Performance Specifications for Grid-forming Technologies

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Abstract—**Standards and specifications for inverter-based resources (IBRs) focus primarily on grid-following (GFL) technologies at present. Therefore, these may generally not be appropriate for application in power systems to ensure acceptable operation with grid-forming (GFM) technologies. In some cases, the direct application of prevailing standards and specifications may not be appropriate for—or may even inadvertently limit the potential of—GFM resources. The Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium is a U.S. Department of Energy funded effort to advance GFM technology. The UNIFI team brings together academic, industrial, and national-lab researchers as well as industry stakeholders (utilities, system operators, vendors) to collaboratively pursue advances in a broad range of GFM technologies. This paper introduces a set of system- and unit-level specifications driven by consensus across the UNIFI project team. These are intended to seamlessly integrate GFM technologies at any scale into power-systems operation and control in a vendor-agnostic manner. A suite of illustrative simulation results that demonstrate the application of and adherence to the proposed specifications are included.**

I. INTRODUCTION

Power-electronics inverter based resources (IBRs) have come to the forefront in energy-conversion application in recent years with the integration of renewable resources of energy, electrified transportation fleets, and flexible demand-side resources, resulting in fundamentally different power system physics and models [1]. Across geographies, system operators and utilities (referred to collectively as operators in the remainder of the paper) are faced with challenges due to the integration of IBRs that they never anticipated in the past. To facilitate seamless integration, operators require accurate inverter models so they can assess system stability and resilience under a wide spectrum of anticipated real-world operating conditions. Certifying operation with such a strategy is challenging on several counts. First, IBRs present uniquely different operational characteristics compared to synchronous generators, and it is difficult to anticipate edge conditions in the field. Furthermore, inverter models, particularly details on internal controllers, are not typically disclosed by manufacturers since they are averse to revealing intellectual property (IP)-protected control algorithms [2]. Even if models were perfectly known, it must be emphasized that nonlinear elements, the wide range of control capabilities, and the possibility of updating control functionality by vendors further complicate stability assessment and performance certification in IBR-based networks.

Existing standards (IEEE 1547-2018 [3], IEEE 2800-2022 [4]) in this broad area are in different stages of adoption. At present, these standards focus primarily on grid-following (GFL) technologies, and thus their requirements are generally not designed to ensure acceptable performance with grid-forming (GFM) resources. (See Fig. 1.) In some cases, those requirements may not be appropriate for, or may even inadvertently limit the deployment of GFM resources. The Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium is addressing fundamental challenges facing the integration of GFM technologies in electric grids alongside other grid assets (rotating machines and other IBRs, including GFL). This paper summarizes a set of specifications—synthesized by driving consensus across a wide range of UNIFI team members (spanning researchers, operators, and vendors)—that outline system- and unit-level performance requirements for GFM technologies [5]. The underlying intent is to ensure that the specifications are vendor and technology agnostic; also, that they are outlined with sufficient generality to ensure they can evolve with (material, device, computing, and control) technology with time. We anticipate these specifications to facilitate the integration and seamless operation of GFM technologies at any scale in electric power systems, particularly unifying their operation smoothly with synchronous generators.

Of direct relevance to this work are other technical reports and roadmaps published (and in development) around the world that are focused on GFM specifications. National Grid ESO's specification [6] appears to be one of the most detailed GFM performance specifications at the time of this writing. Groups within the Australian Energy Market Operator (AEMO) and the North American Electric Reliability Corporation (NERC) are both drafting GFM specifications, but neither is published at the time of this writing. A previous NERC guideline on GFM technology establishes a qualitative definition for GFM inverters but does not attempt to specify minimum GFM performance [7]. The Energy System Integration Group recently published a detailed report outlining its vision on the role of GFM technology in the ongoing energy transition [8]; this report identifies an urgent need for clear specifications on GFM technology. See [9] for a comparison of recent roadmaps and technical reports on GFM technology.

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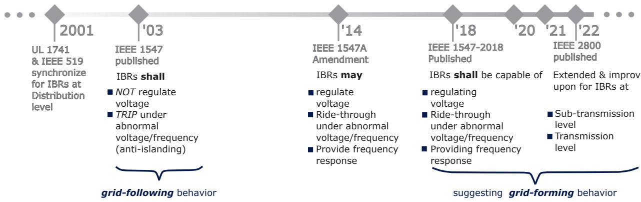

Fig. 1: Tracing the evolution of relevant standards.

Prior to presenting the specifications, it is incumbent on us to compare GFL IBR technology with GFM IBR technology in terms of operational similarity and points of departure. A traditional GFL IBR has a control objective wherein, in the sub-transient (0-5 cycles after a disturbance) time frame, it aims to maintain a constant output-current phasor magnitude and angle, and the current phasor begins changing within the transient (tens of cycles) time frame to strictly control the active and reactive power being injected into the network. On these shortest timescales (sub-transient), a conventional GFL inverter's control objective is to maintain a desired active power and reactive power, so it does not maintain a fixed voltage magnitude or phase angle on those timescales. On longer timescales (transient and steady-state), it can also pursue other control objectives such as maximum power point tracking (MPPT), frequency response, and voltage regulation (usually based on commands provided by a plant controller). A GFM inverter's control objective, on the other hand, on the shortest timescales (sub-transient), is to maintain a desired voltage magnitude and phase angle and prioritize the support of voltage magnitude and frequency at its terminals. Thus, it does not maintain fixed active or reactive power on those timescales, but still operates within the equipment limitations. Further, in the transient time frame, a GFM inverter continues to prioritize the support of voltage magnitude and frequency. On longer timescales (tens of seconds), it can also pursue other control objectives such as active-power and reactive-power setpoint tracking. It is worth mentioning that all capabilities discussed above is limited to the inverter's capacity (energy and/or power) limits which depends on the energy source. Further details on nuances associated with the differences between GFL and GFM can be found in [10].

The specifications that are discussed subsequently for GFM Technologies establish functional requirements and performance criteria and provide uniform technical requirements for integrating GFM IBRs in electric power systems at any scale. It is however understood, that local system conditions and scenarios, hardware device limits, and limitations of the source behind the inverter can impact the ability of the GFM resource to meet the performance criteria. This will require detailed studies and assessments when it comes to pursuing deployments in the field. These specifications are also not meant to supersede IEEE 1547 and IEEE 2800 series of standards. They are instead meant to extend/enhance these standards for GFM technology. Additionally, few specifications may also apply to newly interconnecting GFL resources.

The remainder of the paper is organized as follows: Section II lists out the specifications under normal grid operating conditions, while Section III lists out the specifications outside of normal grid operating conditions. Few time-domain simulation examples of GFM behavior are provided in Section IV, with concluding remarks are provided in Section V.

II. GFM PERFORMANCE UNDER NORMAL GRID CONDITIONS

Normal grid conditions are defined based on constituent systems and the network operating at (or close to) nominal values of voltage and frequency. Indeed, excursions away from nominal values can be (and are anticipated to be) common for short periods of time (driven by events such as motor starting, load changes, generation changes, and other similar events on the system). Described subsequently are universal performance expectations from GFM resources connected to an electric power system under normal grid conditions. These universal performance behaviors are to be provided regardless of the type of energy source used in the GFM resource, and the operating condition of the resource and the strength of the grid it is connected to.[1] The majority of the performance requirements outlined in this specification are defined at the level of an individual IBR unit, but they may also be applicable at the point of interconnection between an IBR plant and the remainder of the electric power system. Further, it is understood that the ability to meet these specifications are subject to physical limitations of the GFM IBR unit.

A. Autonomous Grid Support

GFM IBR resources are expected to autonomously respond to changes for locally measured signals (e.g., terminal voltage and current) to support the power system at large. For example, in the transmission network, if an IBR's local voltage drops, the IBR is expected to increase the reactive-power output to help raise the grid voltage. Similarly, if the frequency drops, the IBR is expected to increase the active-power output. Notably, these specifications do not prescribe the inputs, outputs, or states of the controller, but the relationship of signals at the IBR terminals. When an islanding event occurs (islanding of an area in the transmission system, or formation of a microgrid in the distribution network), a GFM IBR is expected to be capable of continuing to support voltage and frequency of the island/microgrid assuming that energy sufficiency and power transfer capability conditions within the island are met.

B. Dispatch via System Operator

When operating as part of a large interconnected grid, both GFM and GFL IBR plant's steady-state power output,

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[1] Strength of power systems in a specific area is often described as being *strong* or *weak*. This high-level description refers to how much voltage or frequency change in response to disturbances, and this notion can impact the design, tuning, and operation of control algorithms in IBRs. There are several measures that are used to evaluate the relative strength of a power system. These include the short circuit ratio (SCR), the Rate of Change of Frequency (RoCoF) during grid disturbances, and changes in voltage during current injections into the grid. In a grid with high percentage of IBRs, these measures may have to be re-defined. As a result, we try to avoid use of these measures to define GFM performance requirements.

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at nominal value of voltage magnitude and frequency, should be dispatchable either through a system-operator command or by a locally determined objective based upon a market clearing solution. An IBR whose primary input is a variable resource (e.g., wind or solar), may follow the peak power expected from the resource, unless local operating conditions, system-operator commands, or delivery of grid services require an adjustment in power output. (Admittedly, this may diminish the services provided by GFM IBRs.) If there arises a constraint on the network that requires the IBR's steady-state power output to be changed, it should be possible to do so by a remote command.

C. Damping Voltage & Frequency Oscillations

GFM IBRs should present a non-negative impedance to the grid and associated devices within a frequency range of common electrical resonances in order to prevent initiation of any adverse interactions or oscillations. If a resonance or oscillation occurs, the GFM IBR should be able to provide damping through the use of its locally measured signals and without requiring observability of the network and control algorithms of other devices connected to the power system. The GFM IBR is also expected to not introduce any new unstable oscillatory modes in the grid.

D. Power Sharing

Upon the occurrence of an event, similar to a conventional synchronous generator, a GFM IBR is expected to share additional power burden using droop characteristics. Here, droop is not meant to signify the type of GFM control, but rather implies that the GFM control trades off conflicting control objectives (e.g., frequency stability versus following a dispatch) to allow for interconnected operation. The expectation is that the system will converge near a steady state (potentially off-nominal) operating point subsequent to a disturbance. Incidentally, with the approval of IEEE 2800-2022, even transmission connected GFL IBRs are expected to share the burden of a disturbance using droop characteristics [4].

E. Voltage Balancing

A three-phase GFM IBR should trade off negative- and positive-sequence current within its total current capability to facilitate voltage balancing. When it operates within its negative-sequence and total-current capability, it should aid in reducing the Voltage Unbalance Factor (VUF) measured at the point of connection [11]. The negative-sequence current capability should be sufficient to meet the load characteristics of the network as determined by site-specific detailed studies. This implies that a GFM IBR should not actively control negative sequence current to zero for small levels of voltage unbalance.

III. GFM PERFORMANCE OUTSIDE NORMAL GRID CONDITIONS

Abnormal conditions on the electric power system (e.g., temporary faults and permanent failures, oscillations, motor stalls, delayed voltage recovery, generation loss, load loss, blackouts) cause voltage and frequency to go outside of nominal operating ranges. This section provides an overview of anticipated GFM performance for such conditions.

A. Response to Abnormal Voltage

1) Ride-through Behavior: Both GFM and GFL IBR are expected to inject current during and after a voltage sag to aid voltage recovery. The current to be injected is expected to have a characteristic that supports the voltage regulation at each GFM IBR unit's terminals as close as possible to its nominal value.

If the IBR output current reaches its maximum current limit, it is expected that the it will continue to inject current within its ratings (e.g., to meet protection requirements such as negative-sequence current phase angle for directional elements), and/or to help damp oscillatory behavior, in a manner consistent with providing a benefit to system-wide stability. Upon fault clearance, it is expected that the GFM IBR will seamlessly resynchronize with the post-fault network.

2) Response to Asymmetrical Faults: During asymmetrical faults, a GFM IBR is expected to impose a well-defined and stable voltage at the point of connection that minimizes voltage unbalance. This naturally makes the IBRs output unbalanced currents, including negative-sequence current. In both GFM and GFL IBRs, if the output current for any phase exceeds the current limit, the time the current exceeds its limit should be limited such that it does not cause component damage.

B. Response to Abnormal Frequency

As long as the frequency remains within the operation limits defined by the interconnecting utility or by a corresponding standard such as IEEE 1547-2018 or IEEE 2800-2022, (both GFM and GFL) IBRs are expected to modulate positive-sequence power as required during and after a frequency excursion event to aid in frequency recovery and stability. In the sub-transient time frame, the power to be injected (from a GFM IBR) is expected to have a characteristic that attempts to reduce the rate of change of frequency and support frequency at its terminals as closely as possible to its nominal value. Beyond the sub-transient time frame, the GFM IBR is expected to adjust its frequency to synchronize with other resources.

C. Response to Phase Jumps

A GFM IBR is expected to absorb or inject active power to reduce changes in positive-sequence voltage phase angle. The response of the GFM IBR to phase jumps may be influenced by its pre-disturbance operating point and active-power limits.

D. Blackstart and System Restoration

In coordination with system operators, and if designed for the purpose, GFM IBRs can provide blackstart services. However, not all GFM IBRs are expected to provide blackstart services since that may require additional balance-of-plant capabilities, additional equipment (e.g., energy storage and real time communication), and, potentially, increased device

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rating. GFM IBRs designated to provide blackstart services should be able to: i) do so without an external electrical supply, ii) establish voltage and frequency from zero state, and iii) provide energization/in-rush current to transformers and motors. The GFM IBR should also support the energization and synchronization of other resources to the network.

E. Surge Current

While providing surge current, the GFM IBR should not lose its ability to regulate voltage and frequency. If the surge current is not considered by the manufacturer to be part of the inverter's continuous current capability, then the GFM inverter data sheet should provide a magnitude and duration for a short-duration surge current that enables the GFM inverter to support events like transformer inrush and motor starting. An example surge current specification would be "1.5 times full-rated current for 2 s."

IV. ILLUSTRATIVE GFM MODEL BEHAVIOR

To showcase the performance of a GFM IBR according to these specifications, a test system is constructed as shown in Fig. 2. Since popular GFM control methods share the same operational characteristics in steady state [12], [13], the performance of only two control methods (droop and virtual synchronous machine (VSM)) will be discussed in this paper. Due to space constraints, only the results of few tests are shown in the paper. A mapping of the tests to the corresponding performance specification is given in Table I. In carrying out these tests, it is assumed that the GFM plant has a capacity of 100 MVA, but is dispatched at 50 MW with a voltage setpoint of 1.0 pu. Further, the reactive-power setpoint is 1 Mvar. A maximum current rating of 1.3 pu is assumed. Finally, an X/R ratio of 10 is assumed for the line between the GFM plant and infinite bus, with an SCR of 3.

The response for step changes in voltage, frequency, and phase are shown in Figs. 3. The responses are compared with that of a GFL plant with similar rating. The GFL plant is modeled to include a plant controller and delivers the technical minimum capabilities specified in IEEE Std 2800-2022 [14]. The plant controller regulates voltage at the low-voltage side of the plant transformer in the GFL in contrast to the GFM where voltage is controlled at the inverter terminals. Although the GFM resource can be stable for values of SCR as low as 0.5, here, results for an SCR of 3 are shown. It can be seen that the GFM device provides a much faster response than the GFL device since the GFM carries out voltage and frequency control at the inverter level instead of at the plant level. Neither the GFM's nor GFL's controllers have been site specific tuned and hence may not perfectly represent a product. The response of a GFL IBR can be made faster through tuning of controls, which may reduce the differences between GFM and GFL.

The response of the device to an unbalanced fault applied 20% of the line length away from the point of interconnection (i.e., $d = 0.8$ in Fig. 2) is shown in Fig. 4. As observable, the GFM device is able to successfully ride through the fault. Additionally, during the fault, reactive power is injected into the network to help support voltage.

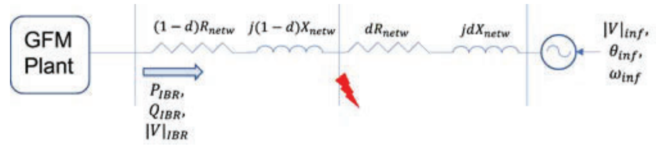

Fig. 2: Single line diagram of example single source network to showcase GFM IBR performance as per specifications.

TABLE I: Mapping of tests to performance specifications

Test	Specification Sections
$\lvert V\rvert_{\mathrm{inf}}$ step	II-A
ω_{inf} step	II-A, II-D
θ_{inf} step	III-C
Double line to ground fault	II-E, III-A1, III-A2, III-B
Trip of synchronous sources	II-A, II-D

To observe the performance of the GFM device to operate in parallel with sources on the network, and to also survive the trip of the last synchronous resource, the multi-source network in Fig. 5 is evaluated. In this network, in addition to the GFM device, another IBR device is assumed to be connected at the same transmission bus. This second IBR device has performance characteristics aligning with capabilities specified in IEEE Std 2800-2022 [14].

The GFM device is once again dispatched at 50 MW while the second IBR device at the same bus is rated at 110 MVA and dispatched at 90 MW. The synchronous generator is rated at 30 MVA and dispatched at approximately 8 MW while the synchronous condenser is rated at 15 MVA. The total load in the network is 145 MW. The IEEE 2800-2022 IBR device is assumed to be able to provide frequency response at the plant-control level. Once a steady state is achieved in the simulation, both synchronous sources are assumed to trip at $t = 1.0$ s. The GFM device response and the frequency measured by the IEEE 2800-2022 IBR device are shown in Fig. 6.

It can be seen that the GFM device is able to sustain the island that is created and a stable post-disturbance operating point is achieved. Upon trip of the synchronous resources, voltage rises across the network due to the long transmission line. As a result, both the GFM device and the IEEE 2800-2022 IBR device increase their absorption of reactive power to help control the voltage levels in the network.

From these examples, the adherence of GFM models to the proposed specifications can be observed. While verification of responses related to time-domain specifications have been shown in this paper, verification of frequency-domain specifications are equally important. In order to do so, specifications ought to recommend the development of various input-output transfer functions such as $\mathrm{V_{IBR}}$ - $\mathrm{I_{IBR}}$, $\mathrm{P_{IBR}}$ - θ_{inf}, $\mathrm{Q_{IBR}}$ - $\lvert\mathrm{V}\rvert_{\mathrm{inf}}$, and θ_{IBR} - θ_{inf}. Detailed insight into the structure and response of these transfer functions is however out of scope.

V. CONCLUSIONS & FUTURE WORK

With the rise of IBR integration in the power system, GFM technology can be a beneficial resource for stable operation.

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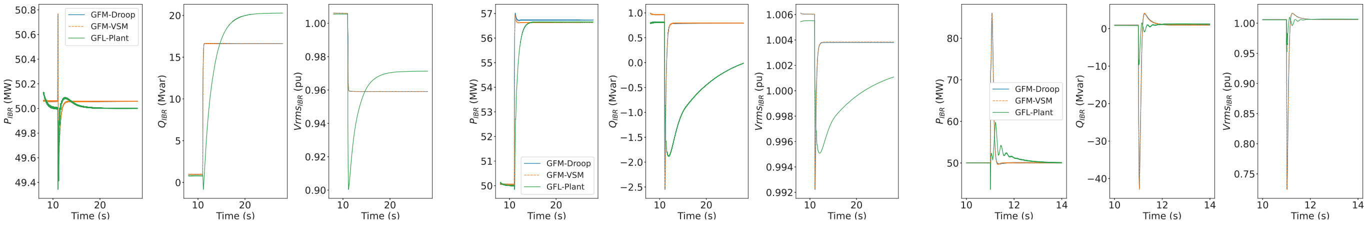

(a) (b) (c)

Fig. 3: Response of GFM and GFL to (a) 10% step change in $|\mathrm{V}|_{\mathrm{inf}}$, (b) 0.2 Hz step change in ω_{inf}, and (c) $40°$ step change in θ_{inf}.

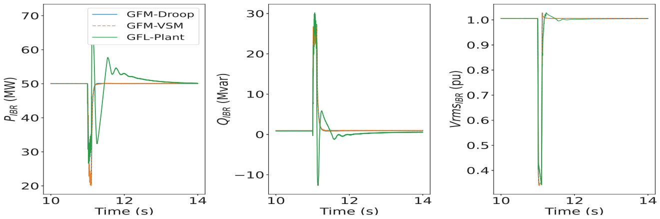

Fig. 4: Response of GFM and GFL to unbalanced fault applied 20% of the line length away from the point of interconnection.

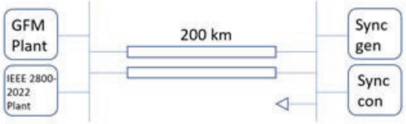

Fig. 5: Single line diagram of example multi-source network to showcase GFM IBR performance as per specifications.

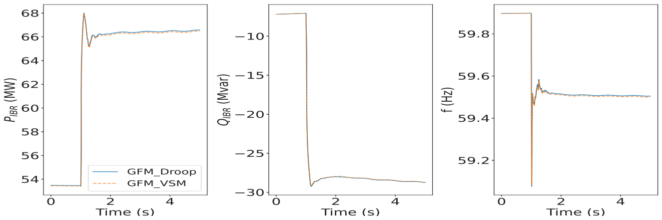

Fig. 6: Response of GFM device for trip of last synchronous sources while operating in parallel with another IBR device.

However, since GFM technology for bulk power system use is still very much in its infancy, it is timely to develop a set of universal performance requirements that system planners and operators can use to ensure stable and reliable grid operations with large amounts of IBRs. This paper has described an initial set of such specifications from both system and unit levels. An example verification of these time-domain specifications have been carried out through a simulation exercise. As the industry improves its knowledge on GFM technology, the specifications will have to be refined and augmented. It will be equally important to translate these specifications into detailed procedures and metrics that would allow for rigorous verification of (and potentially guarantee) reliable operation.

VI. ACKNOWLEDGMENTS

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REFERENCES

[1] B. Kroposki et. al, "Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy," *IEEE Power Energy Mag.*, vol. 15, no. 2, pp. 61–73, 2017.

[2] P. Pourbeik et. al, "Generic dynamic models for modeling wind power plants and other renewable technologies in large-scale power system studies," *IEEE Trans. Energy Convers.*, vol. 32, no. 3, pp. 1108–1116, 2017.

[3] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," *IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003)*, 2018.

[4] "IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems," *IEEE Std 2800-2022*, 2022.

[5] B. Kroposki et. al, "UNIFI Specifications for Grid-forming Inverter-based Resources—Version 1," UNIFI Consortium, Tech. Rep., UNIFI-2022-2-1, 2022. Available at: https://sites.google.com/view/unifi-consortium/publications.

[6] "Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability," *GC0137*, 2022.

[7] North American Electric Reliability Corporation, "Grid Forming Technology - Bulk Power System Reliability Considerations," Tech. Rep., 2021.

[8] Energy Systems Integration Group, "Grid-Forming Technology in Energy Systems Integration," 2022.

[9] D. Venkatramanan et. al, "Grid-forming Inverter Technology Specifications: A Review of Research Reports & Roadmaps," UNIFI Consortium, Tech. Rep., UNIFI-2022-1-1, 2022. Available at: https://sites.google.com/view/unifi-consortium/publications.

[10] D. Ramasubramanian, W. Baker, J. Matevosyan, S. Pant, and S. Achilles, "Asking for fast terminal voltage control in grid following plants could provide benefits of grid forming behavior," *IET Generation, Transmission & Distribution*, vol. 17, no. 2, pp. 411–426, 2023.

[11] R. Dugan, M. McGranaghan, S. Santoso, and H. Beaty, *Electrical Power Systems Quality, Third Edition*. McGraw Hill LLC, 2012.

[12] O. Ajala, N. Baeckeland, S. Dhople, and A. Domínguez-García, "Uncovering the kuramoto model from full-order models of grid-forming inverter-based power networks," in *IEEE Conference on Decision and Control*, 2021, pp. 4944–4949.

[13] B. Johnson et. al, "A generic primary-control model for grid-forming inverters: Towards interoperable operation & control," in *Hawaii International Conference on System Sciences*, 2022.

[14] "Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants: PV-MOD Milestone 2.7.3," EPRI, Palo Alto, CA., Tech. Rep., 2022. [Online]. Available: https://epri.app.box.com/v/pvmod-milestone-2-7-3

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