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Summary

Battery Energy Storage Systems (BESS) play a crucial role in frequency control for renewable energy projects that utilize solar and wind power plants. Due to their rapid response time, on the order of milliseconds, batteries assist in inertial response, mitigating frequency drops in the power grid. Larger battery systems, capable of delivering power for tens of minutes, support primary and secondary frequency regulation. To ensure optimal energy contribution at the Point of Common Coupling (PCC), it is crucial to accurately estimate battery efficiency, as well as State of Health (SOH) and State of Charge (SOC), particularly during periods of maximum discharge. Additionally, monitoring the Depth of Discharge (DoDmax) helps improve long-term reliability. With megawatt-scale batteries, BESS can support the Grid-Forming (GFM) concept, providing synthetic inertia through active power injection and voltage regulation via decoupled active and reactive power control techniques. The operational lifespan of batteries significantly affects their power delivery capacity. Initially, a battery's SOH is approximately 100% of its nominal capacity. Still, after a long period of operation, for example, 17 years, it can degrade to 65% or more, impacting energy availability at the PCC. The global Round-Trip Efficiency (RTE), which combines charge and discharge cycle efficiency, starts at approximately 85% of nominal capacity in the first year but drops to around 50% in later operational stages. Such degradation must be precisely modeled to optimize power system performance. Advanced machine learning techniques, including reinforcement learning, supervised neural networks with Long Short-Term Memory (LSTM) and Kalman Filter estimators, for example, are increasingly used to predict battery duty cycles [1]. These predictive models enable the forecasting of both active and reactive power, ensuring improved grid stability and optimized resource utilization. The primary focus of this paper is to analyze the leading research from the past decade, identifying the main constraints and challenges associated with implementing grid-forming batteries in the power grid.

Keywords

BESS, Grid Forming, Distributed Energy Resource, Predictive Models

1 Introduction

Due to the high penetration of Inverted-Based Resources (IBRs) in electrical networks over recent years, the conventional treatment of these sources as constant current sources has exposed vulnerabilities in control systems, particularly in terms of frequency support, voltage regulation, and inertia emulation. These challenges are even more pronounced in weak grids, where the lack of system strength exacerbates stability concerns. As the share of IBRs expands, new control strategies are being developed to mitigate these issues. However, relying solely on Grid-Following (GFL) inverters presents a fundamental limitation, as these inverters require an external voltage reference to synchronize with the grid. In scenarios where a significant portion of the generation is inverter-based, the absence of a voltage-forming source raises concerns about the system's ability to maintain stable and reliable operation. To address this, adopting GFM inverters has been increasingly recognized as a necessary evolution in power system control. Unlike GFL inverters, GFM inverters establish and regulate voltage and frequency autonomously, providing the essential references for proper network operation. This capability enables enhanced grid resilience, ensuring that even in high-renewable penetration environments, the system can maintain stable operation without relying solely on synchronous generation. The GFM inverter technology has become a pivotal topic in the energy transition, particularly in BESS application. Despite its commercial availability, the adoption of GFM remains limited in some countries [2] due to gaps in its deployment pathway. A key challenge is the lack of comprehensive studies and models that demonstrate its value and reliability in large-scale, considering interconnected power systems. According to [2], a study team evaluated GFM models from multiple original equipment manufacturers to address this issue. being tested against NERC-GFM functional specifications and test procedures [3]. The GFM BESS models were integrated into the American Transmission Company (ATC) network in weak and strong grid conditions. The research highlighted the importance of implementing GFM controls in BESS to enhance grid reliability at a low cost. Without clear incentives or regulations, most batteries in interconnection queues are likely to employ conventional grid-following controls, necessitating the installation of additional stabilizing equipment in areas with high renewable energy penetration. This paper is structured as follows: Session 2 presents some potential uses of GFM and the base-case simulation. Session 3 presents the systematic bibliography research, and Session 4 concludes the paper.

2 Grid Forming Concept Review and Base-Case Simulation

According to [4], GFM controls are designed to maintain a constant internal voltage phasor within the sub-transient to transient timeframe. This characteristic enables GFM with IBRs to immediately respond to variations in the external grid, ensuring stability under challenging network conditions. To achieve seamless integration, the voltage phasor must be synchronized with other grid components while regulating active and reactive power to support system operation effectively. GFM and GFL controls exhibit varied implementations depending on the specific control algorithms and operational objectives. However, all types of IBR controls are subject to several key constraints, including electrical limitations (voltage, current, and energy constraints), mechanical constraints, particularly in Wind Turbine Generators (WTGs), and external power system limitations, such as network strength and inertia conditions. GFM inverters must comply with many of the same performance requirements as GFL unless specific exemptions are explicitly stated. This means that GFM inverters are expected to adhere to standard operational criteria, ensuring grid reliability and stability while providing voltage and frequency support in modern power systems. Still in [4], the key functional capabilities of GFM inverters are summarized as: 1) Weak grid operation – Ensuring stable performance under low Short Circuit Ratio (SCR) conditions, improving system robustness in weak grids, 2) Damping of voltage and frequency oscillations, 3) Resisting voltage phase angle change and frequency change or limiting Rate of Change of Frequency (RoCoF) as a supplement inertial response of synchronous machines, 4) Fast fault current injection, 5) Mitigation of sub-synchronous control interactions, 6) Support of islanded operation, and 7) Black start.

2.1 Benchmarking Case-Study: GFM + BESS + PV

According to [5], the benchmarking system adopted for the simulation evaluates the GFM's capabilities to respond adequately when a contingency occurs in a hybrid photovoltaic system with one BESS. The model is modeled to react according to the requirements of the IEEE 2800 standard [6]. This system represents a 100 MWp PV Plant with a 60 MWh BESS. A series of parameters is used to define the operation of the GFM, including the emulation of direct and quadrature axis reactance, inertia, leakage reactance, and others. These parameters also incorporate data from the substation collection system and the external network, such as short-circuit power and short-circuit ratio. The BESS system is modeled with two modes of operation: Virtual Synchronous Machine (VSM) and Drop-Controller. The controller Dispatchable Virtual Synchronous Machine (DVSM) Control was not implemented in this benchmark case study.

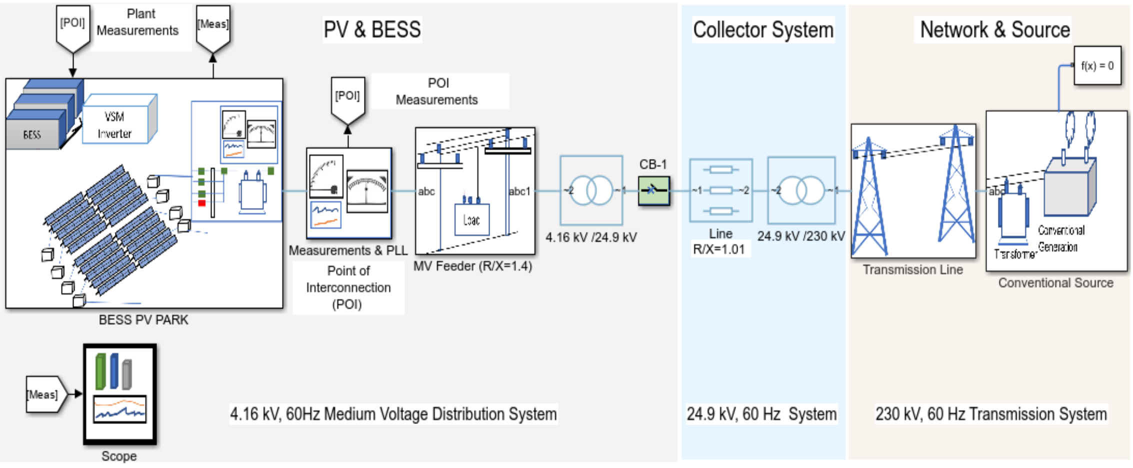

***Figure 1* – a) Benchmarking Case Study. Source [5].**

To demonstrate the response of the BESS system operating as a BESS GFM-VSM control, a 45% variation in the load connected to the 4.16 kV busbar was applied. The network is considered a weak grid, with SCR of only 0.43. In Figure 2-a, the BESS system is configured to operate in Grid Following mode, and the voltage and frequency responses at the PCC are observed. Figure 2-b presents the variable response with the BESS system functioning as a GFM. In this case, where SCR < 1, considered a weak source, the BESS GFM presented an adequate response, and the system offered a stable point of operation in the post-fault event. Legacy grid-following systems can be migrated, depending on the construction characteristics of each manufacturer, to grid-forming systems through firmware updates, for example. It is then expected that such systems will contribute to the transient and dynamic stability of the power grid, as well as enhanced controllability, by emulating the behavior of a synchronous machine.

a) b)

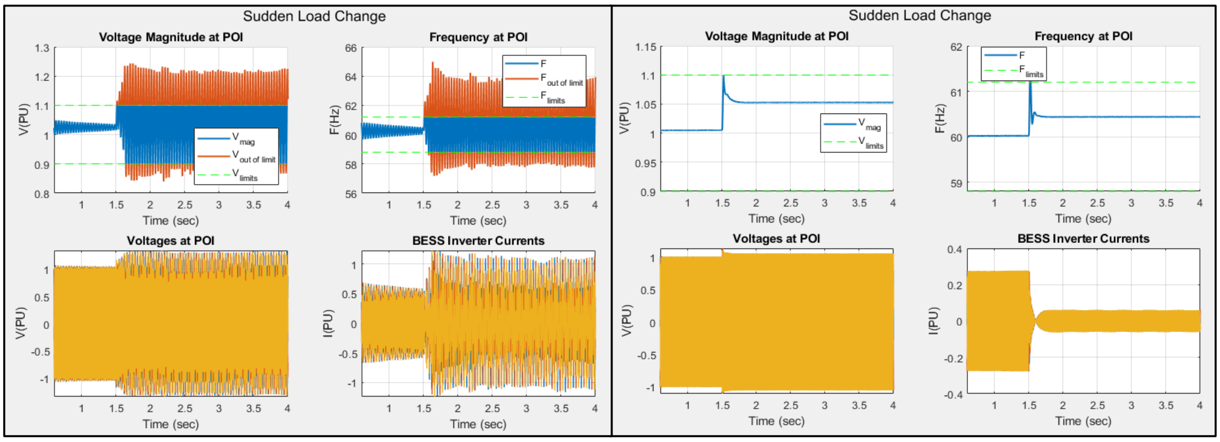

***Figure 2 -** a) Simulated Event - BESS as Grid Following, b) Simulated Event - BESS as Grid Forming [5].*

1 Systematic Literature Review

Bibliography research using the Web of Science database and VOSviewer tool, considering periodicals published in the last ten years in leading journals and important indexed conferences, revealed 46 papers found using the string "Grid Forming" AND "BESS", as presented in Figure 3. Figure 4-a) shows the coupling with the papers' keywords, and Figure 4-b) illustrates the citation connections among authors. Tables 1 to 9 present the clusters identified according to their topologies, characteristics, advantages, and constraints. According to Figure 4-b, the highest number of citations came from Zuo et al. (2021) [45], in cluster 7, with 54 citations; Fusero et al. (2019) [29], in cluster 4, with 25 citations; Zhao et al. (2022) [19], in cluster 2, with 36 citations; Moon et al. (2019) [37], in cluster 6, with 15 citations; Shahparasti et al. (2022) [48], in cluster 8, with 11 citations; Ali et al. (2023) [41], in cluster 6, with 10 citations; and Abadi et al. (2023) [40], in cluster 6, with 8 citations. The bibliographic research also identified Cluster 09, which comprised 5 papers [49-53] that were not connected to the other 8 clusters, either by keyword coupling or author affiliation. The results revealed that all of them primarily focused on GFM microgrid applications. By grouping the clusters, it was possible to identify related topics, incorporating contributions from previously published works, and highlighting the various applications and benefits that grid-forming systems will bring to both distributed generation and transmission systems. The constraints presented challenges that needed to be overcome so that these solutions could gain a broader scale of application in both short- and medium-term scenarios.

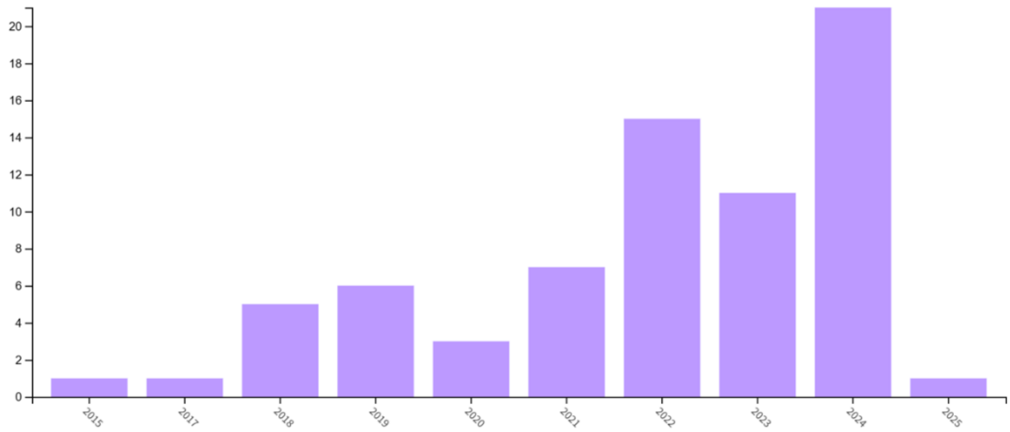

***Figure 3 -** Number of Publications over the last 10 Years*

a) b)

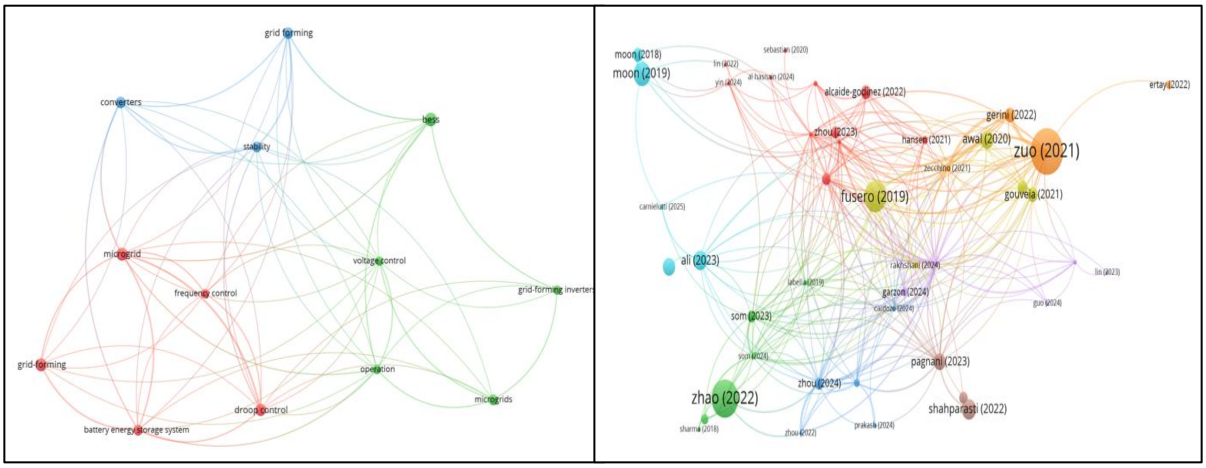

Figure 4 – a) Coupling via Keywords, b) Coupling via Authors

The number of publications has trended over the years, highlighting the interest and significance of topics related to GFM applications. The tables below present a resumed analysis of all 46 papers. Table 09 displays the papers not associated with the other 8 clusters.

Table 1 – Cluster 01 – 10 Papers

Paper	Method	Topology	Characteristics	Advantages	Constraints
Coordinated Control of Battery Energy Storage and a Dump Load **[7]**	Coordinated control with dump load	Isolated systems with BESS and controllable loads	Robust control for stability and energy discard management	Flexibility and efficient control of stored energy	Complexity in scenarios with high load variability
Development of GFM/GFL Inverter Control in Microgrid Network, Ensuring Grid Stability and Frequency Response **[8]**	MATLAB/Simulink simulations and experimental validation using a 1 kW grid-connected system	Solar PV-battery microgrid integrating grid-forming (GFM) and grid-following (GFL) inverters	GFL inverters use PLL and GFM inverters with VSM control for voltage and frequency regulation	GFM inverters enhance grid resilience, improve weak grid operation, and provide fast frequency support	GFM control requires complex algorithms and hardware support, with further large-scale validation needed for widespread deployment
Frequency Control using Grid-forming and Grid-following BESS **[9]**	Frequency control with grid-forming and grid-following inverters	Grid-forming and grid-following inverters operating in parallel	Capability to operate in islanded or grid-connected mode	Stability in low-inertia networks	Dependence on proper configurations for parallel modes
Frequency Support from Multiple Utility-Scale Grid-Forming BESS **[10]**	Frequency support with multiple utility-scale BESS	Multiple BESS integrated into utility networks	High resilience and inertia support at a large scale	High efficiency in frequency support	Need for precise synchronization between BESS
Grid-Forming Inverter and Applications to Support System Strength **[11]**	Grid-Forming inverters to enhance system strength	Grids with high penetration of inverter-based resources	Grid stabilization under low-inertia conditions	Improvement of system strength with advanced control	Requires careful parameterization to avoid instabilities
Inertia Evaluations on Grid-Forming Inverters with Virtual Synchronous Generator Control **[12]**	Inertia evaluations on grid-forming inverters with VSG control	Photovoltaic systems with virtual synchronous control	Configurable virtual inertia control	Mimics behaviors of physical synchronous generators	Challenges in practical implementation due to complexity
Oscillation Identification and Frequency Damping Controller Design **[13]**	Oscillation identification and frequency damping controller design	Distributed control based on subspace identification	Reduction of oscillations and improved dynamic response	Effective damping of critical oscillations	Requires accurate models for effective identification
Power Fluctuation Suppression in PV-Battery GFM **[14]**	Power fluctuation suppression in PV-Battery GFM systems	PV-battery systems with GFM inverters for local stability	Control of fluctuations in local PV-battery grids	Improved local stability and reduction of fluctuations	Potentially high implementation costs
Regional Power System Black Start with Run-of-River Hydropower and BESS **[15]**	Black starts of the grid with run-of-river hydropower and BESS	Run-of-river hydropower plant and BESS	Coordinated use of BESS to stabilize frequency and voltage	Enhanced stability during black start	Dependence on specific hardware support
The Use of Synchronverters for Fast Frequency Response **[16]**	Synchronverters for fast frequency response and automatic voltage regulation	Low-inertia grids with BESS and sync converters	Simulation of virtual synchronous generators with fast response	High precision in frequency and voltage regulation	Need for filtering harmonics due to power electronics

Table 2* - *Cluster 02 – 5 Papers

Paper	Method	Topology	Characteristics	Advantages	Constraints
A universal model for power converters of BESS utilizing impedance-shaping concepts **[17]**	Impedance-shaping for enhanced converter dynamics	Generalized impedance model for power converters	Flexible control strategy applicable to various BESS setups	Improved dynamic performance and compatibility	Requires detailed impedance parameterization
BESS Reserve-Based Frequency Support During Emergency in Islanded Residential Microgrids **[18]**	Reserve-based frequency support for islanded microgrids	Islanded residential microgrid with BESS	Focus on emergency scenarios and frequency stability	Ensures frequency stability in emergency conditions	Relies heavily on accurate reserve estimations
Control Interaction Modeling and Analysis of Grid-Forming BESS for Offshore Wind Power Plants **[19]**	Interaction modeling and analysis of grid-forming controls	Offshore wind power plant with grid-forming BESS	Detailed modeling for control interactions	Enhanced understanding of control interactions	Complexity in implementation and validation
Power Management Analysis in PV-BESS Islanded AC Microgrid **[20]**	Droop-based primary control for PV and BESS	Islanded AC microgrid with PV and BESS	PV operates in grid-feeding mode	Stability under diverse operational scenarios	Challenges in precise reactive power-sharing
Power Management and Economic Load Dispatch in Hybrid PV-Battery-Diesel **[21]**	Economic load dispatch and power management for hybrid systems	Hybrid PV-BESS-Diesel standalone AC system	Incorporates DC synchronization and economic dispatch	Efficient and reliable system operation under load variations	Dependence on real-time data for economic dispatch

Table 3* - *Cluster 03 – 5 Papers

Paper	Method	Topology	Characteristics	Advantages	Constraints
Promises and Challenges of Grid-Forming **[22]**	Performance-based requirements and control optimization	Generalized grid-forming strategies for various systems	Focus on optimizing GFM performance for system needs	Allows flexibility and cost-efficiency in GFM designs	Intellectual property constraints on design sharing
Control Principles for Island Operation and Black Start by Offshore Wind Farms **[23]**	Integration of GFM converters with BESS for black start	OWF with GFL turbines and centralized GFM-BESS	Hybrid operation of grid-forming and grid-following systems	Achieves black start capability with renewable integration	Challenges in the simultaneous control of multiple components
Offshore Wind Farm Black Start with Grid-Forming Control **[24]**	Black-start of OWF using hybrid GFM-BESS and electrolyser units	Islanded offshore wind farm with GFM-BESS and electrolyzer	Use of electrolyzes to support BESS during startup	Enhances efficiency and integrates green hydrogen production	Requires advanced modeling and coordination of electrolyzers
Sub-Synchronous Damping by Battery Storage System in Grid-Forming Control Mode **[25]**	Grid-forming control for damping sub-synchronous oscillations	Wind farms connected to weak grids with GFM-BESS at PCC	Impedance-based analysis for SSO mitigation	Improved grid stability with effective SSO damping	The trade-off between damping effectiveness and costs
Subsynchronous Damping by Battery Storage System in Grid-Forming Control **[26]**	Decoupling damping and droop coefficients for SSO damping	External and internal BESS integration in WT systems	Reduced power requirements with decoupled control	Maintains SSO damping while reducing battery sizing	Complexity in control design and implementation

Table 4* - *Cluster 04 – 5 Papers

Paper	Method	Topology	Characteristics	Advantages	Constraints
A Grid-Forming Multi-Port Converter using Unified Virtual Oscillator Control **[27]**	Unified Virtual Oscillator Control (uVOC) for multi-port converters	Multi-port AC-DC hybrid microgrid converter	Seamless transition between islanded and grid-tied modes, fault ride-through	Enhance fault tolerance and robust synchronization	Requires advanced control hardware and complex configuration
Influence of Load Dynamics on Converter-Dominated **[28]**	Dynamic load modeling for BESS sizing in converter-dominated systems	Isolated power systems with 100% converter-based generation	Focus on induction motor (IM) dynamics and load recovery post-faults	Improved load recovery and reduced oversizing of BESS	Relies on accurate load modeling for adequate BESS sizing
A Comprehensive Inverter-BESS Primary Control for AC Microgrids **[29]**	Virtual Generator Mode (VGM) and Grid Support Mode (GSM)	Microgrid with inverter-based BESS for both grid-forming and grid-support operations	Combines frequency/voltage regulation with fast secondary control	Scalable for large systems with improved frequency and voltage stability	Requires careful tuning for parallel operations
Enhancing Low-Inertia Power Systems with Grid-Forming-Based Hybrid Storage **[30]**	Integration of hybrid energy storage systems with grid-forming converters	Hybrid storage systems with battery and ultra-capacitor in low-inertia systems	Provides virtual inertia and supports grid stability with hybrid storage	Efficient, cost-effective solution for grid stability in weak grids	Dependency on hybrid technology increases system complexity
Grid-Forming Inverters Sizing in Islanded Power Systems: A Stability Perspective **[31]**	Dynamic stability analysis for grid-forming BESS sizing	Islanded power systems with mixed renewable generation	Ensures stability under N-1 contingencies	Optimizes BESS capacity for transient stability	High dependency on transient modeling accuracy

Table 5 - Cluster 05 – 5 Papers

Paper	Method	Topology	Characteristics	Advantages	Constraints
Replicated real-world load-shedding events for performance validation **[32]**	Enhanced grid stability and reduced load-shedding frequency	Requires standardization for GFM deployment in bulk systems	Replicated real-world load-shedding events for performance validation	Enhanced grid stability and reduced load-shedding frequency	Requires standardization for GFM deployment in bulk systems
Direct conversion via PMLG, energy smoothing with DC-link BESS **[33]**	Efficient, eco-friendly energy conversion, optimized power smoothing	Challenges in synchronizing WEC and BESS control for dynamic conditions	Direct conversion via PMLG, energy smoothing with DC-link BESS	Efficient, eco-friendly energy conversion, optimized power smoothing	Challenges in synchronizing WEC and BESS control for dynamic conditions
Review of the droop, VSG, and other advanced GFM control methods **[34]**	Provides a holistic overview of GFM technologies and their challenges	Lack of real-world implementation details in some reviewed studies	Review of droop, VSG, and other advanced GFM control methods	Provides a holistic overview of GFM technologies and their challenges	Lack of real-world implementation details in some reviewed studies
Dynamic adjustment of power and ride-through capability for weak grids **[35]**	Ensures grid compliance and fault tolerance in weak grid conditions	High dependency on accurate system modeling and grid codes	Dynamic adjustment of power and ride-through capability for weak grids	Ensures grid compliance and fault tolerance in weak grid conditions	High dependency on accurate system modeling and grid codes
Multi-objective optimization incorporating BESS reactive power limits **[36]**	Improves voltage stability and utilizes BESS more effectively	It relies on advanced optimization algorithms and detailed modeling	Multi-objective optimization incorporating BESS reactive power limits	Improves voltage stability and utilizes BESS more effectively	It relies on advanced optimization algorithms and detailed modeling

Table 6 - Cluster 06 – 5 Papers

Paper	Method	Topology	Characteristics	Advantages	Constraints
Autonomous Active Power Management in Isolated Microgrid Based on Proportional and Droop Control **[37]**	Proportional and droop control for autonomous power balance	Isolated microgrid with grid-forming BESS and RES integration	Uses BESS frequency signal for power sharing and autonomous control	Ensures real-time power balance with minimal communication requirements	Limited by high variability in RES outputs and SOC dependency
A Master-Slave Model Predictive Control Approach for Microgrids **[38]**	Finite Control Set Model Predictive Control (FCS-MPC) in master-slave configuration	Microgrid with NPC inverters, BESS, and PV panels in grid-connected and islanded modes	Supports fast dynamic response, multiobjective control, and robustness to uncertainties	Handles parametric variations effectively, supports multivariable control	Complex tuning and computational requirements for MPC
Decentralized Active Power Control Strategy for Real-Time Power Balance in an Isolated Microgrid **[39]**	Frequency bus-signaling combined with droop control for decentralized active power control	Isolated microgrid with diesel generators, BESS, and renewable energy sources	Minimizes frequency/voltage deviations during disturbances	Autonomous operation with improved reliability in case of generator trips	Challenging implementation in systems with high load variability
Effective Utilization of Grid-Forming Cloud Hybrid Energy Storage Systems **[40]**	Grid-forming battery-supercapacitor hybrid systems for transient voltage stabilization	Islanded DC multi-nano-grids (MNGs) with centralized hybrid storage	Improves voltage stability and reduces battery stress via hybrid storage	Extends battery life and optimizes energy storage capacity	Dependency on advanced controllers and the initial cost of hybrid systems
Model Predictive Control of Consensus-Based Energy System **[41]**	Energy management system using FCS-MPC for GFM and GFE modes	DC microgrid with distributed renewable energy sources and BESS	Dynamic control of GFM and GFL converters	Efficient energy management with reduced overshoot and settling time	Requires precise tuning of MPC cost functions for optimal performance

Table 7 - Cluster 07 – 4 Papers

Paper	Method	Topology	Characteristics	Advantages	Constraints
Local Effects of GFM Providing Frequency Regulation **[42]**	Experimental analysis using PMUs for frequency regulation	720 kVA/500 kWh BESS interfaced with a 20 kV distribution grid	Introduces new local metrics for GFM and GFL comparisons	Confirms GFM's higher efficacy in low-inertia grids	Focuses on local grid impacts rather than bulk system effects
Real-Time Simulations for Testing of LV Microgrid with MMC-DSTATCOM **[43]**	Real-time testing of MMC-DSTATCOM with renewable energy and BESS	LV microgrid with MMC-DSTATCOM, RES, and lithium-ion BESS	Tests grid-forming and grid-following modes under real-time conditions	Enables realistic testing of microgrid controls with low overruns	Real-time setups are computationally complex and expensive
Optimal Grid-Forming Control of BESS Providing Multiple Services **[44]**	Three-stage control: robust optimization, MPC, and real-time adjustments	BESS with GFM control connected to a 20 kV distribution feeder	Integrates feeder dispatch ability, FCR, and voltage regulation	Provides robust, adaptable control under uncertainties	High computational resources are needed for real-time adjustments
Performance Assessment of GFM and GFL BESS on Frequency Regulation **[45]**	Dynamic simulations comparing GFM and GFL modes in low-inertia grids	IEEE 39-bus low-inertia system with converter-interfaced renewables	Detailed dynamic modeling for comparative performance metrics	Demonstrates superior frequency control of GFM over GFL	Limited to simulation; lacks practical implementation results

Table 8* - *Cluster 08 – 3 Papers

Paper	Method	Topology	Characteristics	Advantages	Constraints
Energization of Transformers in Medium Voltage Island Microgrids **[46]**	BESS operating in the grid-forming mode for soft-start transformer energization	Islanded medium voltage microgrid with PV, BESS, and synchronous generators	RTDS-based validation eliminates inrush currents and voltage sags	Reduces mechanical stress on transformers; robust control under variable conditions	Requires careful parameter tuning for BESS inverter control
Integrating Black Start Capabilities into Offshore Wind Farms **[47]**	GFM batteries combined with OWFs for staged black start procedure	Offshore wind farm with integrated GFM battery energy storage systems	Three-stage restoration: power island formation, grid energization, resynchronization	Improves grid resilience; provides additional services (e.g., inertia, reactive power)	Dependent on OWF capacity and wind availability; cost of BESS integration
Inrush Current Management During Medium Voltage Microgrid Black Start **[48]**	Droop and voltage-current control loops to limit transformer inrush currents.	Medium voltage microgrid with 1 MVA BESS and multi-transformer configuration	Proposed methods independent of transformer parameters or CB timing	Simple implementation; maintains voltage quality and current limits	Performance may vary under complex transformer saturation scenarios

Table 9* - *Cluster 09 – 5 Papers

Paper	Method	Topology	Characteristics	Advantages	Constraints
Grid Forming BESS for a Highly Unbalanced Hybrid Mini-Grid **[49]**	Per-phase dq control with Fictive Axis Emulation (FAE)	Three-phase mini-grid with diesel genset, BESS, and RES	Provides balanced voltage under highly unbalanced loads	It improves power quality, reduces genset dependence	Complex control requirements in real-world scenario
A BESS Control System for Reducing Fuel Consumption in Diesel-Hybrid **[50]**	Multi-functional control system with genset support and grid-forming modes	Diesel-hybrid mini-grid with high renewable penetration	Compensates reactive power, optimizes diesel genset operation	Reduces fuel consumption and maintenance costs	It does not fully address frequency variations and variable renewable
A Technical and Economic Feasibility Study of Campus Microgrid **[51]**	MATLAB Simulink-based modeling of grid-tied and islanded modes	Campus microgrid with PV, BESS, CHP, and utility grid	Hybrid energy system with real-time analysis of grid performance	Ensures energy resilience, integrating renewables	Economic feasibility depends on policy incentives and funding availability
Adaptation of Microinverter for BESS in Microgrids **[52]**	Modification of Texas Instruments microinverter for bidirectional power	Single-bus topology integrating BESS and PV through DC bus	SCADA for real-time control, bidirectional energy transfer	Enhances energy efficiency, enables DC-AC grid interaction,	Additional hardware modifications, increased system complexity
Interfacing of Grid-Forming Inverter for Microgrid Islanding Studies **[53]**	Hybrid Interface Algorithm with Partial Circuit Duplication (PCD)	Microgrid with BESS, PV, and utility grid connection for PHIL testing	Stability and protection schemes short-circuit conditions	High-fidelity real-time simulation evaluates system dynamics	Requires precise calibration; sensitive to inaccuracies in interface impedance

2 Conclusion

This paper explored the use of BESS systems with grid-forming technology, highlighting their advantages over grid-following systems through a benchmarking case study. Challenges arise during project implementation, as BESS systems are modeled as synchronous machines, which exhibit characteristics such as inertia behavior and short-circuit conditions. Verifying expected response times in line with different grid codes and network compliances is vital; therefore, understanding power and control electronics techniques, which influence the dynamic and transient behavior of electrical networks, is essential. A systematic literature review was conducted using search tools and clustering analysis, with a focus on bibliographic coupling and author citations. This review examined 46 technical papers published in indexed journals over the past decade. Most publications center on transmission systems, while few address microgrid systems. However, integrating BESS with GFM systems into distribution networks within distributed energy resources is expected to lead to significant developments. Consequently, this work represents a notable advancement in research and real-world applications worldwide, reflecting the rising trend of grid-forming systems in recent years. As progress continues to accelerate, it is increasingly crucial to foster collaboration among academia, manufacturers, industry stakeholders, and research centers to enhance knowledge transfer, particularly about the control strategies adopted by different manufacturers for emulating synchronous machines, as well as the associated response times.

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