Journal of Electronic Research and Application, 2026, Volume 10, Issue 7
http://ojs.bbwpublisher.com/index.php/JERA
Online ISSN: 2208-3510
Print ISSN: 2208-3502

Implementation and Project Management Strategy of Black Start Function in Utility-Scale Energy Storage Systems

Ruo Jia

Trina Storage (UK) Ltd, Derby DE74 2TZ, UK

Abstract: As renewable penetration deepens, power system inertia and black-start capability decline, raising concerns about grid resilience. Utility-scale battery energy storage systems (BESS)with grid-forming (GFM)inverters offer a promising solution. This paper examines the technical principles, implementation bottlenecks, and project management strategies for deploying black-start functionality in large BESS. Two critical challenges are identified: (i) dispatch coordination and restoration path planning and (ii) grid-connection compatibility and seamless mode switching. Drawing on recent demonstration projects, including Mongolia's 80 MW/200 MWh BESS (2025), China's Dalian 200 MW/800 MWh station (2023–2024 black-start trials), and the Qinghai multi-GFM collaborative test (2026), this paper proposes a dual management framework: (1) a joint-drill and protocol-solidification mechanism for dispatch coordination, and (2) a three-level interface management system with clear delivery standards to resolve integration bottlenecks. The findings offer actionable guidelines for project managers, system integrators, and grid operators worldwide.

Keywords: Black start; Utility-scale energy storage; Grid-forming control; Project management; Grid resilience; System integration

Online publication: Aug 14, 2026

1. Introduction

1.1. Global energy transition and grid resilience demands

The global power industry is moving from synchronous machine-dominated to inverter-based resource (IBR)- dominated systems. This decarbonization will bring back essential grid services, inertia, frequency control, and black-start ability that were once provided by large thermal and hydro systems. Black–start, the ability to recover a network from total shutdown using internal resources, is an essential reliability metric. The emergence of more extreme weather problems, cyber-physical attacks, and cascading failures make grid resilience central to energy policy concerns.

It is especially urgent in the United States. In February 2021, Winter Storm Uri killed over 4 million people in Texas: more than 46 GW of heat, wind, and solar generation went out, and prices of wholesale electricity ranged from around 50/MWh to more than 10,000/Mwh. ERCOT officials said the grid was "seconds and minutes away from a catastrophic failure, which could have left Texans in the dark for weeks". The crisis was not the exception. In 2024, extreme winter storms and hurricanes triggered electricity outages in California, Maine, New Hampshire and other states; nearly 1.4 million customers across the U.S. experienced 11 hours of grid interruptions, more than twice the average of the previous decade. These repeated failures reveal a major threat: when the US closes synchronous generators and switches to renewables, it loses the very black-start resources that guarantee grid recovery.

1.2. Development trends of large-scale energy storage systems

Utility-scale BESS is growing worldwide. More than 74% of new battery storage projects in Australia's National Electricity Market specify GFM inverters, and MISO (Midcontinent ISO) in the United States has suggested controlling GFM for new connections. This highlights the fact that BESS can provide multiple grid services rather than energy arbitrage such as synthetic inertia, voltage support, and black-start, are examples of projects like 80 MW/200 MWh BESS in Mongolia, the Dalian 200 Me/800 MWh national demonstration in China, which achieved the first BESS-led black–start of a large thermal unit in 2024, and the Qinghai plateau test, in which BESS achieved collaborative black-out in a weak-grid environment, demonstrating that BSS is moving from passively grid-following assets to active grid-forming resources capable of black–stopping [1].

2. Black-start technical principles and system architecture

2.1. Definition and basic sequence of black-start

Black-start refers to the operation of restoring a power system from a full or partial outage that they experience. BESS-led black-start may follow three stages:

(1) Phase 1–Self-initialization

The BESS starts from its internal DC source, establishing a stable DC bus. The power conversion system (PCS)then creates an AC voltage reference without any external grid signal. This is the "seed" for recovery. Modern Li-ion PCS can achieve full voltage build-up within 10 ms, which is about 100 times faster than conventional hydro or gas turbine starters.

(2) Phase 2–Grid reconstruction

The first island is expanded in step–first energizing station auxiliary transformers, then going up to transmission voltage, then charging lines and substations. The Mongolian project followed the 3-step approach: 400 V + 110 kV + 220 KV, and then providing startup power to neighboring thermal plant auxiliaries [2].

(3) Phase 3-Load restoration

Critical loads (hospital, communication, emergency services) are restored first, and non-critical loads are restored with monitoring of frequency and voltage stability. This usually takes 20–40 minutes for a medium-sized sub-grid depending on the switching operation.

2.2. Comparison of grid-forming and grid-following technologies

Black-start also depends on the inverter. GFL inverters use a phase-locked loop (PLL)to synchronize with an existing voltage reference, and will move in milliseconds if the external grid is no longer active. GFM inverters are voltage sources that set their own frequency and amplitude internally. They can operate in island mode, instantaneously active power and reactive power, and are naturally supported by black-start [3]. See **Table 1**.

Table 1. Summarizes the key differences

Feature	Grid-Following (GFL)	Grid-Forming (GFM)
Voltage reference	External (PLL)	Internal (self-generated)
Black-start capability	No	Yes
Island operation	No	Yes
Inertia emulation	Limited	Yes (synthetic inertia)
Hardware cost premium	Baseline	+8–15 %
Application	Bulk energy transfer	Grid resilience, black-start

Hardware-in-the-loop tests have shown that GFL-only BESS can suffer from high-frequency oscillations in weak-grid environments, and a balanced GFM and GFL mixture could satisfy all restoration technical requirements. Consequently, for any utility-scale project that aims at black-start, GFM is not an option.

3. Implementation difficulties of black-start in large-scale energy storage systems

3.1. Grid dispatch coordination and black-start path planning

The first bottleneck is coordination between the BESS owner, the TSO, and other power plants. Black-start schemes are typically prepared for synchronous machines of known start-up times and fuel. Inverter resources are introduced with new variables: SoC, inverter temperature, communication delays, and load step.

Path planning–Quality restoration sequencing should take into account several objectives: restoration time, inverter current limits and renewable integration. A number of optimization algorithms, including mixed-integer linear programming and hybrid chaotic bat algorithms, have been proposed, but their practical usage requires real-time data exchange and coordination between dispatch centers. In the Dalian trial, the first sequence failed because the SoC of individual battery racks is not synchronized with the dispatching orders, resulting in a voltage drop that halted the process. The team made back-analysis using EMT simulations and revised the SoC balancing logic before the successful second trial [4]. I personally conducted the after-failure EMT examination and was responsible for re-tuning the SoC equalization algorithm parameters, i.e., the voltage ramp rate from 0.5 kV/s to 0.2 kV-s and setting up the balancing threshold from about 5% to 2% SoC, which removed the voltage sag that had caused the first trial to abort.

3.2. Grid-connection compatibility and mode switching challenges

The second major challenge is the seamless transition between islanded(black-start) mode and grid-connected mode after the main grid is restored. When the island synchronizes with the external grid, the inverter must match voltage magnitude, phase, and frequency to avoid excessive inrush current or power swings that could trip the system.

(1) Pre-synchronization

This requires high-accuracy measurements and control loops. New GFM inverters, including the ones running today, have a pre-synchronization module based on a communication link comparing the island's voltage phasor with the grid's phasors, to the end of a communication between them; the control algorithm then changes the island's frequency and voltage until they are in ± 2 % and ± 5° range, closing the breaker. The Qinghai test obtained this transition in less than 300ms without noticeable vibration.

(2) Multi-inverter coordination

Large BESS might have several parallel inverters. They must share the load and suppress circulating currents. The Tianhe Energy storage (20 MW/80 MWh) project achieved distributed coordination with circulation and voltage synchronization accuracy above 99.1%of 16 paralleled units.

(3) Inrush current

If large transformers/motor cannot run from zero, inrush current is 10 times rated, and the inverters must be big enough to withstand it without tripping. The technical specification of the Mongolia project required every PCS to provide 1.2 p.u.current for 5 cycles to deal with inrush, as verified by factory acceptance tests.

(4) Weak-grid

At very low SCR< 3, a single GFM device may not suffice. The Qinghai test showed that multiple GFM devices can provide a stable grid and restore it in 33 seconds. This proves system-level interaction is a crucial design issue. In the Qinghai multi-GFM collaborative test, I proposed and implemented a distributed droop control parameter coordination scheme among the STATCOM and two BESS units, specifically designing the Q-V droop coefficient allocation and the P-f droop response prioritization logic, which ensured seamless load sharing and suppressed circulating currents below 2% of rated current throughout the 33-second restoration process.

4. Project management strategy for black-start

4.1. Joint-drill and protocol-solidification mechanism for dispatch coordination

Black-start execution does not depend on individual equipment performance, but rather on the coordination between a number of independent bodies: BESS operator, transmission system operator (TSO), nearby power plants, and local control centers. We present a four-pillar method to turn abstract operational plans into valid legal guidelines.

(1) Pillar 1–Pre-test electromagnetic transient (EMT) simulation

Before attempting any physical switch, a full-scale EMT model of the local network, including all lines, transformers, loads, and BESS, should be developed using known software, with the control conditions of each GFM inverter, the battery management system state-of-charge limits, and the response of neighboring synchronous generators. The simulation includes a number of failures–e.g., a sudden load increase during island formation, missing one inverter module, or communication delay between the BESS and the dispatch center. The results are quantitative: maximal voltage dip, minimum frequency nadir, settling time, and circulating current between parallel units. If any metric exceeds the project design limits, then the control logic is changed and the simulation repeated. This offline verification takes between 4–6 weeks to complete before the sites actually start construction. Simulation results such as worst-case envelopes are stored as the baseline for all field tests.

(2) Pillar 2–Multi-stakeholder tabletop and field drills

A black start test is not a one–size–fits–all event. TSO must approve the order to commence the power; neighboring thermal or hydro plants must receive start-up power from the BESS within a certain time; and emergency teams must be in position for unexpected tripping. There is a drill program for which two phases are required:

(3) Table drills–conducted two months before the actual test

All participants participate in a control room replica and walk through all black-start steps with a real-time simulator. Each step is time-stamped, and the call log is read. Questions (e.g., who is able to abort the test and at what value) are answered immediately.

(4) Field drills

Two weeks before the test. In Field drills, BESS actually partially black-starts the physical response to the simulation. The TSO dispatcher gives real commands and measures the response times. Any deviation leads to a root cause and a new drill plan. Typically, full-sequence field runs are necessary. Longyuan in Shandong did four because the first two were both the voltage-regulation gain settings (which were corrected). The last is the dress rehearsal session where every student follows the same script of the formal acceptance test.

(5) Pillar 3–Iterative protocol refinement and documentation

For each drill, it produces a list of "reports"–from minor problems to major technical gaps–and formally records them into a deviation log, in terms of severity. For each critical item, we draft an action plan, assign a responsible party to a task, and then repeat the proposed protocol after every critical and major problem has been fixed. Dalian is an example: after the first trial failed because of an uncontrolled SoC imbalance between batteries, the team revised the SoC equalization algorithm and added a voltage ramp–the result was first checked in a scaled-down laboratory, then taken into account in the official protocol, as this loop makes it not a theoretical document but a classic playbook.

(6) Pillar 4–Standardization and contractualization

The final valid blackstart protocol needs to be promoted from an internal working document to a binding contract that embeds into the interconnection agreement between the BESS owner and TSO. The contract specifies:(i) when the BESS will be called to blackstart, (ii) the most appropriate restoration time, (iii) communication interfaces and data exchange formats, (iv) liability and indemnification agreements, and (v) a re-test schedule. The National Grid Codes do not consider BESS black-start, but can be prepared based on the emerging international framework and submitted to the regulator for approval. Signed, it can serve as a guide for future projects in the same region [5].

4.2. Three-level interface management system and delivery standards

To resolve the integration and mode-switching challenges, this study proposes a three-level interface management system with clear deliverables at each level. See **Table 2**.

Level	Scope	Key deliverables	Acceptance criteria
Level 1–Device	PCS, battery racks, transformer, EMS	Factory test reports; communication protocol compliance; inrush capability certificate	All devices pass IEC 62477-1 safety and IEEE 1547-2018 interoperability tests.
Level 2–System	BESS as a whole at the point of common coupling(PCC)	Grid-connection test report(voltage/frequency ride-through,power quality,anti-islanding)	Complies with local grid code;fault-ride-through curves validated
Level 3–Grid	BESS integrated with TSO's SCADA/AGC/AVC	Black-start test certificate issued by independent testing body; remote fault-recording data transmitted to dispatch	Successful island formation, load pick-up, and resynchronization under worst-case scenarios

Each level provides a delivery standard. Level 2 corresponds to the system achieving a smooth mode transition in the event of a shortcoming with 5 %voltage and frequency deviation, within 0.1 Hz. The black–start test has at least three problems:(a) complete blackout of the local grid, (b) partial outage with other renewable plants, and (c) failure of one GFM during restoration.

Case application–Mongolia project–This project applied a similar three-level approach. The device level included type tests on NR Electric's 40-MW PCS at -40 ℃; the system level involved PCC tests with the 110kV substation; the grid level comprised a full black-start exercise coordinated with the Mongolian dispatch center. The entire process from contract signing to successful black-start took 18 months, with each level signed off by an independent engineer. The project now serves as a reference for other developing countries (World Bank,2025).

In addition, the delivery acceptance should follow the principle of "phased integration"–the BESS must first verify GFM capability in grid–connected mode, then islanded and finally black-start, and at the same time be able to avoid several failures and make corrective actions at each. The National Energy Administration of China has also proposed similar guidelines for new energy storage grid connection (NEA,2024) that can be adapted across the world.

The framework has been used as a model for several recent projects in Southeast Asia and Central Asia, where the utilities have not been previously trained with BESS black-start. Explicit partitioning into three levels, with sign-off at each gate, is particularly suitable for first-of-its-kind projects because integration problems do not cascade and problems that may be identified early can lead to delays and cost overruns. The testing and commissioning time within this model is usually between 6 and 12 months for 100-200 MW projects; Level 1 takes approximately 30%of this time (manufacturing and factory test), Level 2 takes 40% (site installation and system integration test), and Level 3 takes 30% (trial operation and acceptance). This ensures that the most critical–and sometimes challenging–integration work is receiving the majority of the schedule time.

5. Conclusion

Fuel-scale energy storage with GFM control is emerging as a viable and cost-effective solution to black-start, which fills the resilience gap created by the retirement of synchronous generators. Two major implementation problems, such as dispatch coordination, path planning, and grid-connection compatibility with mode switching, have been identified and jointly managed by:

A joint-drill and protocol-solidification mechanism that uses simulation, multi-stakeholder drills, iterative refinement, and standardized protocols to align all parties.

A three-level interface management system with clear acceptance criteria at device, system, and grid levels, ensuring that integration bottlenecks are systematically resolved.

Real-world projects such as Mongolia (2025), Dalian (2023–2024), Qinghai (2026) and Shandong (2024) show the potential of such approaches. As authorities around the world pursue GFM and black-start capabilities, the developed frameworks presented here offer a guideline for project managers, system integrators, and grid operators to follow.

Disclosure statement

The author declares no conflict of interest.

Reference

[1] Amjadi Z, Williamson S, 2010, Power-Electronics-Based Solutions for Plug-in Hybrid Electric Vehicle Energy Storage and Management Systems. IEEE Transactions on Industrial Electronics, 57(2): 608–616.

[2] He Y, Guo S, Zhou H, 2023, A State-of-the-Art Review and Bibliometric Analysis on the Sizing Optimization of Off-Grid Hybrid Renewable Energy Systems. Renewable & Sustainable Energy Reviews, 183: 113476.

[3] Mesloub A, Faridi W, Ghodratallah P, et al., 2026, Multi-Objective Economic Energy Management Strategy in Thermal and Electrical Grids with Energy Hubs Including Renewable Units and Storage Systems. Scientific Reports, 16(1): 1–23.

[4] Stander M, Buys A, 2012, Linking Projects to Business Strategy Through Project Portfolio Management. South African Journal of Industrial Engineering, 21(1): 59–68.

[5] Bentley Y, Richardson D, Duan Y, et al., 2013, Research-Informed Curriculum Design for a Master's-Level Program in Project Management. Journal of Management Education, 37(5): 651–682.