Islanded Grid Reliability Enhancement: Guam's Experience with Synchronous Condensers and Grid-Forming BESS

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***Abstract*—This paper presents a comprehensive integration study evaluating the impact of synchronous condensers (SC) and grid-forming (GFM) battery energy storage systems (BESS) on the stability of the GPA's system with high penetration of inverter-based resources (IBR). The study examines various system integration levels, including mixed synchronous and inverter-based generation and full IBR scenarios. Using short-circuit assessments and dynamic simulations, the study evaluated the impact of sizing and placement strategies for synchronous condensers and GFM BESS. Results demonstrate that transitioning existing energy storage units to GFM significantly enhances system reliability, reducing the need for additional system support assets. Comparative analyses reveal that while both synchronous condenser and GFM BESS technologies improve stability, GFM BESS offers better dynamic response for the cases and contingencies under study. The study concludes with recommendations for strategic deployment and backup planning, emphasizing the importance of GFM capabilities in modern power systems.**

***Index Terms*—energy transition, GFM, synchronous condenser, dynamic stability, PSLF**

I. Introduction

The increasing penetration of IBRs such as solar photovoltaic (PV) systems and BESS introduces new challenges to power system stability. This study examines the integration of SCs and GFM BESS to increase the system strength and enhance the dynamic stability of the GPA power system (Figure 1). The study builds on GPA's extensive renewable integration efforts, including the Phase I and II Renewable Energy Acquisition system impact studies, the 2014 Energy Storage Feasibility Study, the 2018 System Renewable Integration Study, and the Phase IV Acquisition studies [1]. These foundational analyses have consistently focused on evaluating emerging technologies and renewable energy assets to improve reliability, resiliency, and affordability. In this context, this study evaluates multiple operating scenarios with varying levels of renewable penetration, considering the planned expansions of solar generation and energy storage on the island. The performance of SCs and GFM BESS is assessed across these scenarios to determine their effectiveness in mitigating instability risks and supporting GPA's transition to a more robust and sustainable grid.

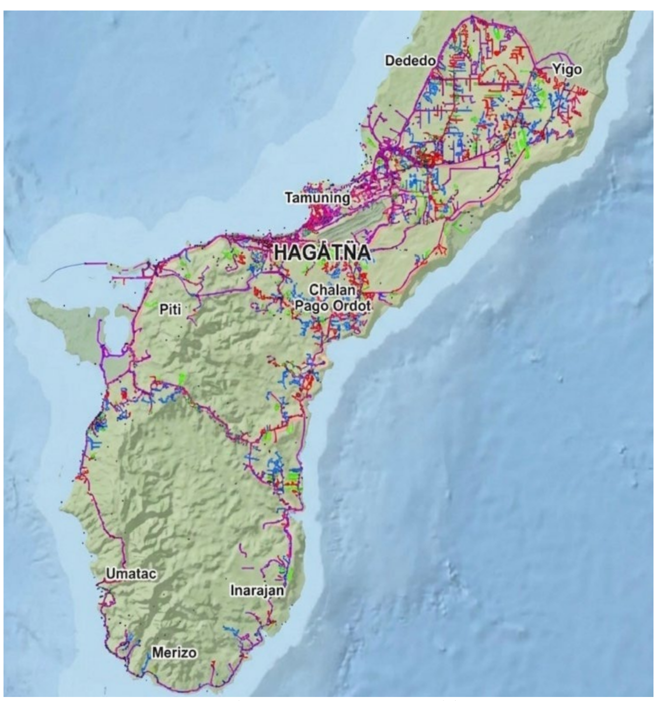

Figure 1. Guam power grid

II. Objectives

The study aims to assess the impact of increased IBR penetration on the GPA system, determine the optimal sizing and placement of SCs and GFM BESS to support system strength, compare the performance of SCs and GFM BESS in supporting grid stability under various contingencies and operating conditions, and evaluate the economic benefits associated with each technology.

III. Study Framework

This section outlines the study's assumptions, simulation scenarios, methodology, simulation setup, and contingencies.

A. Study Assumptions

The simulations were jointly conducted by S&C and GPA, ensuring alignment with real-world operational conditions and planning expectations. To maintain consistency and accuracy across all cases and scenarios, the following key assumptions were adopted:

- Generation Dispatch: Typical operations with renewable, storage, and conventional units based on merit order and availability.
- Resource Protection Settings: Frequency and voltage ride-through schemes and protection settings were modeled to reflect reality.
- Dynamic Models: A combination of actual and generic industry-standard dynamic models and parameters (e.g., REGFM approved by the Western Electricity Coordinating Council (WECC) [2]) was used for all system components to represent actual behavior.
- Clearing Time: All fault scenarios assumed an improved clearing time of five cycles, consistent with system protection upgrades.

B. Simulation Cases and Sets

The study considered three dispatch scenarios and two IBR penetration levels for the study cases. These cases aim to capture

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the system's dynamic behavior under varying load and generation profiles, particularly under high IBR penetration.

Table 1. Simulation sets and cases for the study.

Set	Case	Time	Remarks
Set A – Minimum Synchronous Generation: Realistic scenario with minimal conventional generation (66 MW).	Case 1 (C1)	10 AM	Morning light load with high PV and min load
	Case 2 (C2)	12 PM	Afternoon peak load with high PV and high load
	Case 3 (C3)	8 PM	Evening peak load with PV generation offline
Set B - 100% IBR: Fully IBR-operated scenario with no synchronous generation online.	Case 4 (C4)	10 AM	Morning light load with high PV and min load
	Case 5 (C5)	12 PM	Afternoon peak load with high PV and high load
	Case 6 (C6)	8 PM	Evening peak load with PV generation offline

This two-set approach enables a comparative assessment of system performance under various high-renewable configurations.

C. Methodology and Simulation Setup

A comprehensive simulation-based approach was utilized to evaluate system performance under various integration scenarios. The study incorporated short-circuit, steady-state, and dynamic simulations to assess the grid behavior under various operating conditions and contingency events.

The simulation workflow leverages PSLF's built-in reports and tools, combined with custom Python scripts, to automate model development, simulation execution, data extraction, and results visualization. This streamlined process ensured consistency, repeatability, and efficiency throughout the study.

All simulations were conducted using validated models and industry-standard tools to ensure the accuracy and credibility of the results. The methodology supported both baseline assessments and comparative evaluations of mitigation strategies, including the deployment of SCs and/or GFM BESS. The primary criteria for sizing SCs and GFMs are to minimize resource tripping and ensure that the system quickly reaches a stable post-contingency operating state.

D. Contingencies

To evaluate the system's robustness under stressed operating conditions, the following contingencies were analyzed:

- Transmission Line Faults and Trips: A total of 28 faults and outage scenarios were simulated on key transmission lines.
- Transformer Outages: The impact of two (2) transformer failures was assessed.
- Renewable Energy or Storage Project-Associated Radial Line Outages: Eleven outage scenarios were considered on radial lines connected to major renewable resources.

This analysis is crucial for identifying potential vulnerabilities and determining the necessity of mitigation measures.

IV. Results and Discussion

This section presents the findings based on the simulation scenarios and methodologies outlined in Section III. Each analysis aims to identify potential operational constraints, evaluate the effectiveness of mitigation strategies, and support decision-making on integrating new GFM resources. The assessments include load flow, short-circuit, and dynamic stability studies. Key observations are discussed with respect to voltage profiles, thermal loading, system strength, and dynamic stability.

A. Location Identification

A short-circuit assessment was conducted using ASPEN OneLiner across multiple grid points to identify the optimal placement for a GFM resource. The evaluation focused on two representative scenarios: C2, representing peak solar output, and C3, reflecting maximum BESS dispatch in the absence of solar generation. These scenarios capture the extremes of IBR dominance and allow for evaluation of system performance under high IBR conditions.

System strength is quantified using the Short-Circuit Ratio (SCR), defined as the ratio of the available short-circuit MVA to the rated capacity of the connected equipment. For this study, a Composite SCR [3] was used. A substation near the new stand-alone battery (SAB) consistently exhibited the lowest SCRs (1.66-2.41 for C2), making it the most critical candidate for mitigation. Reinforcing this location with an SC or GFM BESS would enhance local system strength and improve overall grid resilience under high-IBR dispatch conditions. Mitigations on other low-SCR parts of the grid were also carried out; however, only the location of the new SABs addressed the identified issues.

B. Reference Simulations with GFL IBRs

This section presents the baseline results, which serve as a foundational reference for evaluating the system's dynamic performance across various configurations and contingency scenarios. The reference simulations were conducted with IBRs (solar PV and BESS) operating in grid-following (GFL) mode to understand the system's inherent behavior, both without and with additional mitigation measures.

1) No additional SC and GFM BESS

The reference simulations assume all IBRs operate in GFL mode, with no additional SCs or GFM BESS integrated. This simulation setup reflects the current system configuration, incorporating the planned clean energy resources in their basic form. It serves as a benchmark for evaluating the system's dynamic performance and identifying the need for additional grid support elements.

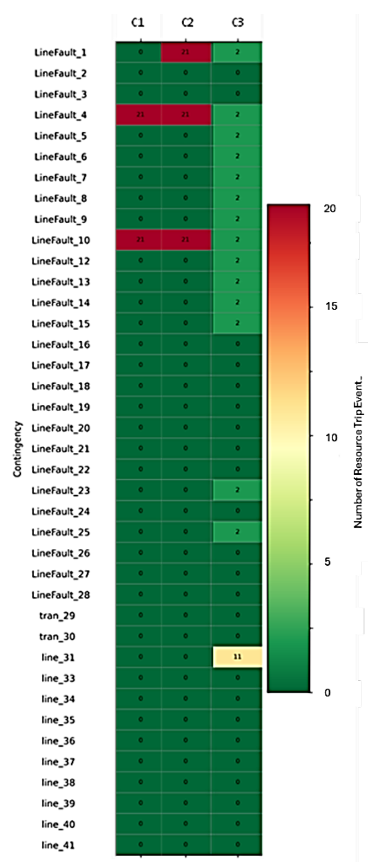

Figure 2. Reference simulation's heatmap results.

Figure 2 presents a simulation results matrix that summarizes the baseline dynamic performance results. Each row corresponds to a specific contingency event, while each column represents one of the three operating scenarios: C1, C2, and C3. Each cell in the matrix represents the number of resource trip events associated with a particular contingency and a specific operating case. A value of zero (green) is ideal, indicating that all resources remained online

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and that the grid maintained synchronous operations throughout the disturbance. This reflects a resilient grid response. Higher values (red color) indicate increased vulnerability, highlighting areas where the system may struggle to maintain stability and where additional support may be needed to maintain it.

This heatmap provides a snapshot of how the system responds to disturbances across various scenarios, enabling the identification of weak areas and the prioritization of mitigation strategies for future system enhancements. While all cases exhibit some level of vulnerability, C2 shows the highest tendency for cascading outages, in which multiple resources trip in response to a single disturbance. This reflects the system's heightened sensitivity during periods of high demand and high IBR penetration, especially when GFM support is insufficient.

C1 exhibits fewer cascading events but still demonstrates instability in some contingencies. A lower load may reduce system stress, but the presence of solar generation without sufficient GFM capability can still cause resources to trip under fault conditions.

C3 has a broader spread of contingencies, resulting in at least one outage. However, the severity of these events is lower than that of C2. This suggests that while the system remains vulnerable, the likelihood of widespread cascading failures is reduced under this configuration.

The results show that all scenarios required support in managing increased IBR penetration. This underscores the need for enhanced GFM support and strategic mitigation measures, particularly during periods of high solar output and peak demand.

2) With an additional SC

This subsection evaluates the required size of additional SCs to meet dynamic performance criteria under the reference cases. As a reference, various condenser ratings (25 to 100 MVAR in 25 MVAR increments) were tested to determine the capacity required to improve system inertia and short-circuit strength, thereby enhancing voltage and frequency stability. The results provide a technical basis for potential investments in SCs as a mitigation.

For the results, each case will be presented with its own results matrix. In these matrices, the rows correspond to specific contingencies, while the columns represent varying sizes of SCs. Each cell reflects the number of resource outages for a unique combination of contingency and condenser size. Figure 3 illustrates the results for SC sizing for C1, C2, and C3.

In C1, no resource outages were observed after SC support was introduced. The resource trip events observed at 0 MVAR are fully mitigated with condenser sizing at or above 25 MVAR.

C2 shows a more nuanced response. While 'LineFault_4' and 'LineFault_10' exhibit excessive resource trip events at 0 MVAR and again at 100 MVAR, no resource trip events are recorded at intermediate condenser sizes (25 to 75 MVAR). This pattern suggests a non-linear relationship between condenser sizing and system response, where mid-range sizes provide optimal damping and fault ride-through capability, while larger sizes may inadvertently amplify system sensitivities. The absence of resource trip events at these mid-range sizes underscores the importance of tuning SC support, rather than assuming that increased capacity always yields better performance.

In C3, cascading outages are observed for the 'line_31' contingency. This results in the disconnection of the largest online unit, leading to a significant frequency drop and subsequent underfrequency tripping of other units. These cascading outages persist in the reference case and with the 25 MVAR SC case, but are successfully mitigated at 50 MVAR, where the added synchronous inertia is sufficient to arrest the frequency decline and prevent further tripping. This highlights the crucial role of SCs in maintaining system stability, particularly in situations involving the loss of major resources.

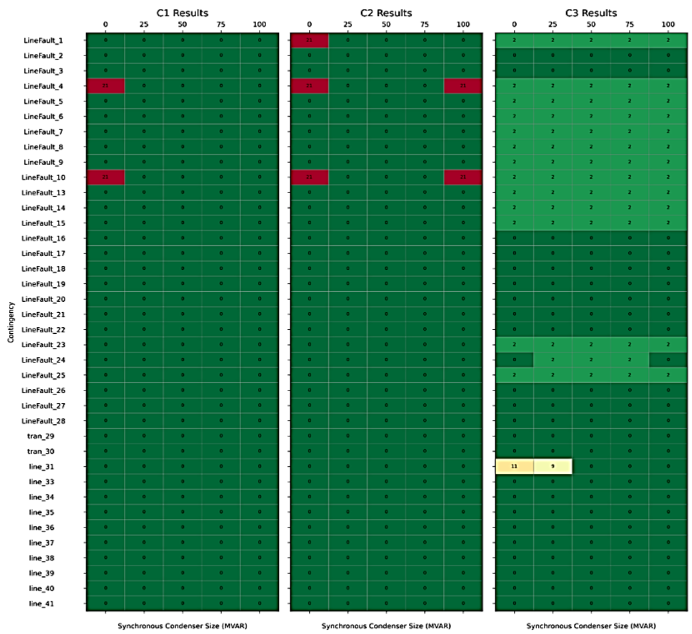

Figure 3. Resource outages with additional Synchronous Condenser

Across all three cases, SC support improves system stability, though effectiveness varies by fault scenario and condenser size. Based on the simulation results, an SC size of 50 MVAR is recommended as the minimum effective level of support to ensure stability across all tested scenarios. It provides sufficient inertia and reactive power support to prevent resource trip events, prevent cascading outages, and maintain system stability across the range of tested high IBR penetration scenarios.

3) With additional GFM BESS

The simulations in this subsection evaluate the minimum GFM BESS capacity to achieve comparable or improved performance compared to the reference case and the case with SC. GFM BESS sizes were also tested from 25 to 100 MVA in 25 MVA increments to determine the capacity required to arrest frequency decline and ensure system stability following a major contingency. The sizing results for C1, C2, and C3 are illustrated in Figure 4.

In C1, resource trip events are observed for 'LineFault_4' and 'LineFault_10', under the no-GFM BESS condition. However, once GFM BESS support is introduced, no resource trip events are recorded across all contingencies. C2 exhibits a similar trend. Several contingencies, including 'LineFault_1', 'LineFault_4', and 'LineFault_10', show an elevated number of resource trip events in the absence of GFM BESS. However, with the addition of GFM support for SCs of 25 MVA or greater, all resource trip events are eliminated. This indicates that even minimal GFM support is sufficient to stabilize the system across a broad range of faults in C1 and C2.

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In C3, the system is generally stable with GFM support, but the results highlight the importance of appropriate sizing. The 'line_31' contingency results in 11 resource trip events without GFM BESS, indicating that the existing system support is insufficient to arrest frequency decline following the loss of a major unit. This issue is mitigated by introducing a 25 MVA GFM BESS, which eliminates resource trip events for 'line_31'. However, some residual resource trip events persist for other contingencies at 25 MVA. These issues have been fully resolved with the deployment of a 50 MVA GFM BESS, confirming that this size provides sufficient support to prevent such outages.

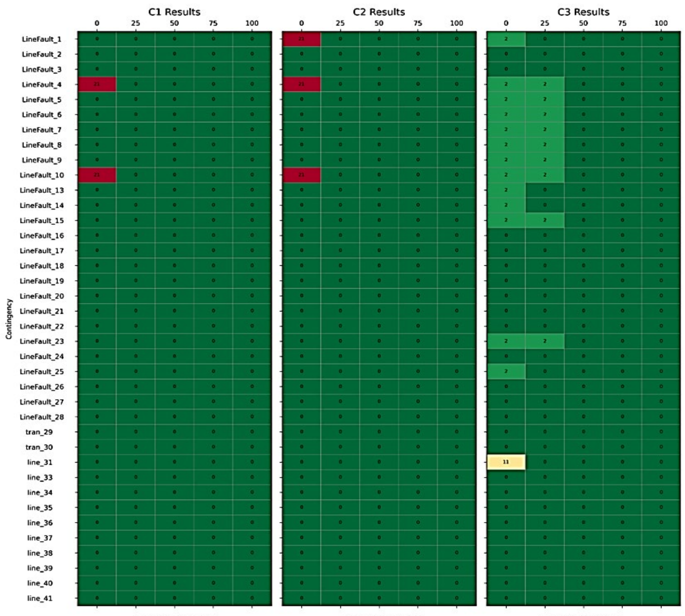

Figure 4. Resource outages with additional GFM BESS (MVA).

Across all cases, the introduction of GFM support consistently improves system stability, suppresses resource trip events, and prevents cascading outages. Notably, 50 MVA emerges as the minimum adequate GFM BESS size that reliably mitigates all observed disturbances across the full range of tested scenarios.

4) Sync Condenser and GFM BESS Response Comparison

This subsection presents a comparative analysis of the dynamic responses of SCs and GFM BESS under a sample fault scenario. The objective is to evaluate their effectiveness in improving system stability during disturbances.

- Sample: C2 with cascading resource outages: 3-phase fault at a 115 kV line with additional 100 MVAR SC or 100 MVA GFM BESS.

While a 50 MVA GFM resource is already sufficient for operational needs, this sample was chosen to illustrate dynamic behavior. For most simulations, both technologies performed effectively under the given system and fault conditions, with terminal voltages remaining close to their nominal values and reactive power outputs well regulated. This indicates that under the given system conditions, either technology can provide adequate dynamic support.

However, in the above sample, despite identical conditions—location, reactive power rating, and initial system state—the technologies exhibited distinct behaviors. The SC exhibited significant fluctuations in reactive power and delayed voltage recovery, as illustrated in Figure 5. This response is primarily attributed to the nature of the disturbance and the SC's reliance on passive electromechanical dynamics, which are inherently slower and less adaptable to rapid system changes. The size of the GFM resource also plays a critical role in system impact. Both technologies can provide adequate support at 50 MVA; however, increasing SC capacity to 100 MVA resulted in tripping, whereas a 100 MVA GFM BESS did not. This contrast highlights how sizing also impacts effectiveness, reliability, and operational risk.

In contrast, the GFM BESS maintained a well-damped and stable response throughout the disturbance, with voltage and reactive power quickly returning to nominal levels, as illustrated in Figure 5. Its inverter-based control system actively regulates voltage and frequency, enabling precise and immediate reactive power injection during faults. The same qualitative response trends are expected for the recommended 50 MVAR SC and 50 MVA GFM BESS configurations, though with smaller magnitude differences.

As shown in the last two rows of Figure 5, the SAB and solar plants tripped in the SC case, resulting in zero active power generation. Conversely, the case with the GFM BESS recovered and returned to its pre-disturbance generation levels.

The performance difference highlights the critical role of technology-specific control characteristics in dynamic behavior. The improved response from the GFM BESS under the given system and fault conditions can be attributed to its advanced control capabilities and fast-reacting inverter-based design.

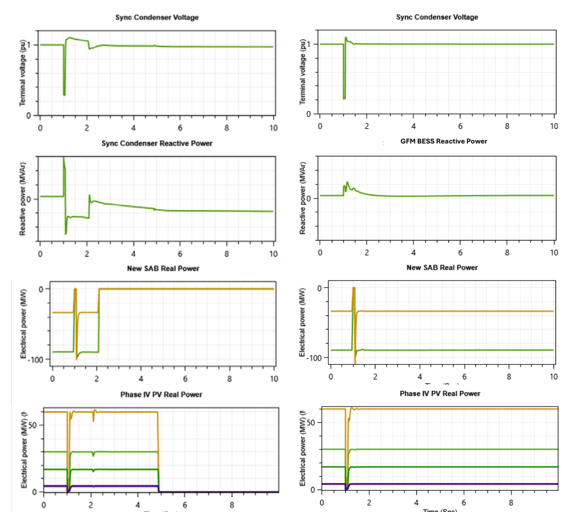

Figure 5. Responses of additional SC (left) and GFM BESS (right) during a fault at a 115 kV Line, considering C2.

It is essential to recognize that system response and stability are influenced by a combination of factors beyond the fault voltage level alone. Fault location, duration, proximity to critical buses, short-circuit ratio, and pre-disturbance operating conditions all affect the system's response. These factors were evident in the simulations and should be taken into account when evaluating each technology's impact. These simulation results align with the broader comparison of GFM technologies described in the Grid-Forming Technology in Energy Systems report [4].

In summary, both technologies are suitable for supporting the tested system and the tested fault conditions. However, in the considered system and scenarios, GFM BESS demonstrates greater stability and control support, making it a more robust solution for this grid, which has high generation variability and

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low inertia. SCs remain valuable for providing inertia and fault current support but may require further tuning to respond effectively to a range of events.

C. Full GFM Integration for BESS

Full GFM integration is the scenario where existing BESS projects transition from GFL to GFM. In this setup, both voltage stability and frequency response show significant improvements. Simulations showed that none of the C1 through C6 resulted in resource outages. To compare the system responses before and after GFM implementation, contingency ‘LineFault_2’ (a fault on a 34.5 kV line) in C3 was thoroughly evaluated. Figure 6 presents a comparative analysis of terminal voltage responses for key resources, both without (left) and with GFM (right).

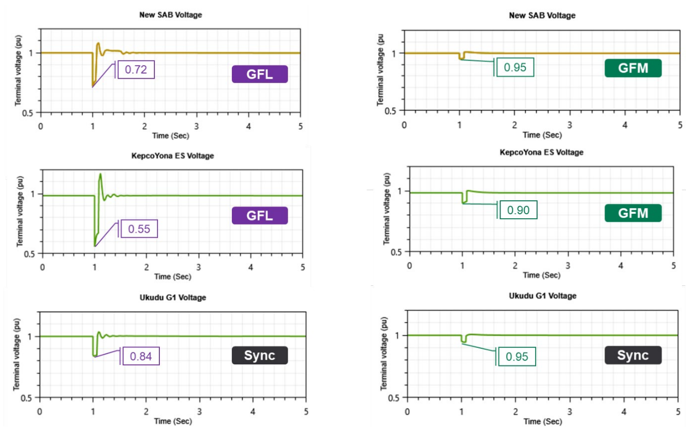

Figure 6. Resource responses with GFL (left) and with full GFM (right) for storage projects.

When the IBRs were operating in GFL, the voltage levels across the monitored resources were notably lower. The voltage at the new SAB under GFL control reached 0.72 per unit (pu), while the Phase IV Yona BESS voltage dropped to 0.55 pu. Even the synchronous generator Ukudu G1 showed a limited response, and its voltage only reached 0.84 pu. With GFM integration, the new SAB voltage improved to 0.95 pu, Phase IV Yona BESS’ voltage to 0.90 pu, and Ukudu G1 rose 0.95 pu, all benefiting from the enhanced grid support. These results underscore the stabilizing effect of GFM support, which enhances voltage recovery (and frequency recovery) and supports the grid during disturbances.

Figure 7 compares system frequency behavior during the same contingency. With GFL, frequency deviations are more pronounced, indicating a lack of system-wide inertial support. In contrast, the GFM-enabled scenario exhibits a more stable frequency response, demonstrating GFM resources’ ability to emulate inertia and provide rapid frequency support.

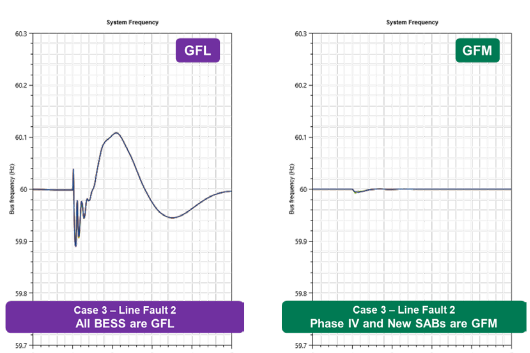

Figure 7. System frequencies at various substations (left) with GFL and (right) with GFM for storage projects.

This improved dynamic behavior is critical to maintaining system reliability, especially in grids with high IBR penetration. GFM integration not only enhances frequency stability but also significantly improves voltage recovery, resource coordination, and overall system damping during disturbances. These capabilities contribute to better disturbance ride-through, more resilient grid operation, and a stronger foundation for future renewable and storage deployments.

D. Summary of Results

Reference simulations indicate that the system is vulnerable to cascading outages without GFM support, particularly during periods of peak solar generation and high evening demand. The introduction of a 50 MVAR SC or a 50 MVA GFM BESS mitigated these risks. Also, proper sizing of the SC is critical, as oversizing can adversely impact dynamic responses. Notably, operating all BESS units in GFM eliminated the need for further support.

V. Conclusions and Recommendations

This study evaluated the dynamic performance of the GPA system under various configurations and sizes of SCs and GFM BESS. Simulations covered a range of operating conditions, represented by C1 through C6, which included different generation and demand mixes and levels of synchronous generation.

Results indicate that if all IBRs remain in GFL and synchronous generators operate at minimum load, approximately 50 MVA of GFM resources would be required to maintain acceptable system performance. However, if the BESS units are transitioned to GFM mode, this additional capacity is no longer necessary. Under full GFM implementation, the system exhibits stable voltage and frequency responses even in scenarios with 100% IBRs.

Nonetheless, additional considerations must be addressed. BESS units are constrained by their available state of charge (SOC), which must be managed during operations and planning. In scenarios with low solar availability or prolonged energy shortages, GFM BESS may not maintain sufficient energy to provide grid support. In such cases, an SC may be required as a backup support. Therefore, it is recommended that a 50 MVAR SC be provisioned as a contingency measure.

While this study provides insights into and recommendations on the potential integration of GFM resources, further investigation is recommended once actual connection details and models become available. Future work should include economic assessments, multi-GFM coordination, electromagnetic transient (EMT) studies, harmonics studies, and SOC management studies to tune parameters and ensure that GFM units operate without adverse control interactions, achieving reliable system performance.

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