NERC

NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems

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RELIABILITY | RESILIENCE | SECURITY




3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

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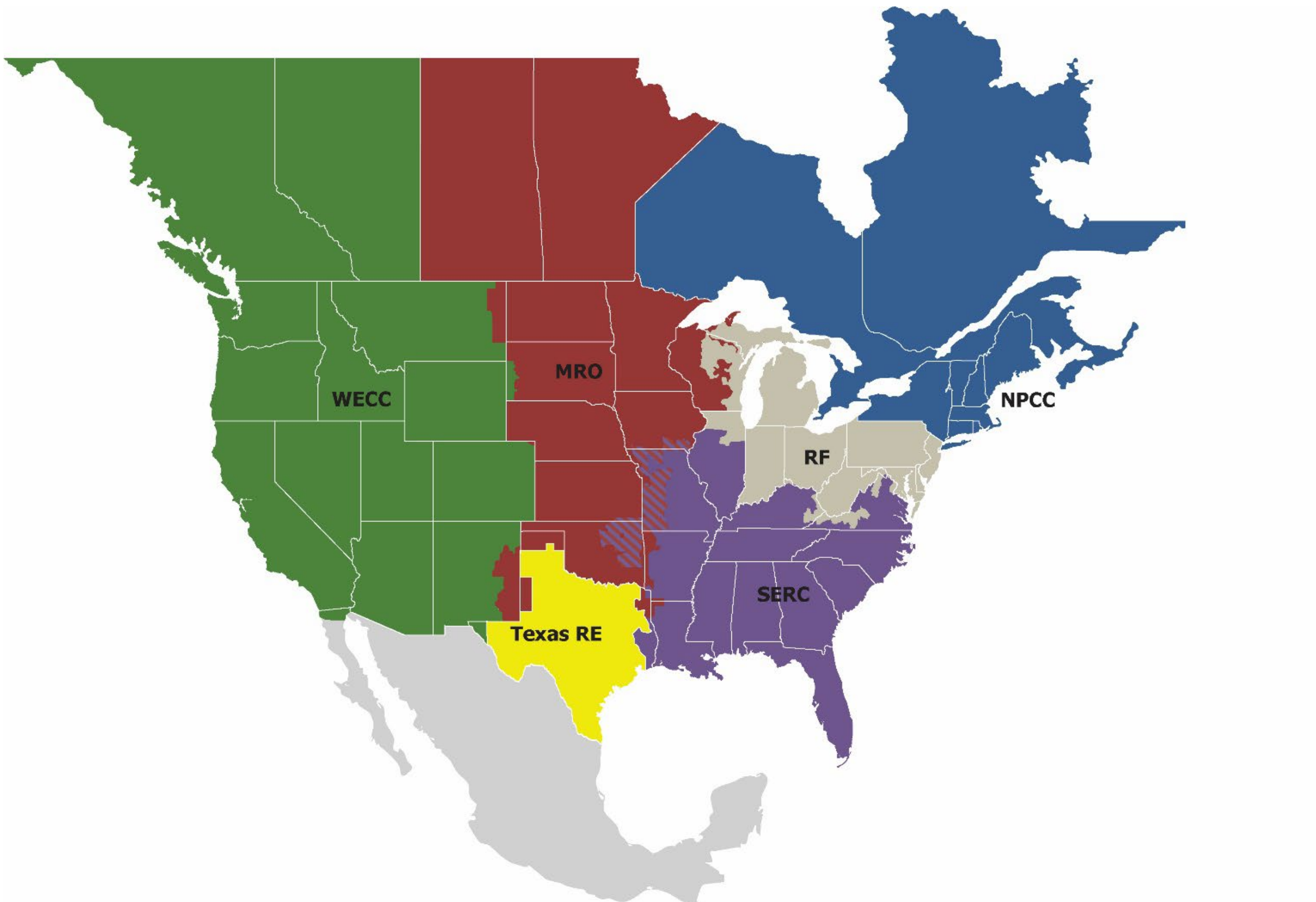
Preface

Electricity is a key component of the fabric of modern society and the Electric Reliability Organization (ERO) Enterprise serves to strengthen that fabric. The vision for the ERO Enterprise, which is comprised of NERC and the six Regional Entities, is a highly reliable, resilient, and secure North American bulk power system (BPS). Our mission is to ensure the effective and efficient reduction of risks to the reliability and security of the grid.

Reliability | Resilience | Security
Because nearly 400 million citizens in North America are counting on us

The North American BPS is made up of six Regional Entities as shown on the map and in the corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one Regional Entity while associated Transmission Owners/Operators participate in another.



MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
Texas RE	Texas Reliability Entity
WECC	WECC

Executive Summary

Studies have shown that grids dominated by inverter-based resources (IBR), in the absence of supplemental synchronous machine-based solutions, need grid forming (GFM) IBRs to maintain stable operation. While some smaller islanded systems are already facing these challenges today, it is expected that the need for GFM technology will accelerate with the rapid growth of IBRs across North America and the world. Industry needs to proactively plan to ensure sufficient GFM IBRs are installed on the system under these future operating conditions. One of the most significant obstacles of deploying GFM IBRs on the bulk power system (BPS) is establishing clear interconnection requirements regarding the expected performance, testing, and validation of the technology. This paper addresses how Transmission Owners (TO), Transmission Planners (TP), and Planning Coordinators (PC) can establish these requirements and test interconnecting resources to ensure they meet the GFM specifications. Generator Owners (GO) will also have clear performance expectations for GFM resource interconnections and can work with their respective equipment manufacturers prior to interconnection studies being conducted to help streamline the interconnection queue process, where possible. TPs and PCs will need to test new project models to ensure they meet the GFM specifications. The recommended set of GFM tests are provided in this paper, designed to verify the unique characteristics of GFM. The paper also addresses GFM model quality and accuracy as a prerequisite to any studies being conducted.

A common question posed by industry stakeholders is "how many future IBRs should be deployed with GFM functionality enabled?" The answer is system-specific and requires detailed reliability studies to determine. Studies conducted thus far indicate these numbers may be upwards of 30%.[1,2,3] Since the current percentage of GFM resources is near zero in nearly all large, interconnected power systems, it is recommended to start requiring and enabling GFM in all future Battery Energy Storage System (BESS) projects for multiple reasons. GFM technology is commercially available but has not yet been widely deployed. While this technology has great potential in its ability to help improve stability and reliability in areas with high IBR penetration or low system strength areas, responsible entities should evaluate GFM IBR benefits and performance on their system before following up with wide-scale implementation.[4] New BESS can be equipped with GFM technology at a relatively low incremental controller and hardware cost.[5,6] Implementing GFM controls at existing grid following (GFL) BESS projects may only require controls changes. However, these changes to an existing plant, as a material modification, will require additional studies to determine any impacts to BPS reliability. Due to the potential costs, time delays and complexities of this retroactive process, it is recommended that all new BESS projects are commissioned with the ability to perform GFM control, with GFM controls being enabled after being sufficiently studied. Enabling GFM in all future BESS projects is a relatively low-cost solution that helps ensure system-wide stability that is difficult to quantify today due to study limitations. Industry should begin specifying, requiring, and implementing GFM for all new BPS-connected BESS quickly to mitigate any potential BPS reliability risks that could be posed under high IBR penetration levels expected in the near future. Though the focus of this paper is on near-term BESS applications, GFM technology may need to be considered when developing new inverter-based transmission applications, such as static synchronous compensators (STATCOM) or high-voltage direct current (HVDC) converter stations.

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[1] https://ieeexplore.ieee.org/document/9875186

[2] Using the full capabilities of modern inverters may enable lowering this threshold somewhat.

[3] This percentage results from a study performed outside of the North American BPS and is intended to be informational. To determine an appropriate percentage for a specific area, similar studies should be performed using large area electromagnetic transient (EMT) models.

[4] For example, ERCOT presented the results of ERCOT Assessment of GFM Energy Storage Resources at the Inverter-Based Resource Working Group meeting on August 11, 2023. As the next step, ERCOT will work on the requirements for GFM Energy Storage Resources including but not limited to performance, models, studies, and verification. See Appendix B of this paper for more details.

[5] New interconnection studies are recommended for the existing GFL project updated to GFM.

[6] Cost to implement GFM technology varies due to variations in the hardware on-site and the performance intended to be enabled.

Key Takeaways and Recommendations

The following key takeaways and recommendations should be considered and implemented by the associated entities for adoption of GFM to improve overall BPS reliability under conditions of increasing penetrations of IBRs:

- GFM technology is commercially available and field-proven for transmission-connected applications, particularly for BESS (including standalone BESS[7] in ac-coupled hybrid plants) as well as dc-coupled solar photovoltaic (PV)+BESS[8] applications. GFM requirements, policies, and/or market incentives should be developed for BESS or hybrid plants that include BESS, as mentioned above. (*Original Equipment Manufacturers* (*OEM), developers, GOs, Generator Operators (GOP), TPs, PCs, Transmission Operators (TOP), Reliability Coordinators (RC), regulatory entities, policymakers)*
- All newly interconnecting BPS-connected BESS should be designed, carefully studied by responsible entities, and commissioned with GFM controls[9] enabled to improve overall system stability across the BPS, particularly with increasing levels of IBRs. Developers and GOs can ensure requirements[10] are in contractual language with OEMs. Existing BESS may be able to be retrofitted at relatively low incremental controller and hardware costs; however, they will need to be restudied by the TP, PC, TOP, RC, or Balancing Authority (BA) and potentially retuned, as determined by the study results. In cases where the responsible entities conclude that barriers to deploying GFM BESS exist at this time, responsible entities should consider specifying IBRs that can be configured for both GFL controls and GFM controls; this will allow for the controlled testing of the technology under both owner and responsible utility oversight. *(GOs, TPs, PCs, RCs, TOPs, BAs, developers, OEMs)*
- TOs in consultation with their TPs and PCs, should leverage the information in this white paper to begin the process of establishing GFM functional specifications for BESS in their interconnection requirements (or provisions in power purchase agreements) in anticipation of future GFM BESS installations. As with any other resource, GFM BESS should be studied to assess its impact on the BPS before interconnection. Additionally, it is recommended to require adequate fault recording and sequence of event recording equipment before installing a GFM IBR to ensure adequate assessment of the performance of the GFM controls during BPS disturbances.
- TPs and PCs should begin training their staff in conducting studies to assess the functional differences in GFM controls so that they can be properly prepared to integrate GFM functional testing requirements in their interconnection study processes, ensuring that newly connecting GFM is able to meet performance requirements. *(TPs, PCs)*
- GFM technology has been shown to operate reliably and provide stabilizing characteristics in transmission systems outside of the BPS in areas of high IBR penetrations and areas of low system strength. GFM BESS presents a unique opportunity to support system stability (e.g., transient, oscillatory, voltage) with a relatively low incremental cost to all resources and end-use consumers *(Developers, OEMs, GOs, GOPs, TPs, PCs, TOPs, RCs)*. While the results seen by others outside of the North American BPS are very encouraging, careful testing and validation of GFM performance by responsible entities is still needed before broad deployment of this technology in their system.
- GFM technology will continue to develop and improve beyond where it is today. Future research efforts can help aid in accelerated development and adoption, particularly focusing on GFL-to-GFM conversion possibilities, equipment standardization, GFM in blackstart applications, technical specifications for GFM blackstart, and GFM controls in other IBR technologies such as wind and solar PV. *(U.S. Department of Energy, national laboratories, research institutes, academic institutions)*

[7] World's largest 'grid-forming' battery to begin construction in Australia – pv magazine International (pv-magazine.com)
[8] Hybrid Solar and Storage in Hawaii | T&D World (tdworld.com)
[9] As functionally specified in this paper
[10] See, for example: Appendix J-1 Oahu RDG PSA (hawaiianelectric.com)

Introduction

Background

NERC *White Paper: Grid Forming Technology*[11] defined GFM controls for IBRs as:

> **Grid Forming Control for BPS-Connected Inverter-Based Resources** are controls with the primary objective of maintaining an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame. This allows the IBR to immediately respond to changes in the external system and maintain IBR control stability during challenging network conditions. The voltage phasor must be controlled to maintain synchronism with other devices in the grid and must also regulate active and reactive power appropriately to support the grid.

This uniquely differs from conventional GFL IBR controls in that the primary GFL control objective in the sub-transient time frame is to maintain a constant output *current* phasor magnitude and angle, with adjustments to control the desired active and reactive power being injected into the network. Hence, GFL does not maintain fixed voltage magnitude or phase angle on those timescales. On longer timescales (seconds), it can also pursue other control objectives such as maximum power point tracking, frequency response, and voltage regulation.

A GFM inverter's control objective, on the other hand, in the shortest (sub-transient) time frames (e.g., 0-5 cycles after a disturbance), is to maintain *voltage* phasor magnitude and angle internally, and prioritize the support of terminal voltage. Therefore, it does not maintain fixed active or reactive power on those time frames. On longer time frames, a GFM inverter must also synchronize with other sources and may also pursue other objectives including tracking of active power and reactive power set point. In all cases, the inverter controls could be restricted by the inverter and primary energy source capability limits (e.g., available energy, current limits, voltages).

Benefits of Enabling GFM Controls in BPS-Connected BESS

It is estimated that there was 427 GW of BESS capacity (including both standalone BESS capacity and BESS capacity as a part of hybrid plants) in the interconnection queues around the United States as of the end of 2021.[12] By the end of 2022, this number increased to 680 GW.[13] In the absence of any requirements or incentives for GFM capability, all of these resources are being planned with GFL controls. Many of these BESS will be deployed in IBR-dominated areas of the BPS with existing stability constraints. Installing these resources as GFL will likely further reduce stability margins and may result in new stability constraints. This will lead to further reduction of low-cost generation from existing IBRs in these areas (i.e., curtailment of IBRs during real-time operation) due to stability constraints that could be addressed by GFM, thus increasing overall energy costs. To relieve these constraints without considering GFM in BESS, additional transmission assets such as synchronous condensers,[14] GFM STATCOM[15] with energy storage, or new transmission lines[16] will be needed which will drive transmission costs higher.

GFM controls can provide grid stabilizing characteristics that support reliable operation of the BPS under increasing penetration of IBRs. Enabling GFM in BPS-connected BESS allows for system-wide enhancement of stability margins as these resources are interconnected. Therefore, system stability enhancements can be achieved at much lower cost than through the addition of transmission assets.[17] As discussed above, GFM controls can be implemented on any type of IBR including new solar photovoltaic and wind plants with some limitations; however, GFM controls in BESS

[11] https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_Grid_Forming_Technology.pdf
[12] https://emp.lbl.gov/sites/default/files/queued_up_2021_04-13-2022.pdf
[13] https://emp.lbl.gov/sites/default/files/queued_up_2022_04-06-2023.pdf
[14] https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/congestion-information/sa-transition-to-fewer-synch-gen-grid-reference.pdf?la=en
[15] STATCOM Technology Evolution for Tomorrow's Grid (nxtbook.com)
[16] Adding new transmission lines will decrease the transfer impedance (make it a stiffer/stronger system).
[17] Transmission assets still serve critical roles for overall BPS reliability in addition to the considerations for GFM BESS presented in this paper.

are particularly low-hanging fruit for assuring BPS reliability since they already have the needed energy buffer on the dc side, which makes the enhancement purely software-based (minimizing much more costly hardware-based improvements and/or the moderate level of curtailment that may be needed for other IBR technologies).

While some areas, like the Hawaiian Islands, already need to enable GFM BESS to maintain grid stability and prevent large-scale outages, many areas of the United States are reaching relatively high penetrations of IBRs now or in the future and will face similar challenges. Industry is faced with a unique window of opportunity to procure, test, and gain experience with GFM technology now before significant adverse reliability issues arise in the future due to the lack of sufficient GFM resources.

Testing and Demonstration of Services Ahead of Requirements

Existing GFL technology can provide a number of essential reliability services to the BPS. Demonstration projects[18] have illustrated these capabilities for many years, and modern IBR facilities can provide regulation services, primary and fast frequency response, dynamic voltage support, etc. GFM controls do not preclude a resource from providing any of these critical features to the BPS. Rather, GFM controls enable additional features from BESS beyond what can be provided from GFL today. Examples include operating in low system-strength conditions, improving overall system stability, helping stabilize the system following large generator loss events (supporting arresting frequency changes), and potentially enabling blackstart capability from IBRs.

Multiple GFM projects around the world have been deployed, with more GFM projects under procurement. See **Table I.1** and more details in **Appendix A**. However, widespread adoption has been relatively slow due to limited pilot projects (particularly of large numbers of GFM resources in one area) and difficulties establishing GFM performance specifications and testing procedures. Furthermore, detailed studies of GFM technology require EMT modeling, which is challenging for large areas due to lack of expertise and computational limitations today.

Table I.1: GFM BESS Projects Deployed or under Construction

Project Name	Location	Size (MW)	Time
Project #1	Kauai, USA	13	2018
Kauai PMRF	Kauai, USA	14	2022
Kapolei Energy Storage	Hawaii, USA	185	2023
Hornsdale Power Reserve	Australia	150	2022
Wallgrove	Australia	50	2022
Broken Hill BESS	Australia	50	2023
Riverina and Darlington Point	Australia	150	2023
New England BESS	Australia	50	2023
Dalrymple	Australia	30	2018
Blackhillock[19]	Great Britain	300	2024
Bordesholm[20]	Germany	15	2019

While GFM capability in batteries can be delivered at relatively low incremental cost, there may still be some costs associated with project and product development simply due to the newness of the technology. Widespread adoption of GFM IBRs will ensure an adequate level of BPS reliability moving forward. In addition, market operators may establish market-based mechanisms that can drive GFM adoption at a rapid pace, where appropriate.

[18] Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant (nrel.gov)
[19] Zenobē breaks ground on pioneering 300MW battery in Blackhillock - Zenobē (zenobe.com)
[20] The Bordesholm stand-alone grid ensures power supply even in the event of a grid failure - Sunny. SMA Corporate Blog (sma-sunny.com)

The Cost of Inaction

This is a unique moment in the industry when a need is becoming fully understood and an effective, relatively low-cost GFM solution has emerged. GFM capability in BESS is a viable and effective solution to address declining stability margins system-wide and to manage decreasing system strength and the issues that arise under these conditions (e.g., wind and solar PV curtailments). The industry is at the cusp of a rapid growth of BESS capacity on the system in the next few years. Without GFM functional specifications and test procedures established by TOs, TPs, and PCs, and the appropriate incentives or requirements in place, much or all of the newly installed BESS capacity will likely not have GFM capability enabled (either precluding the possibility of GFM or requiring significantly more costly retrofits or network upgrades). If GFM capability is not adopted very soon, the outcome will be reduced transfer limits for existing IBRs and consequently growing levels of solar PV and wind curtailment, and additional costs of supplemental stabilizing equipment (e.g., synchronous condensers) in the future.

Independent System Operators/Regional Transmission Operators/utilities should work with stakeholders to carry out studies of the implementation of GFM technology in low grid-strength areas[21] and act quickly to implement pilot projects (similar to how the provision of ancillary services from GFL IBRs has been tested in the past). Experience from GFM BESS project installations around the world, particularly Great Britain and Australia (see **Appendix A**), can be used as a guide.

Presently, the recommendation is that all new BESS connecting to the BPS should have the capability for GFM operation or future capability to be upgraded with GFM controls (if necessary). TOs should establish this requirement in their interconnection requirements or power purchase agreements (PPA). Developers and GOs can also ensure that these requirements are in contractual language with the equipment manufacturers. To support enhanced BPS reliability, it is strongly recommended that newly interconnecting BESS enable GFM capability or have the capability for GFM controls. Additionally, GFM controls should be enabled only after being studied by the responsible entity, as with any new resource or qualified change.

Functionally Defining GFM Performance

Although the concept of GFM technology has been around for many years, mainly in small islanded systems or microgrids, the term has caused confusion in recent years when the concept is applied to the BPS. Various documents have proposed definitions to try to reduce confusion (see **Appendix A:** for reference). Most definitions agree that at a minimum, GFM controls tend to hold their voltage magnitude and angle at the device terminals constant in the period immediately following a system event. This tends to provide a resistance to change in the external system and thereby grants certain stabilizing properties. Although there is general consensus on what GFM is as a concept, opinions differ on the degree and extent the concept should be used when qualifying an interconnecting device as GFM, as well as how to test the capability. Specifying GFM may be done in a number of ways, including the following:

1. *Control topology:* The theoretical behavior of a device may be defined based on specific types of control topologies such as virtual synchronous machine or droop-based topologies. It is not recommended to define GFM behavior based on control topology, to leave room for innovation.
2. *Quantitative response metrics:* The precise behavior of a device in response to external system events can be defined, with no regard to the internal control topology. Quantities like active and reactive power rise time in response to a network event can be used to test whether the controls provide the stabilizing influence expected from GFM.
3. *Frequency domain characterization:* GFM controls tend to have signature responses to stimuli with varying frequencies. It is likely possible to provide an accurate determination of the GFM capabilities of a device by

[21] Due to loss of the last synchronous machine, an extremely low system strength scenario manifests in the tests described in this document.

measuring its response to external perturbations across a range of frequencies.[22] Significant promising research work is underway in this field.[23,24]

4. *General testing definition (***Recommended***):* It is possible to determine whether a device functionally meets the definition for GFM control by observing whether the device is capable of performing well during certain well-defined simulation tests. For example, GFM IBRs can be subjected to severe external events that are generally difficult or impossible for conventional GFL devices to stably operate through. For example, a GFM device, like a synchronous generator, is able to operate and serve load with no other synchronous machines in service. It is generally able to operate in synchronism with other synchronous machines, continue stable operation when those machines are disconnected, and continue stable operation when those machines are re-connected. GFL IBRs are generally not able to do all these things. Even if a GFM plant will not be subjected to these events in real-time operation, the tests indicate that the controls can provide the stability benefits needed.

To avoid confusion and conflicts in understanding, the fourth approach is proposed until sufficient research and field experience is available to fairly and effectively use other methods. This approach is further described in **Chapter 2**. It provides confidence that GFM controls will provide the necessary stabilizing characteristics even if the specific test scenarios never occur during real-time operations. The general testing definitions in this white paper are not intended to be overly prescriptive and should be used to inform the development of future qualitative GFM performance requirements. The method is simple to implement and agnostic to GFM control topologies, and similar approaches have been successfully implemented in BESS procurements around the world.[25,26]

Minimum Necessary Capacity of GFM Inverters for Future High IBR Grids

It is well understood that as the penetration of IBRs continues to rise and the stabilizing effects provided by synchronous machines decrease, the grid will need some amount of GFM-enabled resources to ensure system stability.[27] This logically raises the question of a necessary or recommended capacity (presumably a % value) of GFM-enabled IBRs relative to the total capacity of IBRs and/or machines on the BPS. While industry does not currently have a rule-of-thumb to prescribe the minimum necessary capacity of GFM IBRs needed to stabilize a given system, recent research provides a few points of reference. This section outlines current industry recommendations on this topic.

Relatively few studies have been performed, particularly for large, interconnected power systems. However, smaller islanded systems have explored this issue in much more detail. For example, power hardware-in-the-loop (PHIL) tests of the HECO Maui system illustrated the percentage of GFM inverters needed for stability at various system inertia levels.[28] This work found that as system inertia dropped toward zero (an entirely inverter-based system), the amount of GFM inverters necessary to maintain system stability increased relatively linearly. When the system has zero mechanical rotating inertia, the percentage of GFM inverters relative to total system capacity (consisting of only GFM and GFL inverters) was around 30% (see **Figure I.1**). The GFL IBRs in this system consisted primarily of IBRs with no voltage or frequency support capability, with only a few grid supportive GFL IBRs providing voltage support or fast frequency response. HECO also highlighted the need for some reliability margin, therefore recommending that this ratio be increased to account for unexpected issues like legacy distributed energy resource momentary cessation issues or unexpected inverter tripping issues. This study also highlighted that the necessary capacity of GFM IBRs

[22] Small-signal frequency-domain methods can be used as screening methods which are typically followed up by time-domain verification that consider both large and small-signal stability.

[23] Sequence Impedance Measurement of Utility-Scale Wind Turbines and Inverters - Reference Frame, Frequency Coupling, and MIMO/SISO Forms (nrel.gov)

[24] https://www.nrel.gov/docs/fy23osti/84604.pdf

[25] https://www.nationalgrideso.com/document/250216/download

[26] https://www.youtube.com/watch?v=2e5ET0L1j5g

[27] Note that, alternatively, adequately sized and placed synchronous condensers can also be used to ensure system stability with high IBR. However, with GFM capability provided by IBRs themselves, installation of these additional grid assets can be avoided.

[28] https://ieeexplore.ieee.org/abstract/document/9875186

does not necessarily depend on the total percentage of generation from IBRs (which was above 95% in all cases studied). Instead, low total online synchronous machine capacity (as quantified via system inertia constant, for example) was a much better predictor of the need for GFM.

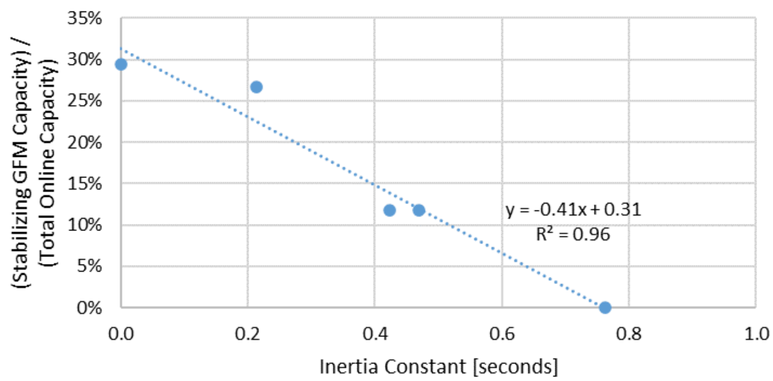

Figure I.1: HECO Study of GFM Needed for Stability at Various Inertia Levels

Similarly, a recent paper[29] from the European Union-funded project, MIGRATE, studied the composition of GFM and GFL inverters in various systems and identified a need for at least a 37% ratio of GFM IBRs to total IBRs in the system. There were sensitivities based on numerous factors that modified that number slightly.

It is important to note that the actual GFM capacity needed for system stability will vary from system to system and can also depend on the type of contingency being studied. Issues could be system-wide (e.g., need for stable fast frequency response) or could be more localized (e.g., need for operation in low short-circuit strength networks). This could drive the need for stabilizing services from additional resources, or from existing installed resources. The needed capacity of GFM is also impacted by the dynamic characteristics of other sources in the network such as GFL inverters and load. With the approval of FERC Orders 842 and 827 and IEEE 2800-2022, the response of GFL resources may be more advanced than that of legacy IBRs, which could impact the necessary capacity of GFM to maintain grid stability.

As an example, a study on an island power network[30] identified that the minimum percentage of GFM required to maintain frequency and voltage stability was 11% if frequency and voltage support were provided by other IBR resources per IEEE 2800-2022. However, if GFL IBRs had no frequency and voltage response capability, the study identified that a minimum of 23.5% GFM IBR was necessary to maintain stability. Therefore, it is important that TOs, TPs, and PCs ensure adequate levels of GFM resources moving forward to maintain system stability, with suitable margin to avoid any adverse reliability impacts from unexpected performance issues.

[29] https://www.h2020-migrate.eu/_Resources/Persistent/5d0f8339650bcf53cd24a3006556daa1da66cb42/D3.4%20-%20New%20Options%20in%20System%20Operations.pdf
[30] “Services from IBR for future systems”, 2022 ESIG Reliability Working Group Meeting, October 2022

Chapter 1: Functional Specifications for GFM BESS

This chapter defines the recommended functional specifications for GFM BESS that applicable entities can use to inform inclusion of GFM specifications in their requirements. For effective and efficient adoption of GFM technology, TOs will need to establish functional specifications that define GFM functionality. The GFM specification can then be provided to OEMs by developers and GOs to ensure procurement of GFM resources.

Functional Specifications for GFM and GFL Battery Energy Storage

All BPS-connected generating resources are required to meet applicable interconnection requirements and performance-based standards. Requirements often establish specifications related to, but not limited to, the following:

- **Dispatchability:** Capability of the facility to be dispatched (or curtailed) to a specific active-power set point
- **Steady-State Voltage Control:** Capability of the facility to control steady-state voltage at the point of interconnection to a specific voltage schedule (set point and operating band)
- **Dynamic Reactive Power Support:** Capability of the facility to provide dynamic reactive support in response to normal and emergency grid conditions within the expected ride-through performance range
- **Active-Power Frequency Control:** Capability of the facility to respond to changes in system frequency by changing active power output when the resource has available headroom/tailroom
- **Disturbance Ride-Through Performance[31]:** Capability of the facility to ride through normal grid disturbances within a defined set of parameters or expectations including but not limited to faults and phase jumps
- **Fault Current and Negative Sequence Current Contribution:** Capability of the facility to provide fault current, including negative sequence current to mitigate unbalanced voltage conditions and facilitate relay operation[32]
- **Security:** Capability of the facility to have cyber and physical controls in place to ensure resilience to potential threats

Functional Specifications Defining Grid Forming BESS

Additionally, functional specifications need to be clearly defined for GFM-specific functions. Following are performance characteristics specific to GFM BESS: These characteristics shall be provided within GFM BESS equipment rating limits:

- **GFM-Specific Voltage and Frequency Support:** GFM shall provide autonomous, near-instantaneous frequency and voltage support by maintaining a nearly constant internal voltage phasor in the sub-transient time frame, including:
  - **Phase Jump Performance:** GFM shall resist near-instantaneous voltage magnitude and phase angle changes by providing appropriate[33] levels of active and reactive power output in the sub-transient time frame.
  - **System Strength Support:** GFM shall help reduce the sensitivity of voltage change for a given change in current in the sub-transient time scale.

[31] GFM BESS fault ride through capability and performance during and after the fault is critical to grid stability and should be tested just as it would be for a GFL facility.
[32] This can be achieved, for example, by maintaining balanced GFM resource internal voltage during asymmetrical faults.
[33] As an example, if the phase difference between the inverter terminal and the grid increases, the resource should increase (or make less negative) its active power injection in the sub-transient time scale. If the phase difference reduces, it should result in a reduction of its active power injection in the sub-transient time scale.

- **Ability to Stably Operate with Loss of Last Synchronous Machine:** GFM shall be able to stably operate through and following the disconnection of the last synchronous machine in its portion of the power grid.[34]

There are additional desirable characteristics for GFM performance; however, present technology may not be able to widely meet these performance specifications. Therefore, they are listed here as specifications to consider in future GFM technology. They include the following:

- **Passivity:** GFM should present a non-negative resistance and present a passive characteristic to the grid within a wide frequency range (0–300 Hz) to prevent adverse interactions.
- **Negative Sequence Current during Continuous Operating Region:** GFM plant should provide negative sequence current.
- **Balanced GFM Internal Voltage:** The GFM resource should also ensure its internally generated voltage remains balanced during all near-nominal operating conditions (e.g., 0.9–1.1. pu voltage range).

Blackstart Considerations

GFM and blackstart-capable are not synonymous terms; however, GFM functionality is a prerequisite for an IBR to be eligible for blackstart capability. The TO, TOP, or RC may establish additional requirements for blackstart capability[35] beyond the general specifications for GFM, which may necessitate extended capability for the short-term overcurrent, more stringent ride-through capability, longer energy duration needs or additional hardware to supply sufficient and reliable start-up power to restore the electricity system from a blackout. These unique local requirements may preclude certain GFM resources from participating in blackstart services. It should be noted that a GFM IBR does not necessarily have to provide blackstart services, and blackstart capability requirement should be specified separately.

Additional Considerations

The following are additional considerations for the functional specification of GFM in BESS:

- All the functional specifications listed above are applicable when the BESS is within its limits of the energy source behind the inverter and the equipment ratings of the inverter.[36] These functional specifications do not impose any requirements for fault current capability beyond equipment ratings.
- GFM BESS shall continue providing GFM operational characteristics even at its highest and lowest allowable state of charge. If the BESS remains connected to the network, it shall remain in GFM mode as defined in the Introduction of this document. There should be no state of charge condition where the BESS should need to operate in GFL mode.
- Performance requirements for BPS-connected IBRs such as, for example, IEEE 2800 may also apply to GFM resources unless explicitly stated by the local interconnection requirements. To the extent that existing requirements in IEEE 2800 may create any barriers to GFM applications, exceptions may need to be considered and specified by the TO, TOP, RC, or BA. Simultaneously, industry can contribute toward improvements of the relevant standards to accommodate the requirements for GFM.

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[34] While generation capacity in the system can still meet the load

[35] https://www.hawaiianelectric.com/documents/clean_energy_hawaii/selling_power_to_the_utility/competitive_bidding/20220531_exh_5.pdf

[36] Transient conditions can cause GFM BESS to reach current limits, resulting in transient behavior that differs from the GFM performance characteristics described above.

Chapter 2: Verifying GFM Functionality

This chapter describes the functional performance verification tests that determine whether an interconnecting BESS can be classified as GFM. TPs and PCs should integrate these tests as part of the interconnection study process in coordination with TOs, PCs, BAs, or TOPs establishing GFM requirements for newly interconnecting BESS. GOs, developers, and OEMs can ensure that planned facilities meet these functional specifications prior to interconnection studies, which will help expedite the process. Verifying GFM functionality with test simulations[37] (referred to herein as "GFM functional tests") using accurate and detailed EMT models provided and certified directly from the OEM is necessary, in addition to attestations and detailed descriptions of the control modes from the OEMs.

Model Quality Fundamentals

The most important prerequisite to model-based performance verification is establishing confidence in the model quality. Ensuring an accurate and verified model is a fundamental prerequisite to conducting any reliability studies using the models, and clear model quality requirements and checks should be established by TPs and PCs in all instances. As with all model representations of actual facilities, the following fundamental aspects of modeling and verification are needed before GFM-specific testing is conducted:

- OEM-provided validated models and validation test reports against lab or field test, or hardware-in-the-loop (HIL) test of the product to be used in this project. This model validation test may include a generic representation of the overall facility but must include the actual control and converter level protection of the product that will be installed in the project. The following validation tests are recommended at a minimum:[38]
  - Balanced and unbalanced faults
  - Grid voltage disturbance – step change in magnitude and phase
  - Grid frequency disturbance – step change in frequency and frequency ramp at slow and fast rate of change of frequency (ROCOF)
  - Active and reactive power dispatch command step change
  - Loss of the last synchronous generator[39]
  - Load rejection
- Attestation from the inverter OEM(s) that the model provided matches the expected as-built configuration and settings to the degree known at the time of model submission.[40]
- Attestation from the plant-level controller(s) OEM(s) that the model provided matches the expected as-built configuration and settings to the degree known at the time of model submission.
- Model quality checks conducted by the TP/PC to ensure appropriate representation and parameterization of the model provided by the GO/developer.
- Model documentation is provided that describes the functionality and operation of the resource being deployed and model used.
- The model meets the quality criteria outlined in the NERC EMT Reliability Guideline.[41]

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[37] One of the best mechanisms to gain confidence in simulation models is to compare them against real event data. Current availability of this type of data is limited for GFM installations, but as more are obtained in the coming years it will be beneficial to review this performance and integrate the learning into future GFM guides.

[38] Refer to IEEE 2800.2 once published for additional benchmarking tests that could supplement or augment those listed.

[39] For model validation using hardware testing, OEMs may choose to leverage tests similar to those outlined in "Verification Test for GFM Functionality" section.

[40] The final tuning parameters/setting of the project should be accompanied with the provided model parameters/settings update to GO/TO.

[41] https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline-EMT_Modeling_and_Simulations.pdf

Description of GFM Functional Test System

The GFM functional test system (see **Figure 2.1**) consists of the following components connected to a single bus without any impedance:

- A synchronous generator with a simple excitation system model (e.g., SCRX) and turbine-governor model (e.g., TGOV1), with circuit breaker[42]
- A load[43] with both active and reactive power (inductive) components, with a maximum power factor of 0.9
- The GFM BESS plant model under test
- A duplicate of the GFM BESS plant model, rated at or near half (MVA and MW) of the model under test[44]

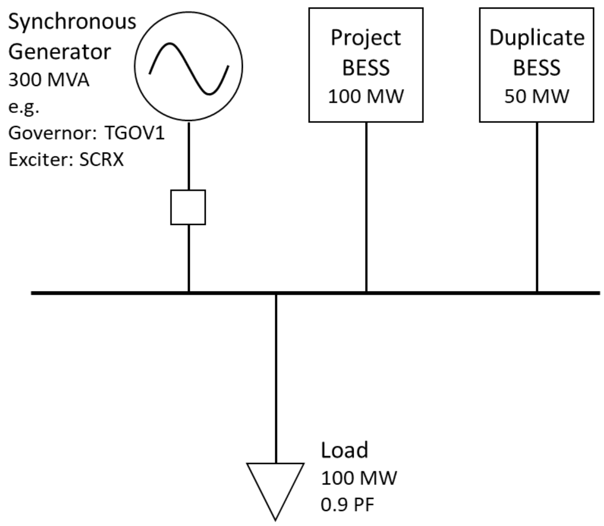

Figure 2.1: GFM Functional Test System[45]

The combined MVA rating of the BESS models must be sufficient to fully supply the load upon disconnection of the synchronous generator. The synchronous generator MVA rating must be sufficient to simultaneously serve the load and charge both BESS at their rated maximum charge power. Both BESS models should be in voltage control mode with the same voltage and frequency droop settings and set points. All protection settings in the BESS should reflect the equipment planned to be installed in the field; however, settings should be set as wide as possible within the equipment ratings and capabilities (as recommended in NERC reliability guidelines)[46] since the tests are intended to subject the GFM BESS to extreme frequency, voltage, and phase jump events.

Description of GFM Functional Tests and Success Criteria

Using simulated disturbances that only a GFM BESS meeting the functional specifications could survive, the following suite of GFM functional tests are designed to ensure that each proposed project meets the GFM BESS functional specifications as described in this document.[47,48]

[42] For simulating the loss of the synchronous generator
[43] Constant impedance load model is used in the example tests described later in this chapter.
[44] The purpose of adding the duplicate BESS is to consider control interaction between multiple GFM devices, including droop response and to provide flexibility in post-event power balancing.
[45] BESS ratings and synchronous generator ratings are for example only.
[46] https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline-EMT_Modeling_and_Simulations.pdf
[47] TP/PC may require additional tests such as load rejection, faults, etc.
[48] For example: *Hawaiian Electric Facility Technical Model Requirements and Review Process*, August 2022: https://www.hawaiianelectric.com/documents/clean_energy_hawaii/selling_power_to_the_utility/competitive_bidding/20210901_cbre_rfp/20210825_redline_lanai_appxb_att3.pdf

- **Test 1 – BESS Initially Discharging and Ends at Higher Level of Discharging:** This test assesses the GFM BESS performance following the generator trip when operating within its limits and in discharging state.
- **Test 2 – BESS Initially Charging and Ends Up Discharging:** This test assesses the GFM BESS performance when operating within its limits and transitioning from charging state to discharging state after the generator trips.
- **Test 3 – BESS GFM Performance at Maximum Active Power:** This test assesses the GFM BESS performance following the generator trip when operating at or near its limits.

Each test is conducted using different initial operating conditions, as outlined in Table 2.1–Table 2.3. Once the system is stable at the given power flow conditions (without oscillations), the synchronous generator is disconnected. Each test then includes a set of pass/fail success criteria that must *all* be met. TPs/PCs should add additional qualitative or quantitative criteria specific to their own systems, as applicable. GFM BESS under test must pass all three tests to qualify as GFM. [49]

Although the tests require the BESS to be operated in the absence of any synchronous generation, many GFM BESS will never be operated that way. Regardless, the ability to survive such tests indicates that the controls have the necessary properties of GFM in grid-connected conditions. Conversely, if the resource is unable to meet the performance requirements in these tests, the controls will not have the desired characteristics for future BPS operating conditions.

These tests do not guarantee that the facility will be stable for a specific location on the grid. Interconnection studies are critical for ensuring reliable operation of the BPS for each specific interconnecting resource.[50] If settings change during interconnection studies, the model with the new settings should still pass these tests.

Test 1: BESS Initially Discharging and Ends at Higher Level of Discharging

Table 2.1: Test 1 – Setup and Success Criteria	
Initial Dispatch	
• The project BESS is dispatched at 20% of its maximum discharge power limit. • The duplicate BESS is dispatched at 20% of its maximum discharge power limit.	
Test Sequence:	
▪ Run until the system is stable at the given power flow conditions, without oscillations. ▪ Trip the synchronous generator.	
Success Criteria	
Pre-Trip:	**Pass/Fail**
• Each BESS's active power output matches dispatched levels.	
• Synchronous generator active power output matches the rest of the load.	
• Frequency should be 1 pu.	
• Voltage at Bus 1 should be within 5% of nominal.	
• Phase voltage and current waveform should not be distorted.	
• There should not be oscillations in the root mean square (RMS) quantities.	

[49] GFL BESS can potentially form an island with load under very specific power flow and resonance conditions. Hence, it's important to subject the project model to all three tests.

[50] Other tests such as ride-through capability, voltage control, etc., are necessary to be conducted for all resources, including GFM and GFL.

Table 2.1: Test 1 – Setup and Success Criteria	
• Reactive power output from all devices should be within limits.	
Post-Trip:	**Pass/Fail**
• Immediately following the trip, BESS output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady-state levels for any significant amount of time.	
• Voltage settles to a stable and acceptable operating point.	
• The final voltage is as expected based on the droop and deadband settings.	
• Frequency settles to a stable operating point.	
• The final frequency is as expected based on the droop and deadband settings.	
• Any oscillation shall be settled.	
• Any distortion observed in phase quantities should dissipate over time.	
• Active power from each BESS should move immediately to meet the load requirement and settle according to its frequency droop setting.	
• Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	

Test 2: BESS Initially Charging and Ends Up Discharging

Table 2.2: Test 2 – Setup and Success Criteria	
Initial Dispatch	
▪ The project BESS is dispatched at half of its maximum charge power limit. ▪ The duplicate BESS is dispatched at half of its maximum charge power limit.	
Test Sequence:	
• Run until the system is stable at the given power flow conditions, without oscillations. • Trip the synchronous generator.	
Success Criteria	
Pre-Trip:	**Pass/Fail**
• BESS's active power output matches dispatched levels.	
• Synchronous generator active power output matches the load and BESS charging.	
• Frequency should be 1 pu.	
• Voltage at Bus 1 should be within 5% of nominal.	
• Phase voltage and current waveform should not be distorted.	
• There should not be oscillations in the RMS quantities.	
• Reactive power output from all devices should be within limits.	
Post-Trip:	**Pass/Fail**
• Immediately following the trip, BESS output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady-state levels for any significant amount of time.	
• Voltage settles to a stable operating point.	
• The final voltage is as expected based on the droop and deadband settings.	
• Frequency settles to a stable operating point.	
• The final frequency is as expected based on the droop and deadband settings.	
• Any oscillation shall be settled.	
• Any distortion observed in phase quantities should dissipate over time.	
• Active power from each BESS should move immediately to meet the load requirement and settle according to its frequency droop setting.	
• Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	

Test 3: BESS GFM Performance at Maximum Active Power

Table 2.3: Test 3 – Setup and Success Criteria	
Initial Dispatch	
▪ The project BESS is dispatched at 0 MW. ▪ The duplicate BESS is dispatched at its steady-state maximum discharge power limit.	
Test Sequence:	
• Run until the system is stable at the given power flow conditions, without oscillations. • Trip the synchronous generator (no fault).	
Success Criteria	
Pre-Trip:	**Pass/Fail**
• Each BESS's active power output matches dispatched levels.	
• Synchronous generator active power output matches the rest of the load.	
• Frequency should be 1 pu.	
• Voltage at Bus 1 should be within 5% of nominal.	
• Phase voltage and current waveform should not be distorted.	
• There should not be oscillations in the RMS quantities.	
• Reactive power output from all devices should be within limits.	
Post-Trip:	**Pass/Fail**
• Immediately following the trip, BESS output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady-state levels for any significant amount of time.	
• Voltage settles to a stable operating point.	
• The final voltage is as expected based on the droop and deadband settings.	
• Frequency settles to a stable operating point.	
• The final frequency is as expected based on the droop and deadband settings.	
• Any oscillation shall be settled.	
• Any distortion observed in phase quantities should dissipate over time.	
• Active power from BESS 1 should move immediately to meet the load requirement and settle according to its frequency droop setting. Active power from BESS 2 should not exceed its max discharge power limit at steady state.[51]	
• Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	

Example Conducting GFM Functional Tests

To illustrate conducting the GFM functional tests, an OEM-provided GFM model, including a power plant controller model, was subjected to each test outlined above. Appendix B provides additional examples of the GFM functional

[51] BESS 2 output may exceed momentarily depending on the active power availability at the inverters.

tests applied to a GFM model supplied by a different OEM. Table 2.4 shows the BESS voltage and frequency droop settings used for these tests.

Table 2.4: BESS Voltage and Frequency Droop Settings for Example Tests

Parameter	Value
Voltage Droop	2% (on Qmax)
Frequency Droop	2% (on Pmax)
Frequency Deadband	0.03 Hz

Test 1: BESSs Initially Discharging and Ends at Higher Level of Discharging

The test system is initialized with power flow conditions shown in Figure 2.2. BESSs are discharging at a quarter of their maximum discharge site limit, with the synchronous generator servicing the rest of the load.

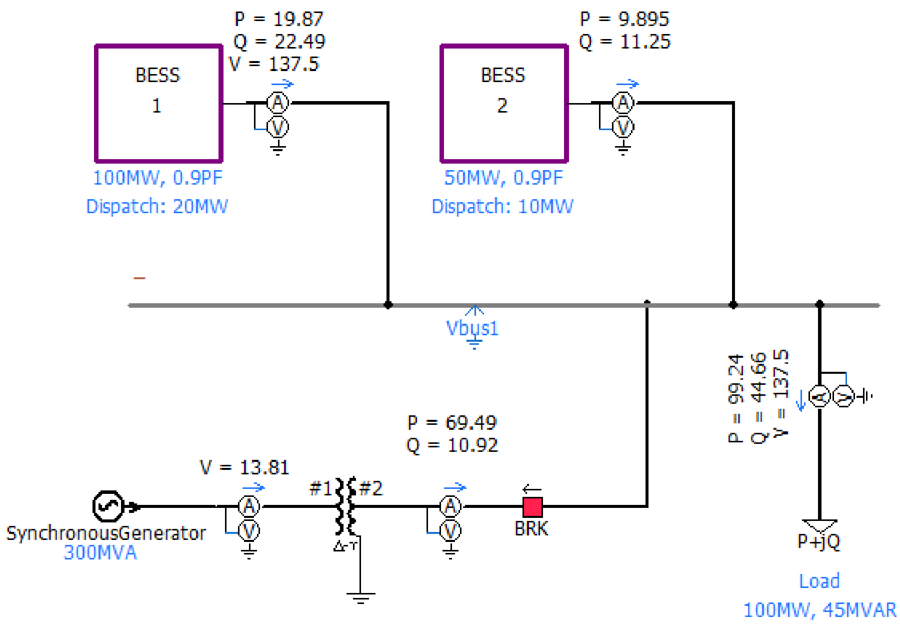

Figure 2.2: Example Test 1 – Initial Power Flow

Figure 2.3 shows the RMS quantities of the Test 1 simulation results including bus voltage (Vbus1_rms), frequency, synchronous generator active power (P_SyncGen), load active power (P_Load), project BESS (BESS 1) active power (P_BESS_1) and duplicate BESS (BESS 2) active power (P_BESS_2), reactive power, and current. The following observations are made:

- Near-instantaneous jump in active and reactive power from both BESS (see Point 1), followed by dynamics driven by specific GFM control topology and parameters
- Minimal deviation in voltage thus resulting in small change in voltage-dependent load power (see Point 2)
- Final steady-state quantities (see Point 3 for values indicated by O-marker at *t = 40 sec* in Figure 2.3) can be verified against the droop parameters in Table 2.4

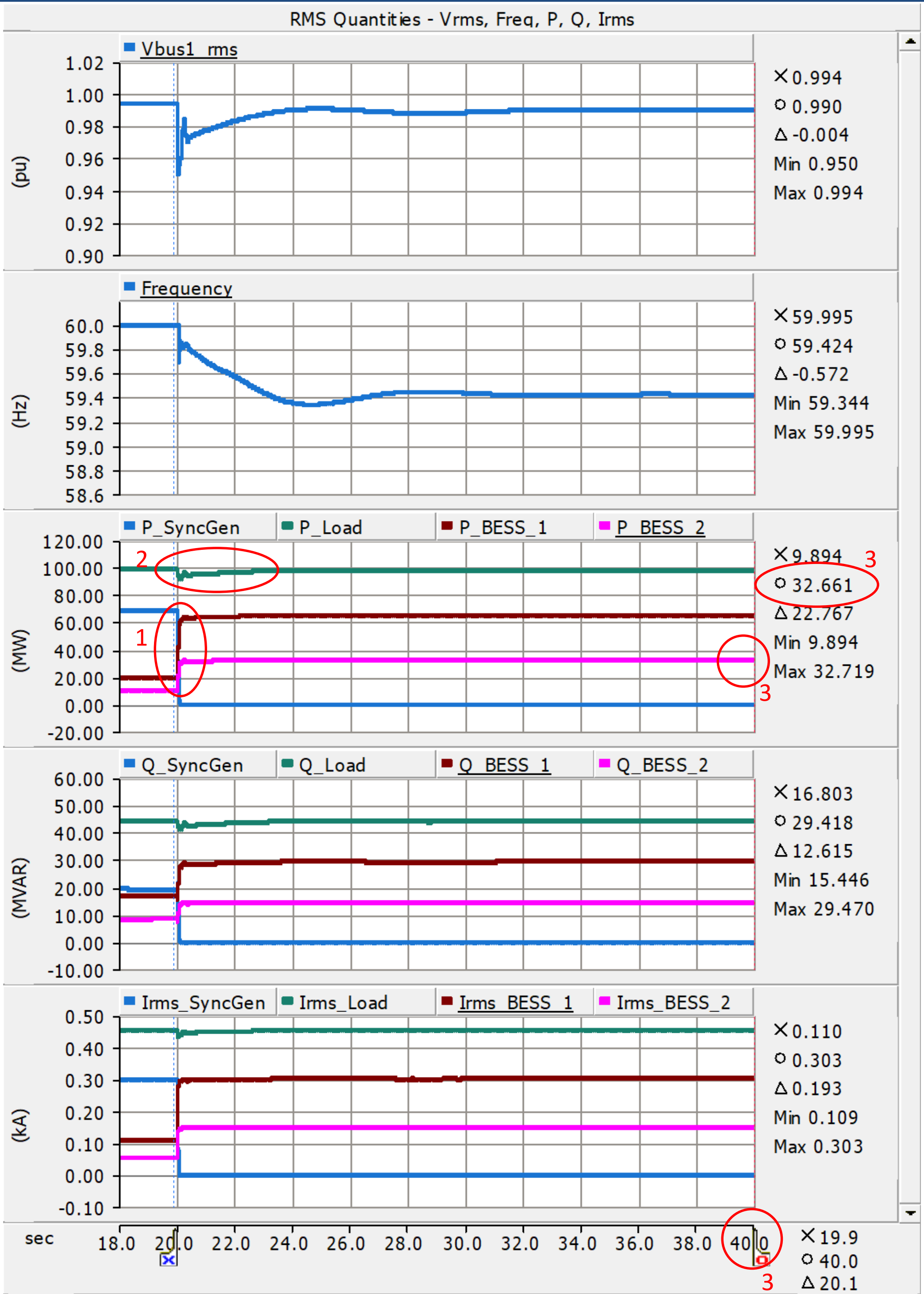

Figure 2.3: Test 1 Results – RMS Quantities

Figure 2.4 shows the instantaneous quantities of the Test 1 simulation results, including bus voltage (Vbus1), synchronous generator current (I_SyncGen), load current (I_Load), BESS 1 current (I_BESS_1) and BESS 2 current (I_BESS_2), with the following observations made:

- Phase angle shift in bus voltage (see Point 1)
- Sub-cycle increase in BESS currents (see Point 2)
- Sub-cycle change in BESS current phase angle; this is more observable in the Test 2 results

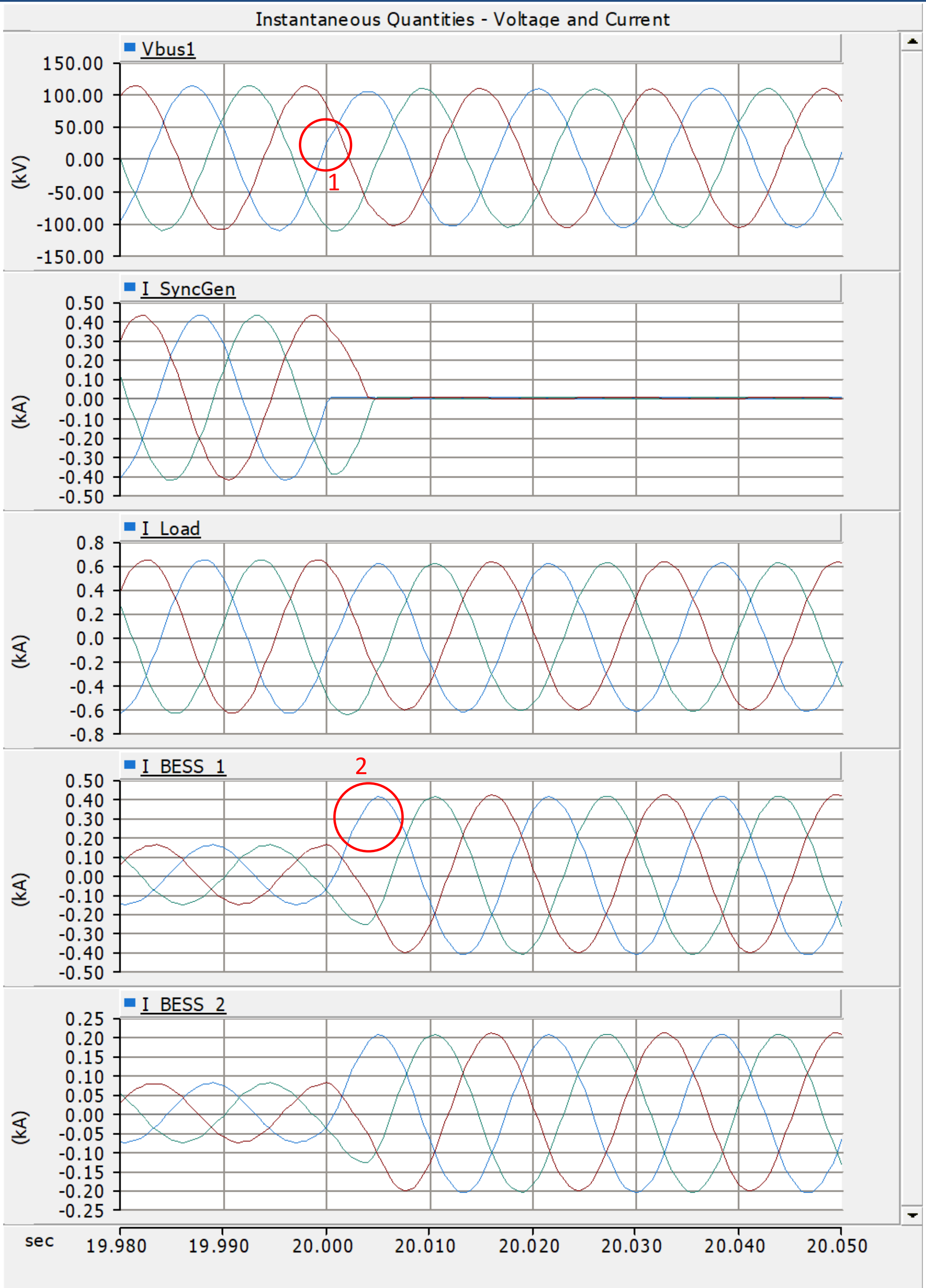

Figure 2.4: Test 1 Results – Instantaneous Quantities

As summarized in **Table 2.5**, the model passed Test 1.

Table 2.5: Evaluation of Test 1 Results	
Pre-Trip:	**Pass/Fail**
• BESSs active power outputs match dispatched levels.	Pass
• Synchronous generator active power output matches the rest of the load.	Pass
• Frequency should be 1 pu.	Pass
• Voltage at Bus 1 should be within 5% of nominal.	Pass
• Phase voltage and current waveform should not be distorted.	Pass
• There should not be oscillations in the RMS quantities.	Pass
• Reactive power output from all devices should be within limits.	Pass
Post-Trip:	**Pass/Fail**
• Immediately following the trip, BESS output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady-state levels for any significant amount of time.	Pass
• Voltage settles to a stable operating point.	Pass
• The final voltage is as expected based on the droop and deadband settings.	Pass
• Frequency settles to a stable operating point.	Pass
• The final frequency is as expected based on the droop and deadband settings.	Pass
• Any oscillation should settle.	Pass
• Any distortion observed in phase quantities should dissipate over time.	Pass
• Active power from each BESS should immediately move to meet the load requirement and settle according to its frequency droop setting.	Pass
• Reactive power from each BESS should move according to its voltage droop setting.	Pass

Test 2: BESS Initially Charging and Ends Up Discharging

The test system is initialized with power flow conditions shown in **Figure 2.5**. BESS are initially charging at half of their maximum charge rating, with the synchronous generator supplying power to the load and both BESS.

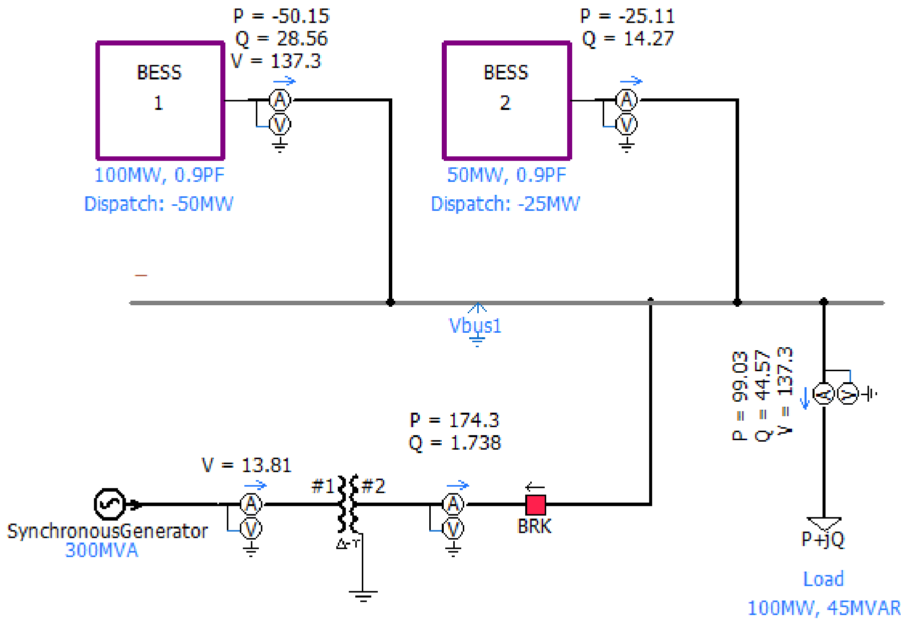

Figure 2.5: Example Test 2 – Initial Power Flow

In addition to similar observations as those from Test 1, the following can be noted in **Figure 2.6** which shows the RMS quantities of the Test 2 simulation results:

- Due to the larger differences between initial output power level and final settled output power level, driven by load, the frequency settled according to the frequency droop setting.
- Frequency spike (see Point 1) is an artifact of frequency measurement algorithm in response to the shift in voltage phase angle (see Point 1 in **Figure 2.7**).

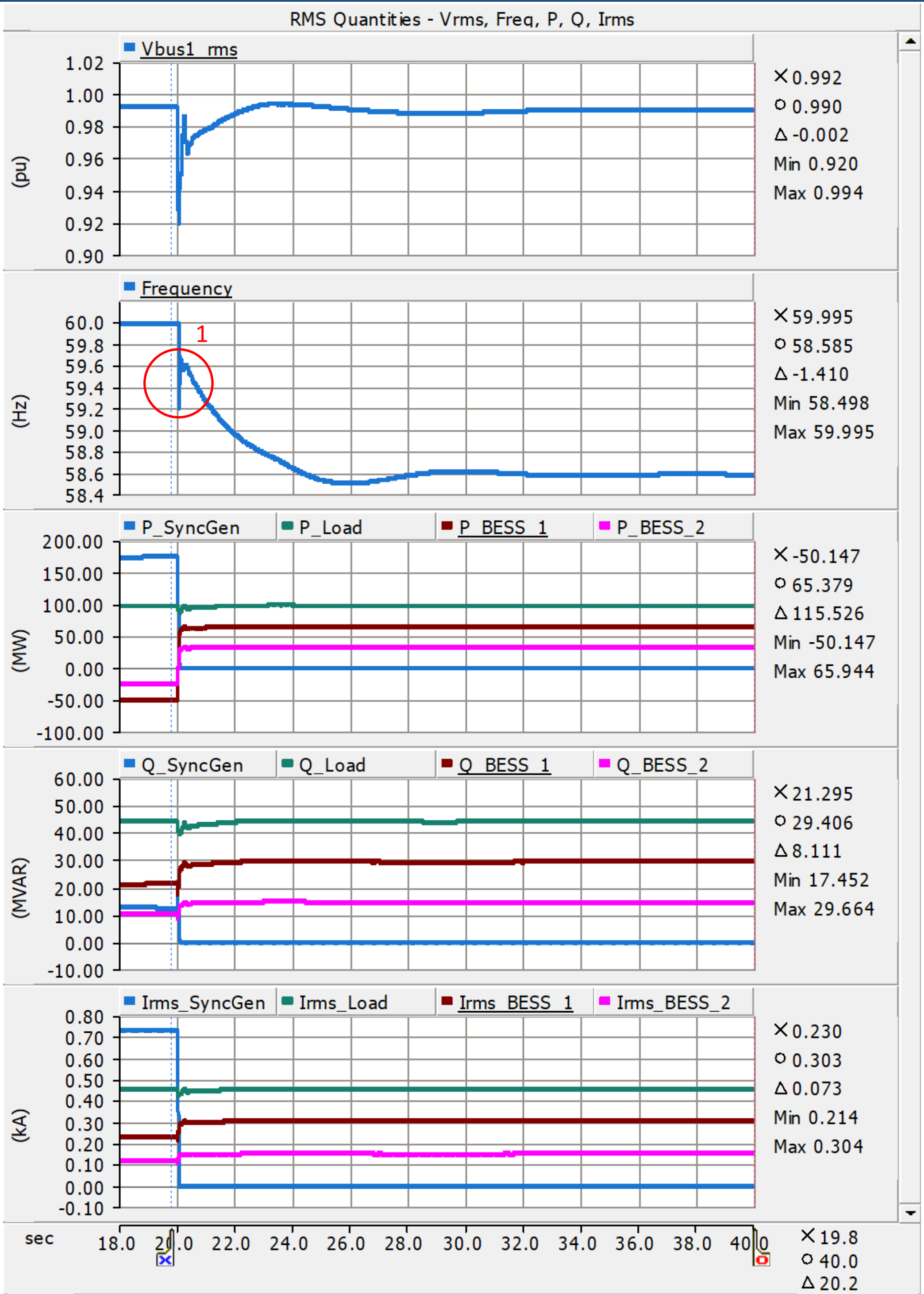

Figure 2.6: Test 2 Results – RMS Quantities

Figure 2.7 shows the instantaneous quantities of the Test 2 simulation results, with the following observations made:

- Current from both GFM BESSs increased within a quarter-cycle to make up for the loss of synchronous generator current (see Point 2).
- Change in BESS current phase angle as BESSs transition from charging to discharging within a quarter-cycle to serve the load (see Point 3).

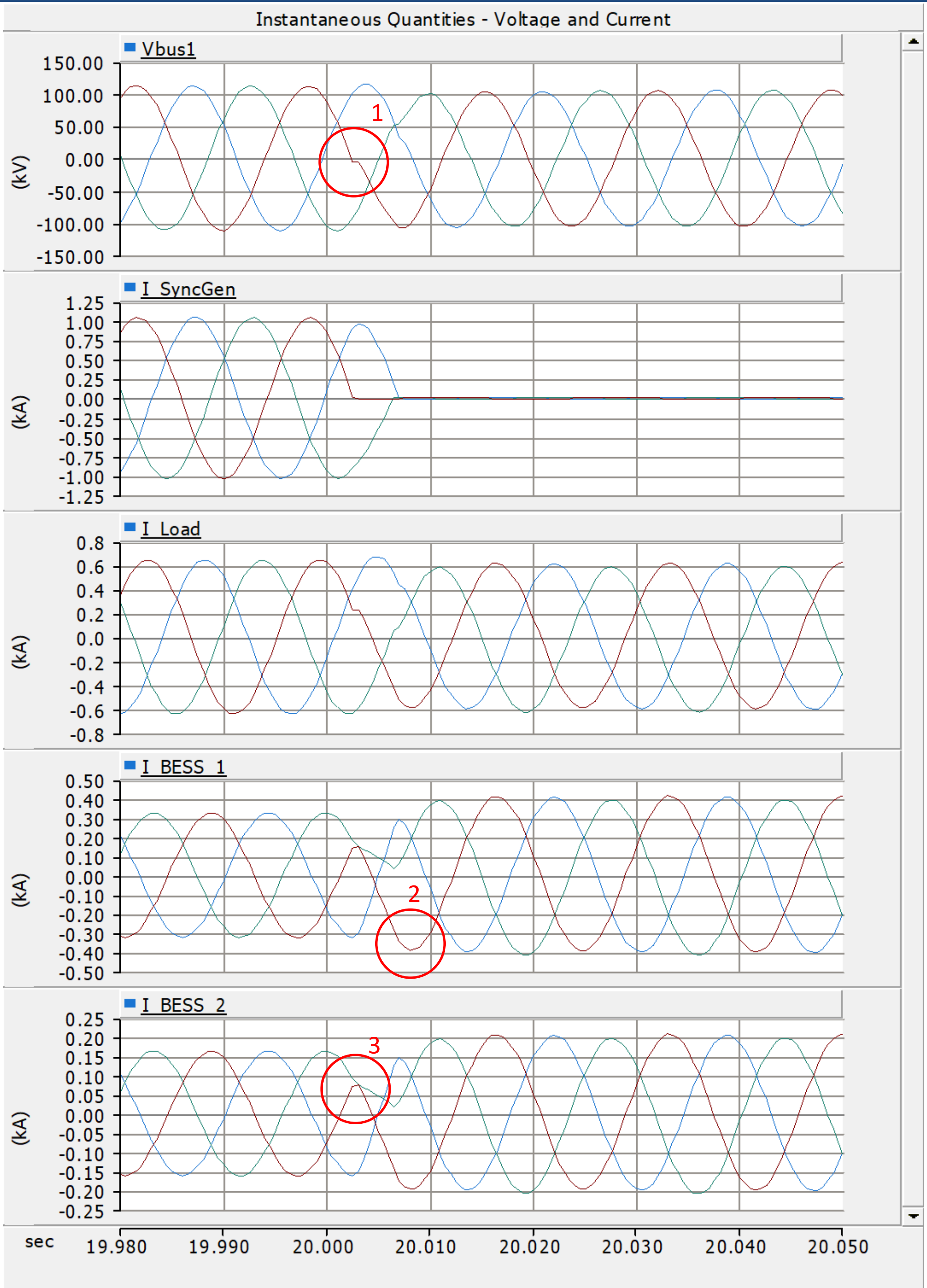

Figure 2.7: Test 2 Results – Instantaneous Quantities

As summarized below in **Table 2.6**, the model also passed Test 2.

Table 2.6: Evaluation of Test 2 Results

Pre-Trip:	Pass/Fail
• BESSs active power outputs match dispatched levels.	Pass
• Synchronous generator active power output matches the rest of the load.	Pass
• Frequency should be 1 pu.	Pass
• Voltage at Bus 1 should be within 5% of nominal.	Pass
• Phase voltage and current waveform should not be distorted.	Pass
• There should not be oscillations in the RMS quantities.	Pass
• Reactive power output from all devices should be within limits.	Pass
Post-Trip:	**Pass/Fail**
• Immediately following the trip, BESS output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady-state levels for any significant amount of time.	Pass
• Voltage settles to a stable operating point.	Pass
• The final voltage is as expected based on the droop and deadband settings.	Pass
• Frequency settles to a stable operating point.	Pass
• The final frequency is as expected based on the droop and deadband settings.	Pass
• Any oscillation should settle.	Pass
• Any distortion observed in phase quantities should dissipate over time.	Pass
• Active power from each BESS should move immediately to meet the load requirement and settle according to its frequency droop setting.	Pass
• Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	Pass

Test 3: BESS GFM Performance at Maximum Active Power

The test system is initialized with power flow conditions shown in **Figure 2.8**. BESS 1 is dispatched to zero active power and BESS 2 is dispatched to its steady-state maximum discharge site active power limit. The synchronous generator serves the remainder of the load.

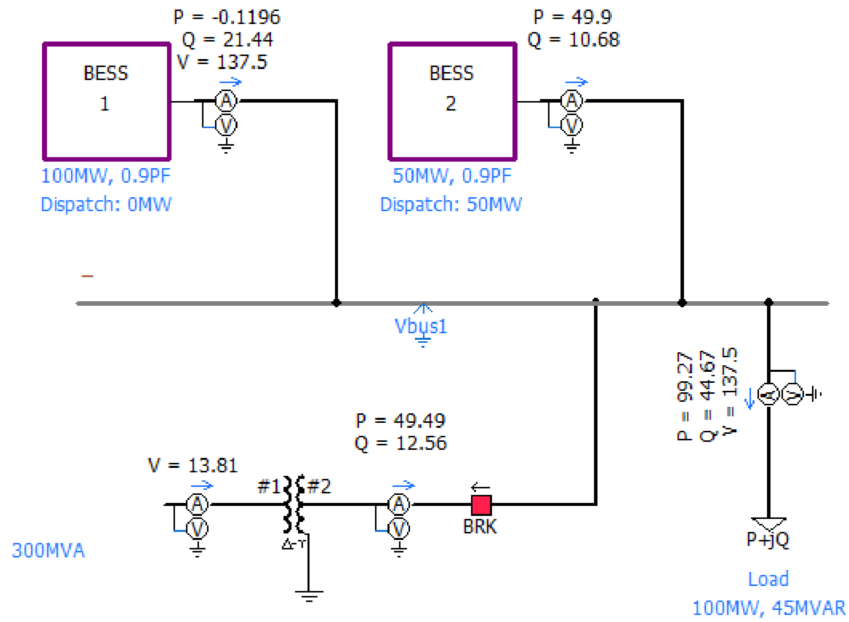

Figure 2.8: Example Test 3 - Initial Power Flow

Figure 2.9 shows the Test 3 simulation results with the following observations made that are unique to this test:

- BESS 2 (discharging at maximum active power) will not follow the droop curve past its maximum discharge power limit (see Point 1). BESS 1 makes up the active power difference to meet load demand, reaching the final frequency based on droop and deadband settings.[52]

[52] BESS 2 has extra power capability at the inverter level, allowing it to momentarily exceed site power limit.

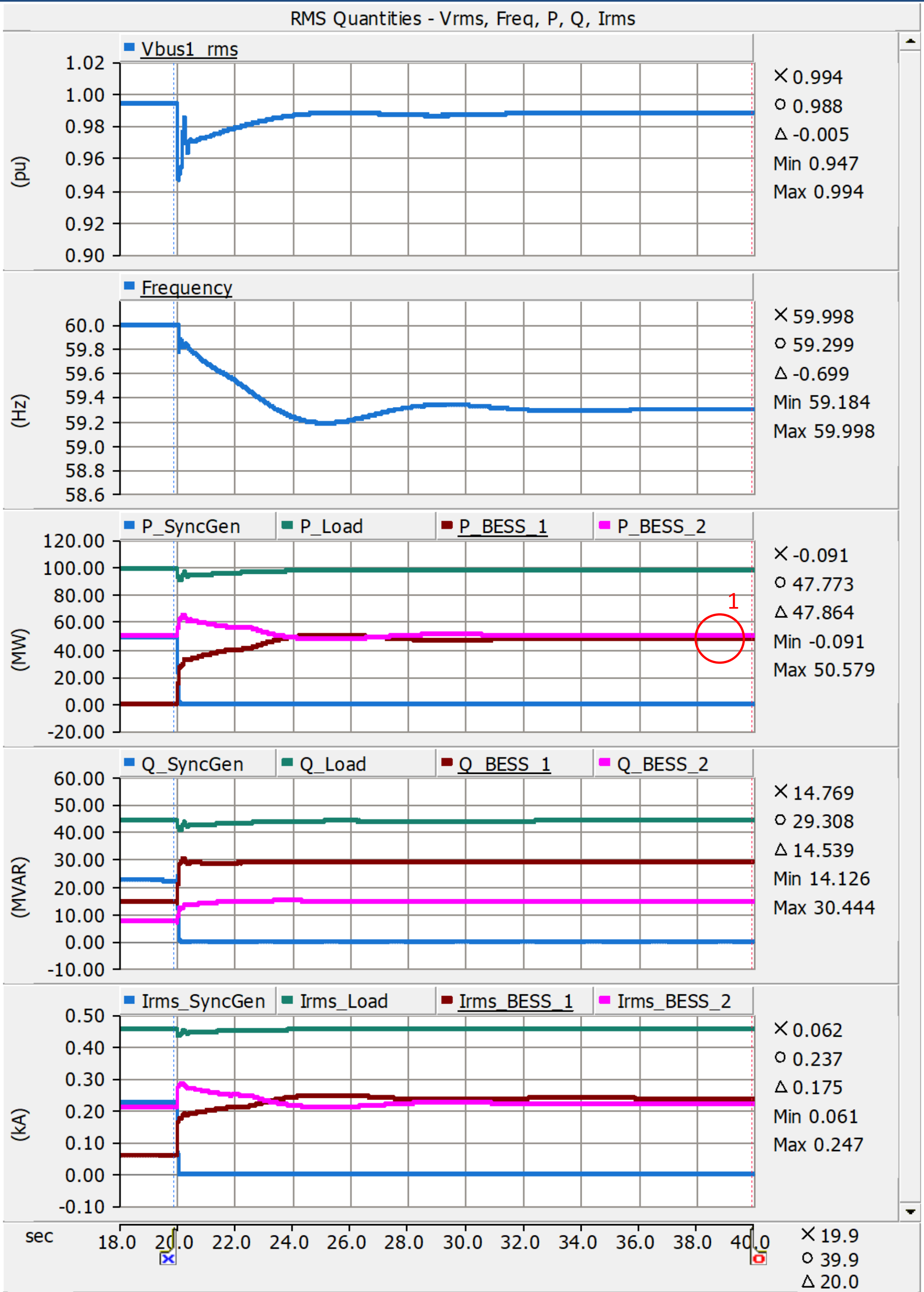

Figure 2.9: Test 3 Results – RMS Quantities

Figure 2.10 shows the instantaneous quantities of the Test 3 simulation results. Similar to the previous tests, it shows GFM BESS currents changed within a quarter cycle to match the load current (see Point 1).

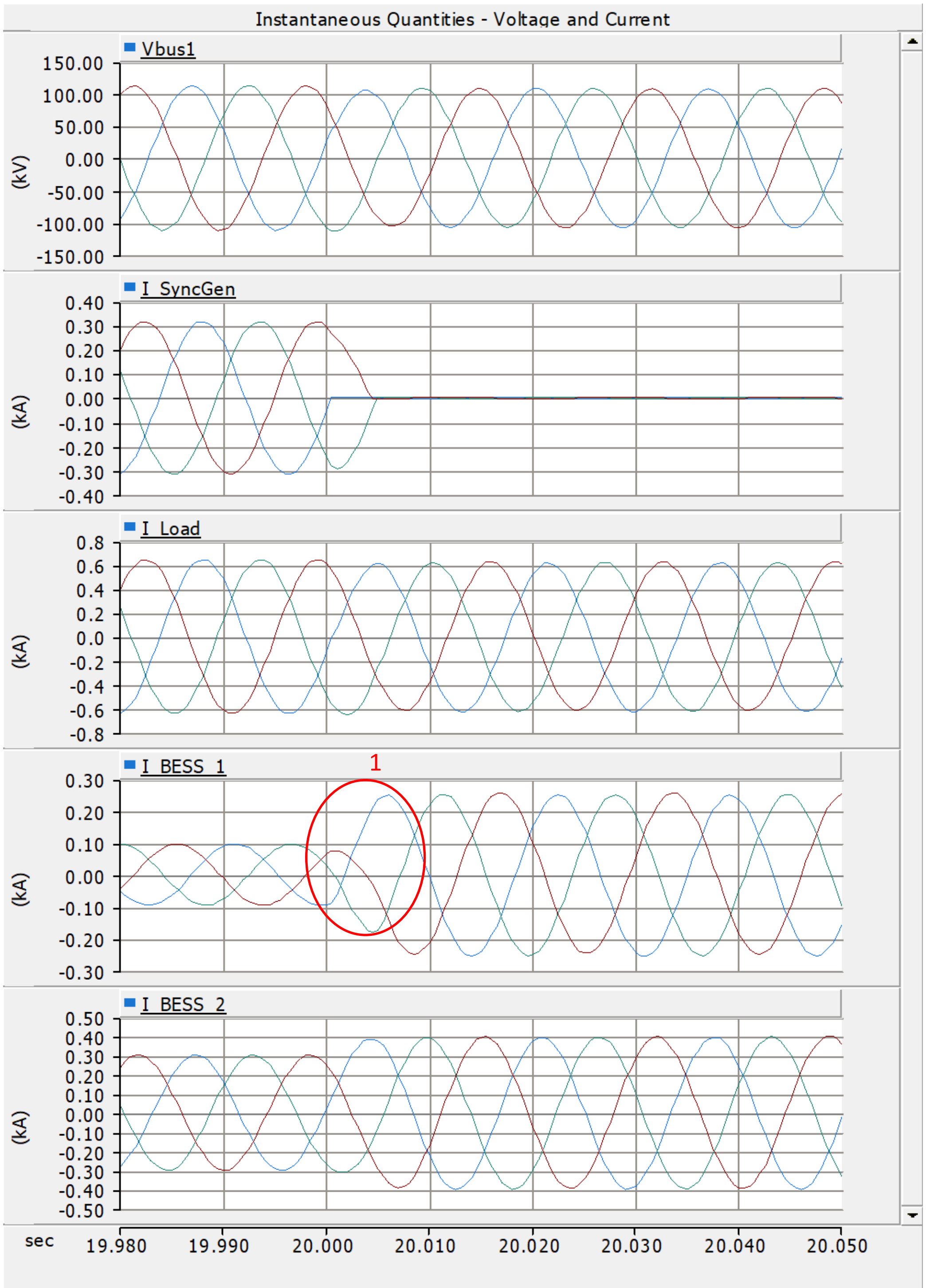

Figure 2.10: Test 3 Results – Instantaneous Quantities

As summarized below in **Table 2.7**, the model also passed Test 3.

Table 2.7: Evaluation of Test 3 Results

Pre-Trip:	Pass/Fail
• BESSs active power outputs match dispatched levels.	Pass
• Synchronous generator active power output matches the rest of the load.	Pass
• Frequency should be 1 pu.	Pass
• Voltage at Bus 1 should be within 5% of nominal.	Pass
• Phase voltage and current waveform should not be distorted.	Pass
• There should not be oscillations in the RMS quantities.	Pass
• Reactive power output from all devices should be within limits.	Pass
Post-Trip:	**Pass/Fail**
• Immediately following the trip, BESS output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady-state levels for any significant amount of time.	Pass
• Voltage settles to a stable operating point.	Pass
• The final voltage is as expected based on the droop and deadband settings.	Pass
• Frequency settles to a stable operating point.	Pass
• The final frequency is as expected based on the droop and deadband settings.	Pass
• Any oscillation should settle.	Pass
• Any distortion observed in phase quantities should dissipate over time.	Pass
• Active power from BESS 1 should move immediately to meet the load requiremnt and settle according to its frequency droop setting. Active power from BESS 2 should not exceed its max discharge active power limit in steady state.	Pass
• Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	Pass

Illustration of GFM versus GFL Performance in Functional Tests

To illustrate the response of a grid following BESS for comparison with GFM, the same EMT model is put through Test 1 on the same test system *without* GFM functionality enabled. Note that frequency and voltage trip settings were widened to demonstrate the unstable behavior. **Figure 2.11** shows GFL failing Test 1 criteria, resulting in instability.

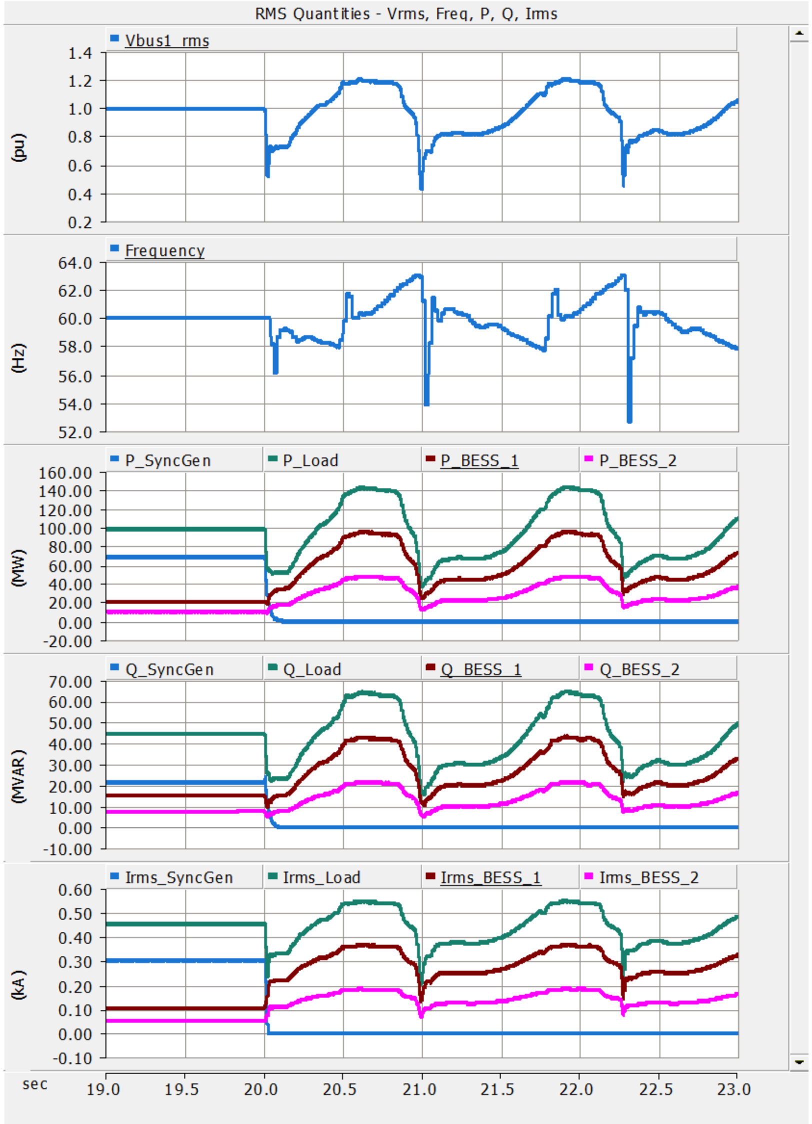

Figure 2.11: Test 1 Results with GFL

As summarized in **Table 2.8**, the BESS in GFL mode failed to settle to a steady-state operating point, although the distortion in voltage and current waveforms are reasonable.

Table 2.8: Evaluation of GFL for Test 1	
Pre-Trip:	**Pass/Fail**
• BESSs active power outputs match dispatched levels.	Pass
• Synchronous generator active power output matches the rest of the load.	Pass
• Frequency should be 1 pu.	Pass
• Voltage at Bus 1 should be within 5% of nominal.	Pass
• Phase voltage and current waveform should not be distorted.	Pass
• There should not be oscillations in the RMS quantities.	Pass
• Reactive power output from all devices should be within limits.	Pass
Post-Trip:	**Pass/Fail**
• Immediately following the trip, BESS output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady-state levels for any significant amount of time.	Fail
• Voltage settles to a stable operating point.	Fail
• The final voltage is as expected based on the droop and deadband settings.	Fail
• Frequency settles to a stable operating point.	Fail
• The final voltage is as expected based on the droop and deadband settings.	Fail
• Any oscillation shall be settled.	Fail
• Any distortion observed in phase quantities should dissipate over time.	Pass
• Active power from each BESS should move immediately to meet the load requirement and settle according to its frequency droop setting.	Fail
• Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	Fail

Figure 2.12 and **Figure 2.13** are zoomed-in versions of **Figure 2.11** to compare the GFL response (left) to GFM response (right). Notable differences include:

- Sub-cycle response in GFM current that GFL does not provide (see Point 1 in **Figure 2.12**)
- Fast active and reactive power response from GFM that GFL does not provide (see Point 2 in **Figure 2.13**)

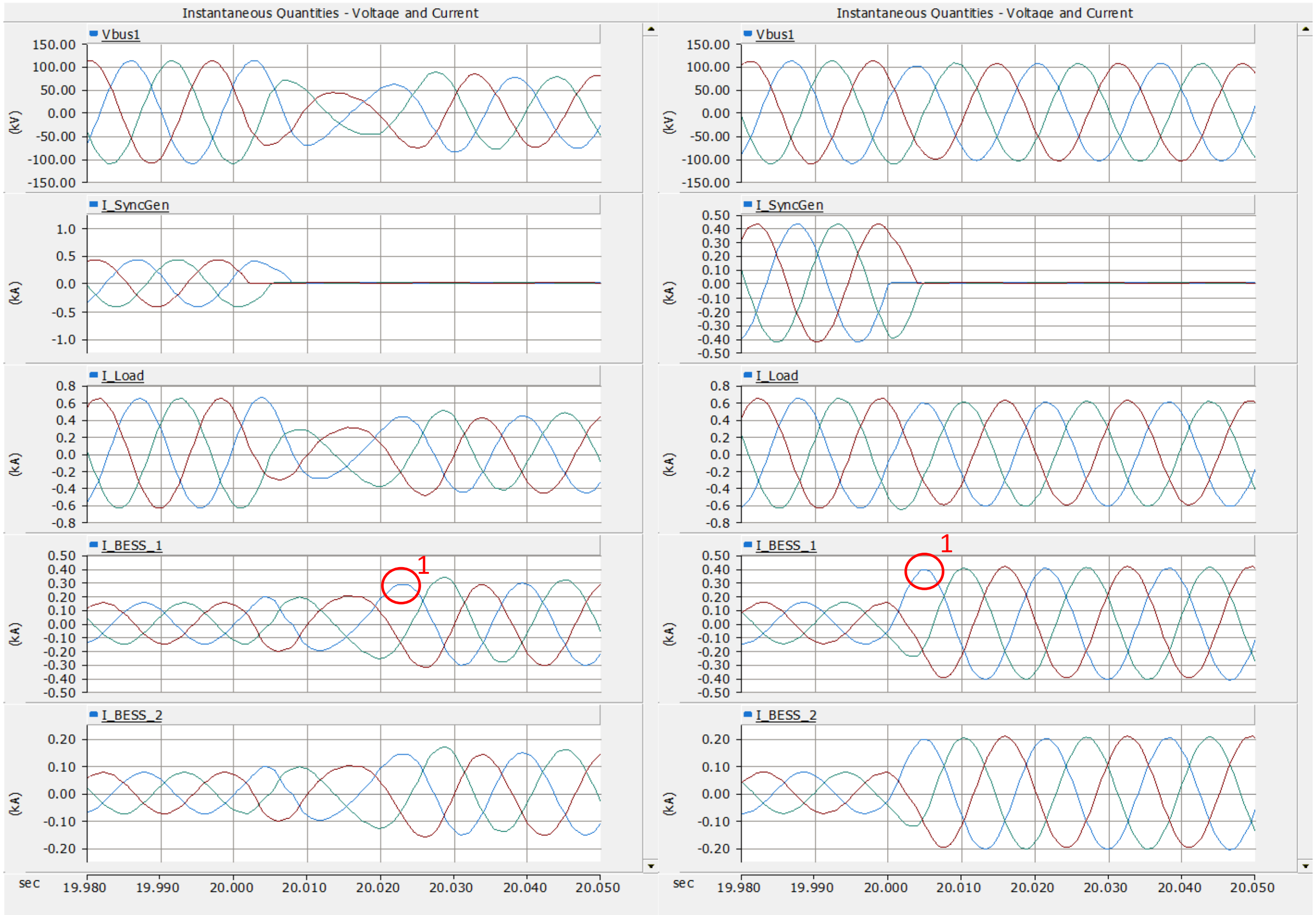

Figure 2.12: Comparison between GFL (Left) and GFM (Right) Responses – Instantaneous Quantities

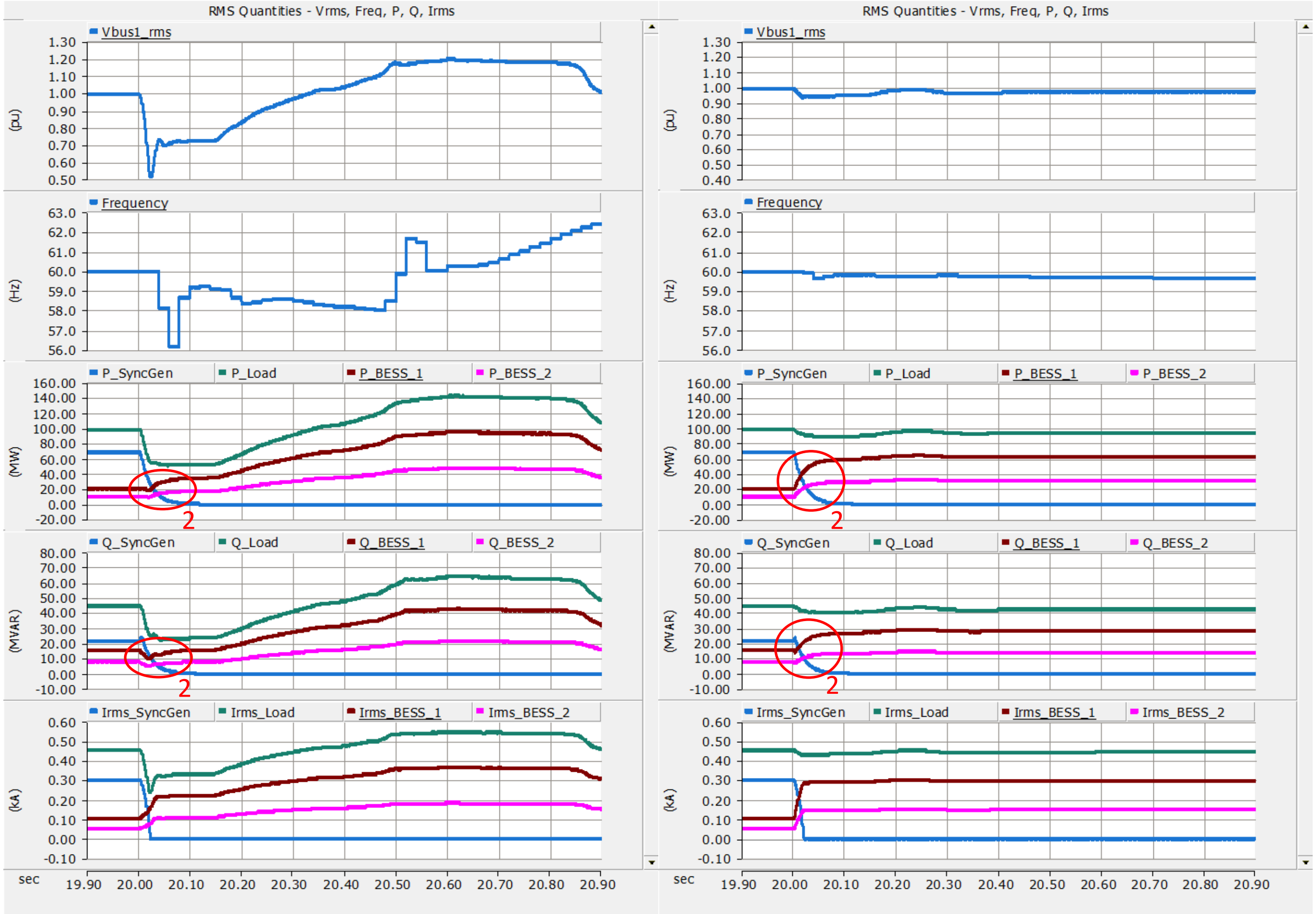

Figure 2.13: Comparison between GFL (Left) and GFM (Right) Responses – RMS Quantities

Appendix A: Industry Experience with GFM Integration

This appendix shares industry experience with integrating and operating GFM BESS technology on the BPS around the world.

Forum Network Technology/Network Operation (FNN) Guideline

The German FNN institute published a guideline[53] on GFM behavior of HVDC systems and dc-connected power plant modules in 2020. The guideline is a supplement to VDE-AR-N-4131.[54,55] The FNN guideline describes the dynamic active-power frequency behavior and dynamic voltage control without reactive current specification. It consists of a conformity verification procedure for GFM resources, which includes methods for specifying the reference behavior, test description (networks and scenarios) as well as validation criteria. GFM resources are characterized with an immediate response and "network-stabilizing behavior" expected to counteract system events. This guideline includes tests that cover:

- Phase angle steps of 10 and 30 degrees
- Linear frequency change with 2 Hz/s ROCOF over 0.5 seconds
- Voltage magnitude step of 5% and 10% within normal operational ranges
- Grid distortion including the presence of negative sequence (2% unbalance in one phase), harmonics (including ranks 2, 5, 7, 19, and 31), and low frequency subharmonics (at 5, 10, and 15.9 Hz)
- Changes in the network impedance leading to short-circuit ratio reductions from 20 to 5, from 5 to 2, and from 2 to 1
- Islanding in an active network, with only load or including another GFM converter

Conformity verification is based on time-varying reference "envelopes" that can be applied to instantaneous value signals, giving special attention to the initial behavior up to the first peak. These signals can be obtained from field measurements, EMT simulations, or HIL simulations. Verification can include recalculated quantities to be determined over a certain time period such as active and reactive power. Conformity proof includes delivery of a technical verification report and a digital model with the installation manual and benchmark report.

Massive Integration of Power Electronic Devices (MIGRATE)

The European Union-funded MIGRATE project provides requirements for upcoming IBR-dominated power systems to maximize IBR penetration levels while maintaining stability and reliability.[56] In 2019, MIGRATE proposed high-level definition of GFM functions including:

- Behave as a voltage source
- Be synchronized with other grid forming sources
- Operate in standalone after seamless islanding
- Limit output current magnitude (preserving voltage source behavior and preferably avoiding control switches during voltage dips, for instance)
- Be compatible with all devices connected on the system, especially synchronous machines and GFL IBRs

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[53] VDE/FNN Guideline: Grid forming behavior of HVDC systems and DC-connected Power Plant Modules, August 2020: https://shop.vde.com/en/fnn-guideline-hvdc-systems-2

[54] Verband der Elektrotechnik (VDE) is Europe's largest technical scientific association

[55] Technical Connection Rule for the connection of HVDC systems and generation plants connected via HVDC systems

[56] PowerPoint-Präsentation (h2020-migrate.eu)

Additionally, within this project a number of studies were carried out demonstrating compatibility of GFM IBRs with various control types operating in parallel in a fully IBR system.

European Network of Transmission System Operators for Electricity (ENTSO-E) Report

ENTSO-E published *High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters*[57] defining seven properties of a GFM inverter:

- Creates system voltage (does not rely on being provided with firm clean voltage)
- Contributes to fault level (positive and negative sequence within first cycle)
- Contributes to total system inertia (limited by energy storage capacity)
- Supports system survival to allow effective operation of low frequency demand disconnection (LFDD) for rare system separations
- Controls act to prevent adverse control system interactions
- Acts as a sink to counter harmonics and inter-harmonics in system voltage
- Acts as a sink to counter unbalance in system voltage

While the MIGRATE, definition focuses on capabilities regarding standalone operation and synchronization, the ENTSO-E paper adds a response deployment dimension.

Great Britain Grid Code GC0137

Grid Code GC0137 *Minimum Specification Required for Great Britain GFM Capability*[58] was approved and published in February 2022. This grid code was applied by National Grid Electricity System Operator (NGESO) to address grid stability issues arising from increasing penetration of IBRs. Although the requirements are non-mandatory, the provider of GFM IBRs will declare how much capability is available so that these GFM IBRs could be selected and remunerated for those capabilities.[59] Successful implementation of this grid code would provide additional grid stability services by these GFM resources. To help relevant IBR stakeholders understand the GFM requirements, NGESO released the *GBGF Best Practice Guide*[60] in April 2023. GFM IBRs are expected to provide the same type of performance as synchronous generator to:

- Limit the rate of change of system frequency
- Inject instantaneous active power and instantaneous fast fault current into the grid
- Contribute to damping power
- Limit vector shift
- Contribute to synchronizing torque
- Contribute to voltage performance during a fault

GC0137 specifies the following minimum technical, design, and operational capability for GFM IBRs:

- Withstand 2 Hz/sec ROCOF over a rolling 500 ms period
- Operate at a minimum short-circuit level of zero MVA at the grid interconnection point

[57] https://euagenda.eu/upload/publications/untitled-292051-ea.pdf
[58] GC0137 Authority Decision (ofgem.gov.uk)
[59] https://www.nationalgrideso.com/industry-information/codes/grid-code/code-documents
[60] https://www.nationalgrideso.com/document/278491/download

- Fast short-circuit current injection on both magnitude (typical 1 pu or 1.5 pu at zero voltage) and response speed (start in 5 ms and full in 30 ms)
- Active power responds to changes in the grid at bandwidths below 5 Hz to avoid ac system resonance problems
- Provide damping factor between 0.2 and 5.0

UK Stability Pathfinder

While a market for GFM capability is under development, NGESO needs some of the stability services such as improved system strength and inertia in certain locations today. Currently those are being procured through a series of tenders called Stability Pathfinder.[61] Phase 1 was only open to synchronous solutions and awarded to a number of synchronous condensers. Phase 2 was open to new technologies and five GFM BESS projects[62] were awarded in April 2022 with in-service dates between March 2024 and April 2026. These projects must comply with the requirements set forth in GC0137. Stability Pathfinder tenders are an exploratory temporary solution for broader procurement of stability services from a variety of capable technologies. NGESO is currently in the process of designing a market for new stability services, which will allow them to procure additional stability services through a market mechanism.

Optimal System Mix of Flexibility Solutions for European Electricity (OSMOSE)

EU-funded project OSMOSE Deliverable 3.3 *Analysis of Synchronization Capabilities of BESS Power Converters*[63] was released in March 2022, defining GFM minimum technical capabilities, technical requirements to formulate these capabilities, and recommendations to add these requirements into European-level and national grid codes. According to this specification, a GFM unit shall, within its rated power and current, be capable of self-synchronization, standalone operation, and providing synchronization services. GFM capabilities shall include:

- Standalone operation
- Synchronizing active power (in response to phase-jump)
- Inertial response (immediate active power output following a frequency change)
- System strength (immediate reactive power output in response to grid voltage variation)
- Fault current (immediate current output within installation capabilities following voltage dips; active/reactive current sharing during the first instances of the fault dependent on system impedance (not control action), and during asymmetrical voltage dips; prioritization between positive and negative sequence current can be defined by a system operator)

The report proposed separating GFM resources into four types based on the capabilities shown in **Figure A.1**.

[61] https://www.nationalgrideso.com/future-energy/projects/pathfinders/stability
[62] Stability Phase 2 Master Results Final with Tech Type.xlsx (live.com)
[63] https://www.osmose-h2020.eu/wp-content/uploads/2022/04/D3.3-Analysis-of-the-synchronisation-capabilities-of-BESS-power-converters.pdf

- **Type 4:**
  - Services provided: Type 3 + **high fault current** (> 2 pu)
  - Criticality: if protection fail to detect faults
  - Cost: high for converters (oversizing), null for synchronous machines
- **Type 3:**
  - Services provided: Type 2 + **inertial response**
  - Criticality: when system inertia decreases system-wide
  - Cost: limited due to the need of an energy buffer from a few seconds to 1 minute
- **Type 2:**
  - Services provided: Type 1 + **synchronizing power**
  - Criticality: when system inertia decreases locally
  - Cost: very limited due to the need of an energy buffer < 1 s (other FFR resources can then take over)
- **Type 1**
  - Services provided: stand alone + system strength+ fault current (within ratings), wide range of SCR operation
  - Criticality: when system strength decreases locally
  - Cost: null, only software changes

Figure A.1: Type of Grid Forming Resources as proposed by OSMOSE project[64]

A delineation is made in the report between capabilities that can only be provided by GFM resources versus capabilities that can also be provided by GFL resources (e.g., power oscillation damping, provision of negative sequence current, phase jump withstand capability, harmonics mitigation). The paper defined synchronization services and concluded that due to criticality and geographic dependence, some of these services need to be required at the time of interconnection from all new large transmission-connected IBRs and some additional services should be required from new transmission-connected BESS. It was recognized that synchronous machines may be needed in the interim to provide additional short-circuit current or, alternatively, higher overcurrent capability of IBRs can be incentivized.

UNIFI Consortium

The Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium is a U.S. Department of Energy-funded effort to advance GFM technology. The consortium developed the first version of a set of specifications that outline plant- and unit-level performance requirements for GFM technologies.[65] These specifications are intended to facilitate the integration and seamless operation of GFM resources, particularly unifying their operation smoothly with synchronous generators. The purpose of the UNIFI specifications for GFM IBRs is to provide uniform technical requirements for the interconnection, integration, and interoperability of GFM IBRs of any size in electric power systems of any scale. These specifications establish functional requirements and performance criteria for integrating GFM IBRs in power systems at any scale which includes GFM devices used as the local load, in microgrid, distribution, and transmission systems. These specifications cover all GFM technologies including, but not limited to battery storage, solar PV, wind turbines, HVDC, STATCOM, UPS, supercapacitors, fuel cells, or other yet-to-be invented technologies. While each GFM resource has different dc side and energy limitations, the specifications focus on the ac side performance requirements.

These UNIFI specifications cover both normal and contingency operation conditions. Under normal operation conditions, performance requirements for GFM include (but are not limited to) autonomous voltage and frequency support of the grid, active and reactive power sharing, robust operation in low system-strength grid, and unbalanced

[64] Adapted from Carmen Cardozo's OSMOSE project presentation at 2022 ESIG GFM Workshop: https://www.esig.energy/event/2022-special-topic-workshop-grid-forming-ibrs/

[65] B. Kroposki, et. al, "UNIFI Specifications for Grid-forming Inverter-based Resources – Version 1," UNIFI Consortium, UNIFI-2022-2-1, December 2022 (Available at: https://sites.google.com/view/unifi-consortium/publications)

grid operation support. In contingency operation conditions, performance requirements for GFM include (but are not limited to) fault ride-through behavior, response to asymmetrical faults, response to phase jumps, and intentional islanding events. The requirements are considered to be the minimum capability from GFM resources; additional capabilities such as blackstart capability and short-term over current capability are also covered in the specifications.

ESIG Grid Forming White Paper and Workshop

The Energy Systems Integration Group (ESIG) published a technical report on GFM technology in March 2022.[66] The report covered the following topics:

- GFM versus GFL inverter basic principles and an overview of types of GFM controls
- How BPS needs are changing with increasing penetrations of IBRs and the trade-offs between system needs and resource needs
- System services provided by GFM and technical requirements around the world, specifically around breaking the "chicken-and-egg" problem regarding deployment of GFM and requirements/incentives
- Advanced characterization and testing of GFM resources, including field tests
- Simulation tools needs (stability, analytics, economics, etc.) and the need for compatibility
- Recommendations for GFM technology moving forward

ESIG also held a technical workshop dedicated to GFM technology in June 2022, structured around steps needed to solve the "chicken-and-egg" issue around GFM technology deployment.[67] Topics addressed system operator experience with high shares of IBRs, OEMs with commercial GFM products, research and development in this space, and the low-hanging fruit of enabling GFM in BESS to provide core GFM capabilities (excluding high overcurrent and blackstart capability). Key points highlighted that commercial offerings for GFM BESS are already available today from multiple OEMs; however, the absence of clear GFM requirements is leading to customized site-specific applications that drive higher implementation costs. It was also recommended to distinguish between equipment specification/minimum capability requirements and system needs/services.

Finland Specific Study Requirements for Grid Energy Storage System

A large number of BESS are planned to connect to the transmission grid in Finland. Studies have shown that GFL IBR are not able to operate in a stable manner when the share of IBRs is increasing in the future. The solution is to use GFM IBRs to compensate for the reduction of synchronous generation and improve external system strength required by present GFL inverters to function properly. The need for GFM control has been identified already in weak grid regions, where connection of more GFL IBRs is not possible without further grid strengthening. As a result, Fingrid defined Specific Study Requirements for BESS (30 MW, ≥110 kV) connected to the specific locations where use of GFM controls is seen as necessary. The document describes functional requirements, modeling requirements, simulation studies and field tests for GFM BESS. Fingrid finalized and sent the requirements to their customers in June 2023. Their requirements have been posted on Fingrid's website in August 2023.[68] Currently the plan is to require GFM capabilities from BESS that interconnected to the grid with high penetration of IBRs. Fingrid plans to gather more experience from the current GFM projects and aims to make it a general requirement for all BESS projects next year.

According to Fingrid requirements, GFM IBR shall be able to self-synchronize, operate in stand-alone mode, and provide the following synchronization services: synchronizing power, system strength, fault current and virtual

[66] https://www.esig.energy/grid-forming-technology-in-energy-systems-integration/
[67] https://www.esig.energy/event/2022-special-topic-workshop-grid-forming-ibrs/
[68] Specific Study Requirements for Grid Energy Storage Systems (fingrid.fi)

inertial response (within current inverter rating). The requirements are in addition to existing grid code specifications for energy storage systems; in case of conflict, GFM requirements prevail.

Switching to GFL mode from GFM mode at the current limit is not permitted. When the GFM BESS is reaching the current limit, stability and grid support must still be maintained. GFM BESS shall continue providing GFM operational characteristics even at its highest and lowest allowable state of charge.

GFM shall provide autonomous, near-instantaneous frequency and voltage support by maintaining a nearly constant internal voltage phasor in the sub-transient time frame, including:

- Phase jump performance: resist near-instantaneous voltage phase angle change in sub-transient time frame
- System strength: resist the change in voltage magnitude in the sub-transient time frame
- Seamless transition: between islanded operation and grid-connected operation
- Positive damping: GFM shall present a positive resistance to the grid within frequency ranges 0–47 Hz and 53-250 Hz to prevent adverse interactions

GFM BESS shall provide a closed loop path for unbalanced current to flow, i.e., GFM shall present negative sequence current to ensure that its internally generated voltage remains balanced during normal operation and disturbances. The specification includes additional clarifications on how existing active power/frequency control and reactive power/voltage control requirements for BESS should be interpreted for GFM BESS.

Similar to HECO requirements, the document provides a table with a list of disturbances to be tested and acceptance criteria, simulation software, and BESS operating scenarios (prescribed values of SOC, P, and Q). The list also includes loss of last synchronous generator in the test network model, identical to the one recommended in this document, Test 3 in **Chapter 2**.

In addition to software simulations, hardware type test reports are required. The document also provides the list of site tests such as for phase jump, island operation (upstream 110 kV breaker is opened), and measurement of power quality, accompanied with high-level acceptance criteria.

AEMO GFM Voluntary Specification

AEMO published Voluntary Specification for Grid-forming Inverters in May 2023.[69] The document provides guidance to stakeholders while the regulatory environment around GFM technology develops. The definition of GFM IBR provided by AEMO is similar to that from NERC.

Similar to UNIFI, it specifies the "core" GFM capabilities, which require only a small energy buffer and can be delivered through control changes, and "additional" GFM technical capabilities that require a large energy buffer through hardware or operational practices change as well as over current capability. It is recognized that not all GFM inverters need to provide "additional" capabilities, but these capabilities are valuable for secure operation of power systems with a high share of IBRs.

The core requirements include:

- Nearly instantaneous (< 5 ms) reactive response to an external voltage magnitude step, to oppose the change in grid voltage.

[69] https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf?la=en&hash=F8D999025BBC565E86F3B0E19E40A08E

- Nearly instantaneous active power response to a voltage phase angle step, by injecting or absorbing power to oppose the change in phase angle.
- Inertial response from GFM inverters should be inherent (no calculation of frequency), providing a near-instantaneous active power response to a grid disturbance (e.g., load or generation trip). If the inertia is configurable, it needs to be tuned based on network conditions and requirements (high inertia constant may increase risk of power oscillations, particularly in strong systems).
- The response when the inverter is at a limit, and in transition to and from a limit condition, must be smooth and stable.
- The behavior at a limit should not be detrimental to stability and to harmonic performance (for example, clipping of current waveforms).
- Surviving loss of the last synchronous machine (SM): provided that the resultant state of the system is within the operating envelope of the GFM inverter, GFM should operate stably in a grid without any other GFM inverters or SMs; remain stable for a transition from a grid with SMs to one without (and back); provide frequency and reactive support which should be unaffected by these transitions.
- Operate stably under a very low short-circuit ratio, as defined by the system operator; provide system strength support to nearby GFL inverters during and after disturbances.
- Provide positive damping for oscillations: following a disturbance, GFM inverter output should be adequately damped. Add damping to the system for the oscillatory phenomena listed in the document.

"Additional" capabilities include higher current capability above the continuous rating, larger headroom, and energy buffer and power quality improvements.

AEMO is currently working on the development of a test plan and metrics for each of the qualitative capabilities to quantify requirements and to demonstrate that a device meets the specifications, to be published in 2024. The next step will be development of methodology to account for contributions from GFM devices in planning studies (as some contributions are dependent on the operating point).

ERCOT Assessment of GFM Energy Storage Resources

Recent notable events in ERCOT (Odessa 1 in 2021 and Odessa 2 in 2022) have shown the need to strengthen the system and resilience to mitigate reliability risk. ERCOT continues to focus on improving IBR capability and performance combined with improvements on the transmission system, recognizing that both are needed to maintain the reliable operations of the ERCOT grid. Therefore, alongside the adoption of NERC reliability guidelines, IEEE 2800 ride-through requirements, and the recent recommendation for six new synchronous condensers to strengthen the West Texas grid, additional improvements will be needed to support the continued growth of IBRs in the ERCOT grid.

Increasing industry interest in GFM controls for improvement of IBR performance and system support have prompted ERCOT to evaluate the potential application of GFM Energy Storage Resources (ESR)[70] in the ERCOT grid. The results were presented at the ERCOT Inverter-Based Resource Working Group[71] on August 11, 2023.

ERCOT preliminary GFM ESR evaluation focused on three scenarios:

- Scenario 1: a weak grid condition, a simple test case that mimics known stability challenges in ERCOT (in phasor domain)
- Scenario 2: West Texas grid based on 2022 Q4 Quarterly Stability Assessment case (in phasor domain):

[70] Energy Storage Resource (ESR) is a defined term in ERCOT.
[71] https://www.ercot.com/calendar/08112023-IBRWG-Meeting-_-Webex (see presentation slides under Key Documents)

    - West Texas IBRs were dispatched at 55%
    - Include 22 ESRs (existing and planned) with ~2000 MVA capacity behind West Texas Export transmission constraint; all batteries were modelled as GFL first and then as GFM
    - Include potential new condensers in six locations in West Texas
- Scenario 3: an actual ERCOT local area (138 kV) with identified stability constraints (tested in both phasor domain and EMT models)

Two GFM IBR dynamic models used in these tests were developed by Pacific Northwest National Laboratory (PNNL) and Electric Power Research Institute (EPRI).[72] Both phasor domain models and EMT models from these two entities showed similar performance in the study. ERCOT's assessment results from all three scenarios indicate that GFM ESRs could be a viable option to improve system dynamic responses but require headroom or an energy buffer to provide adequate GFM support, proper control setting tuning, and coordination. As the next step, ERCOT will work on the GFM ESR requirements including but not limited to performance, models, studies, and verification. ERCOT expects GFM ESR to be capable of meeting IEEE 2800 and existing ERCOT requirements along with additional performance requirements specific to GFM.

GFM BESS Projects around the World

BPS-connected GFM BESS are commercially available from different OEMs and GFM BESS projects are quickly emerging around the world.[73] Some major GFM BESS projects are summarized here.

Kauai Experience

Kauai Island Utility Cooperative (KIUC) has had the BESS portion of a 13 MW ac-coupled solar PV+BESS plant operating in GFM mode since 2018, which is a significant portion of the 70 MW system peak load. Field experience has shown the plant to operate stably during grid disturbances while providing instantaneous response to frequency and voltage events, avoiding load shedding and possible system outages.

Since April 2022, portions of a second solar PV+BESS plant on Kauai were converted to GFM mode. The second plant is a 14-MW dc-coupled solar PV+BESS plant that uses a different GFM control technique than the first plant. As of August 2022, the second plant now has all inverters in GFM mode. No adverse interactions between the two GFM plants have been observed in the field to-date.[74]

Both GFM plants have been shown to operate stably at all hours of the day, including times when the system is dominated by synchronous generation and times when it is dominated by inverter-based generation (including one other 30 MW GFL solar PV+BESS plant, three other large (6–12 MW) solar PV plants and about 45 MW of aggregate behind-the-meter solar PV). System inertia constant ranges from about 0.5 MW-s/MVA to 2.7 MW-s/MVA (using total online capacity as the MVA base), and the percentage of generation from IBRs ranges from about 6% to 95%. KIUC intends to continue operating both plants in GFM mode going forward and may add additional GFM generation in the future.

No EMT model of the KIUC system was available at the time of either of the two GFM plants' commissioning, so EMT studies were not conducted; instead, issues were addressed by monitoring the plants' performance in the field and working with the plant owners to make control parameter adjustments where necessary. Digital fault recorder data has been crucial for plant performance monitoring. The inverter model for the second plant described was tested extensively at NREL in partnership with the plant owner prior to commissioning and again prior to conversion to GFM.

[72] PNNL's and EPRI's GFM IBR models were provided both in EMT and positive sequence.
[73] ESIG-GFM-batteries-brief-2023.pdf
[74] https://www.youtube.com/watch?v=2e5ET0L1j5g

HECO Experience

Hawaiian Electric (HECO) conducted extensive EMT studies of GFL and GFM solar PV+BESS and stand-alone BESS plants.[75] Studies showed that GFM controls are crucial to stability of the HECO system in the near future.[76] The first GFM plant in HECO is expected to come online in 2023 with several more to follow in subsequent years. As part of HECO's preparation, they also worked with NREL to test a 2.2 MVA BESS inverter's performance by using PHIL simulation to connect it to a real-time EMT simulation of Maui's near-future transmission system.[77] The commercially available inverter tested at NREL can operate in GFM or GFL mode. It was used to represent a planned 30 MVA facility. The PHIL tests established that with the hardware inverter in conventional GFL mode, the Maui transmission system is unstable in certain very low inertia dispatch scenarios. They then demonstrated that with the inverter in GFM mode, the system is stable and resilient to a severe fault and an N-1 generation trip for several dispatch scenarios, including a zero inertia (zero synchronous machine) scenario.[78] This study also indicated that, for the Maui system, approximately 30% of online generation capacity needs to be GFM to maintain adequate damping.[79]

Australia Experience

The Australian Energy Market Operator (AEMO) published *Application of Advanced Grid-Scale Inverters in NEM* in August 2021,[80] describing GFM technology and application in the National Electricity Market (NEM). The Dalrymple BESS (30 MW/8 MWh) was the first transmission connected GFM project in the NEM.[81] The South Australia Hornsdale Power Reserve (HPR) BESS plant has been upgraded from GFL to GFM control with the capabilities of providing grid inertia service[82] in July 2022. The HPR project is described below in more detail. Lastly, development of GFM BESS in Australia continues with BESS plants in New South Wales including:[83]

- Wallgrove GFM BESS by Tesla (50MW/75MWh): Transgrid began commercial operation in December 2022.
- Broken Hill BESS: AGL Energy is commissioning a 50MW/100MWh GFM BESS; construction started in Fall 2022, and it will be operational in 2023.84
- Riverina and Darlington Point Energy Storage System: Edify Energy secured financing for three Tesla GFM BESS85 projects (with total capacity of 150MW/300MWh).
- New England BESS: ACEN has started construction of 50MW/50 MWh GFM BESS in Spring 2022 with expected completion date of 2023.86
- On December 17, 2022, the Australian Renewable Energy Agency (ARENA) announced co-funding of an additional eight large-scale GFM batteries across Australia with total project capacity of 2 GW/4.2 GWh, to be operational by 2025.87

[75] https://dms.puc.hawaii.gov/dms/DocumentViewer?pid=A1001001A21F14B62327F00172

[76] http://www.hawaiianelectric.com/documents/clean_energy_hawaii/selling_power_to_the_utility/competitive_bidding/20211015_exhibit_8_S3_hawaii_model_ESPA.pdf

[77] Power HIL Validation of a MW-Scale Grid-Forming Inverter's Stabilization of Otherwise Unstable Cases of the Maui Transmission System (nrel.gov)

[78] https://www.nrel.gov/docs/fy22osti/83545.pdf

[79] On the HECO systems, additional GFM capacity may be needed to account for possible momentary cessation of GFL generation during transmission faults, which can cause voltage to drop very low system wide. This conclusion may not apply to larger systems where a fault does not reduce voltage system wide.

[80] https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf

[81] Dalrymple ESCRI-SA Battery Project – ElectraNet

[82] https://www.pv-magazine-australia.com/2022/07/27/hornsdale-big-battery-begins-providing-inertia-grid-services-at-scale-in-world-first/?utm_source=dlvr.it&utm_medium=linkedin

[83] Upgrade at Tesla Battery Project Demonstrates Feasibility of 'Once-In-A-Century Energy Transformation' for Australia - World-Energy

[84] Broken Hill Battery Energy Storage System | How We Source Energy | About AGL | AGL

[85] https://edifyenergy.com/energy-storage-systems/financial-close-on-the-largest-approved-grid-forming-battery/

[86] https://www.pv-magazine-australia.com/2022/05/26/acen-commences-construction-of-new-england-big-battery/

[87] https://arena.gov.au/news/arena-backs-eight-grid-scale-batteries-worth-2-7-billion/

Hornsdale Power Reserve (HPR) Experience

The HPR BESS project (150MW/193.5MWh) upgraded from GFL to GFM control to enhance grid stability. The process involved four phases, including:

- **Phase 1 – GFM control testing and benchmarking on EMT model and HIL:** One functional behavior of the upgraded GFM control is shown on a single machine infinite bus (SMIB) testing system. The GFM control performances of the EMT model are well benchmarked with HIL using a variety of disturbance tests. The benchmark results of the virtual inertial response test are shown in **Figure A.2**.

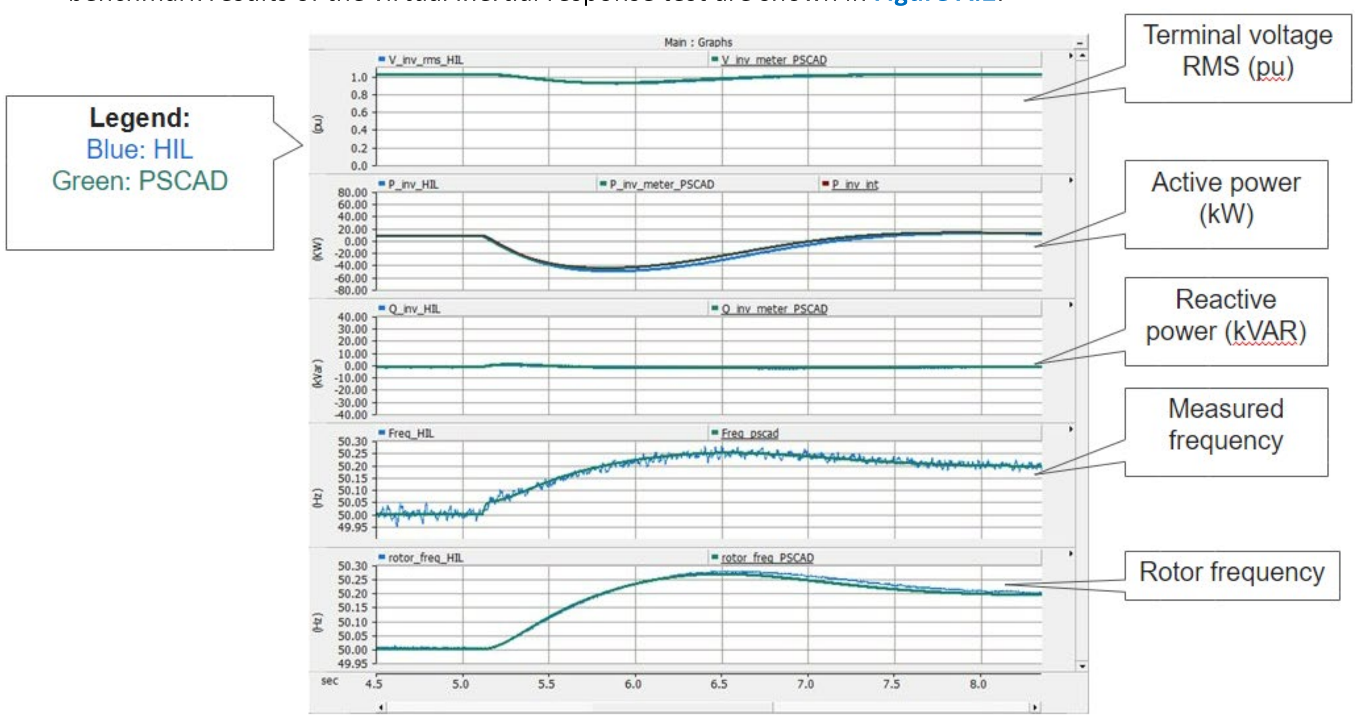

Figure A.2: EMT and HIL (Hardware-in-loop) benchmarking

- **Phase 2 – Trialed GFM control mode at 2 out of 294 inverters at the HPR plant:** Two test inverters were upgraded with the actual GFM firmware while the remaining 292 inverters ran on grid following controls. This verified the different GFM and GFL control responses for the same disturbance. **Figure A.3** and **Figure A.4** show the GFL and GFM active power response, respectively, to the change in frequency. The GFM control contributes maximum power earlier than the GFL control, which is important to support the frequency nadir and avoid underfrequency load shedding. This test shows the GFM controller has faster response for overfrequency as well.

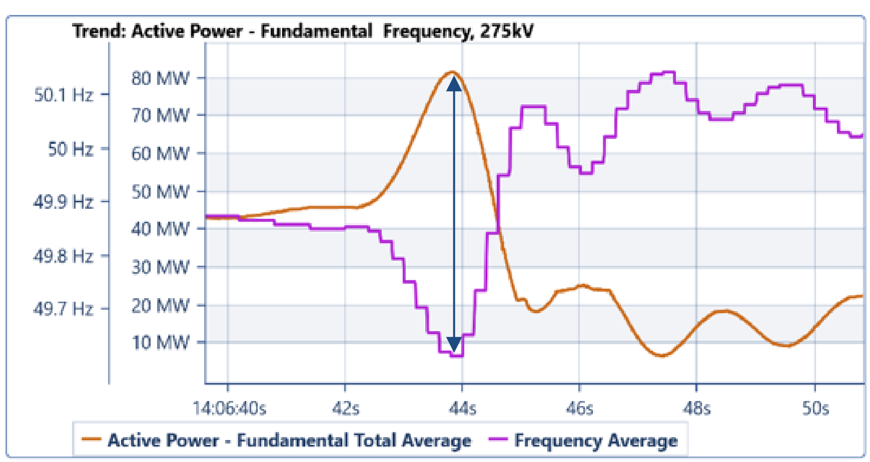

Figure A.3: GFL IBR Response to Frequency Event

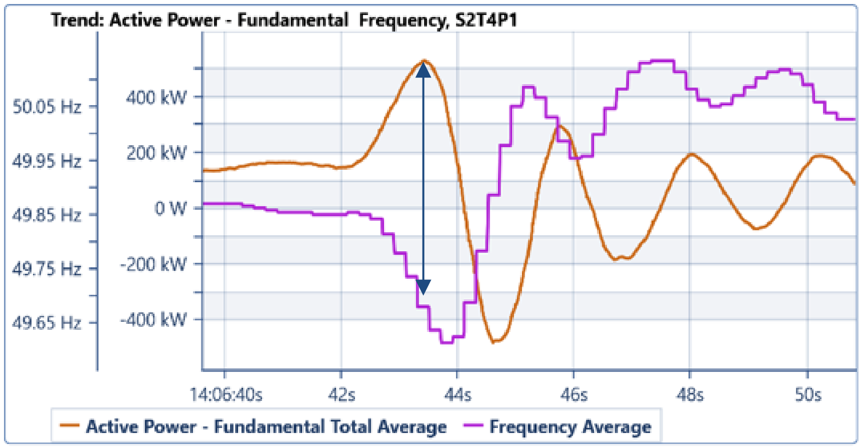

Figure A.4: GFM IBR Response to Frequency Event

- Phase 3 – A new system interconnection study was performed under national electricity rule NER 5.3.9:[88] This was required to prove that the grid performance of the new grid forming resource is similar to or better than the previous grid following resource. The HPR plant virtual kinetic inertial support (2000 MWs) for South Australia was validated[89] and it was noted that grid forming BESS help improve system damping.
- Phase 4 – After studies were approved, GFM controls were enabled for all inverters at the site: The HPR GFM plant performances are verified with the recorded site Elspec data which are also used to validate the BESS EMT model. The site Elspec data performance and the EMT model validation for a voltage dip are shown in Figure A.5. The HPR plant GFM controls provide damping to power oscillations and inertial energy to limit grid ROCOF and also provide voltage support from sub-cycle current injection when the voltage waveform changes at the inverter terminals.

[88] NER Rule 5.3: Establishing or Modifying Connection - AEMC Energy Rules
[89] hornsdale-power-reserve-virtual-machine-mode-testing-summary-report.pdf (arena.gov.au)

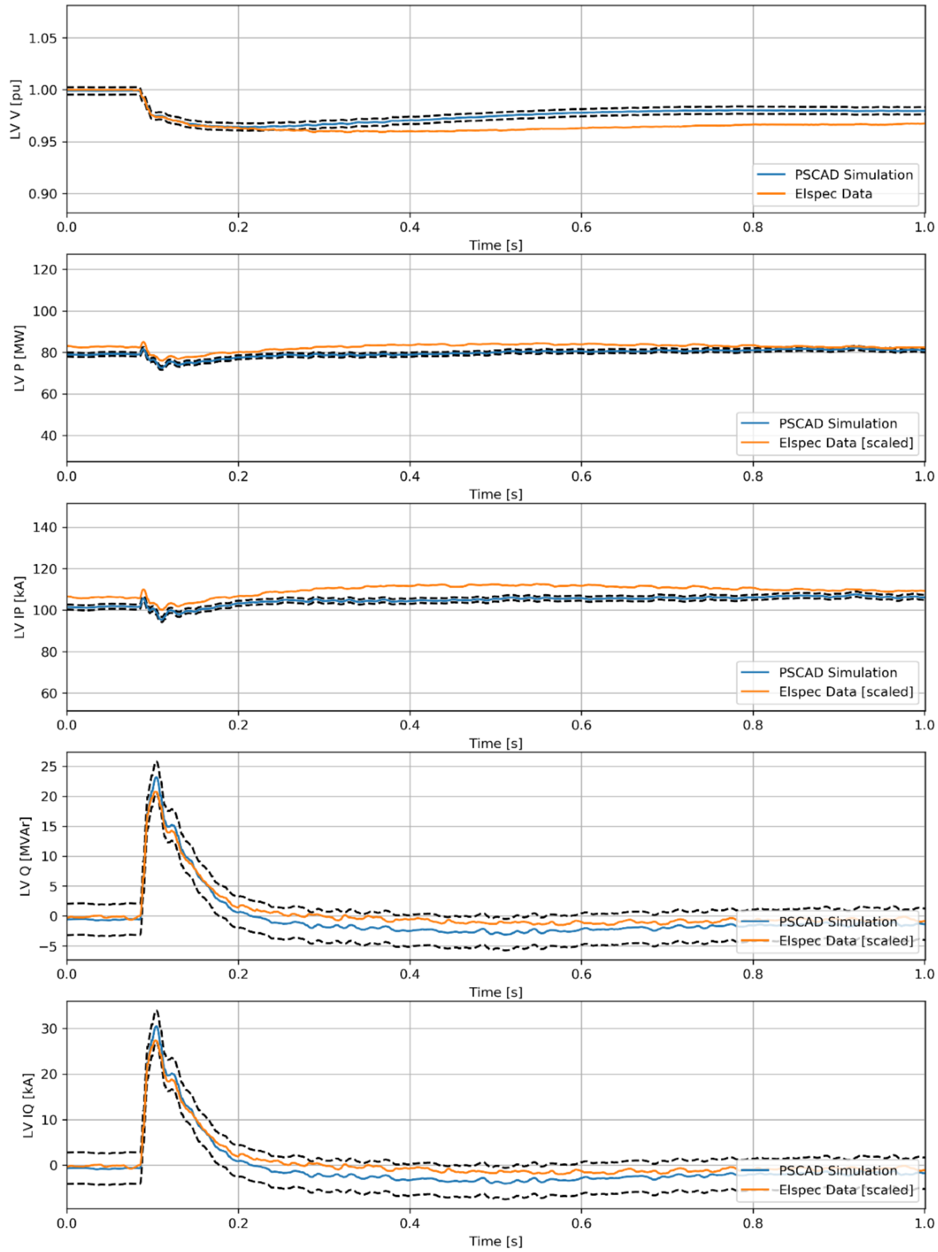

Figure A.5: Response from the Inverter During Voltage Disturbance on the Grid

Appendix B: Example of GFM Functional Test with Different OEM

To demonstrate diversity in commercially available GFM technologies and potential differences in their controls and corresponding responses, the GFM functional tests described in Chapter 2 were repeated with a different GFM BESS model provided by another OEM, using the same initial condition and droop parameters. Despite the differences in their dynamic behavior, both OEMs' BESS EMT models passed all three verification tests and are verified to be GFM. Tests results are shown below in **Figure B.1 – B.3**.

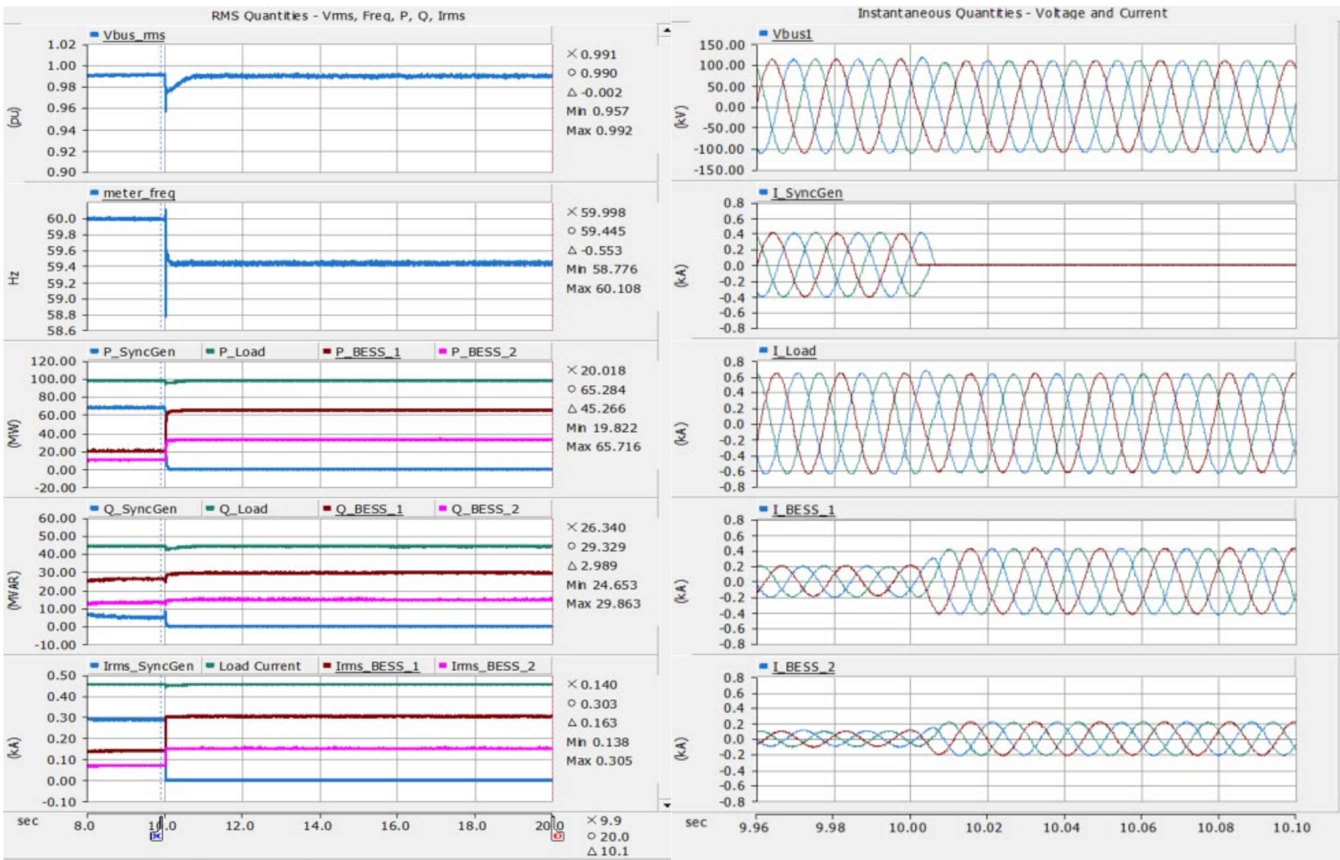

Figure 1 Test 1 Results with Different GFM Model

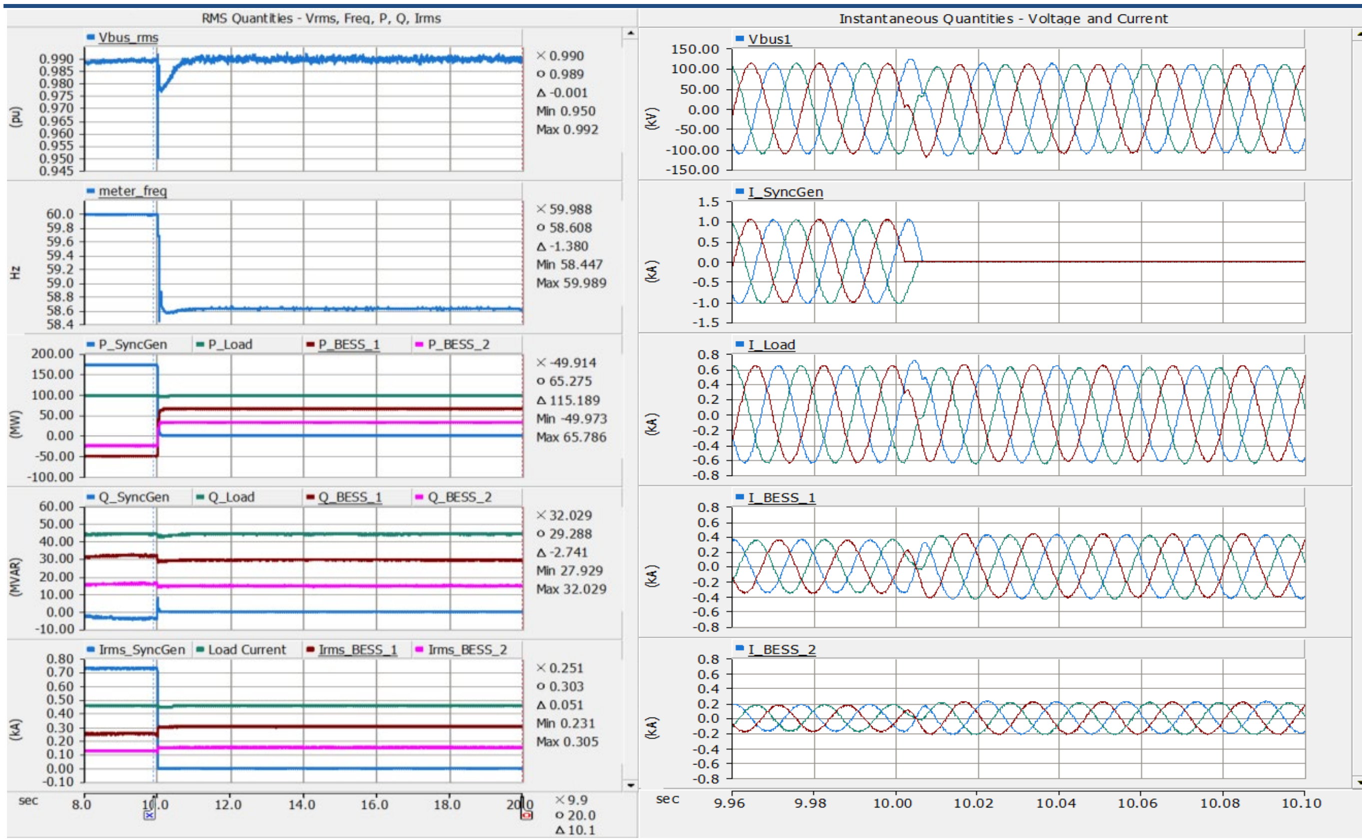

Figure 2: Test 2 Results with Different GFM Model

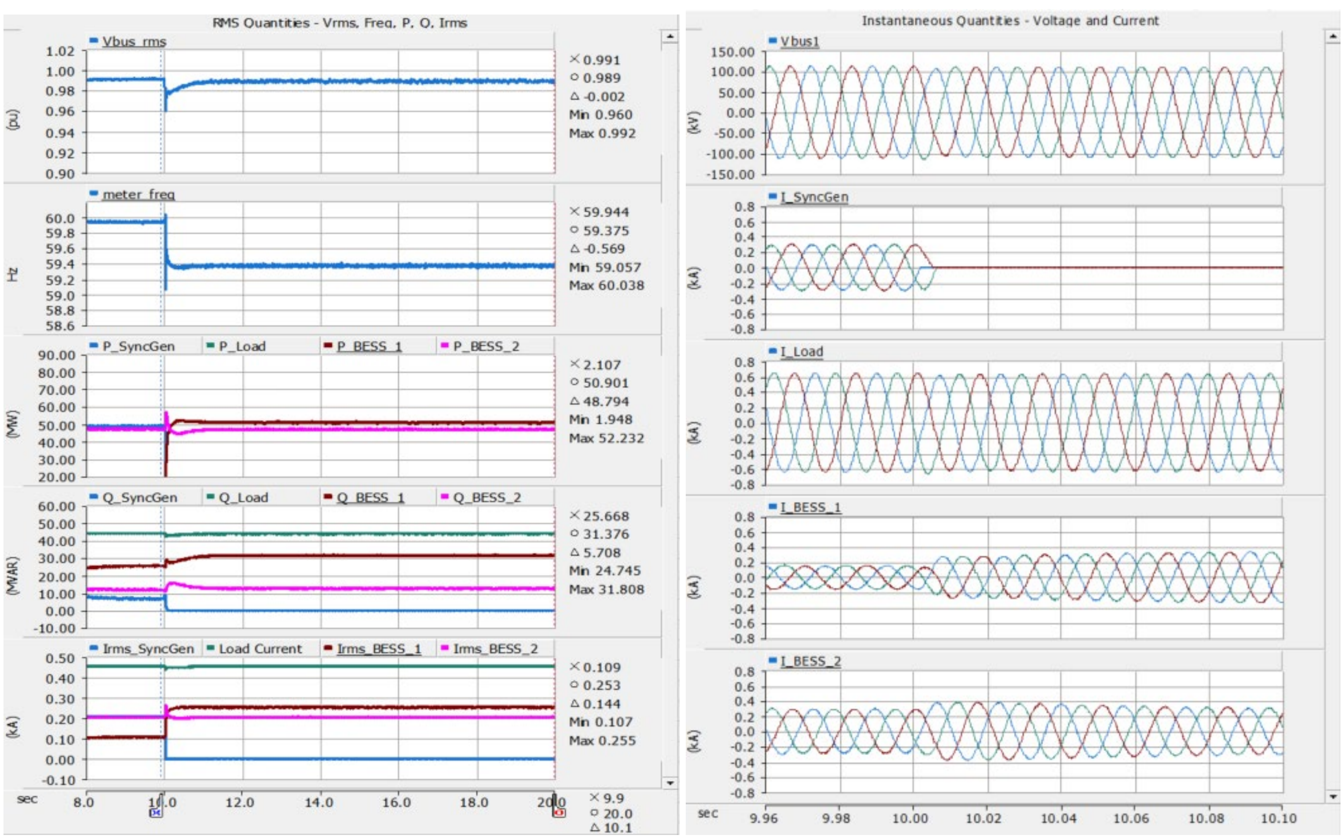

Figure B.3: Test 3 Results with Different GFM Model

Appendix C: Acknowledgements

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Name	Company
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