

Research Roadmap on Grid-Forming Inverters



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List of Acronyms

AGC	automatic generation control
dq	direct quadrature
FERC	Federal Energy Regulatory Commission
FRT	fault ride-through
IEEE	Institute of Electrical and Electronics Engineers
IRPTF	Inverter-Based Resource Performance Task Force
MIGRATE	Massive InteGRATion of power Electronic devices
NERC	North American Electric Reliability Corporation
Omega	frequency
P	real power
PLL	phase-locked loop
PV	photovoltaic
Q	reactive power
V	voltage
VAR	volt ampere reactive

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Executive Summary

Managing the stability of today’s electric power systems is based on decades of experience with the physical properties and control responses of large synchronous generators, usually with the size of hundreds to even thousands of megawatts. Today’s electric power systems are rapidly transitioning toward having an increasing proportion of generation from nontraditional sources, such as wind and solar (among others), as well as energy storage devices, such as batteries. In addition to the variable nature of many renewable generation sources (because of the weather-driven nature of their fuel supplies), these newer sources vary in size—from residential-scale rooftop systems (a few kilowatts) to utility-scale power plants (hundreds to even thousands of megawatts)—and they are interconnected throughout the electric grid both from within the distribution system and directly to the high-voltage transmission system. Most important for our purposes, many of these new resources are connected to the power system through power electronic inverters rather than spinning electromechanical machines. Collectively, we refer to these generation technologies as inverter-based resources.¹

This report is intended to provide a comprehensive analysis of the challenges in integrating inverter-based resources and offer recommendations on potential technology pathways to inform the academic community, industry, and government research organizations. Although the focus of this roadmap is on grid-forming inverter controls, their impact on grid stability, and evaluating crucial system interactions (e.g., protection), we recognize that the large interconnections in North America will comprise both electromechanical and inverter-based resources (in this roadmap, sometimes called a hybrid power system). More importantly, we further recognize that inverter-based resources will comprise both grid-forming resources and other forms of control, such as grid-following resources. Transitioning to a grid with more inverter-based resources poses major challenges because the operation of future power systems must be based on a combination of the physical properties and control responses of traditional, large synchronous generators as well as those of numerous and diverse inverter-based resources (see Figure ES-1). These challenges stem from the recognition that there is no established body of experience for operating hybrid power systems with significant amounts of inverter-based resources at the scale of today’s North American interconnections.

¹ Although the focus of this roadmap is on inverter-based generation, it is also applicable to inverter-based energy storage. The details of grid-forming storage applications—such as during charging, discharging, or state of charge—are beyond the scope of this roadmap.

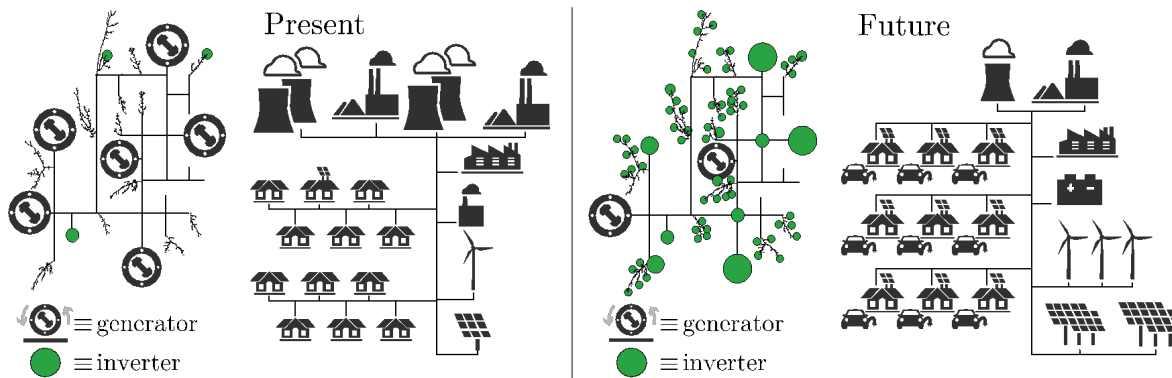


Figure ES-1. The present power system (a) has historically been dominated by synchronous generators having large rotational inertia. Future systems (b) will have a significant fraction of inverter-based generation resources. This implies a need for next-generation grid-forming controllers that ensure grid stability at any level of penetration with inverter-based resources.

This research roadmap is intended to fill the knowledge gap by providing a system view of grid-forming inverter-based resource controls and their impact on grid stability, which we believe is central to meeting some of the challenges to operating the future North American electric power system. This includes the roles and requirements of grid-forming inverter-based resources—including solar photovoltaics, wind generators, and energy storage. For this roadmap, we focus on a specific family of grid-forming inverter control approaches that do not rely on an external voltage source (i.e., no phase-locked loop) and that can share load without explicit communications. Although the roadmap is focused narrowly on system challenges for grid-forming controls and power system stability, including interactions with protection, we hope it serves as a foundational element for future system-of-systems roadmapping needed in a broader grid modernization effort with increasing deployments of inverter-based resources.

The roadmap first introduces formal definitions for the grid stability topics and then describes the differences between grid-forming and traditional grid-following control approaches for inverter-based resources. The core of the roadmap consists of a review of current research and an outline of research needs related to five grid-forming inverter topics:

- Frequency control
- Voltage control
- System protection
- Fault ride-through and voltage recovery
- Modeling and simulation.

The review both delineates contemporary advances and highlights open research questions that must be addressed to enable the widespread adoption of inverter-based resources across the grid. Feedback from industry on these research questions is incorporated, including discussions during the Workshop on Grid-forming Inverters for Low-inertia Power Systems.² The workshop

² The Workshop on Grid-forming Inverters for Low-Inertia Power Systems was held at the University of Washington in Seattle on April 29–30 2019. Presentations and video are available at <https://lowinertiagrids.ece.uw.edu/>.

included industry presentations and discussion of ongoing research, technology gaps, and piloting needs.

This roadmap concludes by offering a multiyear perspective on the gradual field validation of grid-forming inverters (see Figure ES-2). This perspective recognizes that the scale and scope of the types of power systems that inverters will be called on to provide grid-forming services will and should begin modestly. Specifically, this roadmap recognizes that inverter controls today are predominantly grid-following and that future power systems will involve a mix of inverter-based resources with both grid-following and grid-forming control capabilities. Growth over time will depend on how well grid-forming inverters perform and what advantages they bring as penetration levels (instantaneous and average) of inverter-based resources increases. This recognition, in turn, establishes a natural sequence of priorities for the research questions that must be addressed.

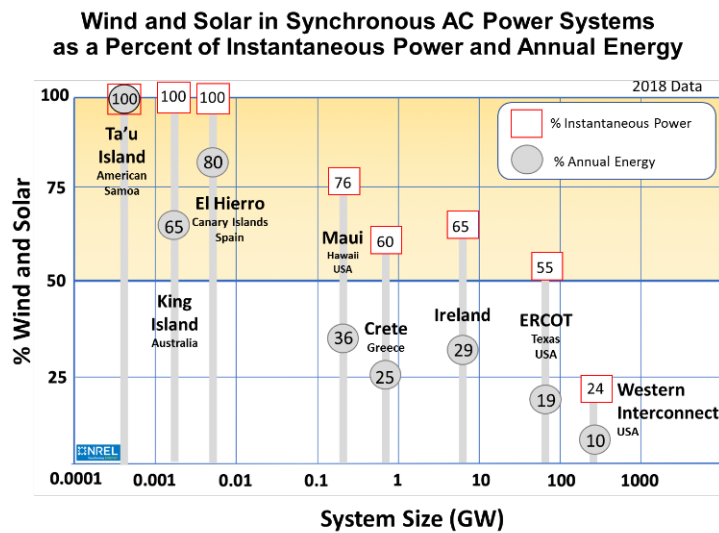


Figure ES-2. (a) Total annual and instantaneous inverter-based wind and solar generation based on power system size

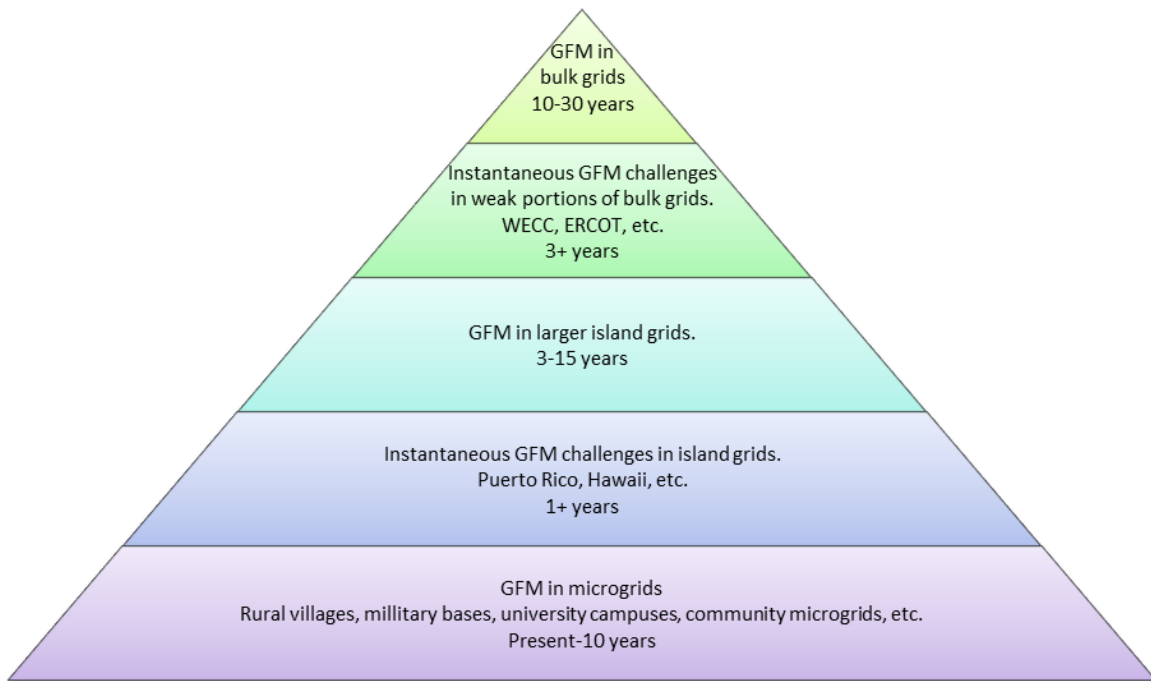


Figure ES-2. (b) Incorporating grid-forming controls into the electric grid will take place gradually after key functionalities have been demonstrated and confidence has been gained by operating them in smaller microgrids and island power systems.

Following this multiyear perspective, the roadmap offers short descriptions of two specific near-term research priorities: the review of regulatory and technical standards and the development of advanced modeling techniques. These priorities are foundational. We recommend immediate pursuit of them in parallel with and in direct support of the research outlined by our multiyear perspective.

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Introduction

Managing the stability of today’s electric power systems is based on decades of experience with the physical properties and control responses of large synchronous generators.³ Today’s electric power systems are rapidly transitioning toward having an increasing proportion of generation from nontraditional sources, such as wind and solar (among others), as well as energy storage devices, such as batteries. In addition to the variable nature of many renewable generation sources (because of the weather-driven nature of their fuel supply), these newer sources vary in size—from residential-scale rooftop systems to utility-scale power plants—and they are interconnected throughout the electric grid, both from within the distribution system and directly to the high-voltage transmission system. Most important for our purposes, many of these new resources are connected to the power system through power electronic inverters.⁴ Collectively, we refer to these sources as inverter-based resources.

This report is intended to provide a comprehensive analysis of the challenges in integrating inverter-based resources and offer recommendations on potential technology pathways to inform the academic community, industry, and government research organizations. The operation of future power systems must be based on a combination of the physical properties and control responses of traditional, large synchronous turbine generators as well as those of numerous and diverse inverter-based resources (see Figure 1). The major challenges stem from the recognition that there is no established body of experience for operating hybrid power systems with significant amounts of inverter-based resources at the scale of today’s North American interconnections.

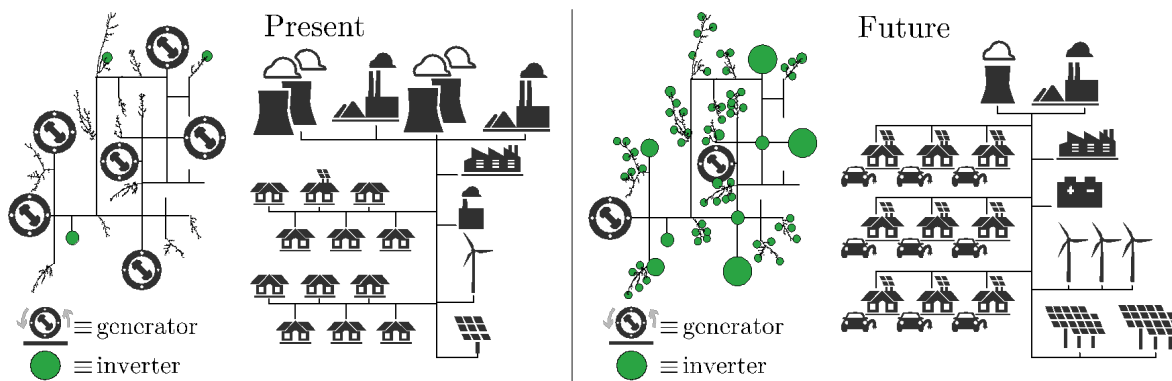


Figure 1. The power system (a) has historically been dominated by synchronous generators having large rotational inertia with a relatively modest amount of inverter-based resources, such as PV, wind, and batteries. Future systems (b) will have a significant fraction of generation interfaced with power electronics and might be dominated by inverters. This implies a need for next-generation grid-forming controllers that ensure grid stability at any level of penetration with inverter-based resources.

³ In an AC electric power system, synchronization is the process of matching the speed and frequency of a generator or other generation sources to an operating grid.

⁴ Power electronics are solid-state electronics for the control and conversion of electric power. Power electronics conversion can be classified according to the type of the input and output power: AC to DC (rectifier), DC to AC (inverter), DC to DC (converter), AC to AC (cycloconverter).

To operate such large hybrid power systems, the assumptions that underlie current generation design and control approaches must be reexamined and, where appropriate, modified or even redefined to take explicit account of the new challenges and opportunities presented by these inverter-based forms of generation. We should expect that new control approaches, operational procedures, protection, and planning tools and processes will be required.

Synchronous generators regulate their terminal voltages and respond to a change in grid frequency through a change in its power output; these are traditionally referred to as generator-excitation and turbine-governor controls, respectively. These types of primary, secondary, and tertiary controls and voltage control are well-known. We refer to these generation sources as grid-forming. Today's inverter-based generation sources generally use phase-locked loops (PLLs), which rely on externally generated voltages by synchronous machines to operate (Yazdani and Iravani 2010; Golestan et al. 2017). We refer to these types of inverter-based generation as grid-following inverters. In case of unintended separation of the power system, islanded systems comprising only these types of inverters will not be capable of functioning autonomously. Similarly, after a blackout, grid-following inverters cannot support the restoration process of the bulk power system unless conventional generators with black-start capability⁵ are present. Also, although this issue is currently being addressed by industry, some of today's inverters might disconnect and/or cease operation as a result of transmission faults, and this behavior is contrary to the desired behavior of resources connected to the bulk power system during a severe event (North American Electric Reliability Corporation [NERC] 2017b).⁶ The performance of PLL-based inverters on the distribution system has also been a major topic of discussion and has resulted in updated equipment standards that are being deployed—for example, the Institute of Electrical and Electronics Engineers (IEEE) updated Standard 1547 (IEEE1547-2018).

These activities have inspired an investigation into other available control methods for power electronic inverters for the seamless integration of renewable energy and battery energy storage into electric grids. These alternative methods are referred to generically as grid-forming controls because the goal is to provide functionalities that are traditionally provided by synchronous machinery. Stated differently, the objective is to engineer plug-and-play (Sadamoto et al. 2019) grid-forming controls that can function in both high-inertia grids as well as future low-inertia grids where inverters might dominate. Inverters must function in a system that might evolve over time. For this roadmap, we focus on a specific family of inverter control approaches that does not rely on an external voltage source (no PLL) and that can share load without explicit communications.⁷ Early work on this topic started in the 1990s (Chandorkar, Divan, and Adapa 1993; Lasseter 1998; Katiraei, Iravani, and Lehn 2005); however, these controls were originally designed to be deployed in power systems with small footprints (e.g., microgrids) and on small

⁵ Black-start generators are the key grid-forming generators when restoring the system from a blackout. As the black-start is successful, other generators then synchronize to the grid before injecting current. Grid-forming, inverter-based resources will need to have similar capabilities during normal and abnormal operations as well as black starts.

⁶ Efforts are currently underway to require improved ride-through capability by inverter-based generation (and storage).

⁷ We recognize that there are other means of implementing grid-forming control functions (including continued reliance on PLLs), but these are not the focus of this roadmap.

islands (such as Kauai, Hawaii). Today, grid-forming controls are being considered for deployment in bulk power systems because of their ability to enhance the stability of these grids in regions or during times when loads are largely being served by inverter-based resources.

To this end, this research roadmap focuses on this emerging topic, which we believe is central to meeting some of the challenges to operating the future North American electric power system. This includes the role of and requirements for grid-forming inverter-based resources, including solar photovoltaics (PV), wind generators, and energy storage. This roadmap leverages insight gained from the project team's past research and research funded by the U.S. Department of Energy Solar Energy Technologies Office on virtual oscillator grid-forming controls and assessing grid-instability points for hybrid systems (grid-following, grid-forming, and traditional synchronous generation). This roadmap also builds on related international efforts, such as the European Union's programs on the Massive InteGRATion of power Electronic devices (MIGRATE)⁸ and the RE-SERVE⁹ project, Australia's Commonwealth Scientific and Industrial Research Organisation effort, as well as the National Grid UK effort. The purpose of this research roadmap is to outline specific research directions appropriate for inclusion in an eventual U.S. national research-and-development program on grid-forming inverter-based forms of generation and storage that can enhance the stability of future electric power systems.

Although the focus of this roadmap is on grid-forming controls and some system interactions (e.g., protection), we recognize that the large interconnections in North America will comprise both electromechanical and inverter-based resources (sometimes called a hybrid power system in this roadmap). More importantly, we further recognize that inverter-based resources will comprise both grid-forming resources and other forms of control, such as grid-following resources.

This roadmap is organized as follows. In Section 1, we introduce formal definitions for the grid-stability topics addressed by this roadmap and clarify the related topics that are outside the scope of this roadmap. In Section 2, we discuss the differences between grid-forming and grid-following control approaches for inverter-based resources and the importance of focusing on grid-forming approaches. In Section 3, we review relevant research and outline research needs related to five grid-forming inverter topics:

- Frequency control
- Voltage control
- System protection
- Fault ride-through (FRT) and voltage recovery
- Modeling and simulation.

Power system stability, protection, ride-through, and the ability to model and simulate these complex systems are foundational technical issues, and these characteristics are central to our discussion of grid-forming inverters.

⁸ See <https://www.h2020-migrate.eu/>.

⁹ See <http://www.re-serve.eu/>.

In Section 4, we introduce a roadmap that provides an outline of an evolutionary vision of grid-forming inverters playing an increasingly greater role within power systems and the consequent nearest term priorities for research to ease these transitions.

This roadmap focuses on these outlined technical research topics to ensure future electric power system stability. Feedback from industry for these research questions included their discussion as part of a Workshop on Grid-forming Inverters for Low-Inertia Power Systems held at the University of Washington.¹⁰ The workshop included industry presentations and discussion of ongoing research, technology gaps, and piloting needs. Note that many related technical areas are outside the scope of this roadmap but would need evaluation in future roadmapping efforts. This includes power electronics device or component design, distribution system engineering and operations for grid-forming inverter controls, sensing and communications systems, load control, high-voltage DC, system costs analysis, economic dispatch, system adequacy and reserves calculations, traditional security evaluation (i.e., contingency analysis, including black-start and in-rush currents for energizing transformers and electric machines), market design, economic regulation, and cybersecurity. It is our hope that this roadmap becomes a cornerstone for roadmapping work on future power systems with higher levels of inverter-based resources.

¹⁰ The Workshop on Grid-forming Inverters for Low-Inertia Power Systems was held at the University of Washington in Seattle on April 29–30 2019. Presentations and video are available at <https://lowinertiagrids.ece.uw.edu/>.

1 Power System Stability Concepts

As described in Kundur et al. (2004), classic power system stability criteria include categories for rotor angle, frequency, and voltage stability, and each category encompasses both short and long timescales. This framework was created throughout many decades and encompasses behavior across generation-level and network interactions as well as the impact of loads. As illustrated on the bottom of Figure 2, this framework for categorizing stability criteria is often considered in terms of timescales and historically focused on how stability was provided by large electromechanical generators.

This roadmap focuses on controls and protection of hybrid systems comprising traditional electromechanical generation and inverter-based generation. We start by focusing on the differences between electromechanical and inverter-based interfaces at the individual generator level and attempt to extrapolate these differences to impacts on system-level stability. Because inverters and machines are primarily distinguished by their response at shorter timescales, we restrict our scope to the short-term stability of frequency dynamics and voltage (see the top of Figure 2).

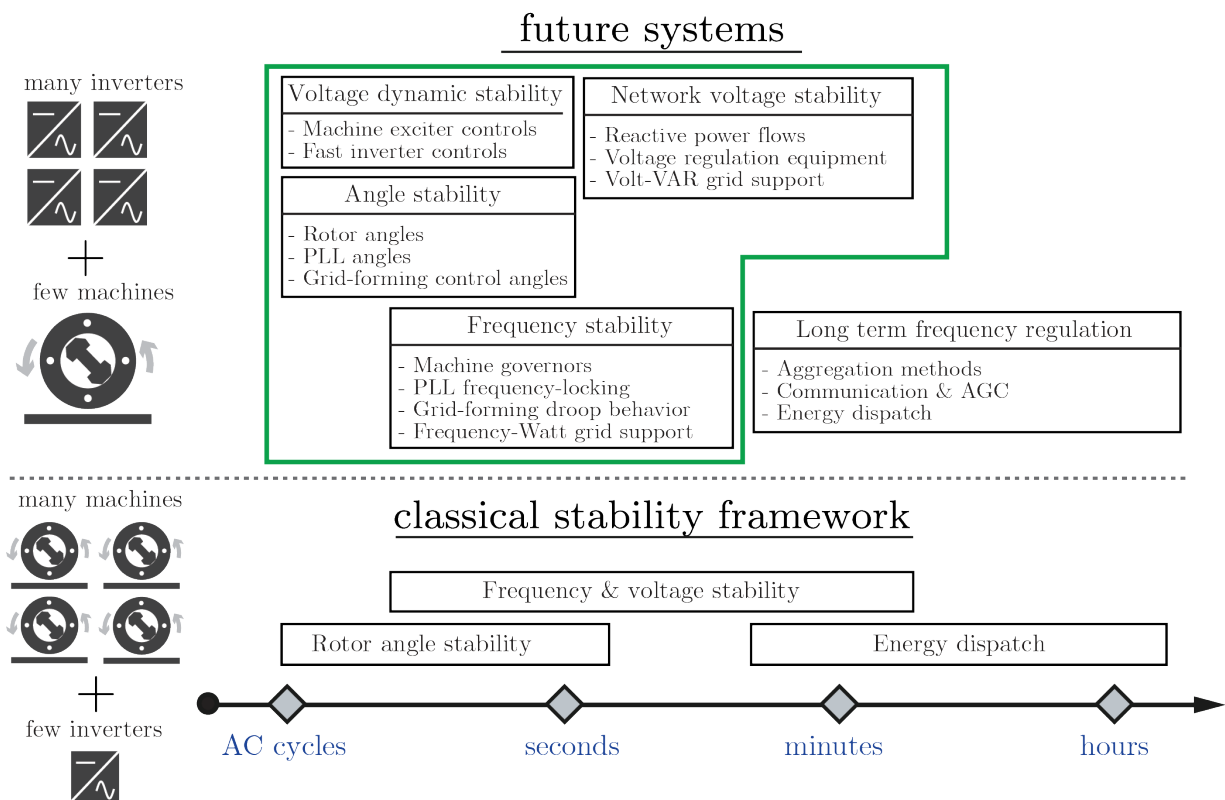


Figure 2. The various timescales and control functions that comprise power system stability. Classic notions for conventional systems are shown on the bottom. We highlight the various phenomena that must be considered as systems transition to inverter-based generation. This document is restricted in scope to the fast-timescale issues enclosed in green. (AGC refers to “automatic generation control.”)

To highlight shortcomings of classic stability criteria for mixed machine-inverter systems, we note that conventional metrics are largely defined in terms of machine dynamics and their system

impacts. Both rotor angle and frequency stability are strongly tied to the dynamics of rotating mechanical components in traditional generators. Given that power electronics have no mechanical components, it is clear that an expanded set of stability definitions is needed to describe the role of inverters in future systems.

As a potential approach to overcome these shortcomings, we can link variables within inverter controllers that have behavior analogous to machine rotor angles. Using such a framework, it might be feasible to obtain a unified set of angle and frequency stability criteria where angular dynamics encompass both mechanical rotors as well as inverter angles that reside within their digital controls. This extension is illustrated in Figure 2, which consider both mechanical and inverter behavior.

On the other hand, voltage stability is strongly tied to reactive power generation and the dynamics of voltage regulation control loops. Focusing first on reactive power, the question is not whether the generation is electromechanically based or power electronics-based; both forms of generation have well-understood capabilities for producing reactive power, and reactive power is needed for certain loads and other system components. Instead, the key issue is the geographic/topologic locations of reactive power generation in a conventional power system versus a future hybrid power system and thus the coordinated control of these hybrid, dispersed resources and the differing line impedances at the transmission and distribution levels. Specifically, traditional generation is generally interconnected at the high-voltage transmission system, whereas inverter-based generation might be interconnected to the transmission system as well as dispersed across and interconnected within medium- and lower voltage distribution systems. Voltage regulation from these dispersed, distribution-connected generation expands stability analysis and control requirements.

Finally, we must also recognize that the character of the initiating, potentially destabilizing events to which a power system must react and respond will also change because of the characteristics and properties of inverter-based resources. One key area of research involves rethinking the logic of and mechanisms relied on for triggering system protection. To a large extent, traditional forms of system protection rely on the high fault currents that are produced by traditional generation sources. Today's inverter-based sources, by design, provide lower—sometimes much lower—fault currents. Inverter-based resources, moreover, do not provide the same fault current phasors as traditional machine generators. System protection methods for hybrid power systems, therefore, will need to be reengineered, accounting for these differing fault currents and conditions.

To further illustrate power system fault response issues, the analysis of several events involving the cessation of inverter-based generation shows that stable operation support is needed during those fault events (NERC 2018a; NERC 2018b; NERC 2017b). The ability of inverter-based generation sources to ride-through faults encompasses several related research topics. First, as noted in the previous paragraph, the ability to sense faults and distinguish them reliably from other voltage fluctuations is more difficult because of the low short-circuit currents available

from today's inverter-based sources. Second, the appropriate criteria for ride-through must be articulated.¹¹ Third, once the fault has been ridden through, recovery must proceed.

Although modern grid-following inverters will contribute to recovery following a fault,¹² black-start following a power system outage could present a challenge for situations in which inverter-based generation sources have replaced most of the synchronous resources (including those with black-start capability). Grid-following inverters might have limited restoration-support capabilities because they depend on external sources that regulate system frequency and voltages. Inverter-based grid-forming sources, in contrast, would be designed to establish frequency and control voltage autonomously, and therefore they might be designed to both provide black-start capability and facilitate system restoration following a blackout.

¹¹ The topic of appropriate ride-through criteria is currently an active area of discussion in the industry led by the North American Electric Reliability Corporation (NERC) Inverter-Based Resource Performance Task Force (IRPTF) and, more recently, the IEEE P2800 industry standard team.

¹² Recent Federal Energy Regulatory Commission (FERC) and NERC activity at the bulk power system level—and IEEE 1547 as updated in 2018 at the distribution level—are now in place to ensure that future nonsynchronous resources support voltage, frequency, and ride-through. Although these rules do not apply to legacy inverters, NERC and the industry are actively working to improve the performance of legacy inverters when this is possible and practical. See, for example, FERC orders 842 and 827, NERC PRC-024, and the work of the NERC IRPTF.

2 Overview of Grid-Following and Grid-Forming Controllers for Inverter-Based Generation

A power electronic inverter converts DC power from an energy resource—such as wind, PV, or batteries—to AC power for use in an AC power system.¹³ As shown in Figure 3, a typical power electronic inverter consists of a DC side, which contains a DC link; a set of switching semiconductor devices; and a grid-side passive filter that prevents switching harmonics from propagating into the grid. The input side of the DC-link interfaces either directly with an energy source or might be connected to additional power electronics-like DC-to-DC converter(s).

Because an inverter power stage is built solely with switching devices and passive filters, closed-loop control is required for any kind of meaningful operation. In modern converters, a significant fraction of closed-loop controllers takes the form of a digital controller. Digital controllers are fully programmable, so they exhibit a high degree of algorithmic flexibility and enable the synthesis of new controllers with relative ease. An overview of inverter controllers is provided in Figure 4.

¹³ Inverters can also be designed for bidirectional operation; however, the details of this are beyond the scope of this report.

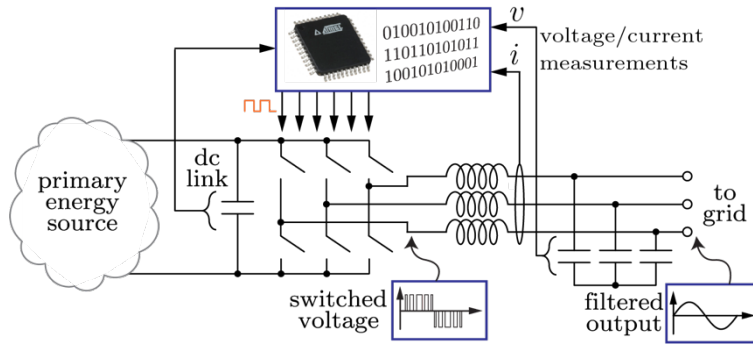


Figure 3. General structure of an inverter system with closed-loop control

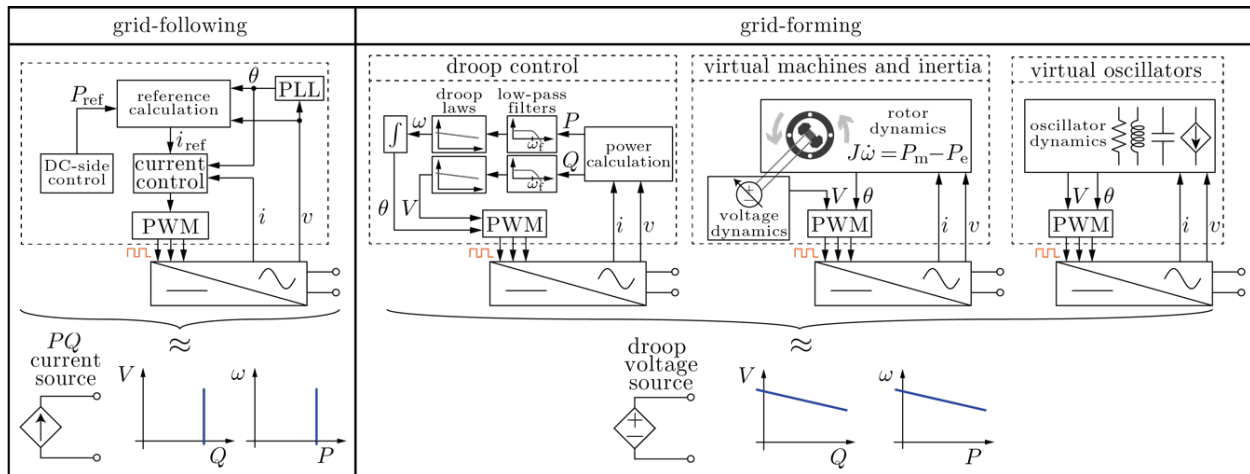


Figure 4. Functional diagrams of grid-following and grid-forming inverters. Grid-following inverters mimic current sources at their output terminals, whereas grid-forming inverters act like voltage sources whose output abides by droop laws.

Figure 4 highlights the functional control diagrams for grid-following and grid-forming inverters. These are further described in the following section. At a high level, grid-following and grid-forming control can be differentiated, as shown in Table 1.¹⁴

¹⁴ Adapted from MIGRATE: <https://www.h2020-migrate.eu/>.

Table 1. Comparison of Grid-Following and Grid-Forming Controls

Grid-Following Control	Grid-Forming Control
Assumes grid already formed under normal operations	Assumes it has responsibility to form and maintain healthy grid
Direct-quadrature (dq) ¹⁵ vector control of current injected into the grid	Control of voltage magnitude and frequency/phase
Decoupled control of P and Q	Slight coupling between P and Q
Needs PLL	It may use PLL control to switch between modes
Needs voltage at the point of common coupling to deliver P and Q	Can black-start a power system
<i>Cannot operate</i> at 100% power electronics penetration; instability thresholds (tipping points) exist	<i>Can theoretically operate</i> at 100% power electronics penetration; can coexist with grid-following
	Not standardized, inadequate operational experience at a systems perspective

Further, note that grid-following and grid-forming control definitions for bulk power system versus distribution connected resources is likely to be different. This is because emerging microgrid functionality (the ability to operate in islanded mode—planned or unplanned) typically is applied to distribution resources, whereas for the bulk power system, generally separation or islanding is avoided. Distribution-focused grid-forming resource stakeholders are therefore likely to assume islanding capability when developing and integrating grid-forming generation and storage.

2.1 Grid-Following Controllers

As illustrated in Figure 4, the grid-following controller contains two main subsystems: a PLL that estimates the instantaneous angle of the measured converter terminal voltage and a current-control loop that regulates the AC current injected into the grid.¹⁶ This is often referred to as current control because the current is the physical quantity that is regulated. In this setting, the PLL provides the angular reference of the current commands and carries out the “following” behavior. As shown in Figure 4, the grid-following AC terminals mimic a current source whose real and reactive output tracks the references. For fixed power commands, an inverter acts like a constant real-reactive power (PQ) source.¹⁷

This control strategy is called grid-following because its functionality depends on each inverter having a well-defined terminal voltage that its PLL can latch onto and follow. In this setting, the system voltage and frequency are regulated by resources external to each grid-following inverter.

¹⁵ dq control refers to control with respect to a three-phase synchronous reference frame.

¹⁶ Although the electromechanics and controls are different, a traditional generator has similar requirements. It also needs to establish equal line voltage, frequency, phase sequence, phase angle, and waveform to that of the system to which it is being synchronized and connected.

¹⁷ PQ control seeks steady-state active and reactive power output according to a reference—for instance, within a certain range of frequency and voltage of the interconnection AC bus, the inverter regulates active and reactive power to reference values.

As the proportion of the grid-following inverters on a grid increases, it might be necessary to embed additional functions that prevent excessive voltage and frequency deviations. These are called grid-support functions, and they are described in Section 4.

Today, nearly all grid-connected inverters are controlled with a grid-following controller such as this. Additional functionalities are typically layered on top of this baseline controller and vary between single-phase and three-phase implementations. Regardless, the grid-following control structure shown in Figure 4 generally holds. Because grid-following methods are currently the default inverter controller and will be into the near future, these properties are key to understanding grid stability operations for many years.

2.2 Grid-Forming Controllers

During the past two decades, a variety of grid-forming strategies have been developed. Here, we use the term *grid-forming* as an umbrella for any inverter controller that regulates instantaneous terminal voltages and can coexist with other grid-following and grid-forming inverters and synchronous generation on the same system. We further restrict our definition to inverter controls that do not require a PLL.¹⁸ This contrasts with grid-following units that act as current sources, require a PLL, and cannot function without an externally regulated voltage. Our use of the term *grid-forming* also excludes single-inverter stand-alone systems or multi-inverter systems that require communications to operate. In principle, grid-forming inverters should allow for the realization of scalable and decentralized AC power systems where system voltages and frequency are regulated by the collective interactions of the grid-forming units themselves. In this sense, the synchronous machine represents the well-understood grid-forming interface. Looking toward the future, we seek grid-forming inverter controllers that yield benefits similar to those of machines while respecting the unique properties of power electronics.

As shown in Figure 4, existing grid-forming controllers can be broadly categorized as droop controllers, virtual synchronous machines (often called synchronverters), and virtual oscillator controllers, to name a few. We consider each method as follows:

- Droop control: The most well-established grid-forming method is droop control, which was first proposed in the early 1990s (Chandorkar, Divan, and Adapa 1993). Its key feature is that it exhibits a linear trade-off between frequency and voltage versus real and reactive power, much like a typical synchronous machine does in steady state. These so-called “droop laws” are referred to as the P-omega (real power-frequency) and Q-V (reactive power-voltage) relationships, and they give rise to the following properties regardless of whether they are machines or inverters:
 - System-wide synchronization: All units reach the same frequency.
 - Power sharing: Each unit provides power in proportion to its capacity (or its programmable droop slope).

These properties arise as a result of the networked interactions from the grid and locally programmed droop laws.

¹⁸ We recognize that there are other means of implementing grid-forming control functions (including continued reliance on PLLs), but these are not the focus of this roadmap.

- Virtual synchronous machines: This approach is based on the emulation of a synchronous machine within the controls of an inverter (Beck and Hesse 2007; Alatrash 2012; Zhong 2016). Specifically, inverter terminal measurements are fed as inputs into a digital synchronous machine model whose emulated dynamics are mapped to the inverter output in real time. The complexity of the virtual machine can vary greatly, from detailed electromechanical models to simplified swing dynamics. Implementations that closely match machine characteristics, possibly even with virtual flux dynamics, have both Q-V and P-omega characteristics and are often called “synchronverters.” On the other end of the spectrum, virtual inertia methods are simpler and capture only the dynamics of an emulated rotor and its steady-state P-omega droop.
- Virtual oscillator controllers: In recent years, another inverter control method based on the emulation of nonlinear oscillators has emerged (Johnson et al. 2016a). Much like a virtual synchronous machine, real-time measurements are processed by the digitally implemented model whose output variables modulate the inverter power stage. As illustrated in Figure 4, the key difference is that the model takes the form of an oscillator circuit with a natural frequency that coincides with the nominal AC grid frequency, and its remaining parameters are tuned to adjust the nominal voltage and control bandwidth. Although the virtual oscillator might appear radically different, it has been shown to exhibit the Q-V and P-omega droop laws in steady state.
- Unified properties of grid-forming controllers: Despite the differences between droop controllers, virtual synchronous machines, and virtual oscillators, all three methods have similar properties that allow us to consider them. In particular, the output terminal behavior of an inverter with any of these grid-forming controllers resembles a voltage source with an amplitude and frequency that varies with reactive power generation and the system load, respectively. This property allows grid-forming inverters to adjust output power nearly instantaneously to balance loads, regulate local voltage, and contribute to frequency control.¹⁹ Although grid-following inverters can be programmed to emulate the aforementioned grid-following properties, they nonetheless require a well-defined terminal voltage as a reference. Presently, grid-forming inverters are typically seen in microgrids and in off-grid installations that require high reliability.

¹⁹ Although it is sometimes natural to equate grid-forming and grid-following with voltage- and current-control modes for inverters, respectively, there are technical subtleties associated with each form of control that we seek to avoid; instead, we focus on describing the grid-related functionalities involved in grid-forming versus grid-following control at a higher level.

3 Inverter Control State-of-the-Art and Open Research Questions

In this section, we provide a brief snapshot of the capabilities of grid-forming controllers within the context of frequency and voltage control. To provide a more complete picture of the current state of inverter technologies, we also highlight relevant grid-support functions that are being used on grid-following inverters today. After delineating contemporary advances, we highlight open research questions that must be addressed to enable the widespread adoption on bulk power and distribution grids.

3.1 Frequency Control

3.1.1 Classic Frequency Control

Frequency control refers to generation control actions that are designed to maintain the system frequency near the nominal value (e.g., 60 Hz in North America and 50 Hz in Europe). For machine-based grids, system frequency is intricately tied to the Newtonian mechanics of the rotating generator masses and the speed-governor droop law at each generator. Lower system inertia leads to higher rates of change in frequency. As a corollary to this property, lower inertia results in the arrest of frequency at lower (higher) frequency values, which is called the nadir (or the zenith), after an abrupt loss of generation (or decrease in load). The nadir (or zenith) is formed when the machines across a system reach a common steady-state frequency with a deviation from the nominal value that is proportional to the P-omega droop slope. These dynamics, which arise as a result of the machine-level physics and droop controls, are referred to as primary frequency control and take place in a matter of seconds. The system inertia primarily correlates with the combined rotating mass of the subset of machine-based generators operating in grid-forming, or synchronous droop, control. As more synchronous rotational mass is added or subtracted from the grid, inertia is proportionally added or subtracted, and, likewise, system damping²⁰ is increased or decreased. Inverter-based resources do not contribute inertia to a power system. As traditional resources are replaced with inverter-based resources, system inertia and thus damping is reduced, making the risk of frequency swings higher (and thus are referred to as “weak grids”; see IEEE/NERC [2018]). Operationalizing grid-forming controls for inverter-based resources, along with headroom operation, would counteract both the loss of inertia and primary frequency control provided by retired synchronous generation. Similar to the natural behavior of synchronous machines, grid-forming inverter-based resources would autonomously detect the frequency swing and autonomously adjust its power injection during a low frequency event.

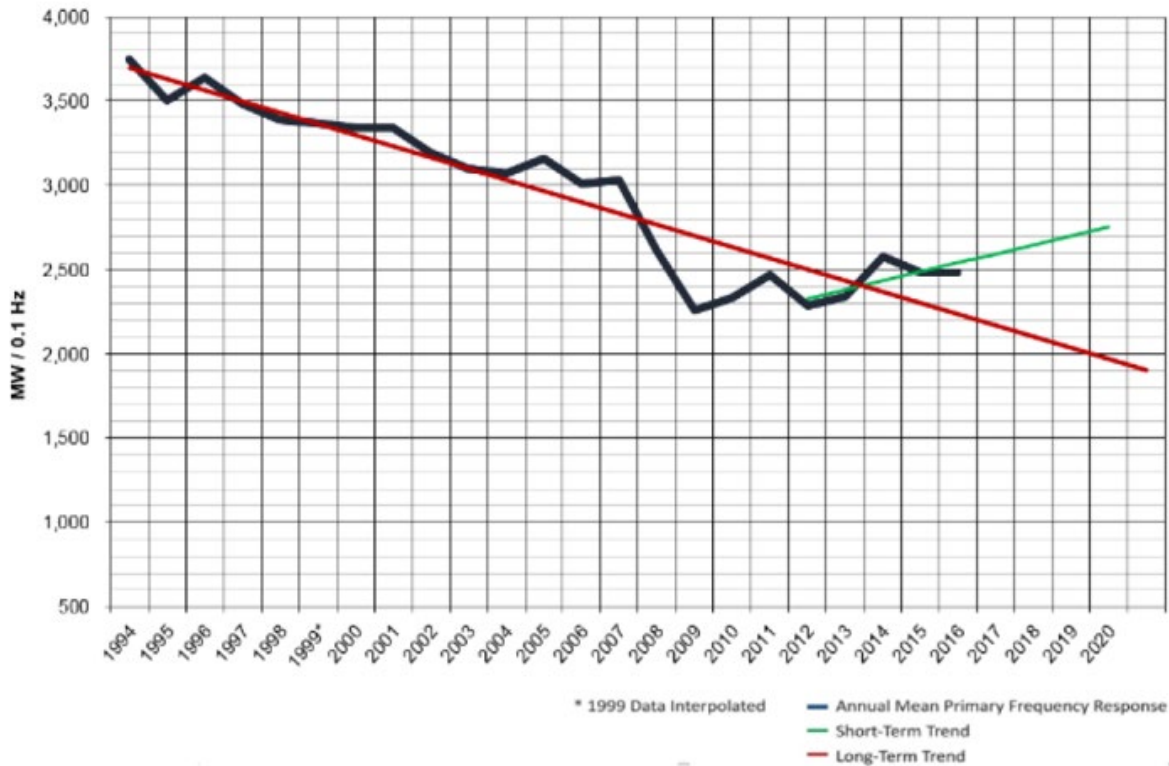
To restore the system frequency to its nominal value, a *secondary* communications-based method, called automatic generation control, issues updates in the generation set points during a period of tens of seconds to a few minutes (Kundur, Balu, and Lauby 1994; Sauer and Pai 1998). At the slowest timescale, a *tertiary* dispatch layer issues updated commands via an economic

²⁰ Additional basic controls theory and power system modal analysis are beyond the scope of this report. Damping is also affected by the electromagnetic characteristics of grid equipment and load response to frequency; see IEEE/NERC (2018). Other key concepts include resonance, tuning gains, deadband, etc. For traditional background information, see Kundur, Balu, and Lauby (1994); Sauer and Pai (1998).

optimization routine that is executed typically every 5 to 15 minutes. It is noteworthy that the primary, secondary, and tertiary controllers act on these distinct timescales. This strategy is also observed on inverter microgrids, as discussed in following sections.

3.1.2 Frequency Dynamics of Low-Inertia Systems

As inverters displace machines on a system, it is evident that the total inertia on that system is reduced (IEEE/NERC 2018), as shown for the Eastern Interconnection in Figure 5. Reduced inertia results in a larger rate of change of frequency and more volatile system dynamics, and it also necessitates faster control actions to arrest frequency swings (Ulbig, Borsche, and Andersson 2014). Because the magnitude of the frequency swing after a disturbance is largely tied to the imbalance between generation and load, enough untapped capacity must be reserved as headroom for frequency control. This can take the form of storage, spinning generators, and/or renewable-powered inverters that are operated at less than their nameplate rating or maximum available power level. Inverter-interfaced batteries can also be deployed. A drawback is that unused capacity could represent an opportunity cost for both renewable and fossil-fueled generation because power output must be throttled to less than the available amount.



Source: NERC 2017a

Figure 5. Decreasing total system inertia for the Eastern Interconnection

Regardless of whether machine- or inverter-interfaced resources are used as reserves, their dynamic time constants must be carefully considered and respected. For instance, the physical time constants of electromechanical machines are relatively slow and act as an intrinsic bottleneck. In low-inertia systems where frequency deviations could be large, spinning mechanical reserves might not be fast enough to provide primary frequency control (Ulbig,

Borsche, and Andersson 2014; IEEE/NERC 2018). This leaves inverters and other fast-acting assets (such as some loads) as the most viable options for primary frequency control.²¹

3.1.3 Inverter-Based Resources for Frequency Control

Referring to the controllers shown in Figure 4, we provide a brief survey of existing frequency control strategies. We first focus on grid-forming controls and recall that they all exhibit P-omega steady-state droop laws despite differences in implementation and instantaneous dynamics. Of particular importance, those relations govern the steady-state frequency deviation after initial transients have subsided. Typically, these relations are tuned such that the frequency stays within a narrow range near the nominal frequency. This mirrors established practice of how governors are tuned in classic machine-based systems.

On this note, there are established control strategies for inverter-based microgrids, which are similar in spirit to hierarchical control methods in classic power systems. In particular, the effective P-omega droop slope at each inverter can be tuned for the desired primary response at the timescale of tens of milliseconds to seconds, and schemes using low-bandwidth communications have been used for secondary frequency restoration and even tertiary-level energy dispatch (Guerrero et al. 2011; Shafiee, Guerrero, and Vasquez 2014; Lasseter et al. 2002). This suite of methods can be used to manage energy on a microgrid from AC cycles to extended periods. Although these approaches have been used on droop-controlled inverters, in principle they could be applied to any other grid-forming controller shown in Figure 4 if each controller has inputs for external set points.

Lacking mature grid-forming solutions for distributed generation, communications and scalability are key issues that hinder the use of hierarchical microgrid strategies on the broader grid. In contrast to microgrids, which are relatively small and contained, bulk systems might have hundreds of thousands to millions of controllable devices throughout a large geographic area. Hence, centralized secondary and tertiary control becomes impractical without appropriate aggregate-control schemes and system partitioning. Note that if partitioned control areas are used, they will likely need to remain relatively small to accommodate the large numbers of inverters per geographic area. This implies that although distributed hierarchical schemes are feasible, they will entail a larger number of control areas and associated communications infrastructure. Detailed communications network upgrades are out of scope for this roadmap.

One can also ask why frequency regulation is needed in an inverter-based system dominated by electronics. For today's AC grid, frequency/phase control is foundational at the primary response timescale, and hence it is needed relative to the prior discussed power system damping requirements during contingency events. To answer this question in detail for the secondary and tertiary timescales, however, recall that power set points are most straightforwardly tracked when the system frequency is restored to nominal. This is because the traditional linear approach works because the machine dynamics are relatively slow, and therefore there is a large linear region for dispatch convergence. If the desired result is to dispatch set points that are optimal in

²¹ The Electric Reliability Council of Texas interconnection, for example, relies on fast (within 0.5 second) interruption of industrial loads that provide half the frequency containment reserve, which the Electric Reliability Council of Texas procures through its ancillary services market.

any sort of system-level economic sense, it might be necessary to restore the system frequency by some means.²²

Although the controllers shown in Figure 4 have similar steady-state characteristics, distinctions arise when comparing how each grid-forming controller reacts dynamically at the shortest timescales. To uncover these differences, we inspect the underlying implementations shown in Figure 4.

Referring first to the droop controller, note that its loop contains filters that are used to remove harmonics and pulsating components from the measured signals (Hart, Lasseter, and Jahns 2016; Guerrero et al. 2011; Johnson et al. 2017; Lasseter 2002). These filters, which often take the form of low-pass and/or notch filters, act as the primary means to adjust the response of a droop-controlled inverter. In droop designs, careful trade-offs must be made between harmonics and speed while ensuring stability. Of the three grid-forming methods considered here, droop control is the most mature and has been validated in multi-inverter setups and in mixed inverter-machine systems (Lasseter et al. 2011). Droop-controlled inverters have also been tested in commercially operated demonstrations (Alegria et al. 2014). Note that additional variants exist for enhanced speed and robustness (Zhong 2013) as well as various types of P and Q versus V and omega trade-off relations (e.g., P-V, Q-omega droop).

In a virtual synchronous machine, the underlying machine model parameters dictate its dynamic response. In particular, the damping, inertia, and flux-linkage parameters are virtual and can be tuned (Beck and Hesse 2007; Alatrash et al. 2012; Zhong 2016). Although the response of a virtual synchronous machine is similar to that of an actual machine, its time constants can be compressed. Virtual synchronous machines were proposed in the mid-2000s (Beck and Hesse 2007) and have been validated in several multi-inverter experiments. Recent improvements include virtual elements to prevent instabilities (Natarajan and Weiss 2017), additional loops for faster response (Dong and Chen 2017), and designs that give bounds for frequency and terminal voltages (Zhong et al. 2017). If we restrict our focus to only virtual inertia methods that emulate rotational dynamics, the number of parameters is reduced to the mass and damping factors, and the design is considerably simpler. Virtual inertia methods are starting to reach early-stage industrial trials (Rahmani et al. 2017).

Because virtual oscillator methods are based on the emulation of nonlinear circuits, the response of these methods is tuned by the selection of the virtual circuit parameters, such as inductance, capacitance, and scaling gains. The virtual oscillator is relatively simple, and its parameters can be unambiguously computed from a set of AC system performance specifications, such as droop slopes, response time, and inverter rating. This control method is relatively new and first appeared in 2013 (Dhople, Johnson, and Hamadeh 2013). Although original incarnations lacked inputs for set points and a trade-off between speed and harmonics, recent advancements include set-point integration and a harmonic-free oscillation (Colombino, Groß, and Dörfler 2017; Seo et al. 2018). To date, virtual oscillators have been evaluated in multi-inverter hardware experiments

²² Future 100% power electronics-based grids might be hybrid AC-to-DC systems and/or operate at varied frequencies. If so, a method of tracking set points under variable frequencies will need to be developed.

(Johnson et al. 2014) and on commercial hardware (Lu et al. 2018), but mixed machine-inverter experiments are still needed.

Although grid-following inverters depend on a well-defined frequency and voltage on a system, they can be programmed to mitigate their contribution to frequency swings. This takes the form of a grid-support function called frequency-watt control. Noting that frequency-watt methods are an extension of established grid-following methods in industry, they have been used in several grids, such as Hawaii's (Johnson et al. 2016b). This function, which mimics the P-omega droop law, has been compared directly to grid-forming droop control via simulation studies (El Khatib, Wei, and Lasseter 2018).

3.1.4 Research Questions

In the following discussion, we provide a summary of open research topics that warrant further investigation based on assuming the eventual deployment of thousands of grid-forming inverters at subtransmission or distribution voltages with automatic frequency and voltage control to replace the loss of synchronous generation inertia. We begin by summarizing some issues that are particular to grid-forming techniques:

- Should grid-forming control actions be partitioned according to timescales, and if so, how?
- Given the second-to-second level potential rate of change of frequency, can we assume autonomous (communications-less) primary frequency response is required? Is this feasible with grid-forming control?
- For secondary and tertiary frequency control, what signals, if any, must be communicated between distribution-level inverters and system operators such that frequency regulation is achieved? What kind of communications infrastructure does this imply (distributed peer-to-peer, aggregators, centralized, bandwidth, and latency)?
- What system operational and dynamic ramifications of grid-forming sources with reserve (standby) energy can be provided for the loss of synchronous generation inertia?
- Grid-forming sources fundamentally provide fast frequency control provided they have the necessary reserves. What reserve requirements keep frequency within acceptable bounds? Does locating grid-forming resources within the distribution or subtransmission system impact this ability to control frequency?
- Can frequency regulation bands be loosened in a strong grid dominated by grid-forming inverters? What are the desired modal damping characteristics of strong and likewise weak grids? As the relative inverter-to-machines proportion changes (instantaneous and throughout time), are passive or active regulation bands desired?

Next, we consider issues related to system heterogeneity and frequency regulation:

- What shares of rotating generators and grid-following and grid-forming inverters can guarantee power system stability?
- Can heterogeneous systems containing grid-following inverters, grid-forming inverters, and machines operate together to guarantee frequency regulation and stability?
- How important is frequency regulation in a system dominated by power electronics?
- To what extent can “must-run” synchronous generators be reduced and replaced by grid-forming inverter-based generation with enhanced functionalities? Could synchronous condensers be replaced as well? For both, is there a limit?

- What is the target scenario for frequency regulation in future interconnected power systems with very high shares of grid-forming inverter-coupled generation? What types of experiments are needed to characterize hybrid systems with grid-following inverters, grid-forming inverters, and synchronous machines?

Active power control of inverter-based renewable generation is technically feasible, but such plants will require sacrificing some energy production by operating below the maximum power point to provide the necessary reserves (Hoke et al. 2017). It is necessary to investigate, develop, and validate ways that inverter-based generation, with and without storage, can support grid frequency control. Last, we look at operational impacts for renewable generation resources:

- What are the fundamental issues related to renewable grid-forming inverters providing frequency control?
- What control and operational requirements enable renewable grid-forming inverters to replace the loss of inertia for frequency control?
- What are the impacts of different levels of PV headroom (0% to 30%) on frequencies during large events, including frequency load shedding? How do these studies include distributed PV?

3.2 Voltage Control

Voltage control refers to generation control actions to increase or decrease real and/or reactive power production and network switching operations (either dynamic or static) required to maintain power system voltages within an acceptable range. The control requirements for these actions depend on the topology of the transmission or distribution system, the electrical distance between loads and generation, and the loading on the transmission or distribution system. Voltage control must be exercised through actions that are local to the voltage issues they seek to manage. Generally, voltage control via real power is not preferred given enhanced voltage sensitivity to reactive power control, and moreover generator revenue is mostly, if not entirely, via real power production. Voltage control is the measured change in voltage magnitude between the sending and receiving end of a grid component, such as a transmission or distribution line. Voltage regulation describes the ability of a system to provide near constant voltage over a wide range of variable load and generation conditions. Passive voltage drop takes place under various load conditions. Grid cables and conductors intrinsically have some amount of resistance, inductance, and capacitance that all change the voltage continuously along the line. Both the magnitude and phase angle of voltage change along the line. Active voltage intervention (increasing or reducing voltage to preferred operational limits) might use electromechanical or electronic components, from generators to other devices, specifically for voltage control. Such devices include load tap changers, voltage regulators, capacitor banks, synchronous condensers, and others, along with early-stage commercialization of solid-state technology (power electronics).

For synchronous generators, their automatic voltage regulator adjusts operation voltage output either by adjusting power output via the main field or real and reactive power output by modulating the exciter field (electromagnetic flux) via controlling the exciter field current. Voltage control coordination among synchronous generators is via their Q-V droop control, expressed as a linear relationship between reactive power and voltage.

Grid-forming inverters natively provide voltage regulation via their Q-V droop laws. Mirroring terminology from frequency control, this is generally called primary voltage control to emphasize that these control actions are done locally. All grid-forming controllers considered here except virtual inertia have a linear trade-off between steady-state voltage and reactive power, which is often called volt-volt ampere reactive (VAR) control. This closely matches the behavior of synchronous machines, which also have such functions in their voltage control loop. Thus, grid-forming inverters can be especially helpful in providing voltage support in weak grids (IEEE/NERC 2018; NERC 2019). In general, Q-V droop enables multiple generation units to be connected in parallel, limits voltage deviations on a system, and mitigates reactive power flows between units.

Recent advances in voltage control for inverter systems are mostly concentrated in microgrid systems with droop control (Lasseter and Piagi 2004) and/or off-grid applications. With respect to primary-level volt-VAR control, virtual impedances have been used to assist with reactive power sharing and to mitigate parameter sensitivity (Erickson, Jahns, and Lasseter 2012; Guerrero 2011; Mahmood, Michaelson, and Jiang 2015). To further enhance reactive power sharing and reduce steady-state errors, communications-based secondary-level controllers have been proposed (Simpson-Porco et al. 2015; Guerrero et al. 2011). To assist with scalability, distributed implementations with reduced numbers of communications links have been formulated. But because inverters would be much more numerous and geographically dispersed on bulk grids, it might be difficult to apply these approaches, which are tailored for microgrids. Typical grid-forming inverters do not provide high levels of fault current that typically stabilize voltage during transient events.

As summarized in Figure 2, the timescales associated with machine voltage exciters and inverter control loops overlap. Recent findings have uncovered adverse interactions between grid-forming inverters and synchronous machine excitation systems that regulate voltages (Khan et al. 2018a), and similar issues have been observed on grid-following control types (Lin et al. 2017). These interactions can destabilize hybrid systems and appear to be common to both grid-following and grid-forming inverter controls. Such phenomena were uncovered recently and form the basis of ongoing and active research.

In recent years, grid-following inverters have also been updated with volt-VAR controls. Just as frequency-watt functionality is a modification of the typical grid-following controller, volt-VAR is a functionality layered on top of the baseline grid-following control loops. In contrast to machinery and grid-forming inverters, which exhibit linear volt-VAR trade-offs, a recent trend is to program piecewise linear volt-VAR relationships on grid-following inverters (IEEE 2018a). To prevent any interactions between volt-VAR controls and the baseline grid-following loops, time delays and filters are often used to segregate volt-VAR control action and artificially throttle its speed; however, such approaches are known to introduce undesired voltage oscillations and interactions between grid-following inverters (Chakraborty, Hoke, and Lundstrom 2015) and voltage-regulation equipment on the same distribution network (Zhou and Bialek 2007). Recent findings indicate that the coexistence of control delays and piecewise volt-VAR relationships might be responsible for such behavior (Farivar, Chen, and Low 2013; Zhu and Liu 2016).

3.2.1 Research Questions

Following is a summary of relevant technical challenges for voltage regulation:

- Investigate the impact on voltage control resulting from the loss of reactive power generation in the bulk system as synchronous generators are replaced by thousands of grid-forming and grid-following inverters across the transmission, subtransmission, and distribution networks. This results in moving the control of reactive power and voltage from the bulk system to an array of distributed inverters with local voltage/VAR control. How do thousands of grid-forming and grid-following inverters at medium voltages and lower affect system voltage stability and control? How do these voltage regulation schemes coordinate with other devices, such as capacitor banks, static VAR compensators, synchronous condensers, and other voltage support devices? With competing volt-VAR support from different devices, how are trade-offs identified and optimization addressed?
- What stability/interaction issues might arise between grid-forming inverters?
- What are the interactions between machine excitation systems and inverters with either grid-forming or grid-following controls? Can inverter and machine-side controls be tuned to eliminate such interactions? Should grid-forming inverters be supplemented with oscillation-damping functions that mimic classic power system stabilizers?
- How should we characterize the input and output impedance of grid-forming inverters across a wide frequency spectrum to illuminate the dynamic properties of inverters?
- What are the requirements concerning the geographic distribution of generation and control capabilities? How do grid-following and grid-forming inverters control voltage and reactive power?
- Does reactive power control impact system voltage stability? Are there limits to the mix of rotating generators and grid-following and grid-forming inverters to ensure robust voltage control with minimum circulating VAR?
- How should VAR flow be controlled—at each inverter, at locally aggregated inverters, or through coupled communications networks?
- For distribution connected inverters, how will their voltage support be coordinated with transmission voltage regulation, especially when transmission and distribution might have conflicting control requests? Piecewise linear volt-VAR control for distributed energy resources have inherent instability points. How are these avoided?
- Can grid-following inverters with volt-VAR grid support be operated in tandem with grid-forming inverters?

3.3 System Protection

Protection of the electric grid is a branch of power systems engineering that involves the detection of abnormal grid operating conditions, such as low or high impedance faults, and the mitigation of deleterious effects of those abnormal conditions, such as disconnection of faulted parts of the network. Power system protection is concerned with ensuring the stability of the power system while minimizing how much of the network is disconnected. The overall goal is to minimize the geographic and temporal extent of network outages caused by abnormal conditions through the operation and coordination of protection devices in different areas of the grid. With inverter-based resources replacing synchronous generators, transmission-level protection is evolving. Priority focus today is on identifying weak grids (low short-circuit currents) and continuing to develop improved protection and relaying (IEEE/NERC 2018). Beyond inherently

improving protection for weak grids, this is also associated with inverter-based resources having different magnitude and phase characteristics than synchronous generators. Various adaptive protection schemes have been proposed, and some are being tested in limited field trials. With more extensive inverter-based resources and especially distributed generation, today's protection will need to move away from basic, static schemes to more adaptive, situationally aware protection schemes.

Because of the historical prevalence of synchronous generation on the bulk grid, distribution power system protection has been optimized for radial systems. The recent increased penetration of distributed grid-following resources has produced many technical challenges regarding classic distribution protection, with bidirectional power flow as one example. These challenges come from the nature of incorporating distributed energy resources on the distribution system as well as the dynamics of grid-following controls compared to traditional synchronous machines.

Although the effect of grid-following controls on the incumbent protection system has been studied for a number of protection mechanisms (Martinez et al. 2011; Walling, Gursoy, and English 2012; IEEE PES 2013; Farantatos et al. 2013; Fischer and Mendonca 2012; Howard 2013; Howard, Liang, and Harley 2014; Karaagac et al. 2015; Kocar et al. 2014; Kauffmann et al. 2015), and it has been determined that high penetrations of renewable generation result in potential incorrect operation of traditional protection mechanisms (EPRI 2014; EPRI 2017a; EPRI 2017b; EPRI 2017c; Seguin et al. 2016), the effect of grid-forming inverters on protection is fundamentally different than that of grid-following inverters and has not been extensively studied. The short-circuit currents from grid-forming inverters can be equivalent to synchronous generation but are normally constrained to 4–6 p.u. for short time periods (<10 cycles) before steady-state limits (<2 p.u.) are imposed using secondary current or voltage loops (Lasseter et al. 2011). Brief time period short-circuit response (<10 cycles) is typically limited by semiconductor ratings, whereas steady-state short-circuit response is limited by several inverter hardware parameters (e.g., copper conductor sizes, thermal management system). It is an open question whether the displacement of traditional synchronous machines or grid-following inverters with grid-forming inverters will further exacerbate or alleviate the incorrect operation of protection mechanisms (NERC 2018c). Adaptive protection is suggested as a solution for such hybrid grids, and because of the lack of studies on the issue, we can only speculate on the effects of grid-forming inverters on incumbent protection schemes.

For inverter-based resource implementation to enhance—or at least not hinder—current power system protection schemes, it will be necessary to coordinate the controls of grid-forming inverters with the 81 protection functions currently defined by the relevant protection standard, IEEE C37.2 (IEEE 2008). Although synchronous generation has well-defined and predictable currents and voltages during transient events (or well-understood models/experimental testing) that allow for protection engineers to ensure subtransient and transient reactance are within system specifications, no well-defined set of models and tests are provided from inverter manufacturers. Additionally, inverter behavior is dominated by firmware, which can change significantly throughout the operational lifetime of inverters, altering the faulted current characteristics and invalidating protection system designs. Detailed analytic modeling and simulation efforts, similar to those already underway for grid-following controls, are needed to examine the effects of grid-forming implementations on power system protection and provide a consistent framework for protection design for inverter installations. Without such a framework,

protection engineering must carry out extensive studies on inverter behavior or extensive redesign of the protection system, which increases the risk, complexity, and cost of inverter installations.

3.3.1 Transition to Distribution Bidirectional Power Flow

Historically, the grid has been segmented between transmission, which contains the bulk generation sources, and distribution, which contains loads. Incorporating additional distributed generation sources at the distribution level changes the system paradigm from having unidirectional power flow to having branches that experience bidirectional currents because of the presence of local sources on the distribution network. If this backflow is in the opposite direction of the fault current (and thus decreases the effective net current flow), then the efficacy of traditional protection mechanisms is reduced. This backflow power is particularly challenging in the case of variable generation sources because changes in current level detected might be a result of a fault, change in load, or a change in generation. This variation in current might cause nuisance tripping, fail to trip, underreach/overreach problems, loss of coordination, auto-reclosing problems, and more.

The bidirectional power flow problem is further exacerbated by the inability of grid-following controls to produce high fault currents (Fu et al. 2015). Traditional synchronous machines can produce fault currents of 10 p.u. (Altuve Ferrer and Schweitzer 2010). This large fault current allows enough margin for protection devices to actuate in the presence of a fault while eliminating unwanted tripping events. Conversely, traditional grid-following controls typically provide 2 p.u. or less of fault current in steady state, which is limited by the grid-following control scheme (Alvidrez et al. 2016) and inverter hardware engineering (e.g., copper conductors, switches, thermal management system). This relative lack of fault current makes the detection and mitigation of fault events more challenging and more susceptible to unwanted tripping events, especially when backflow power is considered.

The displacement of grid-following controls with grid-forming inverters will not necessarily mitigate this bidirectional power flow problem. In theory, however, the fault current for grid-forming inverters, though dominated in the steady state by the control scheme, will have a subtransient behavior that more closely mimics synchronous machines and is significantly larger than that supplied by grid-following controls. This larger short-circuit subtransient response will be limited primarily by the short-circuit response of componentry in the grid-forming inverters, which is directly related to its internal impedance. Grid-forming inverters will have an intrinsically faster response to faults (i.e., current output increase) than grid-following inverters because they do not use a fast inner current-control loop. Additionally, the use of robust semiconductor devices with longer short-circuit times would allow for grid-forming inverters to source greater short-circuit currents for longer periods, which would yield an increase in the efficacy of traditional protection mechanisms than the pure grid-following case, although at a subsequent increase in inverter hardware costs.

The short-circuit response of grid-forming inverters is an open question, and significant research is needed to characterize the short-circuit response of grid-forming inverters to many different abnormal grid operations (IEEE/NERC 2018). The short-circuit response should be well characterized and, if possible, increased using either software or hardware to approach the values provided by synchronous machines (Hartono and Setiabudy 2013).

One protection issue unique to grid-forming inverters is operation in islanded/microgrid mode when a portion of the power system is disconnected from the bulk grid. Traditional grid-following controls will automatically shut off without the presence of an external grid signal voltage, but grid-forming inverters can continue to operate islanded from the area grid (in many cases, such resilient microgrid operation is a primary benefit to grid-forming inverters). To protect utility workers and other bystanders, some form of islanding protection will be needed for grid-forming inverters to safely operate in islanded mode while ensuring the safety of electrical personnel and other bystanders. This must be balanced by the need for system resilience because islanded operation is a key benefit of grid-forming inverters as a response to widespread catastrophic events. A robust set of standards is necessary to balance autonomous grid-forming operation in grid-connected mode during islanded/microgrid operation as well as during line maintenance by electrical personnel.

3.3.2 Negative-Sequence Fault Current

One method protection devices use to detect unbalanced fault conditions is to monitor negative-sequence fault currents. Synchronous machines will generate significant negative- and zero-sequence currents during a fault condition that can be used to identify abnormal grid operation. Traditional three-phase grid-following controls will not provide zero- or negative-sequence currents, which can be used to more easily identify the presence of unbalanced fault conditions; grid-following controls are designed to suppress negative-sequence current partially or entirely (Teodorescu, Liserre, and Rodriguez 2011; Erlich et al. 2013; IEEE/NERC 2018). European grid codes have recently been updated to add negative-sequence current injection performance requirements from inverter-based resources. Theoretically, grid-forming inverters should be able to reproduce the effects of synchronous machines in a fault condition, including sourcing zero- and negative-currents; however, no commercially available three-phase grid-forming inverters independently balance phases by providing zero- and negative-sequence currents (both as a result of the current dq control paradigm as well as the tendency of commercial inverters to come in three-wire, instead of four-wire, configurations as a cost-saving measure), so it is unknown if they can source these currents during fault conditions. The ability of current grid-forming inverters to produce zero- and negative-sequence current must be analyzed. Future grid-forming control schemes should allow for the sourcing of zero- and negative-sequence currents. This would yield an increase in the efficacy of traditional protection mechanisms compared to the pure grid-following control case and would significantly simplify the identification of unbalanced faults.

3.3.3 Out-of-Step and Power Swing Blocking Protection

At the transmission level, traditional grid-following controls introduce problems with synchronization, resulting in out-of-step protection tripping and power swing blocking. A power swing is the variation of power flows caused by changes in system state, such as load changes, line switching, and generator disconnect (NERC 2013; Gers and Ariza 2008). During these events, impedance line protection equipment differentiates between a fault and a power swing. If the protection equipment determines that the change in voltage/current is the result of a power swing and not a fault, it blocks protection relays from tripping. Similar to power swing blocking, out-of-step protection tripping is meant to differentiate between a normal power swing and one that is large enough to result in system instability.

Both these protection methods operate based on the rate of change of the voltage/current signal wave because power swing deviation is dominated by synchronous machine inertia and thus has a smaller rate of change than a fault. Because grid-following controls do not have any inherent rotational inertia, systems with high penetrations of grid-following inverters exhibit significant deviations in power swings and out-of-step protection-tripping characteristics from synchronous generation (EPRI 2017b; EPRI 2017c), which might interrupt normal power swing detection and cause unwanted tripping events.

Incorporating grid-forming inverters should significantly mitigate both out-of-step protection tripping and power swing blocking protection concerns. Although they do not have traditional inertia, their response time is fast enough to stabilize power swings, and as long as sufficient headroom exists on the grid-forming generation source, they can simulate the dynamics of synchronous machine inertia. It has been shown that grid-forming-based systems can respond more quickly than inertia-based synchronous machines.

Incorporating high penetration levels of grid-following controls has produced many challenges for traditional protection devices at both the distribution and transmission levels. As this trend accelerates, incorrect operation of protection devices and increases in unwanted tripping events is likely. Grid-forming inverters might significantly alleviate many of these problems because they are capable of more accurately mimicking the inertial response of synchronous machines, on which traditional protection is based; however, the detailed effects of grid-forming inverters on protection devices are relatively unknown, and no detailed studies have yet been conducted on the issue. Therefore, an open question is whether the displacement of traditional synchronous machines with grid-forming inverters or grid-following controls with grid-forming inverters will further exacerbate or alleviate these issues. More research is needed regarding the interaction of grid-forming-based systems with traditional protection mechanisms at both the transmission and distribution levels as grid-forming inverters displace synchronous generation as well as grid-following controls.

Incorrect operation of conventional protection schemes is the most significant immediate barrier to incorporating grid-forming controls into the power system. A detailed understanding of grid-forming interaction with protection is necessary for system planners and designers to incorporate grid-forming controls as a fundamental part of their systems. A robust standards ecosystem that can mandate the consistent behavior of grid-forming inverters from different manufacturers to the same contingency scenarios is most likely needed to improve the protection of grids with grid-forming assets. We must explore whether today's protection schemes are appropriate and effective long-term solutions for a grid with a significant proportion of generation produced by grid-forming and grid-following inverters or whether a new protection paradigm is needed. Significant open research topics regarding the effect of grid-forming inverters on protection schemes include:

- What is the short-circuit response of grid-forming inverters? What is the effect of their control schemes?
- Do grid-forming inverters have the ability to produce zero- and negative-sequence fault current under unbalanced fault events?
- What is the effect of the grid-forming dynamic response on out-of-step protection tripping and power swing blocking protection at the transmission level?

- What analytic and simulation models are needed for grid-forming inverters under fault scenarios that will aid protection engineers in conducting accurate short-circuit studies?

3.4 Fault Ride-Through Capability and Power System Voltage Recovery

Severe disturbances, such as transmission faults or tripping of relatively large generators, can cause deleterious electromagnetic transients that can propagate throughout a large geographic area and trigger system-level problems—a cascading event, for example. To ensure that a power system reaches a desirable operational equilibrium after being perturbed, generators must remain connected and support the grid. The ability of inverter-based generation to remain connected while withstanding abnormal transients at its terminals is referred to as voltage ride-through, disturbance ride-through, or FRT capability (Fairley 2003).

In addition to riding through a fault, power inverters must be capable of supporting the restoration of a power system to normal operating conditions in terms of voltage magnitude and angular speed. This task might be particularly challenging for inverters with grid-following controls because they rely on externally generated voltage sources. On the other hand, inverters with grid-forming controls could be more supportive of the grid because they are able to autonomously generate voltages cycling at a synchronous speed. In general, operating a grid with high penetrations of inverter-based generation is challenging because their power electronics cannot handle momentarily overrated currents as well as synchronous machines can (Kroposki et al. 2017). In the following discussion, we highlight a set of potential research areas pertaining to inverters with grid-forming controls to ensure that they are capable of riding through faults and supporting the grid.

Modern grid codes mandate that inverter-based generation sources not disconnect as long as their voltage magnitudes remain within a prescribed class to regain stable grid operation (NERC 2016; NERC 2018c; Dallachy and Tait 2002; IEEE 2008). Also, some codes stipulate that inverters might be required by transmission operators to inject currents to support the operation of protection systems as well as the recovery of grid voltages during and after faults (Federal Energy Regulatory Commission [FERC] 2005). Notably, modern codes are invariant with respect to the type of the primary energy source, power inverter topology, and controls—see, e.g., FERC (2016) and NERC (2018c)—although FRT standards were first developed in response to the integration of wind energy resources (Tsili and Papathanassiou 2009).

Standard PRC-024-2 (being updated by NERC for precision), for example, specifies a set of fundamental frequency voltage magnitudes that all generation must withstand during severe disturbances, as shown in Figure 6(a) (NERC 2016). Specifically, this set is defined by “high” and “low” time-duration bounds that enclose a “no-trip zone” of normalized voltage magnitudes.²³ The voltages are considered to be measured at the point of interconnection of an inverter-based power plant with the bulk power system. The envelope is constructed from simulated voltage magnitude profiles that consider Zone 1 three-phase transmission system faults

²³ Time-duration curves specify the cumulative uninterrupted time that voltage magnitudes remain within a particular point of interconnection voltage interval.

that can be cleared in no more than nine cycles.²⁴ Recently, NERC issued a new recommendation to relax the high time-duration bound of PRC-024-2, as depicted in Figure 6(b) (NERC 2018c), which relaxes the high-voltage bounds for short-lived overvoltages. This update is motivated by the disconnection of PV power plants and the relatively recent publication of IEEE 1547-2018. The purpose is to ensure that inverter-based generation will also ride through subcycle overvoltage transients that are not included in PRC-024-2 as derived from fundamental frequency studies (Wind Generation Task Force 2007; NERC 2016).

The PRC-024-2 standard also includes a frequency capability envelope, as shown in Figure 7. This is of special interest for generation technologies that have rotating mechanical components. In inverter-based generation applications, frequency might not be a suitable metric to command inverters to trip if inverter voltages and currents remain within operational limits. This fact is recognized in the NERC Inverter-Based Resource Performance Task Force guidelines (NERC 2018c).

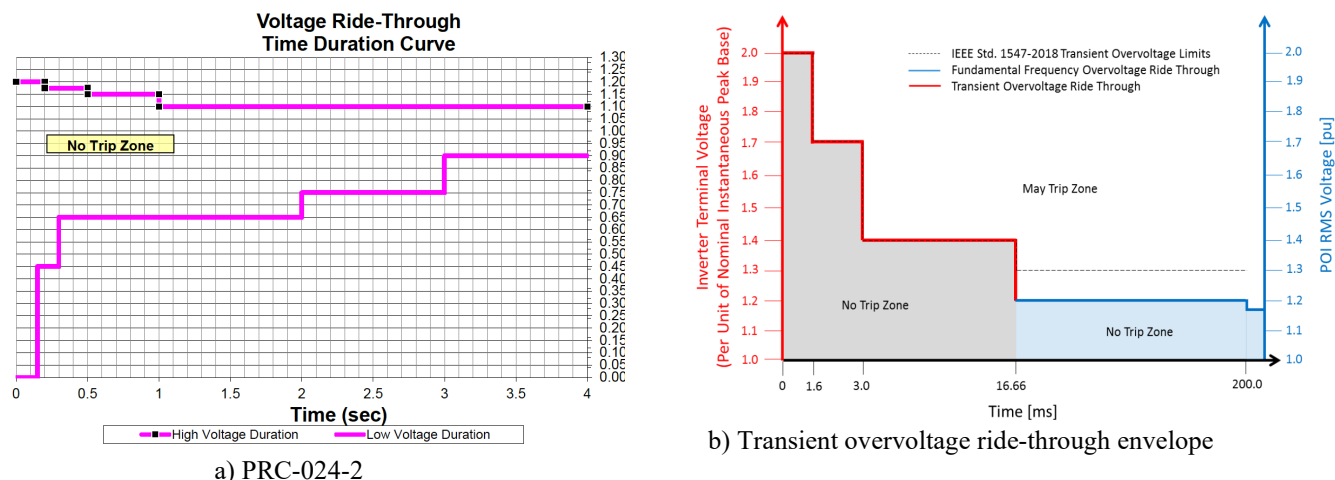


Figure 6. FRT envelopes (NERC 2016)

²⁴ Zone 1 relays protect lines from faults occurring within 0% and 90%, for example, of the total length of the monitored line.

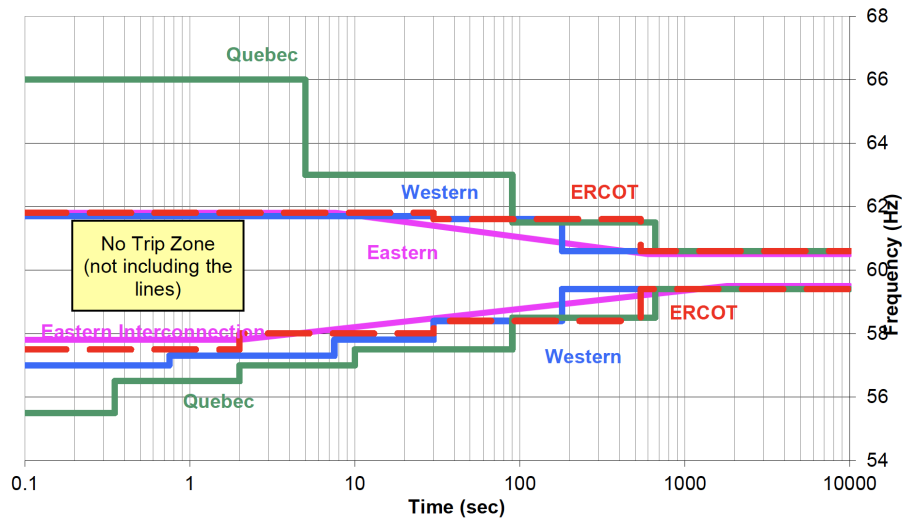


Figure 7. Off-nominal frequency capability envelope (NERC 2016)

As noted, standards for inverter-based generation are based on deterministic simulations of current power systems, which are dominated by synchronous machinery. Specifically, the impact of several severe disturbances—a transmission fault, for example—is simulated to elucidate an envelope of operating conditions under which generation should remain connected. Note that in these simulations, the recovery of power system voltages after disturbances is established by regulated synchronous machine action, flexible AC transmission systems, and the response from loads, to name a few mechanisms. Nonetheless, if a significant number of inverter-based generation displaces synchronous machinery, such voltage recovery ability might be greatly constrained. In contrast to synchronous generators that can supply relatively large off-nominal currents for short periods of time, power inverters have hard current limits that could greatly restrict the current dynamic voltage recovery capability of future power grids. In fact, studies to derive modern voltage ride-through grid codes might no longer apply because they were derived from the observations of conventional power system behavior. For example, inverter-based generation might be limited to support the voltage recovery of grids with high penetrations of motor loads, which might slow down the voltage recovery because of high inrush current (Sun et al. 2019). Hence, inverter-based generation with grid-forming control might need to operate under low-voltage/high-current conditions for longer times than they do today, which leads to the following questions:

- Will modern FRT grid codes apply to power systems with high penetrations of inverter-based generation with grid-forming controls?
- Will FRT codes need to evolve to cover bulk power systems with high penetrations of inverter-based resources considering different fundamental behavior?
- What voltage regulation capability will inverters with grid-forming controls need to provide to recover grid voltages after faults?

In the context of inverter-based generation with grid-forming controls, an additional technical challenge is to ensure that these assets will be capable of satisfying future FRT grid codes (in any form provided). To this end, it would be useful to simulate and test inverters and their controls under extreme physical operating scenarios. This task requires a set of voltage disturbances that

could make grid-forming controls fail. Generating this signal requires appropriate mathematical tools. The objective would be to develop robust grid-forming control strategies that can respond to all possible disturbances specified by FRT codes. A potential approach to solving this problem is the application of reachability analysis. This scientific tool is instrumental for ascertaining the dynamic performance of inverter-based generation driven by unknown-but-bounded disturbances (Villegas Pico and Aliprantis 2014; Villegas Pico and Aliprantis 2016). It is also useful to elucidate deleterious disturbance trajectories—terminal voltages, for example—that might drive a dynamic system such as inverter-based generation to surpass its limits (Villegas Pico and Aliprantis 2018).

Addressing this challenge could be critical to answering the following questions:

- What analysis tools are necessary to model the behavior of inverter-based systems with grid-forming controls in the context of FRT code compliance?
- What set of voltage disturbance trajectories within the no-trip zone of FRT codes could lead to the disconnection of a grid-forming control strategy?

In addition, coordination between the inverter controller and protection devices is very important. PRC-024-02 and similar codes are commonly used to set up automated disconnection schemes in protective relays. Unpredicted inverter controller behavior might cause problems for the schemes, which lead to the following research questions:

- How should FRT codes be coordinated with the operation of protective relays?
- Are the assumed communications-less schemes sufficiently robust for a primary response time period (e.g., <30 seconds)? Do communications and the integration of inverter control and protection technology help solve the problem?

3.5 Modeling and Simulation Approaches

The traditional grid dominance of synchronous machinery has shaped today's state-of-the-art grid analysis tools and their transient response performance. A common assumption applied to a wide range of modern simulation tools is that a power system has a hypothetical synchronous speed reference—i.e., center-of-inertia speed—that remains relatively close to nominal (e.g., rad/s) during and after a transient. Consequently, the power transmission network has been classically represented by an abstract algebraic system in which electrical variables are sinusoids cycling at this reference speed (hence, captured as phasors) (Sauer and Pai 1998; Guttromson 2002). This consideration is advantageous because simulations of bulk power systems with synchronous machines can be conducted efficiently in terms of computational performance. Such an assumption is justifiable in classic systems because synchronous machinery with relatively large rotor inertia constants can maintain close to nominal rotor speed during and after faults. Software that rely on this rationale include PSLF and PSS/E. This assumption is sometimes applied to electromagnetic transient simulation tools as well because voltages and currents within transmission lines can be considered sinusoidal functions of constant frequency (Sauer and Pai 1998). Available electromagnetic transient simulation programs to study bulk power systems include PSCAD, CYME, and MATLAB/SIMULINK + SimPower.

Increased inverter-based generation might invalidate the constant frequency assumption because of the lack of rotating inertia. Specifically, the cycling speed of generated voltages by inverters

with controls such as droop and virtual oscillator control might change abruptly during faults. This can occur because the cycling speed of these controllers depends on the instantaneous power/current that is delivered by the power inverters. For example, AC power provided by an inverter could be as low as zero during faults, which causes the cycling speed to significantly deviate from nominal because of droop laws. Hence, such an operating scenario could challenge the underlying assumptions that underpin positive-sequence simulations, which are widely used today (Miller et al. 2003; Clark, Walling, and Miller 2011; Kosterev et al. 2008). To be able to capture the fast inverter dynamics during transients, electromagnetic transient simulation might be needed. Presently, some independent system operators and developers are using electromagnetic transient simulations to study small systems with high instantaneous levels of inverter generation.

Because of the high computational burden of large-scale electromagnetic transient simulations, synchronous model and positive-sequence simulations will remain the main tool for bulk power system studies in the near future. Thus, there is an important need for appropriate inverter-based generation models for existing positive-sequence simulation tools. Currently, such models are usually highly simplified and often are not able to accurately capture the behavior of the system. Recently, the importance of improving the grid-following model to capture this behavior has been recognized (Ramasubramanian et al. 2017). Similarly, this is an important issue for grid-forming inverters. Because grid-forming controls are still in the early stage, this is an open research question that needs to be addressed.

An additional problem when simulating inverter-based generation in power system simulations is that the characteristics of primary energy sources, such as wind turbines and PV arrays, are typically omitted. Incorporating these energy sources is important in a simulation because they are useful to determining whether generation will be able to meet demand after a large transient. Presently, positive-sequence models such as the DER_A neglect primary energy sources (Pourbeik 2017); therefore, an analyst will be unaware of whether there will be dynamic load-generation balancing problems after a large transient.

Another challenge in modeling inverter-based generation is that compared to synchronous machines, many types of inverter-based generation are small, large in numbers, and connected to the grid at the distribution level. How to best represent many heterogeneous inverter-based generation in bulk power system simulations is an open research question (Clark, Walling, and Miller 2011). One way to bridge this gap is to start with a small unit and design a scaling law to model a collection of units (Khan et al. 2018a; Khan et al. 2018b; Lin et al. 2017; Purba et al. 2018). Another approach is to use system identification methods to develop gray-box models directly at the feeder-head level.

This analysis leads to the following research questions:

- What is the appropriate inverter-based generations model for existing positive-sequence simulation tools?
- What are the limitations of positive-sequence simulations to study the FRT of grids dominated by inverter-based generation during large transients?
- Are the transmission model assumptions valid for studying small and large transients for systems with high penetration levels of inverter-based generation?

- What modeling fidelity of the transmission system and inverter-based generation is necessary/appropriate for a comprehensive study on electric grids undertaking large transients?
- How can the speed of computation of electromagnetic transient simulation software be increased to conduct very large power system simulations with high penetrations of inverter-based generation?
- If aggregation is deemed necessary to increase the speed of computations, especially for characterizing significant distribution-connected grid-following and/or grid-forming inverters, what is the reliable aggregation approach to capture key behaviors?
- Is considering generation capacity variation and dynamics of the primary energy sources critical for transient studies?
- How are the models and simulations validated? Have the simulations covered all the possible contingency scenarios, especially for growth of grid-following inverter-based resources, changing load minimum/maximum/variability conditions, or interaction with other legacy grid devices?
- Is a field trial required and feasible for model validation?
- Is there sufficient industry availability and access to test data sets and public network models?

An additional problem pertaining to the integration of inverter-based generation is that the primary energy sources are variable and thus uncertain. This implies that a framework is needed to assess uncertain dynamic simulations. This signifies that power system tools will be required to solve ordinary differential equations and/or algebraic differential equations with uncertain initial conditions and inputs. If uncertainties are not considered in simulations, deterministic simulations might be unable to predict adverse dynamic behavior introduced by variable initial conditions and inputs. At the present time, a variety of tools have been proposed that are capable of handling uncertainties pertaining to fault clearing time (Sharma et al. 2018) and initial conditions, such as trajectory sensitivity (Hiskens and Pai 2000), probabilistic collocation (Hockenberry and Lesieutre 2004), semidefinite programming (Choi, Seiler, and Dhople 2017), Lyapunov function families (Vu and Turitsyn 2016), and Taylor polynomials (Villegas Pico, Aliprantis, and Lin 2017). A common problem with these tools is the curse of dimensionality, which could be addressed by proper computational algorithms. The iTesla project also led an effort in developing a toolbox for simulating uncertain power systems (iTesla 2016). These considerations raise the following questions:

- What is an appropriate tool to handle uncertainties in inverter-based systems driven by grid-forming controls?
- How should we deal with the computational performance within the tool?

4 Roadmap for the Development and Deployment of Grid-Forming Inverters

Section 3 reviewed the present state of research on power system stability, protection, and modeling/simulation for grid-forming inverters. It outlined a wide range of open research questions that must be addressed. This section integrates and recasts these research questions in the form of a roadmap that discusses near- and long-term research priorities.

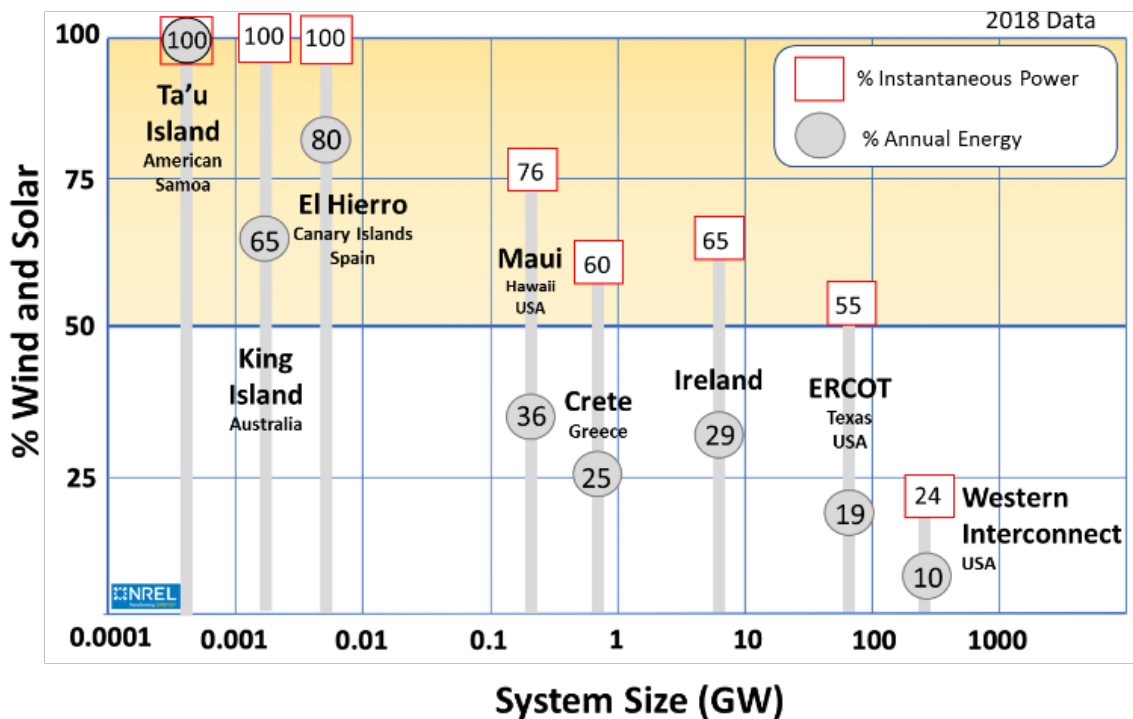
In the near term, significant additional research, development, and field trials of grid-forming inverters are needed to build on and expand early, promising research findings on the opportunities for increased grid control with inverter-based forms of generation and storage (NERC 2018c). In the midterm, priorities will begin to shift (and in some instances have already shifted) to focus on the opportunities for grid-forming inverters to contribute materially to the performance of specific types of grids whose performance cannot be improved through other, less expensive means (such as weak grids with low short-circuit strength). Through these early-stage deployments, consensus will begin to emerge around the best ways to use grid-forming inverters to improve grid operations and deployments will begin to standardize. At this stage, experimentation and one-off deployments will transition to an accepted set of standard design practices and with supporting tools that will enable widespread deployment. See Figure 8.



Figure 8. Key steps for maturing grid-forming inverter technologies

As shown in Figure 9, some small island systems are already operating at or near 100% wind and solar, which include basic grid-forming controls supported by energy storage. The Maui, Hawaii, system now includes both transmission and distribution assets, and it is large enough to warrant formal coordination by the utility of the operation of utility-owned generation plants with a high penetration of residential rooftop solar. Scaling from smaller systems such as these to more complex grids will require a maturing of grid-forming inverter controls and power system stability design and operations experience.

Wind and Solar in Synchronous AC Power Systems as a Percent of Instantaneous Power and Annual Energy



Source: Kroposki 2019

Figure 9. Total annual and instantaneous inverter-based wind and solar generation based on power system size

This roadmap attempts to anticipate the transitions from development to deployment by linking research needs to key stages in the growth of systems integration requirements for grid-forming inverters, starting from microgrids, to island or other smaller weak grids, and eventually to entire interconnections. This multiyear perspective recognizes that the scale and scope of the types of power systems for which inverters will be called on to provide grid-forming services will and should begin modestly. Specifically, it recognizes that the dominant form of inverter control today is grid-following and that future power systems will involve a mix of inverter-based sources with both grid-following and grid-forming control. Growth over time will be paced or enabled by how well grid-forming inverters perform and what advantages they bring. This recognition, in turn, establishes a natural sequence of priorities for the research questions that we must address.

Figure 10 conceptualizes the early multiyear activities. Present efforts map to this roadmap for understanding grid-forming trends and focusing on key grid stability and systems integration areas. As research challenges are resolved, this will lead to lab demonstrations and then field trials, with early deployments for challenging grid conditions such as 100% renewable microgrids or weak grid scenarios on area power systems. With enough industry experience, this will translate into early standards work and the beginning of uniform deployments for grid-forming inverter-based resources.

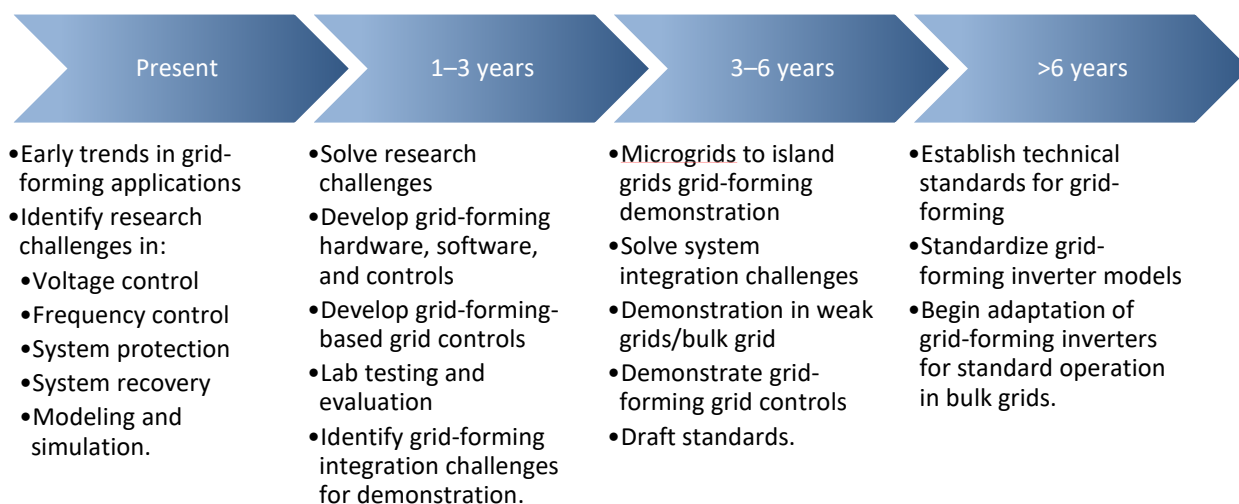


Figure 10. Multiyear systems integration activities for grid-forming inverter-based resources

Scaling applications of grid-forming inverters from microgrids to large interconnections is addressed in the subsequent subsections. We conclude with short descriptions of two specific near-term research priorities: the review of regulatory and technical standards and the development of advanced modeling techniques. These priorities are foundational. We recommend immediate pursuit of them in parallel with and in direct support of the research outlined by our multiyear perspective. We also note that the timeline should reflect a conservative estimate of how technological development is likely to occur. Note that this might depart from actual renewable penetration levels, which are increasing rapidly and might outpace our anticipated timeline. This mismatch highlights the urgency for increased research activities within the grid-forming domain.

4.1 From Microgrids to Isolated Power Systems to Continental-Scale Power Systems

Replacing synchronous machines with grid-forming inverters at the transmission level will, in general, be the most mature iteration of grid-forming usage. This phase has a relatively long timeline (~10–30 years) and will be achieved only once a research base of protection, controls, and interoperability has been established and a robust standards environment defining the required functionality of grid-forming inverters on the bulk grid exists.

In other words, the maturation process of grid-forming inverters will most likely unfold in a staged approach with lessons learned as well as operational experience and expertise gained throughout many years. Microgrid research during the past 20 years has already demonstrated that grid-forming microgrids are feasible in various settings—see, for example, the CERTS microgrid test bed in Lasseter et al. (2011). Also, we are now seeing the emergence of early-stage grid-forming inverters as a solution in islanded microgrids with high penetrations of renewable generation, such as Kauai, Hawaii. Demonstrating operations and reliability in these contexts provides the knowledge base and confidence required to incorporate grid-forming controls into larger electric grids. Bulk system grid planners and operators are already starting to

consider their need for weaker portions within the North American interconnections (NERC 2018c). Short seasonal or situational operating times with instantaneous periods of high inverter-based resources will be the initial focus areas.

To pave the way for integrating increasing amounts grid-forming-controlled generation with decreasing amounts of synchronous generation in the bulk grid, several practical and small-scale applications of grid-forming inverters will need to be realized. Each implementation of grid-forming inverters provides practical knowledge about their use and operations, answers research questions, and brings new questions to the fore. A particularly challenging set of issues will involve adaptations or modifications to existing bulk power system control approaches—all of which have been based on comparatively slower acting electromechanical sources—to take advantage of the much faster acting control that is possible with inverter-based sources.

The industry needs design evaluation and validation for grid-forming inverters. Robust design processes and stakeholder engagement therefore require:

- **Definition:** Inverter manufacturer and power systems/utility engineer agreement on grid-forming definition and high-level capabilities. As highlighted at a high level in Section 2, clearer demarcations are needed for grid-following versus grid-forming capabilities.
- **Requirements specification:** A stakeholder-derived list of device/component, packages, and technology requirements for grid-forming inverters (and/or plant controllers) for generation plant application-level requirements. A stakeholder-derived list of power system requirements for integrating the grid-forming device(s) into the area power system for secure operation.
- **Functional specification:** The requirements specifications list should be mapped to the functional design requirements and development needs for (1) the inverters, (2) any plant supervisory controls, and (3) upgrades or development to the area power system. Functional specification should consider systems integration issues, such as inverter fault current contribution and existing/proposed protection schemes, especially for unbalanced conditions.
- **Modeling and simulation:** Modeling and simulation of the grid-forming inverter-based resource and area power system must be used to evaluate and ensure that functional specifications meet target power system reliability and resilience requirements. Models should consider contingency operation and system end-to-end performance. Simulation results should correlate with subsequent testing and validation.
- **Testing and validation:** Testing and validation should test the grid-forming capabilities against the functional specifications and proceed through robust system end-to-end testing. Testing should start with factory acceptance tests, proceed to preproduction site acceptance testing (possibly including hardware-in-the-loop testing) and production site acceptance testing, and then to commissioning testing.
- **Disseminating results:** Industry will need to inform the design and testing; thus, the results of this process should be shared and debated. This will accelerate early standardization of grid-forming capabilities.

Grid-forming implementation will most likely occur through phased implementations of grid-forming inverters, starting with smaller, more constrained microgrids and eventually moving

toward larger grids (Figure 11). Even within application areas, phased implementation is likely to take place, with initial grid-forming implementation being seasonal or taking place during situational periods when additional firm sources are needed (e.g., instantaneous inverter-based generation periods or to provide voltage regulation under local, specific contingencies) before the widespread adoption of grid-forming-dominated systems. Therefore, there is a staging of implementation between different usage levels as well as stages of usage within application areas (denoted by a color gradient within an application area).

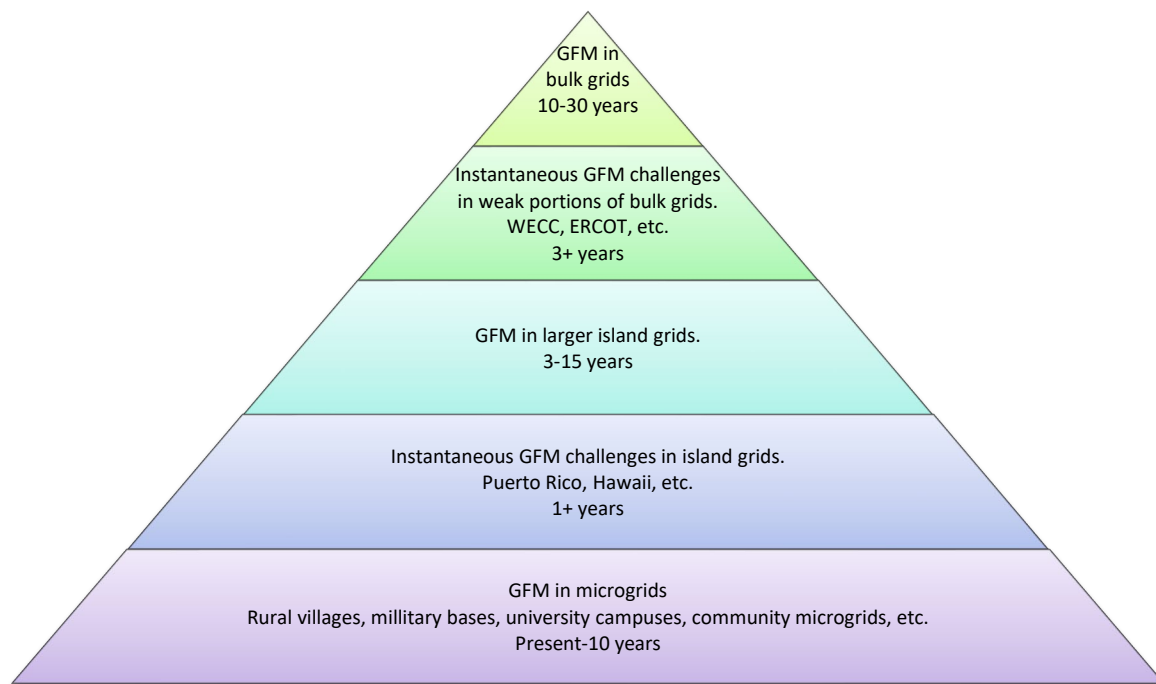


Figure 11. Incorporating grid-forming (GFM) controls into the bulk electric grid will take place gradually after key functionalities have been demonstrated and confidence has been gained by operating them in smaller microgrids and island power systems.

We are currently seeing (and will continue to see for the foreseeable future) the incorporation of grid-forming inverters in island microgrid environments. These microgrids, which are already being incorporated in a variety of areas (for example, rural villages in Alaska, university campuses, and military bases) run hybrid diesel-renewable grids with grid-forming inverters on energy storage. As the technology of grid-forming inverters matures, we will begin to see the emergence of 100% grid-forming islanded microgrids with scalable multi-inverter, multiple grid-forming-based architectures, and energy sources. Such microgrids, although small, can still provide a wealth of practical knowledge in the deployment of grid-forming inverters. Issues that can be examined in such environments include:

- Distribution protection
- Fault ride-through
- Frequency/voltage support
- Interoperability with a few (<10) rotational machines, other grid-forming inverters, and grid-following controls

- Differences in grid-forming operation for various primary energy sources on the back-end source (e.g., battery, solar, and wind).

As the technology for grid-forming-based microgrids mature, grid-forming-based implementations will begin to appear in larger island grid settings (3–15 years), such as in Hawaii and the Caribbean. These grids have a larger number of interoperating sources and loads, are geographically larger, and exhibit much larger and more complex behavior compared to site-level microgrids. Additionally, although site-level islanded microgrids are primarily built at distribution-level voltages, many island grids have subtransmission-level voltages.

One pressing issue is the increase in grid-connected PV sources using grid-following inverters and the resulting difficulty of keeping frequency within bounds. The emerging frequency issues on the Hawaiian island of Oahu are directly attributed to the penetration level of grid-following inverters. This is happening now, independent of a full understanding of the grid-forming technology (El Khatib, Wei, and Lasseter 2018). Hence, tools and study cases need to be developed to bring more understanding to the issues experienced at Oahu and in the Caribbean.

Other specific issues that will be demonstrated in this context are:

- Subtransmission protection
- Interoperability with some (<100) rotational machines, other grid-forming inverters, and grid-following controls dispersed over an island-scale geographic area
- Upgrading existing grid-following inverters to have grid-forming capability
- Stability analysis.

Validations through these comparatively smaller grids will contribute to the irreplaceable field and operational experience, along with supporting technical requirements and standards, needed to guide the large-scale implementation of grid-forming inverters within large interconnected, high-voltage transmission grids. These implementations will begin piecemeal and respond to specific operational problems created by increased inverter-based generation (relative to synchronous generation), such as the need to shore up weaker regions within the interconnection (7–20 years). Although operations in smaller grids will provide key insights about operational practices and interoperability, some fundamental research gaps still exist preventing widespread implementation on large grids that are currently dominated by synchronous machines. These include:

- Transmission protection
- Interoperability with many (>1,000) rotational machines, other grid-forming inverters, and grid-following controls dispersed throughout a continental area
- Bulk system stability.

4.2 The Need to Establish a Technical Standards Environment for Grid-Forming Inverters

Because grid-forming inverters exhibit voltage source-like behavior, they have distinct behaviors that imply a need for tailored standards. For instance, existing IEEE 1547 standards for distribution-level assets emphasize current harmonics limits, reactive power limits, and anti-islanding functions. In contrast, grid-forming units are predominantly used for voltage regulation

instead of current regulation, reactive power can vary for voltage support, and grid-forming inverters natively provide uninterrupted power during islanded conditions.²⁵

The following aspects should be considered in the context of ongoing efforts to modernize standards for grid-connected inverters within IEEE, the International Electrotechnical Commission, FERC, and NERC—see NERC (2018c) for an example of ongoing modernization efforts:

- **Current versus voltage waveform quality:** Under the existing regulatory paradigm, inverters are controlled to inject sinusoidal currents with minimal harmonic content. This aligns with prevailing practices in which harmonics demanded by nonlinear loads are provided by machines and reactive components, whereas inverters inject only 60-Hz components. If machines are displaced by grid-forming inverters, however, then inverters will need to provide these current harmonics, which some loads will require. In the future, the primary function of inverters will be to provide well-regulated system voltages for loads. The challenge is to devise a set of standards that emphasizes voltage control while recognizing the physical current-carrying limits of inverters.
- **Standards for Q-V droop functions:** Industry practice is largely predicated on grid-following inverters that operate at or near unity power factor. In recent years, this constraint has been relaxed with slow-acting volt-VAR controls that are intended to support system voltages. As machines are gradually displaced by grid-forming inverters, the burden of satisfying reactive power demanded by loads will shift further toward these inverters. In this future scenario, grid-forming inverters must be allowed to respond according to their autonomously executed and fast-acting Q-V droop functions to simultaneously satisfy loads and support system voltages. These Q-V droop functions for grid-forming inverters are distinct from the volt-VAR standards currently in place.
- **Rethinking unintentional islanding functions:** Because a grid-following inverter needs a well-defined voltage at its terminals, it can function in islanded settings only under specific conditions (e.g., inverter power must match load demand before the system is islanded). Because grid-forming inverters act like voltage sources, they generally continue operating during islanded conditions. This behavior departs from the existing regulatory framework. Future standards must reconcile the following questions:
 - How can distribution engineers de-energize systems before carrying out maintenance?
 - Should islanded subsystems within a larger grid remain energized to enhance reliability and facilitate a system black-start?

²⁵ If the cumulative capacity of grid-forming inverters on a system exceeds the load, islanded operation can be sustained.

4.3 The Need to Begin Developing Appropriate Models for Existing Simulation Tools as Well as Enhanced Modeling and Simulation Tools

Modern state-of-the-art grid analysis tools have been tailored toward grids dominated by synchronous machines. A widely adopted assumption within these tools is that the synchronous speed of power systems remains relatively close to nominal during and after a transient; however, this widely adopted assumption might not be valid in systems with high penetrations of inverter-based generation because they lack synchronously connected rotor inertia. Hence, researching appropriate modeling and simulation tools that are suitable to study the transition from machine-based systems to inverter-based ones is a high priority. In fact, some independent system operators and developers require this capability immediately, highlighting the importance and urgency of appropriate modeling and simulation tools.

Another important challenge is to simulate inverter controllers as implemented in the field to accurately predict undesirable performance. This problem was highlighted during the recent Blue Cut Fire, Canyon Fire 2, and subsequent events, where disconnections of inverters were not predicted by current simulation (NERC 2017; NERC 2018a). This problem can extend to the future incorporation of inverters with grid-forming controls; hence, appropriate models for existing transient simulation tools should be implemented.

Other modeling and simulation challenges include:

- How can we represent a large number of distribution-connected inverters? How can we include primary renewable energy source models?
- What is necessary to reduce the bulk power system simulation computation burden with added inverter-based generation?
- How are the models and simulations validated? Have the simulations covered all the possible contingency scenarios, especially for growth of grid-following inverter-based resources, changing load minimum/maximum/variability conditions, or interaction with other legacy grid devices?
- When are field trials required and when are they feasible for model validation?
- How can we ensure robust industry availability and access to test data sets and public network models?

5 Conclusions

This report is intended to provide a comprehensive analysis of the challenges in integrating inverter-based resources and offer recommendations on potential technology pathways to inform the academic community, industry, and government research organizations. This roadmap attempted to envision the key short- and long-term research-and-development needs for inverter-based resource grid-forming controls, protection, and modeling as part of hybrid grids. For the next decade and beyond, the large interconnections in North America will comprise both electromechanical and inverter-based resources. Inverter-based, grid-forming resources will be necessary for the stable operation of the bulk power grid. An ongoing assessment of system performance and grid-forming inverter evolution will be needed.

Additional short-term and long-term roadmapping will be needed for detailed inverter-based resource performance, including from distributed energy resources, during contingency events. A key example is inverter-based resource and grid-forming capabilities to support black-start. Small but megawatt-scale challenges are already emerging (Walton 2019). Ongoing roadmapping is needed for a systems perspective given the complexity of these contingency events and lack of industry experience with inverter-based, grid-forming generation.

Detailed system performance metrics will need to be developed that support analyzing this transition. Technology and system roadmaps will need to be created that address technology development, validation, and maturity assessment. These metrics will need to balance the physical performance metrics of hybrid grids with expected improved performance from all generators. Inverter-based resources are capable of faster and more effective grid-support capabilities compared to traditional synchronous generation with electromechanical limits (Loutan et al. 2017). The capabilities of synchronous generators are expected to evolve for better use in conjunction with inverter-based resources. Future roadmapping efforts will need to forecast this evolution to assess how each generator type might evolve for the transitioning grid.

Transitioning to even more inverter-based resources could eventually necessitate establishing a roadmap for 100% power electronics grids ranging from large island grids to weak portions of the bulk grids. This future roadmap could leverage the learning and experiences from instantaneous, high-penetration periods of inverter-based resources. One hundred percent power electronics grids would be based on the physical properties and control responses of inverter and converter systems in conjunction with expanded use of DC interconnections. These challenges stem from the recognition that there is no established body of experience for operating hybrid AC-to-DC power electronics-based power systems at the scale of today's North American interconnections. System design as well as steady-state and contingency operations research and development of 100% power electronics grids will be necessary, and this should be based on a robust roadmap of systems technology development and testing.

Future assessment and roadmapping will also need to address the many areas beyond the scope of this report that more broadly correlate to long-term grid modernization efforts. For instance, future evaluation is needed on the following topics: distribution system engineering and operations for grid-forming inverter controls, a grid of microgrids and effective dynamic islanding topology solutions, unintentional islanding on distribution grids, evolution of sensing and communications systems—including more effective use of synchrophasors (e.g., phasor

measurement units) —considering growth of power electronics-based loads and their control, various other power quality issues (e.g., harmonics), hybrid AC-to-DC systems, system costs analysis, economic dispatch, system adequacy and reserves assessments for power electronics dominated grids, traditional security evaluation (i.e., contingency analysis, black-start), market design, economic regulation, and cybersecurity. Power system stability and protection are foundational technical issues, and these characteristics are central to our discussion of grid-forming inverters, so it is our hope that this roadmap becomes a cornerstone for future work on power systems modernization.

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