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Grid-Forming Battery Storage

Enabling Renewable-Dominant Power Systems for a Sustainable Future

By Yuanbo Chen^{ORCID}, Hongye Guo^{ORCID}, Chongqing Kang^{ORCID}, and Simona Onori^{ORCID}

ACHIEVING ENERGY SUSTAINABILITY REQUIRES a transition from fossil fuel-based to renewable-dominant power systems (RDPSs). However, this shift introduces significant grid stability challenges, primarily due to the reduced synchronous dynamics traditionally provided by conventional thermal power plants. To enhance RDPS resilience, grid-forming battery energy storage systems (GFM-BESSs) have emerged as a pivotal solution,

emulating the dynamic behaviors of synchronous generators (SGs). With efficient bidirectional power interaction and fast response, GFM-BESSs actively enhance grid stability through virtual inertia, voltage support, enhanced synchronization, and restoration capability. In this review, we establish the GFM-BESS as a standalone and integral grid infrastructure in RDPSs. We first identify the stability risks in RDPSs and systematically examine the role of the GFM-BESS in supporting grid stability. We then investigate the coordination between multiple hierarchical control layers of the

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GFM-BESS, including the battery management system (BMS), power converter system (PCS), energy management system (EMS), and grid EMS (GEMS), which collectively address its operational complexities across different timescales. Based on the grid stability requirements, we evaluate the technical benefits of GFM-BESS deployment and discuss potential monetization approaches for the economic value of GFM-BESSs in RDPSs. Finally, highlighting the potential of GFM-BESSs in driving the sustainable energy transition, we conclude with a strategic road map that identifies the collaborative synergies of multiple stakeholders, from hardware manufacturers to policymakers, outlining key opportunities for future research to advance GFM-BESSs as a cornerstone of the 100% renewable energy goal.

Introduction

Driven by the need for decarbonized and sustainable energy supplies, modern power systems are undergoing a major transformation toward RDPSs. The integration of intermittent renewable energy sources (IRESs), such as wind and solar power, has grown rapidly in recent years, gradually replacing the traditional fossil fuel-based SGs and leading to a substantial reformulation of the power system structure.

In the interconnected power system, real-time power balance between grid components, i.e., generators and loads, ensures stability, which can be characterized by the synchronized frequency near-nominal value (typically 50 or 60 Hz), stable grid voltage profiles, and steady phase angle distribution. However, RDPSs are subject to multi-source disturbances in power balance, including small disturbances arising from renewable and load uncertainties as well as large disturbances caused by grid faults or natural disasters. As a consequence, the transition to RDPSs brings significant challenges to grid stability, primarily due to the inability of IRESs to provide inherent electromechanical dynamics and enduring grid disturbances like SGs. The lack of electromechanical dynamics in RDPSs can result in frequency instability, voltage fluctuations, and poor synchronization performance, which impedes a wider deployment of IRESs and sustainable energy transition. As the European Union targets more than 60% of its energy supply from IRESs and less than 10% from traditional fossil fuel-based sources in its 2050 net zero outlook, the European Network of Transmission System Operators for Electricity (ENTSO-E) simulates potential grid scenarios and anticipates a steady decline in inertia

from 2025 to 2040. In the United Kingdom, where IRES generation accounts for nearly 30% of total generation, a real-world blackout in 2019 further demonstrates the increased risk of power outages associated with higher renewable penetration and insufficient electromechanical dynamics.

To address the aforementioned challenges, GFM-BESSs emerged as a promising solution to enhance the grid stability of RDPSs. Several laboratory-scale experiments, such as the 1-MW battery storage installed at the National Renewable Energy Laboratory (NREL) Flatirons Campus, have been carried out to validate GFM performances. Utility-scale pilot projects, such as a 250-MW installation currently under construction in northwest China and a 300-MW project in Blackhill, U.K., have been launched to explore the potential of GFM-BESS commercial deployment.

As typical configurations, BESSs consist of electrochemical power sources, such as lithium-ion batteries, and power inverters that convert between the battery's dc output and ac grid power. A transformer at the point of connection (POC) connects the whole BESS with the external grid. Traditionally, BESSs integrate with the power system as a grid-following (GFL) current source, which passively follows the grid frequency and voltage at the POC. GFL is a cost-effective integration mode in systems with sufficient SGs that can establish stable and strong synchronization references of frequency, voltage, and phase angle. However, the limited presence of SGs in RDPSs compromises the operational environment required by GFL devices and weakens the system's overall stability. In contrast, the GFM-BESS behaves as a voltage source that emulates the SG dynamics and establishes its own synchronization references. It actively stabilizes the RDPS during disturbances by providing device-based virtual inertia to resist deviation from nominal frequency, voltage support to establish a stable grid-side voltage reference, and enhanced synchronization to improve angle stability while also offering restoration capability during blackouts.

Given the promising potential to enhance grid stability, recent research has extensively explored the theoretical principles and simulated the operational mechanisms of the GFM-BESS. However, most studies primarily focus on inverter design and inverter control strategies, typically assuming ideal power sources with unlimited energy and power capacity while overlooking their inherent dynamics and constraints. Recently, researchers have recognized the essential role of power sources for ensuring

reliable GFM integration in power systems, putting an increasing effort into incorporating power source characteristics into utility-scale GFM-BESS design. Addressing the recent trend, this article systematically investigates the GFM-BESS as a standalone and integral grid infrastructure, highlighting its role in supporting RDPSs' stable and efficient operation and examining key technical challenges along with potential solutions for its deployment in RDPSs.

Role of GFM-BESSs in RDPSs

Stability Risk of RDPSs

The overall stability goal of the power system is to effectively maintain grid components, i.e., generators and loads, synchronized at the nominal frequency, voltage, and phase angle level, to ensure balanced and safe operations. However, the increasing penetration of IRESs has significantly changed the power system structure. The IRESs are typically integrated into the grid through GFL inverters, which synchronize with the grid via a phase-locked loop (PLL) but do not inherently correct themselves to match with the true nominal values. In fact, GFL-based IRESs rely on extrinsic synchronization references from the interconnected grid to get synchronized. As the share between IRESs and SGs shifts, the grid strength gradually declines due to the reduced availability of SGs to provide sufficient stability support, making the RDPS vulnerable to external disturbances. Moreover, PLL-based integration without vigorous synchronization references provided by SGs can also lead to adverse interactions among inverters, potentially causing transient angle instabilities or even oscillations, further exacerbating grid vulnerability. With the increasing penetration of IRESs, the stability margin of the grid shrinks and brings higher operational risk regarding grid stability, highlighting the urgent need for advanced strategies to strengthen the RDPS.

Unique Strengths of GFM-BESSs

GFM devices have been introduced to strengthen the vulnerable grid by actively emulating the SG dynamics. By precisely controlling their interactions with the grid, GFM devices provide critical dynamic support to enhance grid resilience. Among various GFM devices, the GFM-BESS stands out as a leading solution due to its unique strengths in the following aspects:

- ▶ *Bidirectional power interaction:* GFM devices are expected to dynamically adjust their power output to maintain balanced grid

operation during disturbances. The GFM-BESS is inherently capable of both absorbing and injecting power from/to the grid with the energy stored in batteries. In contrast, unidirectional power sources such as IRESs must retain a considerable curtailed power reserve for such GFM integrations, limiting their flexibility in providing dynamic support. Furthermore, while IRES outputs are highly stochastic and intermittent, the GFM-BESS ensures a stable and controllable power output for reliable GFM integration.

- ▶ *Fast response:* As one of the primary mitigation measures for grid disturbances, GFM devices are required to possess outstanding real-time response capabilities. Leveraging the electrochemical reactions in batteries, the GFM-BESS can rapidly counteract disturbances and instantly full-power ramp-up/down in less than 100 ms, which complies with the IEEE 2800-2022 standard. Some other energy storage technologies, such as compressed-air systems or thermal-based systems, typically provide minute-scale response and fall short of the speed requirements for GFM integration. In contrast, the subsecond response capability makes GFM-BESSs comparable with SGs in transient stabilization, especially under extreme contingencies to prevent cascading failures.
- ▶ *High efficiency and large capacity:* The GFM-BESS leverages advanced lithium-ion batteries to achieve a roundtrip efficiency of more than 95% (excluding inverter efficiency) and a utility-scale capacity exceeding 100 MWh. Other types of commercial energy storage typically fail to strike a balance between efficiency and capacity; compressed-air systems provide large capacity but low efficiency, whereas flywheel systems have high efficiency but are usually limited in capacity. However, the GFM-BESS combines both advantages. Its high efficiency ensures sustained grid support under dynamic load fluctuations and reduces operational costs while also preserving the state of charge (SOC) for energy arbitrage and ancillary services such as frequency regulation. Its large capacity also enables it to serve as a grid resilience asset in contingency scenarios such as black-start applications and islanded operations, where sustained power delivery is required. This provides reliable alternatives to keeping backup generators in RDPSs.

In addition to the previous technical advantages of the GFM-BESS compared to other GFM devices, the GFM-BESS also benefits from the developed industry of lithium batteries in terms of cost-effectiveness and quality guarantees. Combining both technical and commercial considerations, the GFM-BESS emerges as a highly competitive and practical resource for GFM integration, providing flexible and reliable grid support for RDPSs.

Grid Support Capabilities of GFM-BESSs

The GFM-BESS introduces a new paradigm of grid structure by integrating without a PLL, creating its own synchronization references that comply with the system code. As shown in Figure 1, unlike GFL-based IRESSs, the GFM-BESS behaves as an SG, with battery storage acting as the prime movers to drive the induction-machine-like power inverters. Through this SG emulation, the GFM-BESS contributes to the grid strength by enhancing RDPS stability without vigorous extrinsic synchronization references.

Specifically, the GFM-BESS provides grid support to RDPSs from two aspects, including stabilization capabilities and restoration capabilities. The first aspect tries to maintain the stable operation of the grid, which includes the following:

- *Virtual inertia*: The GFM-BESS actively regulates its frequency reference based on real-time power output to emulate the inertial response of SGs. This virtual inertia effectively contributes to the overall power system inertia, a physical grid characteristic that resists rapid frequency deviations from the nominal value. Virtual inertia primarily

helps mitigate the rate of the change of frequency during disturbances, enabling the RDPS to sustain the operational frequency.

- *Voltage support*: The GFM-BESS operates as a voltage source by establishing an inherent voltage reference and dynamically regulating the operational voltage at the POC through absorbing or injecting reactive power. In addition, during severe over-voltage or low-voltage faults, GFL-based devices will disconnect from the main grid because their PLL-based integration fails without stable synchronization references. In contrast, the GFM-BESS demonstrates superior fault-ride-through (FRT) performance by actively supplying short circuit current, stabilizing the voltage during faults, and protecting the grid from cascading failures.
- *Enhanced synchronization*: Instead of passively following the grid phase via PLL, the GFM-BESS controls its phase angle by virtually mimicking the rotor dynamics of SGs. It incorporates virtual damping to suppress angle oscillations and mitigate transient angle deviations during extreme disturbances. In addition, multiple distributed GFM-BESSs can coordinate their independent phase angles like SGs to establish a robust synchronization in RDPSs, which is particularly critical when IRESSs become the dominant power source.

The restoration capability of the GFM-BESS enables postcontingency recovery by reestablishing the steady grid states and restoring normal grid operations following extreme grid faults, which are represented as follows:

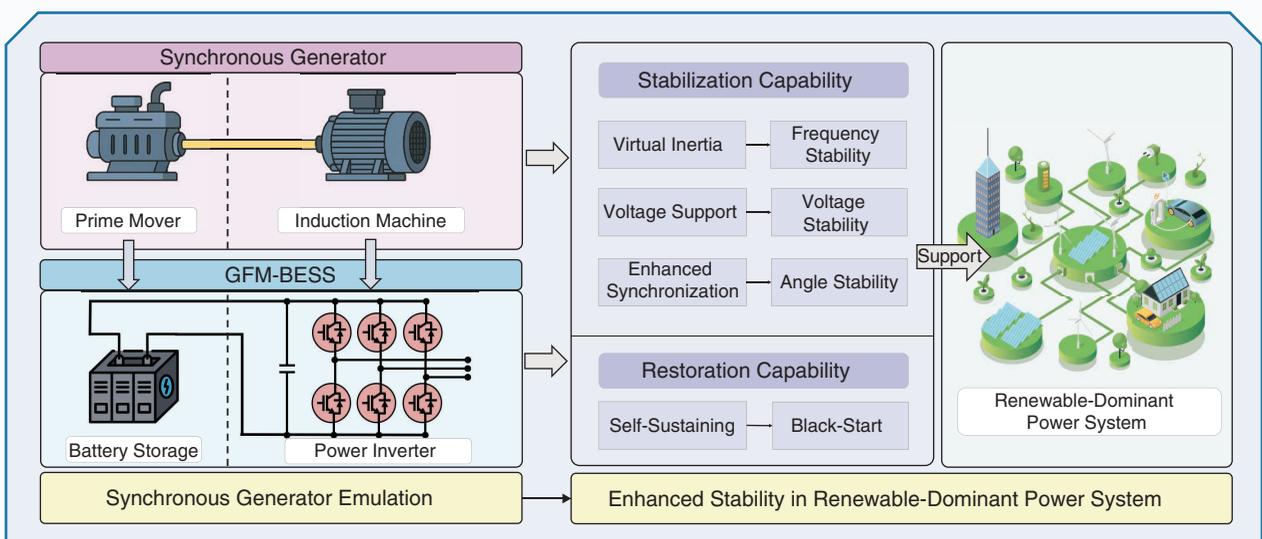


figure 1. GFM-BESS emulation of SG dynamics for grid support in RDPSs.

- **Black-start capability:** Due to the self-sustaining nature of the GFM-BESS, it is possible to utilize the GFM-BESS to restore normal operations after blackouts and reestablish grid-side synchronization references. Leveraging the stored energy in batteries, the GFM-BESS can energize the grid and restart other IRESs without relying on external power sources, making it an ideal solution for black-start when SGs become scarce. During islanded operations, the GFM-BESS also provides the RDPS with stable synchronization references to support its reconnection to adjacent systems.

Overall, the GFM-BESS serves as an effective substitute for SGs in maintaining the grid stability of RDPSs.

GFM-BESS Management Framework

Hierarchical Structure of GFM-BESSs

The GFM-BESS relies on a hierarchical structure to integrate electrochemical devices with power electronics and grid interfaces, along with corresponding control systems to manage the interactions among these components.

Physical Structure

A grid-connected GFM-BESS adopts a modular design to establish a utility-scale station. It consists of the following layers of physical components, as shown in Figure 2:

- **Battery cells:** For utility-scale applications, battery cells are typically based on lithium

iron phosphate chemistry primarily due to safety concerns.

- **Battery packs:** Battery cells are connected in series and/or parallel to form battery packs, which serve as the minimum controllable modular part in the GFM-BESS. They are also the smallest replaceable part during maintenance.
- **Battery units:** Battery packs are further assembled into containerized battery units. Each containerized battery unit integrates with an independent power inverter unit to convert the dc power from batteries to ac power for the grid.
- **Utility-scale station:** A BESS station aggregates multiple containerized battery units with their corresponding power inverter units. The BESS station is connected to the grid through a transformer at the POC. Additionally, the BESS station is equipped with a central server and a communication system, enabling the GFM-BESS operator to monitor and control the station-wide operations as well as exchange real-time data with the upper-level system operators.

Control Structure

The control systems of a utility-scale GFM-BESS align with its modular physical structure, with components hierarchically controlled, as given in Table 1.

- At the battery pack layer, each pack is equipped with a BMS, which continuously monitors the input current and output voltage of battery cells. It utilizes embedded

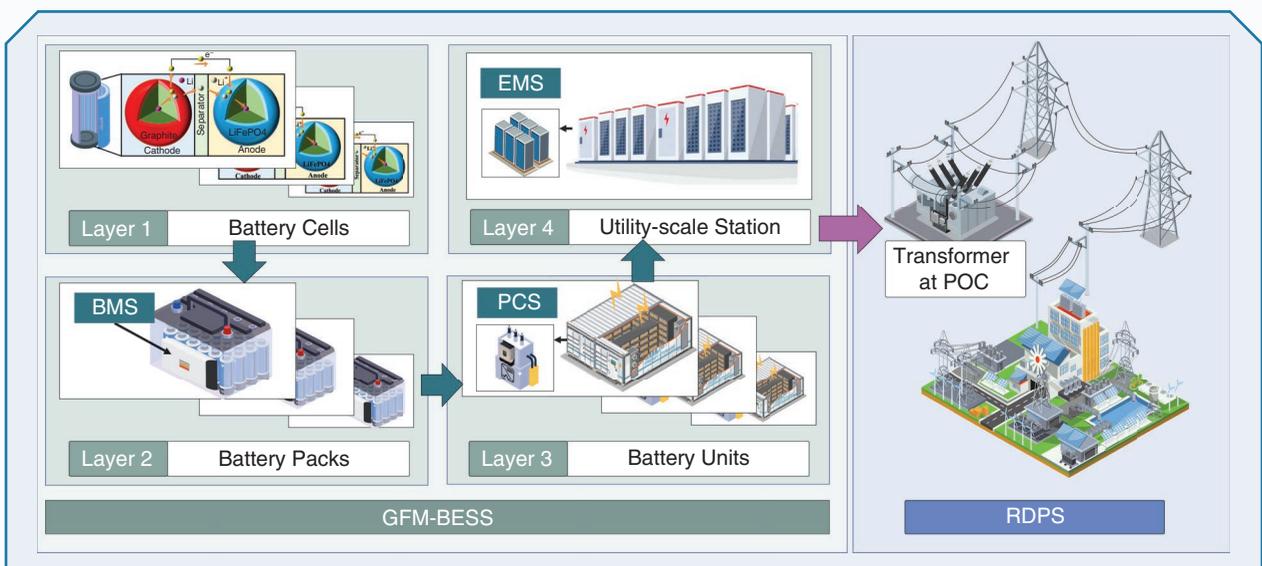


figure 2. The hierarchical GFM-BESS structure.

battery models and algorithms to estimate internal unmeasurable battery states like the SOC and state of health (SOH). The BMS also implements cell balancing through dedicated hardware consisting of sensors, balancing resistors, and switching circuits and provides fault protection using relays to isolate malfunctioning cells when necessary.

- At the battery unit layer, the power inverter unit integrates with advanced control algorithms to form a PCS, regulating the bi-directional power flow between the GFM-BESS and the grid to emulate SG dynamics.
- At the station layer, an EMS coordinates the interactions between multiple BMSs and PCSs while managing the power exchange at the POC to comply with the grid code.
- At the grid layer, the station-level EMS communicates with a higher-level control system, the GEMS. The GEMS enables system operators to receive state information from each station, designate dispatch commands, and coordinate multiple GFM-BESS stations with other grid infrastructures.

GFM-BESS Management Strategy

Unlike traditional BESSs, the GFM-BESS introduces additional managing complexity due to its need for dynamic grid synchronization. To ensure its efficient operation and reliable GFM integration, recent research has proposed effective management strategies to address its unique GFM characteristics and the corresponding complexities across multiple timescales, including real time (subseconds to minutes), day ahead (hours to days), and long term (months to years). Based on the hi-

erarchical structure of the GFM-BESS, bottom-up strategies modularly manage the battery packs, battery units, BESS stations, and RDPSs integrated with GFM-BESSs.

Pack Layer

Managing battery packs primarily relies on the precise real-time estimation of battery states to ensure their safe and efficient operation. To estimate the internal states of the cells within a pack, the BMS measures the input current and output voltage of each cell, generating state estimations using battery models of different fidelities. Among these models, the equivalent circuit model (ECM) utilizes a network of resistances and capacitances to approximate battery response characteristics. It stands out for its computational efficiency and electrical analogy but struggles to capture the nonlinear and time-variant battery behaviors, providing less accuracy in state estimation. To address this issue, the high-fidelity electrochemical model characterizes the electrochemical reactions in batteries, solving partial differential equations to describe the internal physics transition and provide more accurate physics-based state estimation. Unlike the previous analytical methods, data-driven approaches like neural networks look into experimental data to establish a closed-box mapping between input-output pairs and battery states.

For traditional BESSs, low-order ECMs with simplified parameters are sufficient for commercial use when charge-discharge cycles are predictable and contain significant idle periods, given the known temporal distribution of arbitrage opportunities. However, GFM-BESSs operate under volatile grid conditions, continuously

table 1. The control structure of the GFM-BESS.

Control Layers	BMS	PCS	EMS	GEMS
Control scope	Device (battery pack)	Device (power inverters)	Station (utility-scale BESSs)	Grid (microgrid or regional grid)
Main functions	State estimation and fault protection	dc-ac conversion	BESS operation optimization	System dispatch
Control implementation	Software + hardware (autonomous)	Software + hardware (autonomous)	Software based (supervisory)	Software based (supervisory)
Minimum control timescale	<1 s	<0.1 s	~1 min	~15 min
Data processing capability	Medium	Low	High	Very high
Network interface	No	No	Yes	Yes
Platform	Microcontroller	Microcontroller	Central server	Server cluster

responding to the fluctuating grid disturbances. They endure rapid state transitions with additional degradation and increased heat generation due to the highly variable charge-discharge profile. To ensure safe and efficient operations, hybrid models integrating high-order ECMs or electrochemical model with health-conscious neural networks can provide a more robust state estimation and improve the dynamic performance of BMSs in GFM-BESSs.

Unit Layer

The battery unit is the minimum entity that directly interfaces with the external ac power system. It integrates multiple battery packs connected in series and/or parallel, along with an independent power inverter unit for dc-ac power conversion. The ac side of power inverters is physically connected to the low-voltage side of the transformer at the POC, which in turn connects to the high-voltage grid. Within a battery unit, the PCS controls the dc-ac conversion process of power inverters, enabling the GFM-BESS to dynamically respond to grid disturbances and behave as an SG at the hardware level.

Considering high-order SG dynamics, common PCS controller designs, listed in Table 2, replicate only the key SG dynamics that are most critical to system stability, employing

different degrees of simplification. Droop control regulates the output frequency and voltage of a GFM-BESS based on deviations in measured active and reactive power, using a proportional feedback loop to maintain power balance. It provides a simple yet effective PCS controlling strategy, although it offers no virtual inertia. A virtual SG (VSG) emulates the inertial and damping response of SGs based on a second-order swing equation, while the synchronverter additionally accounts for the excitation dynamics of SGs. Different from the previous power-oriented methods, virtual oscillator control (VOC) adopts a voltage-oriented approach and establishes a nominal voltage reference, enabling global synchronization via stabilized voltage distribution across the grid. However, traditional VOC lacks dispatchability since the fixed load parameters and grid impedances determine its power sharing, while dispatchable VOC (dVOC) resolves this issue by integrating additional synchronizing feedback and voltage magnitude control. Leveraging the similarities between SG dynamics and the inherent dynamics of dc-ac conversion, matching control couples the dc-link voltage with the ac-side frequency as an equivalent SG model by rewriting the characterization function of the converting process, providing enhanced compatibility with SGs.

table 2. Typical types of PCS controllers.

PCS Controller	Principle	Key Tunable Parameters	Orders	Virtual Inertia	Transient Stability	Weak Grid Support	Main Characteristics
Droop control	Droop feedback	K_p, K_q (droop coefficients)	1	No	Medium	Low	Simple design
VSG	Swing equation	J, D (virtual inertia and damping coefficient)	2	Yes	Low	Medium	Inertia emulation
Synchronverter	Virtual excitation voltage	J, D (virtual inertia and damping coefficient)	2	Yes	Low	Medium	Excitation characteristics emulation
VOC	Nonlinear oscillator	$g(v)$ (voltage dependence), k_v (feedback coefficient)	2	Yes	High	High	Resistive grid adaptability
dVOC	Oscillator + synchronizing feedback + magnitude control	η (synchronization gain), α (magnitude control gain)	2	Yes	High	High	Dispatchability
Matching Control	Dynamics similarity between the dc-link voltage and frequency	η (matching ratio), k_{dc} (compensator gain)	3	Yes	High	High	Low measurement delay

VSG: virtual SG; dVOC: dispatchable VOC.

Station Layer

Utility-scale GFM-BESSs operate as a standalone infrastructure where the EMS provides decision-making ability, assisting human operators in managing station-wide operations. To improve GFM-BESS efficiency, the EMS executes multiple functions across different timescales.

First, at real timescales, the EMS coordinates the charge/discharge process of multiple battery units to maintain them operating within a safe and feasible region. Optimal power control strategies, such as model predictive control, accommodate the GFM characteristics of the PCS controller under varying battery conditions and dynamic grid fluctuations, simultaneously enhancing battery longevity and improving GFM performance.

Second, at the day-ahead scale, the EMS enables self-dispatch that allows the GFM-BESS itself to determine its interactions with external RDPSs. The rule-based adaptive strategy adjusts the inertial and damping characteristics of the GFM-BESS by tuning GFM parameters (e.g., virtual inertia coefficient and damping coefficient) in the swing equation to enhance grid stability under different disturbance levels. The optimization-based self-tuning strategy achieves a balance between draining the GFM-BESS power and attenuating the deviation of the grid dynamics from their nominal values. In an RDPS with multiple GFM-BESSs, distributed GFM parameter tuning based on reinforcement learning enables the communication-less coordination among multiple stations to collectively contribute to a global optimum of grid stability.

Third, beyond stability enhancement, the GFM-BESS actively participates in multiple grid services such as peak shaving and frequency regulation while complying with the grid code of GFM integration. By formulating operational optimization with forecasted grid conditions and market prices, the EMS schedules the capacity reserve and power flow for different grid services. Considering a market environment, the EMS also assists the GFM-BESS operator in strategic bidding in the power market, addressing a combined consideration of GFM integration, continuous operational constraints, and profit maximization.

System Layer

As the top layer of the control structure, the GEMS manages the overall RDPS by incorporating distributed GFM-BESS stations at various nodes. During real-time operation, the GEMS receives state information from the station-level EMS and

obtains an aggregated system dynamic model to predict the system response after disturbances. By unifying the dynamics of SGs, GFL-based IRESs, and GFM-BESSs, the GEMS analyzes the spatial distribution of system responses using system transfer functions and identifies the least stable regions that require additional GFM support. It also evaluates the impact of varying renewable penetration levels on overall system dynamics through system-wide small-signal analysis.

At the day-ahead scale, the GEMS accounts for the uncertainties in weather-dependent generation and load demand to optimize power flows for IRESs and GFM-BESSs by using stochastic or robust methods. By incorporating frequency or voltage nadir constraints, the GEMS provides the system operator with a stability-constrained day-ahead system dispatch, where nonlinear dynamics are handled via model-oriented approaches like piecewise linearization or algorithm-oriented techniques like dynamic programming.

At the long-term scale, the system operator configures the capacity of GFM-BESSs through stability-constrained planning, with the GEMS simulating system responses under various renewable penetration scenarios. In addition to the total capacity of GFM-BESSs, the spatial allocation of GFM-BESSs is also crucial for grid stability, and the system operator can maximize the GFM-BESSs' deployment efficiency by optimally placing them at the most vulnerable nodes. With well-planned GFM-BESSs, the RDPS will find an opportunity to enlarge its stability margin to accommodate more IRESs.

Coordination in the GFM-BESS Management Framework

To efficiently integrate the GFM-BESS in RDPSs, the GFM-BESS management framework is coordinated across multiple layers to enable cohesive interactions between internal components and tight coupling with extrinsic synchronous references. The multiple management layers are hierarchically organized where the BMS monitors battery cells in a battery pack, the PCS controls power inverters, the EMS manages station operations, and the GEMS supervises system-wide statuses. Their coordinating mechanism is shown in [Figure 3](#), which involves power flow, information flow, and control flow, analyzed as follows:

- *Power flow:* Power flow represents the physical routes of the energy exchange of the GFM-BESS. It follows a bottom-up direction; electrochemical energy is stored in battery cells, producing a certain amount

of dc electrical power for real-time GFM integration. The dc power is then converted to the ac form via power inverters, aggregated at the station level, and finally fed into the grid. Throughout this energy conversion and exchange process, a complete energy transfer pathway is established within the electrical circuits, where the BMS tightly couples with the dc link of the PCS, the PCS interfaces with the EMS via the station-wide ac bus, and the EMS integrates with the GEMS through the grid-connected transformer and the POC.

➤ *Information flow:* Information flow represents data communication and facilitates the decision making of the GFM-BESS. Edge digital devices within a station, like BMSs or PCSs, collect second-scale data from physical entities, process them into state information, and transmit them to the upper-level EMS via a network-based data bus. The BMS continuously updates the SOC and SOH of battery cells. The PCS records the current output and voltage reference of the GFM-BESS while monitoring inverter parameters such as device temperature, converting efficiency, and fault code. Such

second-scale device information of battery cells and power inverters is provided to the EMS for real-time station-wide monitoring, operational strategy adjustment, and fault diagnosis. As the central controller of a standalone GFM-BESS, the EMS aggregates data from edge digital devices and samples real-time grid states at the POC to consolidate the closed-loop control. Additionally, it communicates with the GEMS at a minute-scale frequency to report station statuses and receive dispatch signals. For system operators, the GEMS provides a comprehensive view of the RDPS by compiling data from multiple GFM-BESSs, enabling informed decision making for system dispatch and stability enhancement.

➤ *Control flow:* Control flow represents the command transmission and physical execution process in the GFM-BESS. It aligns with the hierarchical structure of the GFM-BESS with each layer controlling its corresponding components. Following a top-down direction, the GEMS at the system layer issues control commands for energy dispatch and automatic generation control (AGC) signals, distributing them to the EMS

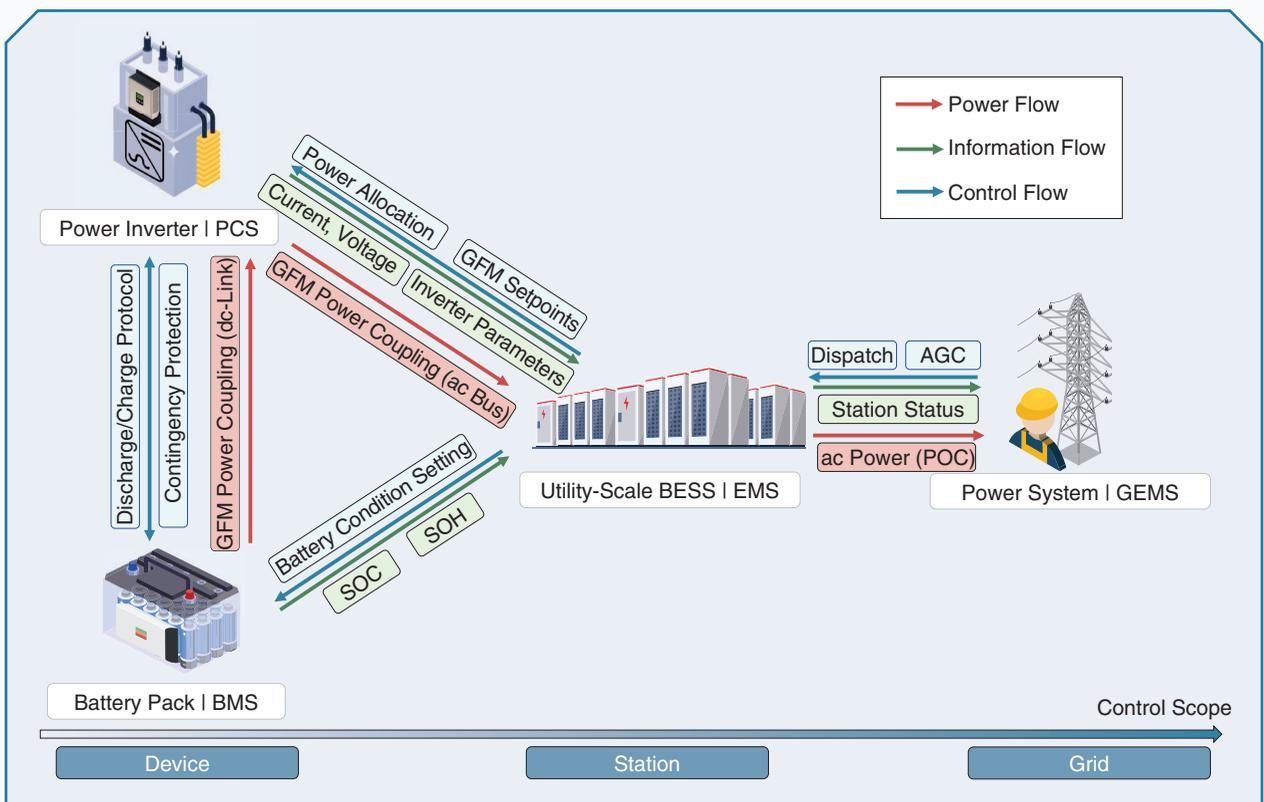


figure 3. The coordinating mechanism across multiple structural layers in the GFM-BESS.

of each GFM-BESS. Upon synthesizing received control commands and station statuses, the EMS accounts for the signal-free GFM integration and adjusts the operational strategy of the GFM-BESS by tuning GFM parameters. With minute-scale communication, the EMS allocates the required power at the POC to multiple battery units and adjusts the set points of GFM parameters in the PCS controller. The EMS also governs the battery condition settings in the BMS, such as the SOC limits and thermal management modes, to adapt to different grid requirements. The PCS and BMS execute control commands from the EMS while being physically coupled to regulate the power flow to emulate SG dynamics. The closed-loop coordination between them ensures that the discharge/charge protocols are compatible with the real-time characteristics of power inverters and batteries. Besides, the PCS also provides the BMS with contingency protection, disconnecting battery units from the ac grid in emergencies.

Integrated Assessment of the GFM-BESS Value

Technical Benefit Evaluation

The GFM-BESS supports flexible deployments in RDPSs and can be integrated at the generation side, grid side, and load side, providing a wide range of grid support capabilities to RDPSs.

Generation Aspect

To improve the dynamic performance of IRESs, there are generally two approaches: retrofitting their inverters to transform GFL-based IRESs into the GFM mode or integrating them with GFM-BESSs. Compared to the former approach, GFM-BESS integration provides a more cost-effective solution by avoiding the renewable curtailment caused by power reserve requirements for GFM integration and reducing the high retrofitting cost associated with large-capacity inverters. Sharing the same POC on the ac side of IRES inverters, the GFM-BESS can dynamically compensate for the mismatch between the real-time IRES power output and emulated SG response by coupling its frequency-domain model with the equivalent impedance of the IRESs. In addition to regulating IRES dynamics, the GFM-BESS can also act as a backup power source to drive the restoration of IRESs after blackouts by switching to recovery mode.

In contrast to traditional SGs, the GFM-BESS can achieve equivalent inertia and damping with significantly smaller capacity due to the electrochemical-based emulation rather than real mechanics. This implies that the GFM-BESS capacity required for making IRESs dynamically comparable to SGs is substantially lower than the total generation capacity of the IRESs. In this context, either upgrading the existing small IRES-coupled BESS to the GFM mode or leasing capacity from third-party GFM-BESS operators is a practical approach for IRESs to improve their dynamic performance without curtailing for power reserve. With GFM-BESS integration, IRESs can primarily operate using maximum power point tracking control while simultaneously acquiring enhanced dynamic performance comparable to SGs. Consequently, GFM-BESS integration at the generation side mitigates stability risk from the origin, enabling the RDPS to treat IRESs as reliable and dispatchable power sources.

Grid Aspect

Standalone GFM-BESS can be directly deployed in the interconnected transmission grid. In real-time analysis and control, GFM-BESS integration reshapes the grid response under disturbances by actively regulating the grid frequency and voltage to the desired nominal values. Enabled by its fast response capability, the GFM-BESS rapidly ramps to counteract disturbances and mitigate the grid contingency within tens to hundreds of milliseconds, preventing further cascading failures. Moreover, the GFM-BESS characteristics will change the eigenvalues of the system transient model, affecting both local and interarea oscillation modes with either positive or negative impacts. Fortunately, since GFM-BESS characteristics are governed by control loops rather than fixed mechanical properties, system operators can fine-tune the GFM parameters within predefined feasible boundaries, optimizing GFM-BESS performance and adapting to varying grid uncertainties. As a grid resilience asset, a higher penetration of GFM-BESS supplements dispatch flexibility and reduces renewable curtailment.

While facing fault events, the voltage source behavior of the GFM-BESS provides a stable voltage reference, preventing rapid voltage collapse and assisting adjacent IRESs with enhanced FRT capability. Under severe weather conditions, large-scale IRESs may disconnect from the main grid due to their PLL-based connection when the

frequency or voltage at the POC exceeds thresholds, whereas the GFM-BESS tightly connects with the grid and acts as a reliable backbone to mitigate the propagation of the cascading process before a complete blackout. Consequently, the GFM-BESS secures the grid operation by providing a larger stability margin. It allows the stability-constrained planning to accommodate more IRESs, supporting the sustainable transition of the RDPS.

Load Aspect

Modern power systems face increasing variable ac loads, like industrial motors, and increasing GFL dc loads, like electric vehicle chargers. These loads are not inherently synchronized with the grid and may exacerbate voltage and frequency deviations during grid disturbances. However, transforming these loads to the GFM mode could disrupt their normal operation and degrade the quality of the power supply. As an alternative approach, GFM-BESS integration on the load side will actively regulate the real-time net load at the same POC by dynamically discharging or charging the batteries. This method emulates synchronized load characteristics, effectively creating GFM-based loads that improve power quality under normal conditions and reduce the need for load shedding during contingencies.

Relying on its advanced control flexibility, the GFM-BESS also enables the heterogeneous distributed energy resources (DERs) connected at multiple POCs to operate in a more synchronized manner by dynamically adjusting their

aggregated response. Assisted by the GFM-BESS, local DERs are coordinated and integrated into a GFM-based virtual power plant (VPP), which more closely resembles the SG-based power plants than conventional VPPs. The GFM-based VPP functions as a unified entity in the RDPS, with enhanced dispatchability and synthetic SG dynamics.

Economic Value Monetization

In conventional power systems, the SG dynamics, such as inertia and damping, are treated as voluntary services for grid stabilization from SGs because they are inherent to the mechanical structure of the SG. However, in RDPSs, when electromechanical SG dynamics become scarce, the system requires additional stabilization support from the GFM-BESS via synthetic SG dynamics. Monetizing such synthetic SG dynamics of the GFM-BESS becomes necessary considering two key factors: 1) the additional cost of the GFM-BESS compared to traditional BESSs, considering factors such as accelerated degradation, extra power consumption, and leveled retrofitting cost, and 2) the scarcity value of SG dynamics as reduced SGs, which depends on the grid stability requirements and the penetration level of IRESs. Based on the different evolution stages of RDPSs shown in Figure 4, this section explores several monetization approaches that economically assess the synthetic SG dynamics from the GFM-BESS and offer corresponding incentives as follows:

- *Contract-based approach:* During the early stages of transitioning to RDPSs, traditional

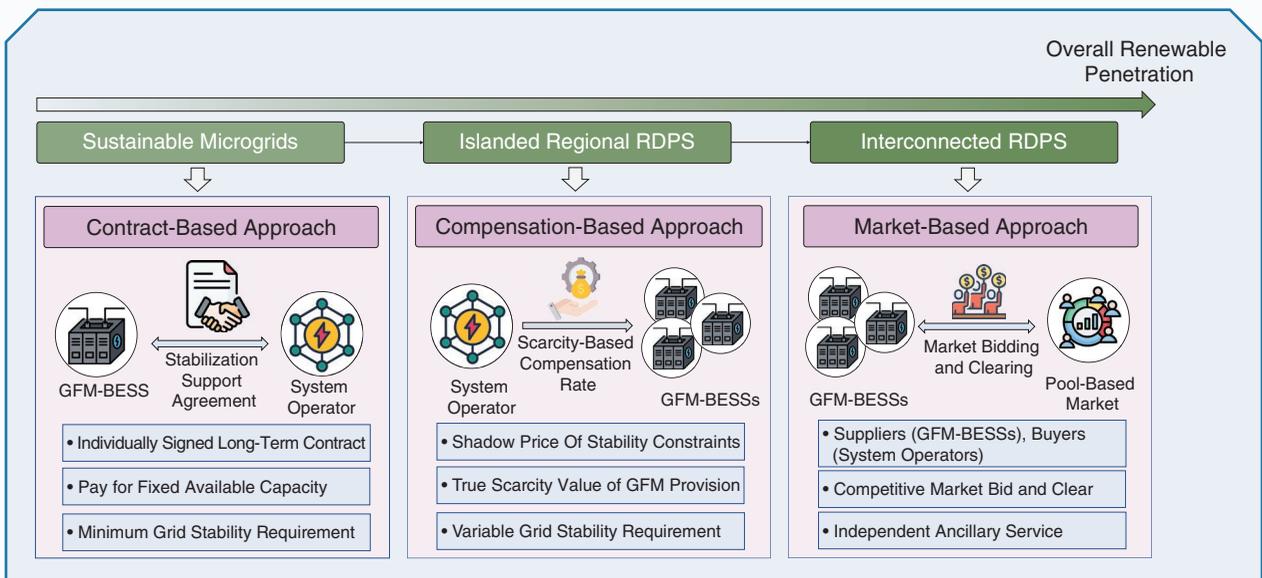


figure 4. Monetization methods of GFM economic value as increasing IRES penetration levels.

SGs continue to provide abundant electromechanical dynamics, reducing the immediate need for additional stabilization support. As a result, the market competitiveness of such support from the GFM-BESS is limited. However, system operators can individually sign long-term contracts with GFM-BESS operators to economically incentivize their participation in stabilizing the grid and to encourage their deployment. These contracts pay for a fixed available capacity of synthetic SG dynamics, which guarantees a reliable revenue stream to offset the operational costs of the GFM-BESS during the early transition period. For the system operators, this approach also secures the minimum grid stability requirements while allowing preparations in advance for higher IRES penetration in the future.

- *Compensation-based approach:* With the increasing penetration of IRESs, the RDPS becomes more fragile due to reduced SG dynamics, and the grid stability margin tightens. Consequently, stability constraints in the dispatch model become strictly binding, yielding nonzero dual variables. These dual variables represent the shadow prices for synthetic SG dynamics from the GFM-BESS, such as virtual inertia. System operators can compensate GFM-BESS operators based on these shadow prices, paying for the actual stabilization support in real-time operations. This approach truly reflects the scarcity value of SG dynamics in RDPSs, ensuring that the compensation aligns with various operational grid stability requirements.
- *Market-based approach:* In a fully developed RDPS, in addition to the scarcity of stabilization support, competitiveness also emerges among multiple providers. As a result, synthetic SG dynamics become an ancillary grid service that can be traded in the power market, establishing the GFM service market. Under a competitive pool-based market framework, GFM-BESSs act as suppliers that submit their price-quantity bids to indicate their marginal cost of the stabilization support, while system operators are buyers that determine the market-clearing price based on the actual grid stability needs. Upon market clearing, all GFM-BESS operators with accepted bids receive a per-unit payment at the clearing price from the system operators for their stabilization support. In addition to inde-

pendent clearing, the GFM service market can also integrate with existing energy or capacity market mechanisms, addressing the stability requirements across different timescales. Although the concept of the GFM service market is still under debate, pilot programs have been initiated in some regions to explore the feasibility of trading synthetic SG dynamics. For instance, the ENTSO-E market in Europe has incorporated voltage support from DERs as a tradable asset, while the AEMO market in Australia actively trades inertia as the rate of change of frequency control service. This market-based approach provides a transparent mechanism to reflect the actual supply and demand of synthetic SG dynamics, which helps reduce overall system stability costs and encourages the efficient utilization of GFM-BESSs.

Road Map and Future Research

Challenges in Commercial Deployments of GFM-BESSs

As shown in Figure 5, despite its potential benefits for grid stability, the GFM-BESS still encounters several technical challenges across different timescales that hinder commercial deployments.

- *Device design:* The transient stability of the current PCS remains insufficient, making it difficult to suppress internal oscillation and ensure robust integration with other GFL-based devices. On the operational timescale, the increased risk of overcurrent also limits the FRT capability of the GFM-BESS, while rapid power fluctuations accelerate the battery degradation, reducing its lifespan and long-term reliability.
- *Operational flexibility:* Although the GFM-BESS improves stability in weak grids, its voltage source behavior may cause increased active power fluctuations and even instability in stiff grids. Moreover, a limited understanding of battery physics in the EMS and PCS control may result in suboptimal operational strategies under different grid conditions, leading to inefficient stabilization support and rapid battery degradation.
- *Grid integration:* The limited low-latency communication between the EMS and GEMS complicates the coordination of multiple GFM-BESSs and makes global synchronization challenging. Moreover, the

lack of standardized grid interconnecting codes also hinders the benchmarking and performance evaluation of commercially deployed GFM-BESSs.

- *Economic feasibility:* The high upfront capital costs and the lack of clear monetization mechanisms create the necessity for careful planning and uncertainties in GFM-BESS investment returns. Furthermore, potential regulatory barriers and the unpredictable need for stabilization support also bring challenges for commercial GFM-BESS deployments.

Addressing these challenges, key research gaps about the GFM-BESS can be summarized as follows: developing a high-performance structural paradigm, optimizing control strategies for cost-effective operation, exploring efficient system integration methods, and establishing a clear economic value monetization framework.

Collaborative Road Map

To advance the GFM-BESS in the RDPS as a major provider of stabilization support, we propose a collaborative road map to tackle the existing challenges and explore synergy from multiple stakeholders to promote the sustainable energy transition. GFM-BESS development is still in its infancy and requires future research to focus on the following aspects:

- *High-performance device:* The systematic design of the GFM-BESS requires further refinement to enhance its transient performance and long-term reliability. Ad-

vanced power inverter controllers should incorporate a deeper understanding of the transient stability of the PCS via detailed modeling of the inverter behaviors in interconnected systems. Robust current-limiting strategies should be developed to ensure the adaptive FRT capability under multiple overcurrent triggering events. At the same time, the long-term reliability of the GFM-BESS relies on accurate battery health estimation, which can be improved through data-mechanism fusion methods in the BMS and real-time health-conscious strategies in upper-level control systems. Hybrid energy storage configurations that combine batteries with supercapacitors or flywheels also offer a promising potential to balance the tradeoff between energy and power density, offloading high-frequency small fluctuations from the health-sensitive battery to achieve an extended system lifespan.

- *Optimal operation:* Optimal GFM-BESS operation is crucial to maximizing its potential for stabilization support while maintaining its operational efficiency and cost-effectiveness. Therefore, advanced EMS management needs to explicitly account for the intrinsic dynamics and constraints of batteries, inverters, and the integrated system. This ensures physically feasible GFM parameter selection and power allocation for real-time implementation. Additionally, the EMS should also assess the economic value of stabilization support and optimize the tradeoff among multiple

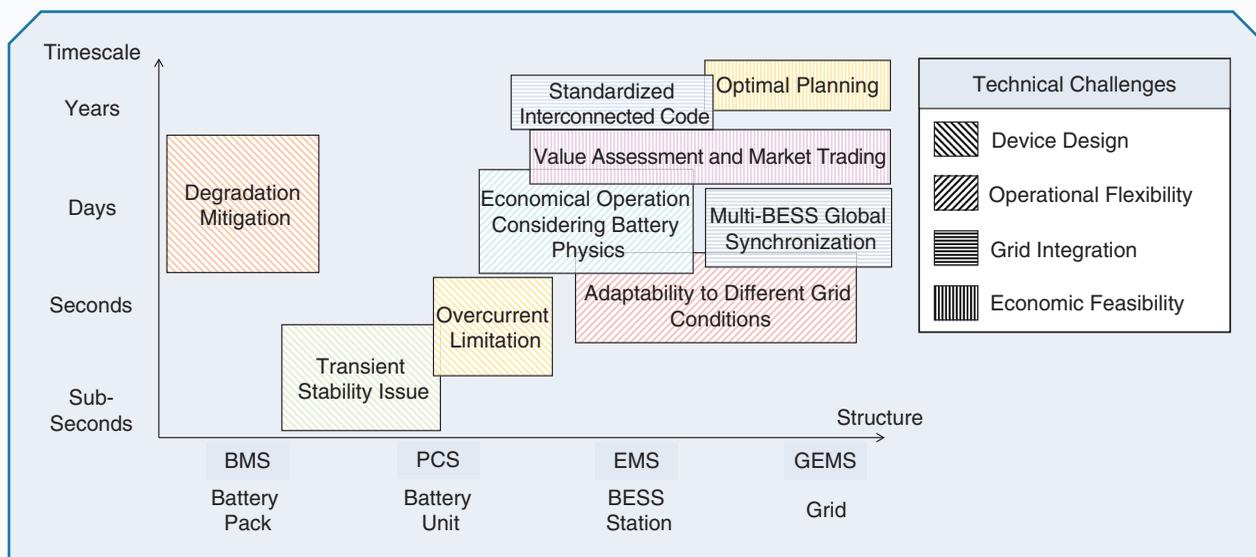


figure 5. Current challenges of GFM-BESS development across different timescales.

grid services through multiobjective optimization, achieving a balance between physical feasibility, grid stability enhancement, and economic benefits. Regarding the algorithms, while analytical optimization methods such as model predictive control provide structured control, data-driven approaches like deep reinforcement learning excel in handling uncertainties and nonlinearities. Leveraging large-scale historical data for offline learning, the data-driven approaches can make efficient online predictions with limited real-time data.

- ▶ **Systematic integration:** To seamlessly integrate GFM-BESSs into RDPSs, efficient real-time estimations of wide-area grid dynamics are essential to synchronize spatially distributed GFM-BESSs and IRESs. Using the phasor measurement unit-based information, an efficient state estimation framework for the global system can monitor the dynamic variation of voltages and phase angles across multiple nodes. This provides real-time feedback to the GEMS and EMS for timely operational adjustments. A VPP-oriented management strategy of a GFM-BESS should also coordinate multiple DERs while considering the differences in electrical characteristics of their interconnecting points. Furthermore, with GFM-BESS as a key asset for grid support, system operators should develop a practical capacity expansion and planning strategy to host increasing IRESs and balance economic objectives with stability requirements.
- ▶ **Policy support:** The commercial deployment of GFM-BESSs requires a supportive regulatory framework during different development stages. In the early phase, subsidies help offset high upfront capital costs and attract commercial investment. As GFM-BESS adoption increases, standardized grid connection codes and benchmarking guidelines will be essential to ensure its interoperability and compatibility with existing grid infrastructure. Establishing such a regulatory framework requires leadership from policymakers and collaboration with industrial stakeholders and system operators. In the long term, once the GFM-BESS becomes a mature and widely deployed grid infrastructure, an independent ancillary service market will economically incentivize the stabilization support while reducing overall system costs. An incentive-compatible

market design, such as the Vickrey–Clarke–Groves mechanism, can be beneficial to align the interests of GFM-BESS operators with system stability requirements.

Pathway Toward 100% Renewable Energy Goal in Sustainable Grids

The tightening stability margin is a major barrier to the higher penetration of IRESs and reduces renewable utilization due to stability-constrained curtailment. To achieve the ultimate goal of 100% renewable grids with few available SGs, the GFM-BESS needs to be the backbone of supporting the ac power grids, providing multiple synthetic SG dynamics to set a strong synchronized rhythm for the entire power system. Although the GFM-BESS behaves as a stable voltage source comparable to the SG, it still contributes significantly lower current than traditional SGs, leading to the requirement of modifying existing ac-side current-triggering protections. Moreover, a complete black-start and restoration paradigm is essential when all the SGs retire. Although the GFM-BESS can energize the grid during blackouts, it is not the default solution due to its limited capacity compared to the whole system. Alternative solutions, such as backup hydro generators and step-by-step islanded restorations, may still remain necessary.

For a structured transition framework, the 100% renewable goal will progress through staged development. This process begins with the RDPS transition, first achieving fully sustainable microgrids, then expanding to islanded regional power systems, and finally, establishing interconnected grids with 100% renewable energy. At the microgrid stage, the primary focus is to explore feasible GFM-BESS integration methods and improve their performance. In regional power systems, the emphasis shifts to coordinating multiple GFM-BESS operations across a vast network and exploring its supportive role in aggregating DERs as a VPP. For the interconnected grid, the key is to fully establish the coordinated GFM-BESS management framework from the BMS to the GEMS and to facilitate the synergy of multi-stakeholders from industrial manufacturers to policymakers by developing efficient GFM-BESS monetization mechanisms.

Conclusion

The GFM-BESS is a critical standalone grid asset that emulates SG dynamics to provide additional stabilization support in RDPSs. This

article examines the role of the GFM-BESS in reducing RDPS stability risks through the device-based provision of virtual inertia, voltage support, enhanced synchronization, and black-start capability. Based on the hierarchical physical structure, this article investigates GFM-BESS management strategies at multiple timescales, highlighting the coordination among the BMS, PCS, EMS, and GEMS to improve overall performance. Integrating the GFM-BESS in RDPSs provides technical benefits in extra flexibility across the generation, grid, and load sides while yielding the potentially monetizable economic value of stabilization support. Finally, by identifying the key challenges, this article proposes a collaborative road map to bridge the current research gaps in GFM-BESS development. The widespread use of the GFM-BESS will accelerate the sustainable transition of RDPSs and provide a structured pathway toward the 100% renewable energy goal.

For Further Reading

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Biographies

Yuanbo Chen is with the State Key Laboratory of Power System Operation and Control, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China, and with the Department of Energy Science and Engineering, Stanford University, Stanford, CA 94305 USA.

Hongye Guo is with the State Key Laboratory of Power System Operation and Control, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China.

Chongqing Kang is with the State Key Laboratory of Power System Operation and Control, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China.

Simona Onori is with the Department of Energy Science and Engineering, Stanford University, Stanford, CA 94305 USA. 