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Grid-forming Inverter Technology Specifications: A Review of Research Reports and Roadmaps

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Contents

1 Introduction

Large power grids provide electricity to millions of people and have evolved to their current state over the last $100+$ years [1]. Current grids are primarily based on synchronous generators powered by coal, natural gas, nuclear and water resources. The physical characteristics of generators and their response to grid events have driven the design of operational architecture and informed the development of analytical methods for modeling and control. The advent of power electronics-based interfaces called inverters and their evolution over the last $50+$ years, the push towards clean energy and the increased interest in electrifying transportation have altered the makeup of the grid.

Accompanying the transition away from synchronous generators, there is a general trend in the migration of (at least a recognizable section of) inverter-based resources (IBRs) from those which synchronized and followed the grid (grid-following (GFL)) to more advance variants that support a range of essential grid services: a technology now commonly known as grid-forming (GFM). See Fig. 1.1(a) for illustration. Put simply, GFL IBRs *follow* an external grid and perform poorly (if at all) in the absence of stiff voltages; on the other hand, GFM IBRs hold the potential to innately *form* grids. Indeed, while a majority of IBR installations across scales today are of the GFL type, there is a growing consensus around the need for GFM IBRs in the future-grid scenario to ensure grid reliability, stability, and resilience [2; 3; 4; 5]. An underpinning feature of GFM IBRs—the ability to operate without external forcing voltage—is a longstanding attribute of standalone inverters meant for islanded small-footprint microgrids and mission-critical backup-power applications. Numerous efforts in this thematic direction are noted in the prior art in the form of patents [6; 7; 8; 9; 10] and research papers [11; 12; 13; 14; 15; 16]; most of these efforts primarily focus on control-scheme innovations for parallel operation of modular inverters and appropriate current sharing under dynamic and steady-state conditions.

Figure 1.1(b) shows the timeline of pertinent regulatory standards and the accompanying functional requirements expected from inverters over the last $20+$ years. The most prominent standard in this area is the seminal IEEE 1547 introduced in 2003 [24]. While 1547 focused exclusively on distribution-scale technologies, the recent IEEE 2800 released in 2022 encompasses IBRs at transmission levels as well [25]. Interestingly, in recent incarnations, both standards (although written for GFL inverters) discuss notions that suggest grid-forming behavior (albeit, with technology-agnostic and non-prescriptive language).

Most major inverter manufacturers have made deliberate recent forays into the power generation business via IBRs; this is driven by favorable economics, a liberal regulatory landscape, and the societal impetus to decarbonize. However, as expected with any nascent technology involving critical infrastructure and requiring cooperation across a wide range of public and private players, poor definitions of capability and functionality have impeded the industry at large. It would appear that system operators are at the forefront of roadmapping the technology, with manufacturers expected to follow along in compliance; but on the other side, manufacturers are quick to innovate and have perennially done so (oftentimes unshackled by governing standards) since they operate in the backdrop of a rapid-paced semiconductor industry. Nonetheless, the unabated interest in GFM technologies is palpable. Further evidence to this is the number of pilot projects that have sprung up recently around the world (see Figure 1.2). Many such initiatives are motivated by specific challenges unique to geography and prevailing grid conditions (e.g. island grids in Hawaii require GFM capability as more synchronous machines are removed from service [17]; other large installations, such as the Hornsdale project in Australia, have focused on providing ancillary services [21]). Anticipating an exponential increase in GFM-based installations, system operators and research laboratories around the world have recently released a slew of reports that focus on: power system considerations, services, capabilities, and applications of GFM technology. In this paper, we focus on such literature authored by agencies anticipated to drive regulation and roadmap needs for the industry at large. Particularly, we review:

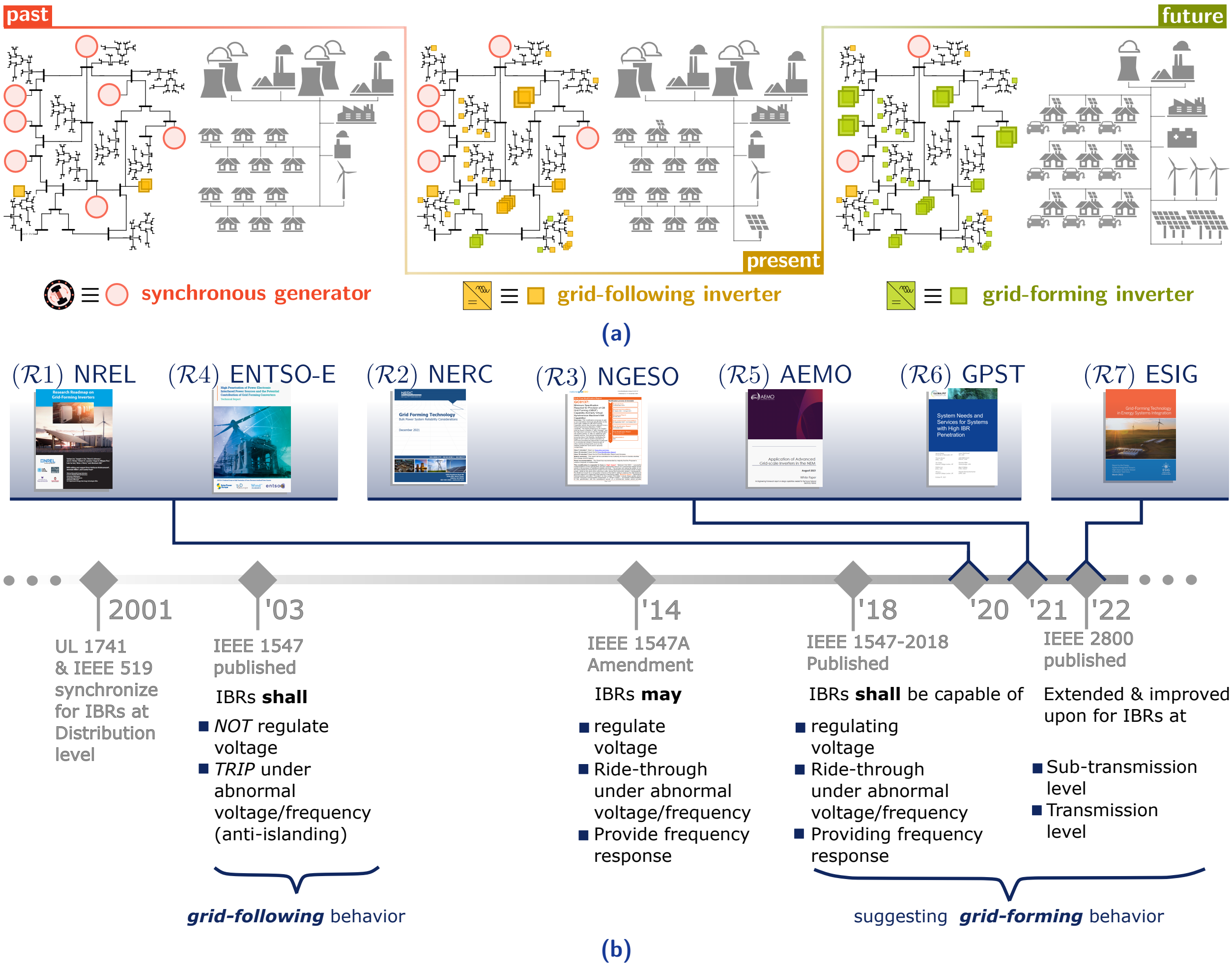

Figure 1.1: Tracing the power-grid transformation over time focusing on: (a) the scale (numbers and ratings) and types of IBRs integrated into the power grid, and (b) accompanying evolution of regulatory landscape as qualified by relevant standards. Recently, there has been pronounced interest by system operators, regulators, and national labs in GFM technology. This has translated to a slew of reports and roadmaps that are critically reviewed in this work.

($\mathcal{R}1$) A research roadmap authored by the National Renewable Energy Laboratory (NREL) [5];

($\mathcal{R}2$) Reliability considerations documented by the North American Electric Reliability Corporation (NERC) [18];

($\mathcal{R}3$) GFM specifications and evolving grid codes outlined by the National Grid Electricity System Operator (NGESO) [19];

($\mathcal{R}4$) An overview of GFM potential and open questions by the European Network of Transmission System Operators for Electricity (ENTSO-E) [20]; and

($\mathcal{R}5$) Recommendations on advanced grid-scale inverters by the Australian Energy Market Operator (AEMO) [21].

While we meticulously examine ($\mathcal{R}1$)—($\mathcal{R}5$), we also derive insights from the thematically related efforts:

($\mathcal{R}6$) A detailed review of evolving system needs and services by the Global Power System Transformation Consortium (GPST) [22]; and

($\mathcal{R}7$) Design considerations and processes to deploy new GFM capabilities authored by the Energy Systems Integration Group (ESIG) [23].

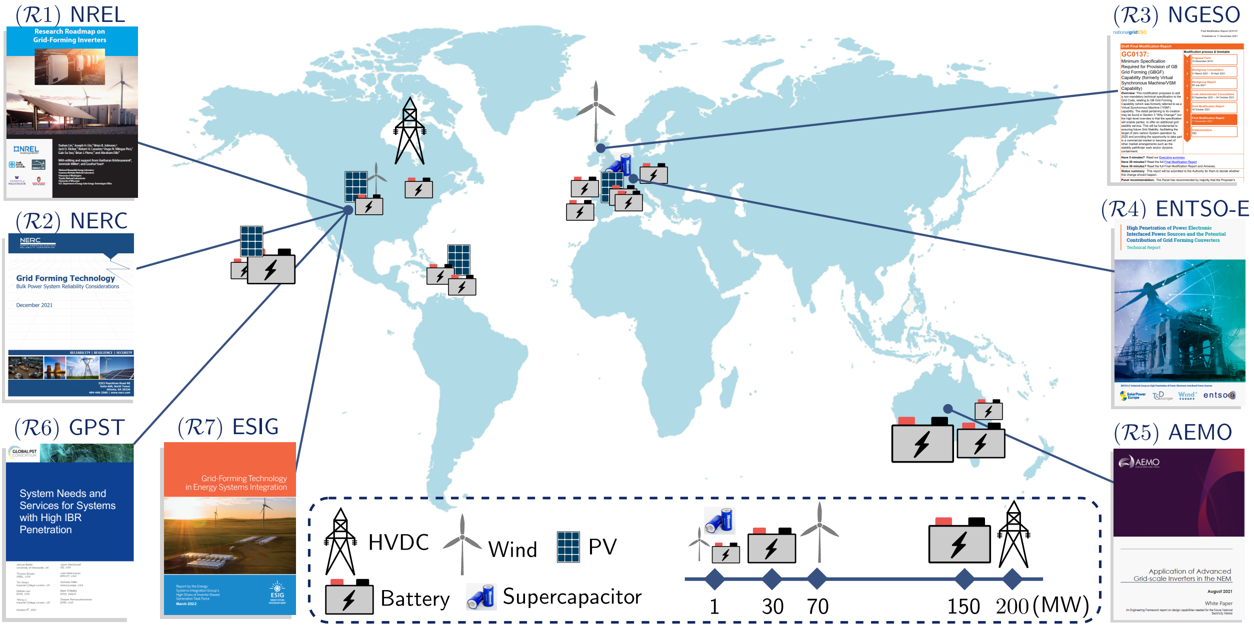

Figure 1.2: Major GFM pilot projects [3; 17] and surveyed literature [5; 18; 19; 20; 21; 22; 23].

Figure 1.2 shows that $(\mathcal{R}1)$–$(\mathcal{R}7)$ have been authored by agencies geographically collocated with the reported pilot projects.[1] Also, from the timeline shown in Fig. 1.1(b), it is clear that these are very recent efforts. Note that we do not focus on the academic literature on GFM IBRs; this is a vast and growing body of work spanning multiple subtopic areas including modeling, analysis, control, and operation (see, e.g., [3; 26; 2]).

This paper discusses points of similarity and departure across $(\mathcal{R}1)$–$(\mathcal{R}5)$. In particular, we focus on:

- definition of GFM technology vis-à-vis GFL;
- anticipated system-level functionality; and
- corresponding unit-level capability.

The scope of the paper is motivated—at a macro level—by themes that ring in unison across the surveyed literature. Discussion points above are natural since they cover a broad technical landscape relevant today and addressing them would facilitate alignment and accelerated adoption. Accompanying our examination of $(\mathcal{R}1)$–$(\mathcal{R}5)$, we also provide recommendations in an effort towards bridging the gap between research needs and practice, aligning the aspirations of vendors with system operators, and addressing some confounding aspects that continue to plague conversations surrounding this technology space.

The remainder of this paper is organized as follows. In Section 2, we succinctly present the distinctions between the GFL and GFM technologies as identified by the surveyed literature. Sections 3 and 4 discuss the prevalent system- and unit-level specifications for the IBR technologies. Finally, we provide some broad recommendations and conclusions in Section 5.

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[1] To the extent possible, in what follows, we refer to particular references as $(\mathcal{R}x)$ with the understanding that the reader can readily cross reference these with Fig. 1.2 and the list above.

2 Grid-following vs Grid-forming

A common thread across the surveyed literature is the acknowledgement of a lack of clear and well-established definition for GFM IBRs and the recognition that the definition is evolving. The lack of specificity with regard to function complicates drawing clear distinctions with GFL IBR technology. That said, there is broad consensus that GFM IBRs involve controls that represent them as controlled voltage sources behind low series impedances (at quasi-static sinusoidal steady state). This establishes a clear distinction with GFL IBRs, which are typically modeled as current sources with high parallel impedances. The key takeaway from these representations is that GFL IBRs achieve the goal of power injection by directly controlling the injected current phasor, while GFM IBRs achieve the same goal by directly manipulating the voltage phasor at their output terminals [18; 2].

Under steady-state conditions, both GFM and GFL IBRs control active and reactive power injection while abiding by the respective hardware and control capability limits. Also, both types of inverters can provide voltage and/or frequency regulation by using additional outer-control loops. The fundamental differences between them lie in the dynamic response to a grid event and their small-signal behavior under weak or stiff grid conditions [5; 18]. When a disturbance occurs in grid voltage, the GFL control attempts to maintain the injected current phasor by allowing the voltage phasor to respond accordingly. While in the GFM control, the voltage-phasor reference is primarily maintained, and the inverter current responds accordingly to satisfy the power injection constraints. This dynamic behavior is more desirable and considered promising towards other anticipated functionalities.

Table 2.1 summarizes how well the surveyed literature aligns on a variety of system- and unit-level attributes expected from GFM and GFL IBR technology. With regard to annotations therein, ✓(✗): indicates the corresponding attribute is discussed (not discussed) as a distinguishing characteristic. The color coding symbolizes groups of characteristics that receive approximately the same level of agreement across the surveyed literature. Our takeaways based on the assessment of how these reports view the differences (and similarities) between GFM and GFL are included in the adjoining text box entitled: "Inferences & Remarks (GFM vs. GFL)." In the next section, we discuss system- and unit-level specifications for GFM inverters as they are brought out in the surveyed literature.

Inferences & Remarks (GFM vs. GFL)

- The interpretation of GFM control via voltage-phasor manipulation is indeed true only for slower time scales; for time scales faster than control bandwidths, it is worth noting that both GFL and GFM inverters (that employ voltage-source topologies and PWM) can be modeled as voltage sources [4].
- The presence of inverter's primary-control loops to explicitly govern the dynamics of voltage and frequency (or phase) such that the inverter is able to generate a voltage signal at its output even in the absence of external grid voltage or load marks a key distinction between GFL and GFM.
- There is broad alignment across the reports in terms of system-level aspects and services (marked in black in Table 2.1), which predominantly concern the system operators. In contrast, the unit-level specifics and capabilities are not well aligned (marked in lighter shades of blue in Table 2.1). This suggests an exigent need to align vendors on anticipated functionality.

Table 2.1: IBR Capabilities and services used for distinguishing GFL and GFM inverters by various research reports. ✓(✗): indicates the attribute is discussed (not discussed) as a distinguishing characteristic in a given report. Color coding groups attributes that receive similar level of alignment.

Capability/service	($\mathcal{R}1$) NREL	($\mathcal{R}2$) NERC	($\mathcal{R}3$) NGESO	($\mathcal{R}4$) ENTSO-E	($\mathcal{R}5$) AEMO
Voltage control, w/o reliance on external source	✓	✓	✓	✓	✓
Fault current and ride-through capability	✓	✓	✓	✓	✓
Contributing to system effective inertia and freq. response	✓	✓	✓	✓	✓
Reactive power support and voltage management	✓	✓	✓	✓	✓
System restoration and black-start	✓	✓	✓	✓	✓
Support power system island	✓	✓	✗	✓	✓
Contributing to fast frequency response	✓	✓	✓	✗	✓
Operation under weak/low system strength	✗	✓	✗	✓	✓
Commentary on use of phase-locked loop (PLL)	✓	✓	✓	✗	✗
Preventing adverse control interactions	✗	✓	✓	✓	✗
Damping and contributing to small-signal stability	✗	✓	✓	✓	✗
Harmonics and unbalance handling capability	✗	✓	✗	✓	✗
Withstand disturbance & active power oscillations	✗	✗	✓	✗	✓
Load disconnection and standalone mode	✗	✓	✗	✓	✗
Re-synchronization and grid reconnection	✗	✓	✗	✓	✗
Distinguishing bulk vs distribution levels	✓	✗	✗	✓	✗

3 System-level Functionality

By *system-level functionality*, we refer to attributes that can only be articulated completely for networked connections of multiple GFM IBRs (and other grid assets). Our examination revealed that system-level functionality common across the studied reports include four major attributes: frequency response, voltage support, stability, and system protection and restoration.

3.1 Frequency Response

Power system frequency is a network-wide quantity, i.e., it is a common constant across a connected network under steady-state conditions. Moreover, for grids dominated by rotating machines, it is a natural proxy for demand-generation (im)balance. In particular, any imbalance between the power supply and load demand manifests as a deviation from a nominal steady-state value. The need for frequency response/regulation following a disturbance event (e.g., loss of generation/ large loads) is multi-fold. Following an event, the objective is to keep the system frequency within specified limits, limit the rate of change of frequency (RoCoF), and ensure subsequent return to nominal value. These can be achieved through active-power injection at slower/faster time scales translating to either typical primary and secondary frequency response or the so-called fast-frequency response (FFR), respectively. In this regard, ($\mathcal{R}5$) explicitly distinguishes inertia from FFR by ascribing the former as an inherent quality of a GFM device to reduce rapid frequency changes by instantaneous power adjustment without requiring any measurement or controlled response; FFR, on the contrary, is a deliberate, controlled capability via measured frequency changes [21].

By and large, frequency-response functionality can be achieved via implementation of a suitably designed inverter active power control that responds to a frequency deviation. However, the GFM (as well as GFL) IBR's capability to provide frequency response is limited by two major factors: the peak current capability of the inverter and the characteristics of the energy source behind the inverter (that includes headroom in energy reserve and limitations imposed by source-side dynamics). The GFM IBR controller will respond naturally to changes in system frequency [19]; however, not all primary controllers can be expected to exhibit similar behavior. Nevertheless, GFM devices are anticipated to rapidly modify their active power injection when the system is operating in over- or under-frequency scenarios [20].

There is consensus across the surveyed literature regarding frequency-response service anticipated from GFM IBRs. However, the natural impulse is to emulate pertinent characteristics of synchronous machines. For instance, ($\mathcal{R}3$) introduces new active-power component definitions such as *active inertia power* and *active RoCoF response power* as a desired capability for GFM IBRs. This can be confounding since inertia—as referenced in the context of electromechanics—is not directly applicable to all GFM IBRs given the variety of primary controls that could be employed. Moreover, analytical formulations for RoCoF are typically tied to machine inertia constants. This brings to question whether such anticipated functionality is indeed drafted in a forward-looking manner, or merely a comforting crutch grounded in practices of the past.

3.2 Voltage Support

In contrast to frequency, voltage is a local quantity as its magnitude varies across the geography of the power system (i.e., transmission/distribution levels) even in steady state. It is mandatory to keep the voltage magnitude as well as its harmonic contents within an acceptable limits for safe operation of all connected equipment.

GFM IBRs are expected to provide voltage support (within operational constraints) during voltage sag/swell and phase jumps caused by disturbance events such as short circuits and line disconnections [19]. Some efforts have attempted to crystallize requirements to contend with such conditions; for instance, $(\mathcal{R}3)$ indicates capabilities such as *active phase jump power* and *voltage jump reactive power* are required to provide necessary voltage support in a timely manner.

A GFM (as well as a GFL) plant has to inject or absorb necessary reactive power attempting to maintain the voltage within stipulated limits at the inverter terminals. (This implies that inverters need to ride through low-voltage events.) Additionally, a GFM plant has to inject or absorb active power following an occurrence of a phase jump in the voltage. Notably, these responses are constrained by the peak current-provisioning capability of the inverter. This limitation implies that the frequency and voltage responses need to be coordinated during a disturbance event to ensure safe operation of the inverter.

3.3 Stability

System stability is referenced in a majority of the surveyed literature to include: i) transient stability and capability to recover after large-signal disturbances, e.g., line faults, and ii) ability to withstand disturbances and maintain small-signal stability during steady-state operation [21; 18; 20]. Grid disturbances include those seen in voltage, frequency, and phase; it is essential to reject these disturbances for maintaining network synchronism. In the context of high IBR levels, key issues with frequency stability are the introduction of new oscillatory modes via negative control interactions and reduced system damping. The following are a few snippets that find mention in the surveyed literature in the context of stability; accompanying each, we comment on why these (are) could be confounding:

- System loads and dynamic behavior of sources in terms of active and reactive power injections are noted to be critical for *voltage stability* [5; 20]. Classically, voltage stability focuses on the ability of a power system to maintain voltages close to the nominal value at all network buses after occurrence of a disturbance [27]. The aspects to be considered for voltage stability critically depend on the considered magnitude of disturbances (small/large) and analysis timescale (short-term/long-term). Furthermore, voltage stability, is a joint attribute of the network, operating conditions, and dynamic behavior of loads/generators. Hence, an isolated emphasis on loads and generators may be limiting, as representation of network dynamics and interactions is also necessary.

- RoCoF is highlighted as a key index for stability and the increase in RoCoF in light of increased IBR shares is brought up as a major power-system stability challenge [20]. Whether there a direct link between RoCoF and large-signal or small-signal stability for IBR dominated grids is a point to ponder.

- The terms *weak grids* and *(low) system strength* generously accompany references to stability and the ability to maintain network synchronism [21; 20]. Unfortunately, these are qualitative and subjective constructs, and tying them to quantify a precise notion such as large- or small-signal stability can be problematic.

- Several references to *short-circuit ratio* (SCR) are also common across the board in the context of stability. Notably, the classical definition of SCR exists, e.g., in [28] for synchronous generator capability, while for grid networks, this is not well defined albeit used extensively in the context of voltage stability. Frequent references to this term in the context of high levels of IBRs can sow the seeds of confusion as it cannot be generalized across systems.

Inferences & Remarks (System-level Functionality)

- Notion of frequency (and accompanying concepts such as RoCoF) in systems with high levels of IBRs may be inadequate.
- The practice of specifying functionality (for, e.g., frequency response and voltage support) dictated by operating conditions (e.g., voltage jumps, phase jumps) may be shortsighted, limit performance, and combinatorially impossible to scale.
- At the distribution level, voltage regulation is typically done at slower timescales with few passive devices. GFM integration offers many more actuation handles as well as the potential for faster and fine-grained regulation, and suggests the need for deeper transmission-distribution coordination.
- Stability is a system-theoretic construct, classifications for power systems are developed in [29] and revised in [27] specifically for IBRs (referred therein as converter-interfaced generators (CIGs)). Alignment with technical language across stakeholders is necessary.
- A critical issue with applying the notion of *short circuit ratio* in the GFM context is that it gives little to no credit (depending on how it's calculated) to GFM IBRs for any ability to strengthen the system. A more appropriate metric that captures contribution of GFMs, e.g., in damping fast modes and reducing the small-signal impedance at interconnection points on the power system, needs to be developed.
- References to poorly defined constructs like *system strength* and *weak grids* can jeopardize the appreciation of core technical challenges and alienate stakeholders from constructive conversations.

3.4 System Protection & Restoration

Prevailing protection systems that defend the grid against short-circuit faults consist of protective relays and circuit breakers that were designed to detect, locate, and isolate large fault currents expected from synchronous generators. While various methods may be utilized to detect and locate overcurrents flowing from generators, these protective relays and breakers are ubiquitous across the electrical grid. To avoid the high costs of redesigning or replacing the present protection equipment that were tuned to the predictable behavior of synchronous generators, [5] and [22] emphasize the importance of the compatibility of IBRs with established protection protocols. However, the protection system philosophy needs to be reevaluated in the future so that it responds to the behaviour of IBRs (in general, and GFM IBRs in particular).

Challenges with IBRs can occur at the distribution and transmission level. In the distribution system, higher risk of incorrect operation of existing protection schemes, which were designed with one-way power flow in mind, is a problem. While IBRs can be designed to provide fault currents that match that of synchronous generators, they are typically not due to the cost of components. Usually, IBRs are programmed to limit fault current to $1.1 - 1.5\times$ of the nominal value so that current ratings of the switches are not breached during operation. Bidirectional current flow may further change fault currents seen by some of the existing protective devices and cause issues with the selectivity of these devices.

At the transmission level, some protection systems rely on synchronous generators injecting large negative-sequence currents to identify unbalanced faults. Hence, [5; 18; 19; 20; 21] seek similar fault current contributions from GFM IBRs to maintain the utility of traditional protection schemes. In addition, [5] notes that protection systems are also in place to detect out-of-step events and power swings caused by changes to the system state. For synchronous generators, protection equipment monitors the rate of change of voltage/current signals in the system, which is dictated by their inertia and therefore smaller than the rate of change inflicted by faults. Substantial power swings are typically observed in networks dominated by IBRs due to their lack of inertia. However, the fast response times of GFM IBRs, even compared to GFL controls, are expected to help stabilize the system after disturbances and avoid false tripping. Broadly, there is agreement across the reviewed literature that further research is needed to understand how GFM IBRs interact with existing protection systems.

For GFM IBRs, it is crucial that they stay connected to the bulk power system to support synchronization and contribute to restoration if needed. Currently, synchronous generators underpin black-start procedures that are initiated after major outages. Some fraction of future GFM inverters may be required to self-start to establish a voltage and synchronize with other generators/inverters to black start a system. Fundamental necessities are also the ability to maintain the system voltage and frequency while load and network segments are being connected to the restored system. Finally, GFM IBRs must be able to operate in islanded operation until they are able to synchronize with adjacent areas to form the larger grid [30; 31].

Our takeaways on challenges and opportunities towards streamlining system-level functionalities are included in the adjoining text box entitled: "Inferences & Remarks (System-level Functionality)." Figure 4.1 provides a snapshot of system-level attributes that govern the control and optimization functions for GFM IBRs. Each system level function can be achieved through a number of unit-level capabilities which are also highlighted as bullet points alongside the system-level function. We discuss these next.

4 Unit-level Capabilities

By *unit-level capability*, we mean the full suite of functions that can be engineered into individual GFM IBRs (extending to plants and aggregations as appropriate) to meet the system-level functions discussed previously. In general, both GFM and GFL IBRs can be anticipated to provide features such as voltage control and variable power factor operation to unlock their full potential. Additional capabilities such as operation in a frequency sensitive mode (i.e., to modify active power injection in response to system frequency variations) may be envisaged from IBRs in general. However, it is expected that GFMs ought to deliver these services faster, and in a more stable and reliable fashion as compared to GFLs [5].

Figure 4.1 summarizes system-level functionalities (described in Section 3) and ties them to unit-level capabilities that will be discussed in detail subsequently. Notably, we will identify fault ride-through as an essential feature for every system-level functionality.[1]

4.1 Ride-through and Fast Fault-current Injection

Ride-through refers to the capability of IBRs to remain connected to the grid during a disturbance. In general, for voltage ride-through, pre-determined levels of high- and low-voltage limits exist which dictate disconnection of inverters from the grid. However, the precise thresholds and the duration for which inverters are required to remain connected/disconnected during grid events is still under deliberation in many grid codes. Both [19] and [20] recognise that reactive current injection is required during voltage sags. To prevent disconnection of assets present in the network during a voltage sag, they specify a fast reaction time (from IBRs) of less than one quarter cycle for terminal voltage dips below below 90% of nominal value.

For faults, fast fault-current injection capability of the IBR is recognized as vital. This refers to the inverter's ability to inject current instantaneously into the system during faults at the point of interconnection. While a synchronous machine provides this type of response inherently due to its electromagnetic physics, a GFM inverter can provide this functionality as a result of its fast control action. Given the specific fault, IBRs will be required to inject current with specific characteristics (such as active and/or reactive current) to sustain the voltage for (possibly) an extended period.

The fundamental issues here are two-fold: i) in case of GFLs, the unit-level controller relies on the external voltage source (i.e., grid) for synchronization. During or after a disturbance, the source voltage

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[1] While most of the surveyed works do not explicitly call out the demarcation between system-level functionalities and unit-level capabilities, $(\mathcal{R}4)$ is an exception. It features a categorization of IBR types into three equipment *classes* based on type of grid-support features and the ability to operate in grids approaching 100% IBR shares.

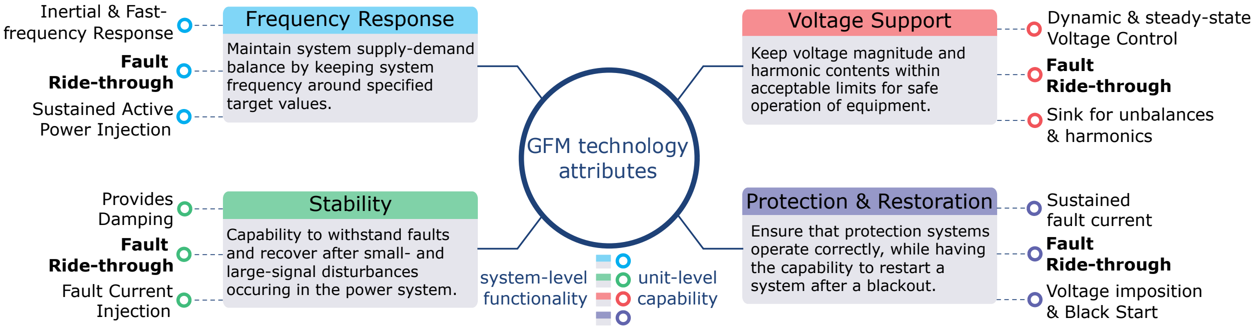

Figure 4.1: Summary of system-level functionality linked to associated unit-level capability. Fault ride-through feature is noted to be an enabling attribute for all system-level requirements.

quality may be severely affected, which makes (re)synchronization and power injection challenging for GFLs. Since GFMs do not rely on an explicit external signal for synchronization, they offer greater potential to tackle disturbances and ensure desired power injection; ii) Inverters cannot handle currents exceeding the ratings, and hence, even in case of GFM, they cannot allow large currents to be injected during faults and maintain the imposed voltage phasor magnitude and frequency (unlike a synchronous generator that can typically support up to $6\times$ the full rated current during faults.). Inverter current-limiting approaches need to trade off inverter hardware limits with system stability concerns.

Additionally, unbalanced faults are of particular concern as they are difficult to handle by IBRs as compared to balanced ones. In this regard, GFL and GFM controls are required to be capable of injecting negative-sequence currents to achieve reduction in voltage imbalance across the network. This may require the usage of alternate control structures (departing away from the conventional direct-quadrature-zero frame) and more expensive hardware (with four instead of three wires) as recognized by [5].

4.2 Inertia and Damping

A frequent concern raised in relation to the loss of synchronous generation is the loss of inertia and damping that they provide. Inertia, in the context of power systems, appears to have extended beyond its original concept as the physical property of the rotating masses of synchronous generators to one that captures an inherent resistance to frequency and phase-angle changes. (Although, it is unclear if this is appreciated broadly.) Power electronics do not possess physical inertia but can offer a similar function as synchronous generators of responding to and arresting system-frequency changes. Thus, the surveyed literature does not explicitly reference requiring inertia from IBRs. Instead, there are references to "frequency control" [5], "frequency regulation" [22], "active inertia power" [23], and "inertial response" [18] that essentially capture the intended functionality.

The frequency regulation capability of GFM IBRs is determined based on the available power and energy headroom, and the current ratings. Requirements at the system level, should therefore, be cognizant of what can be accomplished at the unit level. There are, however, some examples of system-agnostic unit-level requirements; for instance, ($\mathcal{R}6$) requires a response within 5 ms of the onset of changes to system frequency, similarly, ($\mathcal{R}2$) recommends fast responses that match or are quicker than that of the inertial timeframes of the primary controls of synchronous generators. The optimal size of active power reserves that minimizes curtailment and maximizes frequency control functionality is still undergoing investigation and will likely be system specific since it would depend on a variety of network attributes and system loading. On another related note, GFM IBRs will be expected to dampen active power oscillations and stabilize system frequency and power flows after disturbances. With adequate headroom in power, energy, and current, control strategies can be implemented that harness such damping from GFM IBRs. In this spirit, ($\mathcal{R}7$) requires that GFM plants possess active damping power capability and adhere to an operating bandwidth limit of $0-5$ Hz. Damping factors in the range of $0.2-5$ are also prescribed. Heed that the stipulated limits may have been derived from past empirical evidences and may have to be revisited (perhaps on a continual basis) for future grids.

Finally, we note that damping serves are generally in place to protect the mechanical equipment of synchronous generators from damage and fatigue. For IBRs, focus is placed on eliminating high-frequency oscillations that may be introduced by adverse interactions among electronic components and caused by fast control loops. Moreover, the implementation of GFM controls should not produce any unwanted oscillations through unnecessary mode excitation. If oscillations do arise, GFM IBRs should be capable of mitigating them.

4.3 Power Quality

The issue of power quality with respect to individual IBR units is recognized only in $(\mathcal{R}4)$. This is described as a two-fold quality covering: i) sink for harmonics, ii) sink for unbalance. The attribute i) relates to the ability to maintain high voltage quality at the point of connection while providing damping response in the harmonic frequency range by permitting harmonic current flow up to a certain frequency range (this range is not identified precisely, although an upper limit of 2 kHz is considered as a an example in [20]). In terms of damping performance, in view of the inherent control flexibility in IBRs, it is also recognized that GFM IBRs can provide enhanced damping by mimicking inductive-resistive impedance behavior virtually. Additional high-level pointers on share of contribution pertaining to sinking harmonics, impedance selection, and tuning of damping under networked operation are also provided. The attribute ii) pertains to the ability of the IBR to handle unbalanced grid conditions and provide appropriate negative sequence impedance paths to allow (and limit) negative sequence currents, much like the traditional synchronous generators. No further details are provided in this regard.

Mirroring the presentation from before, our takeaways on challenges and opportunities towards establishing unit-level capabilities are included in the adjoining text box entitled: "Inferences & Remarks (Unit-level Capability)."

Inferences & Remarks (Unit-level Capability)

- System-level functionalities have to be translated to specific requirements and capabilities at the unit level of the GFM inverters. In our view, e.g., ride through and fault current capacity can facilitate reliable operation of protective relay systems, damping characteristics in GFM controls can mitigate negative control interactions, ability to provide system voltage reference by GFMs can lead stabilization of GFMs and potentially replace or supplement synchronous generators or condensors in providing system strength (in the same (whichever) sense and context employed by the reports).
- There is a general recognition however that power quality is more of a concern only in steady-state and this feature should receive lower priority than dynamic aspects such as fault ride-through or frequency support for meeting system-level requirements.

5 Recommendations and Conclusions

We conclude the paper by providing big-picture recommendations based on our analysis of the surveyed literature. The recommendations are provided in no particular order.

- There is an exigent need to align system operators (and utilities) with inverter manufacturers on terminology and functionality. Suggested pathways to achieve these include: workforce training events that make deliberate attempts to involve stakeholders from both industries as well as ensuring power-engineering pedagogy spans power systems *and* power electronics.
- While analysis and guidelines based on unit-level capabilities would definitely aid inverter manufacturers, most reports refrain from delving deeper into the unit-level functional details. The delivery of capabilities towards system-level functionalities must be done in a holistic fashion with thought to the unit-level capabilities. This is because there is prior experience (see $(\mathcal{R}4)$) that if done in a manner that treats the system-level challenges individually, there is a possible of conflict.
- At present, terminology and functionality are tethered to the system of yesteryear that was dominated by synchronous generators. This is understandable given the industry finds itself in a state of flux, but will need to be addressed to ensure solutions are forward looking and not limited by preconceived notions and bias. As we look towards a future that could be dominated by IBR, we should make sure to take advantage of the IBR characteristics while ensuring compatibility with synchronous machines.

Realizing future power systems with high shares of renewable resources will require that IBRs provide grid services that are nowadays provided by synchronous generators. Grid Forming technologies show a promising pathway to achieve this goal. In this paper, we have highlighted the several system needs and unit-level functionality in order to align requirements of both inverter manufacturers and system operators. Unifying both aspects is recognized as one of the fundamental challenges to be addressed for a sustainable future, but doing so will ensure a transformation to a modernized power system.

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