	Additional Capabilities
Fast and inherent current injection	
Primary and fast frequency response	Current capacity above the continuous rating
Surviving the loss of the last synchronous connection	Black start capability
Weak grid operation and system strength support	Power quality improvement
Oscillation damping	

> The idea of a hybrid setup, where short-duration storage complements existing dc-linked devices, can transform inverters into GFMs without disrupting their primary functions.

should have the ability to offer a small energy buffer, either through its design or operation. Moreover, for a device to be considered a GFM inverter, the energy must be immediately available to the grid with the minimum delay caused by dc-side control algorithms.

In addition to these core capabilities, certain GFM inverters might be capable of providing additional capabilities that could require substantial hardware upgrades or modifications to operational practices to provide a larger energy buffer. While not all GFM inverters need to provide these additional capabilities, their availability is valuable for supporting secure power system operation, particularly in grids with high levels of IBR. Although listed for GFM inverters, GFL inverters can also provide some of these services.

It is worth noting that the validation of the services that GFM inverters provide will be important. Various software simulation platforms based on electromagnetic transient and root-mean-square techniques, as well as control hardware-in-the-loop, power hardware-in-the-loop, and power-hardware testbeds, are being utilized to provide baseline behavior, capabilities, and interoperability of current GFM inverter technologies. They are further used to evaluate system-level interactions and verify their suitability for implementation into the electric power infrastructure. Some important services are explained briefly in the following sections.

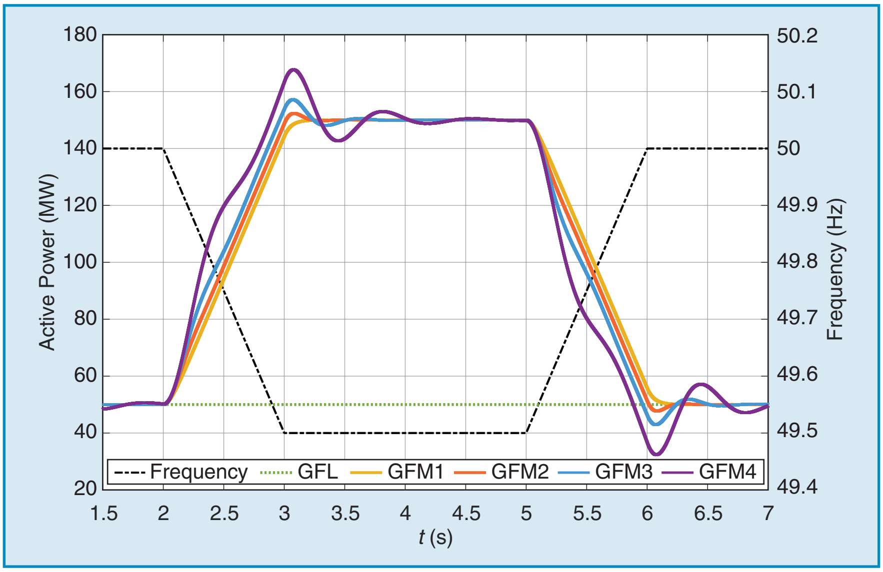

figure 4. Frequency response by a GFL plant compared with GFM plants with various inertial provision capabilities. GFM4 has the highest virtual inertia constant, and GFM1 has the lowest.

Frequency Response

Frequency response service is achieved when a suitably designed active power control responds to a frequency deviation. A GFM inverter will respond naturally to changes in system frequency. The capability will be limited, however, by the characteristics of the energy source behind it, with its own dynamic limitations and peak current capability. GFM inverters are expected to modify their active power injection, responding very rapidly to under- or overfrequency events. Figure 4 compares the frequency response of a GFL inverter without the power control loop or any grid support functions with that of a typical GFM inverter with various virtual inertia constants during a frequency event. As shown, a GFM inverter immediately responds to the frequency event, and due to the provision of virtual inertia, the active power response has an overshoot.

The main research gap is directed toward defining the desired characteristics of the frequency response from GFM inverters. Simply mimicking the behavior of synchronous machines may not be the best solution.

Voltage Response

To maintain the voltage at the inverter terminal within permitted limits, a GFM inverter has to inject or absorb some amount of reactive power. Voltage support is expected to be provided in normal operation and during over- and undervoltages or phase jumps. The main limitation in providing voltage support is the peak current capability of the GFM inverter. This is an important functional difference between GFM and GFL, as with GFL, they do not attempt to maintain voltage at the inverter terminal. Instead, there usually is a plant controller that carries out slow voltage control at the point of interconnection. For low-voltage events caused by grid disturbances, similar to GFL inverters, GFM inverters will have to "ride through" and remain connected. During faults, fast fault-current injection is vital for voltage support. With appropriate control actions, GFM inverters can inject current nearly instantaneously. The main limitation is, again, the peak-current capabilities of the inverters and is one of the research gaps that need to be addressed.

Black Start

Black start is the ability of an isolated generation resource to self-start, establish the voltage, and start the process of restoring other components on an electrical grid after a blackout. This requires GFM inverters to be able to maintain the system voltage and frequency while loads are being reconnected to the system. They should also have the ability to synchronize with other generators from adjacent areas. GFM inverter controls (if combined with sufficient energy storage) can potentially enable both black start capability and the islanded operation of certain IBRs. Future directions could explore enhancements in the automatic load pickup and the development of more intelligent synchronizing methodologies. Moreover, research can also focus on the role of storage in improving the robustness of the black start process, including the optimal use of BESS. Finally, a potential investigation into resilience strategies could strengthen the ability to recover from blackouts and enhance system-wide grid stability.

GFM Inverters in Distribution Networks

GFM inverters, traditionally employed in transmission networks, present promising applications in distribution networks, such as community batteries and electric vehicle battery chargers. As we embrace the decentralization of energy systems, the research landscape shifts to how to accommodate these possibilities. Technical feasibility studies form a crucial part of this new research avenue, analyzing the benefits, challenges, and impacts on local grid stability and power quality when integrating GFM inverters into distribution networks. In addition, there is a need to investigate the optimal placement of these GFM inverters within the distribution network, which involves developing innovative planning tools and algorithms.

It must be noted that a significant aspect differentiating distribution networks from transmission networks is the network's impedance characteristic. The primary control loop for GFM inverters in transmission networks, based on the understanding that real power is proportional to frequency and reactive power to voltage magnitude, might not be directly applicable in distribution networks. The reason is that distribution networks are mainly resistive, which leads to active power being proportional to voltage magnitude and

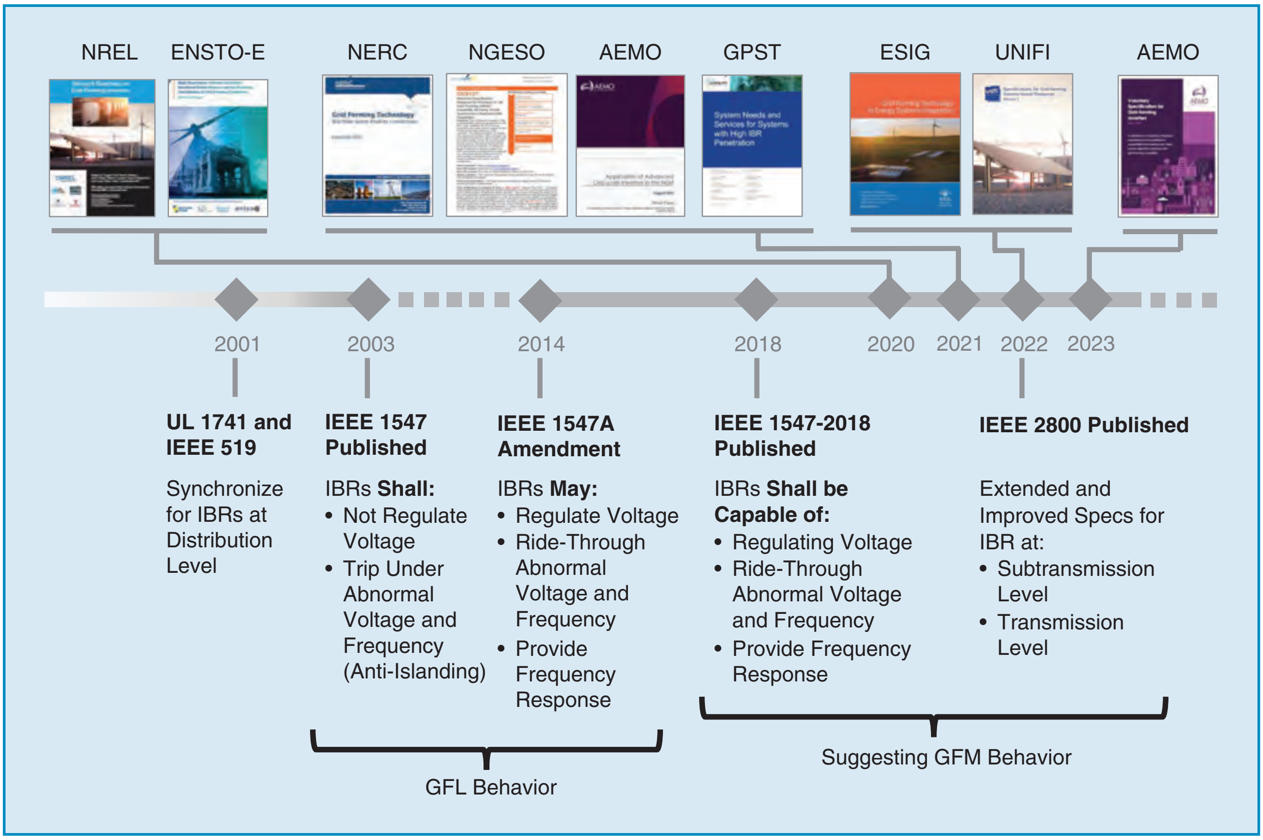

figure 5. Evolution of regulatory landscape for IBRs as qualified by relevant standards. AEMO: Australian Energy Market Operator; ENSTO-E: European Network of Transmission System Operators for Electricity; ESIG: Energy Systems Integration Group; GPST: Global Power System Transformation Consortium; NGESO: National Grid Electricity System Operator Limited; NREC: North American Electric Reliability Corporation; NREL: National Renewable Energy Laboratory; UNIFI: Universal Interoperability for Grid-Forming Inverters.

reactive power being proportional to frequency. Hence, the research must address how control strategies need to adapt for efficient operation in these diverse network conditions.

Introducing GFM inverters into the distribution system could bring about a significant change in how the power system operates. Currently, when there is a problem in a section of the distribution system (like a blackout or an issue with a power line), the standard practice is to disconnect that area from the rest of the grid for safety reasons. This is called *islanding*. The concern is that in an islanded area, there might not be a traditional generator to control and stabilize voltage and frequency. Also, many times, when islanding occurs, it is an unintentional island, and the distribution circuit is de-energized for the safety of personnel who would be working on restoration. When the GFM inverter is present, this same safety issue remains.

Most of the protections in place today for these islanded areas rely on quickly detecting changes in frequency (how fast the electricity alternates) or voltage (the electrical pressure). GFM inverters, which can make these electrical values more stable, might challenge the current protection methods. This is an important topic that requires further study.

In simpler terms, with GFM inverters, we might be able to create smaller, independent power islands during emergencies. However, ensuring that these islands coordinate effectively with the main power grid is a crucial consideration that needs more investigation.

To summarize, the main research direction in relation to the provision of services from GFM inverters is related to control algorithms and strategies. Developing controls calls for requirements and performance specifications. At the same time, overcoming some of the technology limitations (overloading and limited energy buffer) is a topic of research that will most likely have a positive impact on other GFM inverters' characteristics. Finally, the mass adoption of GFM

table 2. The summary of the requirements and additional capabilities recommended for GFM inverters.

	GB Grid Code	AEMO	European Union Grid Code (Draft)(**)	UNIFI
Requirements				
Active phase jump power	✓	✓	✓(A)	✓
Active damping power	✓	✓	✓(A)	✓
Voltage jump reactive power	✓	✓	✓(A)	✓
Fast fault current injection	✓	✓	✓(A)	✓
Voltage source behavior	✓	✓	✓(A)	✓
Frequency domain response	✓	✓		✓(*)
Inertial response	✓	✓	✓(High frequency: B) ✓(Low frequency: C)	✓(***)
Last synchronous machine survival	✓	✓		✓
Weak grid operation and system strength	✓	✓	✓(A)	✓
Oscillation damping	✓	✓	✓	✓
GFM within current limits	✓	✓		✓
Additional capabilities				
Headroom and energy buffer		✓	(✓)(C)	✓(*)
Current capability above continuous		✓		✓
Black start capability		✓		✓
Power quality improvement		✓		✓
Stability when current limit reached		✓	✓	✓

Type A: Connection point below 110 kV and maximum capacity of .8 kW or more. Type B: Connection point below 110 kV and maximum capacity at or above a threshold proposed by each relevant transmission system operator (TSO), which is below 1 MW. Type C: Connection point below 110 kV and maximum capacity at or above a threshold proposed by each relevant TSO, which is below 50 MW. Type D: Connection point above 110 kV or maximum capacity at or above a threshold proposed by each relevant TSO, which is below 75 MW.
*Even if not explicitly stated in the document, it can be inferred from the specifications that it is a desirable behavior.
**At the present situation, GFM for type A is possible but not mandatory.
***In North America, this requirement is categorized under "fast frequency response" and not explicitly defined.

inverters in distribution systems may impact transmission power system operation.

Standardization and Grid Codes

Around the globe, various existing interconnection performance standards are employed to accommodate the emergent features of GFM inverters. Figure 5 provides a timeline of some of these interconnection standards and recent documents that address GFM capability. A noteworthy example is the United States' IEEE 1547-2018 and IEEE 2800-2022 series. While these have reached different stages of maturity and adoption, they may fall short when addressing the capabilities of GFM inverters and ensuring that power systems can operate with any level of IBRs and synchronous machines.

Historically, these standards have mainly sought to prepare power systems where the IBRs are never required to supply the entirety of the load. Hence, they draw heavily from the capabilities of conventional inverter technologies. It remains uncertain whether these requirements can ensure acceptable power system operation or even interoperability between existing resources and new GFM resources. In some instances, the current requirements might not suit or could inadvertently hinder the deployment of GFM resources.

In the pursuit of standardization, the Universal Interoperability for Grid-Forming Inverters (UNIFI) research consortium in the United States has developed the first version of specifications for GFM technologies aimed at providing uniform technical requirements for the interconnection, integration, and interoperability of GFM inverters in electric power systems of any size.

In Europe, GFM requirements are gradually being introduced for power electronics-based components. For instance, Germany now mandates HVdc links to provide GFM capability, including several compliance tests, such as phase-angle steps, linear frequency change, voltage magnitude steps, grid distortion, and network impedance changes. Britain's Office of Gas and Electricity Markets approved a nonmandatory technical specification for GFM units on 31 January 2022. The requirement for the generator connection code is currently under revision in Europe, proposing to add GFM requirements for all types of generators. The requirement has been proposed for it to initially be optional and then followed by a transitional period to allow manufacturers to adjust to this control technology.

Australia's Australian Energy Market Operator (AEMO) published "Voluntary Specification for GFM inverters" in 2023 May to define the technical capabilities that power electronic devices should have to be classified as GFM inverters. Although voluntary, it is intended to guide future regulatory changes in related technical requirements and standards, service specifications, and procurement processes.

Table 2 summarizes the requirements and additional capabilities recommended for GFM inverters in the above-mentioned grid codes. As research continues in the field of GFM control, we anticipate further progress toward international standardization. This will not only ensure interoperability across diverse systems but also promote the efficient integration and operation of renewable energy sources.

Conclusion

Across the globe, the increase of IBRs in power grids is demanding more capabilities from these systems to ensure stable and reliable electricity. GFM inverters are increasingly being looked at as a solution to a variety of integration challenges, akin to skilled dancers setting the rhythm on a dynamic dance floor. However, there is still much work to do to develop accurate models, validate control algorithm performance, and create universal specifications for the proper integration of these technologies. Just like a well-coordinated dance troupe, this harmonious integration is necessary to unify IBRs with synchronous generators in future clean energy grids and ensure the power system dances to a seamless and reliable tune.

Acknowledgment

Some of this work was supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy under the Solar Energy Technologies Office Award No. 38637; and by Monash University Grid Innovation Hub.

For Further Reading

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Biographies

Behrooz Bahrani is with Monash University, Clayton, VIC 3800, Australia.

Mohammad Hasan Ravanji is with the Sharif University of Technology, 14588-89694 Tehran, Iran.

Benjamin Kroposki is with the Power Systems Engineering Center at the National Renewable Energy Laboratory, Golden, CO 80401 USA.

Deepak Ramasubramanian is with the Electric Power Research Institute, Knoxville, TN 37932 USA.

Xavier Guillaud is with the Arts et Metiers Institute of Technology, University of Lille, Centrale Lille, ULR 2697-L2EP, F-59000 Lille, France.

Thibault Prevost is with the Réseau de Transport d'Électricité, 92073 Ile-de-France, France.

Nicolaos-Antonio Cutululis is with the Technical University of Denmark, 4000 Zealand, Denmark.