FIELD VALIDATION AND PERSPECTIVE ON DISTRIBUTION-SCALE GRID-FORMING BATTERY STORAGE FOR SYNTHETIC INERTIA

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Abstract

High penetration of inverter-based resources reduces synchronous inertia and changes frequency dynamics, increasing the need for fast stabilising services. Grid-forming battery energy storage systems (BESS) can emulate synchronous-machine behaviour and deliver synthetic inertia by rapidly modulating active power in response to frequency deviations and their rate of change. This paper presents field-validation insights from a distribution-connected 30 kVA / 68.5 kWh grid-forming BESS prototype deployed at distribution level. High-resolution measurements are analysed to extract disturbance-like events and to evaluate response delay, proportionality, and effective inertia. Under naturally occurring frequency variations of the Continental European synchronous area, the prototype exhibits consistent power–frequency correlation and a measurable inertia-like behaviour, enabling an approximate estimation of an effective virtual inertia constant. The results highlight both the feasibility and the practical limits of distribution-level verification: low disturbance magnitude, frequency-measurement noise, and controller deadbands can mask sub-second dynamics in the field. Implications are drawn for model validation, proving tests, standardisation of distributed stability services from inertia sources and their remuneration, production definition aspects.

1. Introduction

Power systems are undergoing a rapid transition from dominantly synchronous generation to inverter-based resources. While this shift enables deep decarbonisation of power supply, it also reduces the inherently inertial electromechanical behaviour of large rotating machines. Lower system inertia increases the initial rate of change of frequency (RoCoF) following a contingency and reduces the time available for primary control actions and protection coordination. Grid-forming control and virtual-synchronous-machine/virtual-synchronous-generator concepts have therefore attracted strong interest as enabling technologies to restore inertia-like dynamics through power-electronic interfaces [1]. Surveys of grid-forming and synchronverter or virtual synchronous generator approaches show that these controls can emulate the swing dynamics of a synchronous machine (virtual inertia and damping) and can be combined with droop and voltage-support functions. They highlight open challenges related to stability margins, fault behaviour, current limiting, and verification outside laboratory conditions [2][3].

From a system-operators' perspective, the key question is not only whether synthetic inertia is theoretically achievable, but whether it can be specified, measured, and contracted as a verifiable service provision. ENTSO-E implementation guidance documents [4] explicitly discuss the need for synthetic inertia as total system inertia decreases, especially in high non-synchronous penetration areas and during rare but critical system splits; the same guidance also notes that synthetic inertia may interact with other low system-strength phenomena and should be coordinated with broader stability remedies. In parallel, system operators in Great-Britain, Ireland are experimenting with new procurement mechanisms for stability services, moving beyond purely energy-based balancing products [5][6].

The maturity of synthetic inertia technology has already progressed from small-scale demonstrations to grid-scale deployments since 2018–2025. In Great Britain synchronous area, Wärtsilä [7] delivered a 200 MW / 400 MWh battery storage system for a Scottish site. The supplier positions the project as a first-of-its-kind grid-scale deployment providing "true synthetic inertia" and short-circuit-level stability services within a stability pathfinder framework. In Continental Europe, RWE [8] reported commercial operation of an inertia-ready BESS in Moerdijk (7.5 MW / 11 MWh), explicitly based on highly responsive control and grid-forming inverter functionality, with a two-year pilot phase to develop standards and compliance procedures together with TenneT. Taken together, these examples indicate that inertia, and alike close to real time frequency response services have already been moving from concept, demonstrations to qualifying tests, products and emerging market structures.

Despite this progress at transmission scale, the distribution level is still an open research area. Distributed BESS and other inverter-based generators are increasingly connected in medium-voltage networks, where they can influence local voltage dynamics, protection behaviour, and–through aggregation–the wider frequency domain. Yet, field datasets that quantify the synthetic inertia behaviour of distribution-connected, grid-forming BESS under real network conditions remain limited. Methodologically, this is expected: when a device is embedded in a large synchronous area, real frequency excursions are typically small; RoCoF estimation is noise-sensitive; and practical controller deadbands and filtering can dominate what is observable in the time series. As a result, it is difficult for system operators to answer practical questions that are central to standardisation and bankability.

This paper addresses the above gap through a practical field-validation study of a distribution-connected grid-forming BESS prototype deployed by a Hungarian distribution system operator (DSO). The prototype integrates commercial battery hardware and bidirectional power electronics with a dedicated synchronous-generator emulation module and supervisory energy management, allowing parameterised virtual inertia and damping while managing converter and battery limits. High-resolution measurements are used to identify and analyse disturbance-like events and to derive key performance indicators for synthetic inertia behaviour (response delay, magnitude, and decay characteristics), with particular attention to robust RoCoF estimation in noisy field data. The contributions are threefold: empirical evidence that distribution-connected grid-forming storage can provide continuous inertia-like response under real operating conditions; while a measurement-driven performance index framework that clarifies what can (and cannot) be concluded from naturally occurring field events; and lastly a discussion of how distribution-level evidence can support model validation and the design of proving tests for future distributed synthetic inertia products.

The remainder of the paper is organised as follows: Section 2 describes the prototype architecture, measurement setup and KPI-based evaluation method. Section 3 interprets field results and their context. Section 4 summarises conclusions and outlines the next steps required for scalable deployment and marketisation of distribution-level synthetic inertia.

2. Methodology

This chapter introduces the equipment developed and tested, as well as the cost-benefit analysis framework used for evaluating it.

2.1. Equipment

The prototype battery energy storage system developed within the pilot project was conceived as a modular, grid-connected device with not just conventional energy management (EMS) functions, but also capable for providing synthetic inertia through grid-forming control. The overall architecture comprises four tightly integrated systems, as shown on Fig 1.

(i) a lithium-ion battery energy storage unit,
(ii) a four-quadrant bidirectional converter,
(iii) a synchronous generator–emulating control module (SIPIRC), and
(iv) an integrated energy management and supervisory controller (MAB3 Compact EMS).

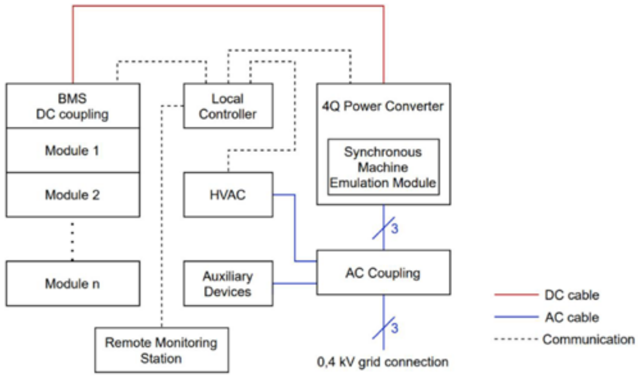

Fig 1. architecture of the device

The system is rated at 30 kVA with a nominal energy capacity of 68.5 kWh. Rather than relying on full-stack hardware development, the project strategically combined commercially available off-the-self component modules with a custom-developed control layer. This approach ensured technical robustness, accelerated deployment, and provided a credible pathway toward replication steps for market readiness. The power coupling between the DC battery circuit and the AC grid is provided by a four-quadrant bidirectional inverter developed by Procon Ltd.

2.1.1. Battery Energy Storage System

The storage system is based on the Intilion Scalebloc outdoor battery cabinet, equipped with Samsung SDI lithium-ion battery cells, implemented in a modular configuration suitable for outdoor installation in an IP55-rated enclosure. The Scalebloc design integrates the full system into a compact, plug-and-play solution. the Scalebloc unit offers scalability both in inverter configuration and in cabinet-level expansion, facilitating system-integration. This is strategically important: although the pilot demonstrator operates at modest power levels, the hardware architecture supports straightforward scaling without redesigning the battery pack.

Physically, the battery system provides the necessary short-term energy buffer to emulate inertial response. Unlike synchronous machines with kinetic energy is stored in rotating mass, the BESS stores electrochemical energy that can be dispatched rapidly and reversibly. Thus, fast DC power delivery, high C-rate capability, reliable thermal management are all essential. The selected solution satisfies these requirements while compiling to industrial safety standards.

2.1.2. Bidirectional Power Converter

In conventional energy storage systems, inverters typically operate in grid-following mode, synchronising to an externally defined grid voltage. For synthetic inertia provision, however, the inverter must be capable of grid-forming operation. In this mode, the inverter establishes its own voltage and frequency reference and dynamically adjusts its output based on frequency deviations. The inverter's programmable control platform allows integration of advanced control algorithms. This bidirectional and rapid power modulation is the functional equivalent of inertial response in rotating machines.

Stability under grid-forming operation imposes stricter hardware requirements than grid-following applications. High inertia emulation settings may introduce oscillatory behaviour if not properly tuned. Therefore, the converter's control bandwidth, protection settings, and synchronisation mechanisms were carefully configured during the pilot. While the inverter hardware is commercially available, its application for synthetic inertia represents a novel use case. This extension increases its future relevance as a solution while grid codes gradually recognise virtual inertia services.

2.1.3. Synchronous Generator-Emulating Control Module (SIPIRC)

The SIPIRC module constitutes the core innovation of the prototype. Developed as a dedicated unit within the inverter that implements a real-time virtual model of a synchronous generator and generates active power reference signals for the inverter. Fig. 2 depicts the architecture of this control module.

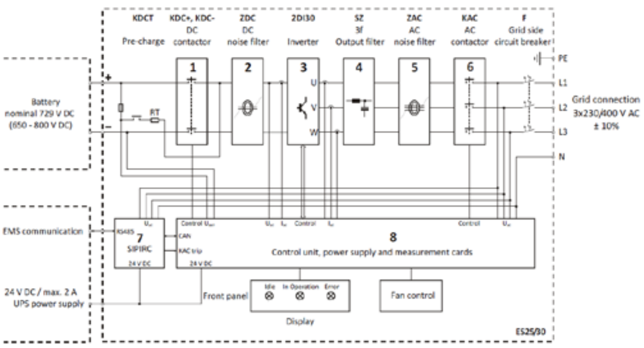

Fig. 2. architecture of the inverter unit and SIPIRC module

Conceptually, SIPIRC emulates the swing equation of a synchronous machine, incorporating virtual inertia, damping, and primary frequency control characteristics. The algorithm processes measured grid frequency and calculates the required power response as if a physical rotating machine was accelerating or decelerating. In effect, the grid perceives the device as possessing electromechanical inertia. A major strength of the module is flexible parametrisation. The virtual inertia constant, damping factor, nominal power rating of the emulated generator, and droop characteristics can all be adjusted via software. This enables adaptation to different network conditions, ranging from weak distribution grids to stronger transmission environments.

Although synthetic inertia is not dynamically identical to physical inertia, experimental results and literature indicate significant improvements in frequency stability and reduction of ROCOF under disturbance scenarios. The SIPIRC module remains at prototype maturity level, and further validation, certification, and potential firmware-level integration into commercial inverter platforms are required before full-scale market deployment.

2.1.4. Energy Management and Supervisory Control

The MAB3 Compact EMS is developed by Infoware Ltd. It functions as the supervisory coordination layer of the device, integrating local control, communication, data acquisition, and operational logic into a single industrial controller platform.

Beyond standard EMS tasks, such as charge scheduling, battery state-of-charge management, and limit enforcement based on BMS signals, the controller was extended to incorporate synthetic inertia prioritisation. In critical frequency events, inertia control takes precedence over routine operational objectives, while safeguards prevent deep discharge or overcharge.

The MAB3 unit acts both as an intelligent electronic device and as a communication gateway. It supports standard industrial protocols (e.g. IEC 61850, Modbus), enabling integration into TSO/DSO supervisory systems. This interoperability is essential for future compliance with evolving grid codes and ancillary service frameworks.

2.2. Cost-benefit analysis (CBA) approach

The CBA applies a discounted cash-flow (DCF) framework over a 15-year operational horizon, using a nominal weighted average cost of capital of 10.5%. NPV and IRR serve as primary decision metrics. The sole modelled revenue stream is an inertia-availability fee, expressed in EUR/MVAs, consistent with the contractual structures of the GB and IE inertia markets. Operational costs (e.g. energy conversion losses) are treated as profit-neutral pass-through, as it is with the GB/IE market precedents [6].

Three deployment scenarios spanning commercialisation trajectory are evaluated: (i) Pilot – a 100 kW / 60 kWh unit (2C, LV-connected, ~34,500 EUR CAPEX), matching the demonstrated prototype class; (ii) Network-integrated – a 2.5 MW / 5,270 kWh system (0.5C, MV-connected, ~1.25M EUR CAPEX), representing a DSO-driven stability investment under regulated return; and (iii) Market-scale – a 20 MW system (0.5C, HV-connected), representing a commercially motivated deployment. OPEX was modelled from benchmarks as a size-dependent fraction of CAPEX, declining from approximately 24% at pilot scale to below 2% at 20 MW.

Sensitivity analyses were conducted across three axes: inertia unit price (0.25 / 0.65 / 2.6 EUR/MVAs, spanning low to upper-bound international references), virtual inertia constant H (1.5 s - consistent with the baseline expectation of the Irish Synchronous Inertia Service for converter-based BESS - and 5 s, representing the upper range achieved with the prototype configuration), and CAPEX subsidy intensity: no subsidy, corporate-eligible 35% and a high case of 80% for a regulated DSO operated development.

3. Results

This chapter summarizes the test measurements and results, and the cost-benefit analysis evaluation results.

3.1. Field validation

Field measurements were carried out on the distribution-connected grid-forming battery storage prototype in normal operation mode. The unit was connected to the public distribution network and operated continuously in grid-forming mode with synthetic inertia enabled. Measurements were recorded in 200 ms time resolution, capturing active and reactive power, grid frequency, and internal control signals.

Unlike laboratory or hardware-in-the-loop environments, the field measurement campaign was not associated with deliberately introduced huge disturbances. Consequently, the recorded dataset primarily contains naturally occurring frequency variations originating from system-level balancing actions, load fluctuations, and switching events in the surrounding network. This measurement context reflects realistic operational conditions but also imposes inherent limitations on the observability of large inertial responses.

3.2. Frequency behaviour during field operation

Across the examined datasets depicted in, system frequency remained close to the nominal value, with deviations typically within ±50–60 mHz. These variations are characteristic of a large synchronous area such as Continental Europe, where aggregate inertia and primary control actions suppress large excursions under normal conditions. The measured frequency trajectories exhibit a combination of slow trends and superimposed high-frequency fluctuations. First, the measured frequency data were processed to calculate ROCOF by computing the frequency change and dividing it by the sampling time (200 ms). The resulting ROCOF values over the full measurement period (in mHz/s) are shown in Fig. 3.

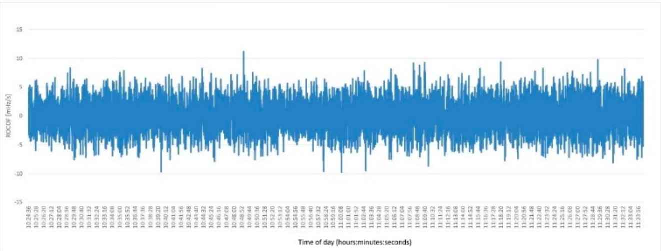

Fig. 3. ROCOF values for the whole measurement campaign

3.3. Active power response to frequency deviations

The most important observation from the measurement campaign is the consistent correlation between frequency deviations and active power output of the storage unit. During intervals where the filtered frequency exhibited a negative gradient, the inverter injected active power into the grid, whereas positive gradients were accompanied by active power absorption. This behaviour confirms that the grid-forming control operated according to the intended virtual synchronous machine logic. During the measurement, no major frequency disturbance occurred, so the virtual inertia effect could not be demonstrated strongly; the maximum calculated ROCOF was 11.2 mHz/s, which is relatively small. Even so, the data confirm stable VSG control and good grid interaction: Fig. 4 shows that, in the first 2000 samples, the device generated power change tracks sudden frequency deviations effectively, and Fig. 5 shows the same behaviour around the transient at 10:49:04, where the largest ROCOF occurred.

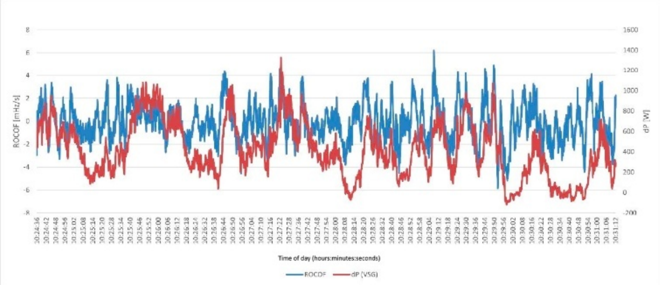

Fig. 4. Evolution of ROCOF and response performance change for the first 2000 sampling points

Although response magnitude was limited – consistent with the small frequency excursions of the Continental European synchronous area and the low rated power of the prototype – a clear proportional relationship between frequency trend and active power is observable across multiple events. This confirms that the synthetic inertia function operated continuously rather than as a threshold-triggered response.

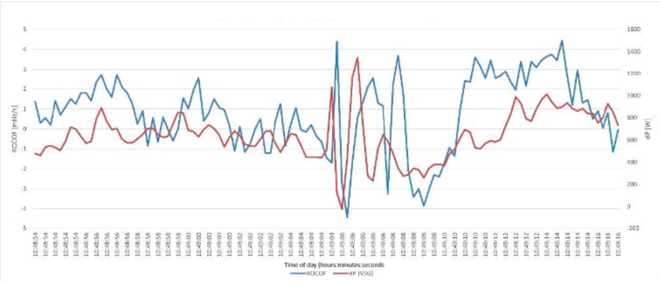

Fig. 5. Response in case of the largest disturbance

Several limitations inherent to the field measurement setup constrain the interpretation of these results. The absence of large disturbances prevents direct evaluation of high- ROCOF behaviour; the prototype's low rated power precludes system-level nadir assessment; and frequency noise complicates RoCoF estimation even with filtering – highlighting the need for standardised measurement methodologies as a precondition for operational service verification. Finally, the evaluation relied on post-processed data; real-time verification and on-line parameter identification remain topics for future research.

These constraints reinforce the necessity of multi-layer validation. Field measurements alone cannot fully characterise dynamic performance, but combined with laboratory testing and detailed modelling they form a comprehensive evidence base for deploying distributed synthetic inertia resources.

3.4. CBA results

Results confirm that an inertia-only, business case viability depends on the combination of inertia service remuneration, potential CAPEX subsidy and the scale of the project. The dominant drivers of net present value are the inertia fee level, achievable inertia constant, and subsidy intensity, with scale acting as an enabler but rarely sufficient on its own.

At pilot scale (100 kW), a positive operational cash flow requires both H = 5 s and the upper-bound availability fee (2.6 EUR/MVAs); even then, IRR reaches only ~6% with 35% CAPEX support, confirming that pilot viability depends on grant funding or a research-infrastructure context rather than market revenue.is contingent on grant funding. Scaling improves economics materially as specific OPEX lowered, but the 20 MW market-scale project still struggles (IRR = 7%) to reach the hurdle rate (WACC) if H = 1.5 s, even with high inertia fee scenarios. It approaches viability only in the high-fee case and/or with support and is most credible when paired with revenue stacking (e.g. FCR/FRR balancing or arbitrage on scheduled energy deliveries). The network-integrated case (2.5 MW) is the most robust as state aid regulation allow high percentage of funding from subsidies for a natural monopoly. It yields an IRR of 9.9% at 1.68 EUR/MVAs with 80% CAPEX support – closely matching the applicable regulated rate of return – while even the lower-price, H = 5 s case holds a stable IRR near 5%. This scenario most closely reflects a near-term deployment pathway in markets where inertia is procured as a network service.

4 Conclusion

This paper presented field-validation insights for a distribution-connected, grid-forming BESS prototype configured for synthetic inertia. High-resolution measurements collected on a 30 kVA / 68.5 kWh unit confirm that, under real operational conditions, the device continuously modulates active power in the expected direction (injection during falling frequency trends and absorption during rising trends), consistent with a virtual synchronous generator concept. The results also clarify the limits of field-only verification. When disturbances are slow and shallow, the apparent response delay is dominated by measurement noise, ROCOF-filtering choices and controller deadbands rather than by inverter actuation capability. Consequently, distribution-level synthetic inertia should be validated through a layered evidence base. Laboratory and hardware-in-the-loop tests to characterise sub-second dynamics and protection interactions, transient simulation models correlated against controlled tests, and long-duration monitoring to demonstrate robustness and availability. Such evidence is increasingly relevant because current developments have moved synthetic inertia from pilot demonstrations to commercial and grid-scale deployments, and system operators are beginning to formalise procurement and standardisation pathways for inertia-like services. The study supports the feasibility of distributed, grid-forming storage as a contributor to future stability portfolios, but it also indicates that marketisation at distribution level must be accompanied by clear measurement requirements, transparent proving tests and model-delivery packages.

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