



## DEGRADATION AWARE ADAPTIVE CONTROL OF GRID FORMING BESS FOR FREQUENCY SUPPORT IN HIGH PV POWER SYSTEMS IN SENEGAL

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### ABSTRACT

Rising photovoltaic penetration reduces the number of synchronous machines online, thereby diminishing local inertia. The resulting inertia deficit accelerates post-disturbance frequency dynamics and exacerbates the frequency nadir. Grid-forming battery energy storage systems (GFM-BESS) can furnish rapid active and reactive power, stabilize voltage, and attenuate frequency excursions. These services are not without cost: repeated high-power injections and pronounced state-of-charge (SOC) swings increase electrochemical stress and hasten ageing. This study introduces an adaptive GFM control scheme tailored to the Senegalese grid that continuously tunes virtual inertia, active-power and frequency droop, damping, reactive-power and voltage support, and SOC headroom as functions of disturbance severity, local grid strength, and battery condition. A battery ageing model assigns marginal degradation costs to the delivered support. The validation framework benchmarks five strategies, spanning from no BESS participation in frequency control to a degradation-aware adaptive GFM controller, under generator and interconnection outages, photovoltaic ramps, load steps, and network faults. Performance is evaluated using RoCoF, frequency nadir, recovery time, voltage quality, converter current utilization, energy exchanged, and cumulative degradation. Operational records from 2025 together with the historical PATRP study serve as validation references. Benefits attributable to the proposed controller are quantified only via time-domain simulation with a validated dynamic model; no numerical gains are claimed without explicit calculation.

**KEYWORDS:** grid-forming converters; battery energy storage; low-inertia systems; frequency stability; virtual inertia; battery ageing; RoCoF; Senegal; West African power systems.

### Nomenclature and abbreviations

The main symbols and acronyms employed in this work

are defined below. Units are stated in the text and in tables where relevant.

| Symbol / abbreviation                     | Definition                                               | Symbol / abbreviation | Definition                                          |
|-------------------------------------------|----------------------------------------------------------|-----------------------|-----------------------------------------------------|
| <b>BESS</b>                               | Battery energy storage system                            | <b>Cdeg</b>           | Incremental battery degradation cost                |
| <b>C-rate</b>                             | Charge/discharge rate relative to rated battery capacity | <b>DNFS</b>           | Degradation Normalized Frequency Support            |
| <b>DoD</b>                                | Depth of discharge                                       | <b>EB</b>             | Rated BESS energy capacity (MWh)                    |
| <b>E<sub>kin,sys</sub></b>                | Equivalent system kinetic energy                         | <b>FFR</b>            | Fast frequency response                             |
| <b>FSDC</b>                               | Frequency Support Degradation Cost                       | <b>GFL</b>            | Grid following converter                            |
| <b>GFM</b>                                | Grid forming converter                                   | <b>Heq</b>            | Equivalent system inertia constant                  |
| <b>Hi</b>                                 | Inertia constant of synchronous machine i                | <b>Hvirt</b>          | Virtual inertia constant/gain of the GFM controller |
| <b>I<sub>conv</sub> / I<sub>max</sub></b> | Converter current / maximum                              | <b>KD</b>             | GFM damping gain                                    |

|                              |                                                 |                                        |                                                                                |
|------------------------------|-------------------------------------------------|----------------------------------------|--------------------------------------------------------------------------------|
|                              | permissible current                             |                                        |                                                                                |
| <b>KVI</b>                   | Virtual inertia gain                            | <b>mp</b>                              | Active power–frequency droop coefficient (P–f)                                 |
| <b>nq</b>                    | Reactive power–voltage droop coefficient (Q–V)  | <b>OMVG</b>                            | Gambia River Basin Development Organization                                    |
| <b>OMVS</b>                  | Senegal River Basin Development Organization    | <b>PATRP</b>                           | Power Africa transmission study / historical 2017–2035 network stability study |
| <b>PBESS / QBESS</b>         | Active/reactive powers exchanged by the BESS    | <b>PV</b>                              | Photovoltaic                                                                   |
| <b>RoCoF</b>                 | Rate of change of frequency                     | <b>SB<sub>rated</sub></b>              | Rated apparent power of the BESS converter                                     |
| <b>SCR</b>                   | Short circuit ratio, a measure of grid strength | <b>SOC</b>                             | Battery state of charge                                                        |
| <b>SOH</b>                   | Battery state of health                         | <b>SPS-2025</b>                        | Senegalese power system model/scenario used for the 2025 study                 |
| <b>VSM</b>                   | Virtual synchronous machine                     | <b>WAPP</b>                            | West African Power Pool                                                        |
| <b><math>\Delta f</math></b> | Frequency deviation from nominal                | <b><math>\Delta SOH_{event}</math></b> | Incremental SOH loss associated with a dynamic event                           |
| $\omega / \omega_0^*$        | Reference/nominal angular frequency             |                                        |                                                                                |

## 1. INTRODUCTION

Short-term frequency resilience is shaped in part by the kinetic energy accumulated in synchronous rotors. When a generation contingency occurs, these machines automatically discharge a portion of that stored energy into the grid, moderating the initial rate of change of frequency. A PV plant interfaced through a conventional grid-following converter does not supply comparable mechanical inertia. As the number of online synchronous units decreases, the same power shortfall therefore produces a steeper and faster frequency excursion.<sup>[12,15]</sup>

A BESS operated with a grid-forming converter departs fundamentally from grid-following behavior. It synthesizes its own voltage and frequency references and can modulate active and reactive power on very short timescales. With appropriate control laws, its response can reproduce classical droop characteristics or selected attributes of a synchronous machine. The literature documents potential improvements to frequency and voltage performance, including under weak-grid conditions, while also showing that converter current limits, network strength, and controller tuning can materially alter the realized benefit.<sup>[1,12,13,19]</sup>

Such rapid support is not without consequence for the battery. High power ramps, state-of-charge excursions, and frequent cycling accelerate degradation and consume lifetime. The core design question is therefore not how large the virtual inertia should be in isolation, but what minimum response is sufficient to contain specified disturbances and what degradation cost that response imposes. The present study evaluates this tradeoff.<sup>[2,4,18]</sup>

In Senegal, the balance is further conditioned by interconnection status. Local synchronous inertia depends on unit commitment, while neighboring systems may or may not be available to provide frequency support at a given time. Prior Senelec analyses already connect system security to renewable penetration, spinning reserve, and cross-border exchanges. We accordingly

treat local inertia, interconnection contributions, and BESS energy headroom as a coupled problem.<sup>[8–11]</sup>

Articles 1–3 addressed PV hosting capacity, BESS investment decisions, and forecast-driven energy management. The current article focuses on subsecond-to-second dynamics. It quantifies the fast support deliverable by the same batteries and examines the longer-horizon implications for ageing.

### 1.1. Research question and contributions

The central question is how a GFM-BESS should tune virtual inertia, P–f droop, damping, and SOC headroom to enhance frequency security under high PV penetration and low local inertia, while avoiding disproportionate degradation.

The contributions are as follows.

- First, an adaptive GFM-BESS control framework is proposed that explicitly links frequency-security metrics to battery ageing.
- Second, the study contrasts a grid-following BESS, a fixed-parameter GFM-BESS, and an adaptive GFM-BESS that internalizes degradation cost.
- Third, the analysis jointly addresses virtual inertia, P–f droop, damping, Q–V support, SOC headroom, and converter current limits within a single decision structure.
- Fourth, performance is assessed across a range of local synchronous inertia levels and regional interconnection scenarios.
- Fifth, the marginal battery lifetime cost associated with incremental frequency-security improvements is estimated.
- Finally, the protocol is applied to dynamic contingencies and operating contexts salient to Senegal, anchored in 2025 operating records and historical PATRP benchmarks.

## 2. Literature review and research gap

As converter-based resources proliferate, grid-forming control has attracted sustained attention. Droop-based strategies and virtual synchronous machine concepts can deliver rapid frequency and voltage support, but their efficacy is contingent on grid conditions and converter hardware constraints. In particular, during faults, current limiting modifies transient behavior; models that neglect this effect risk overstating achievable support.<sup>[1,6,7,13,17,19,20]</sup>

Three research threads underpin this work. Studies of grid-forming BESS paired with large PV plants evaluate contributions to systems with substantial solar penetration.<sup>[1]</sup> Other contributions adapt GFM parameters to available energy and grid strength rather than fixing them *ex ante*.<sup>[2]</sup> Severity-aware schemes adjust synthetic inertia or allocate response between grid-forming and grid-following modes according to disturbance magnitude.<sup>[3,5]</sup>

Battery ageing models add a critical dimension, since repeated fast frequency and voltage support can shorten useful life.<sup>[4,18]</sup> Much of the existing literature treats adaptive control, weak-grid phenomena, current limits, regional support, and ageing in isolation. Here, these elements are integrated into a single protocol tailored to Senegal, where SOC, state of health, converter headroom, and interconnection status can vary concurrently.

The resulting control problem is to select virtual inertia, droop, damping, and reactive power contributions conditioned on the prevailing system state and the

disturbance class, while satisfying current and SOC constraints and internalizing degradation. We test whether such adaptation can satisfy security criteria with lower energy throughput and reduced ageing relative to an aggressive fixed GFM configuration.

## 3. Dynamic system model

### 3.1. Synchronous generation and system inertia

$$E_{kin,sys} = \sum_i H_i S_i \quad (1)$$

$$H_{eq} = (\sum_i H_i S_i) / S_{base,defined} \quad (2)$$

$$2 H_{eq} / f_0 \cdot df/dt = P_m - P_e - D_{sys} \Delta f + PBESS \quad (3)$$

For each scenario, the power base used in the denominator of the equivalent inertia will be stated explicitly. In addition, inertia contributed by synchronous generators within Senegal will be distinguished from the effective response of the interconnected system when external equivalents are represented.

### 3.2. Grid forming BESS model

A generic grid-forming active power and frequency control law is represented by  $\omega = \omega_0 - m_p (P - P) + \omega_{VI}$  (4)

$$P_{VI} = -K_{VI} \cdot d(\Delta f)/dt \quad (5)$$

Here,  $\omega$  denotes the internal frequency setpoint,  $\omega_0$  the nominal frequency,  $m_p$  the active-power droop coefficient,  $P$  the active-power dispatch reference, and  $\omega_{VI}$  the virtual-inertia term whose power counterpart is  $P_{VI}$ . The virtual inertia action is proportional to the measured frequency derivative, scaled by  $K_{VI}$ , subject to converter current and SOC constraints.

### Degradation aware GFM-BESS control loop

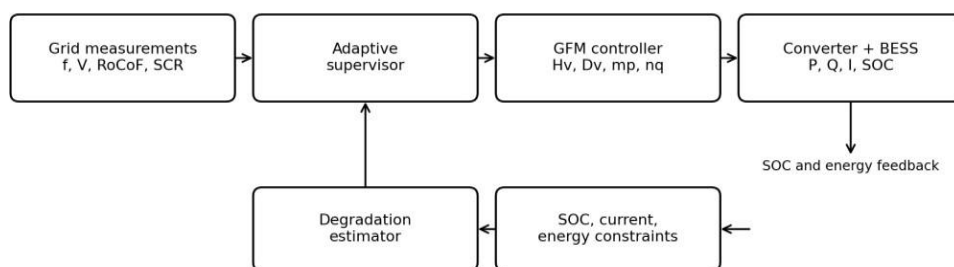


Figure 1. Functional architecture of degradation aware adaptive GFM-BESS control (author's illustration).

$$P_{damp} = -K_D \cdot \Delta f \quad (6)$$

$$PBESS = P_{schedule} + P_{VI} + P_{damp} + P_{droop} \quad (7)$$

Reactive power and voltage control are represented by a Q-V droop characteristic or by an equivalent voltage-regulation loop.

$$V = V_0 - n_q (Q - Q^*) \quad (8) \quad [13,14,16,17,20]$$

This framework can be realized via classical droop control or a virtual synchronous machine. To ensure reproducibility of numerical results, the study must explicitly detail the control architecture, signal-

conditioning filters, measurement delays, saturation mechanisms, and all tuning parameters.

### 3.3. Operational constraints

$$|PBESS| \leq P_{B, rated} \quad (9)$$

$$\sqrt{(PBESS^2 + QBESS^2)} \leq S_{B, rated} \quad (10)$$

$$|I_{conv}| \leq I_{max} \quad (11)$$

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (12)$$

$$E_{headroom, up} = (SOC - SOC_{min}) EB \quad (13)$$

$$E_{headroom, down} = (SOC_{max} - SOC) EB \quad (14)$$

The current constraint is a primary physical limitation rather than a mere implementation nuance. Under severe faults, semiconductor protection can enforce current saturation, which reduces the deliverable active and reactive power. We therefore model this limitation explicitly instead of assuming an ideal voltage source converter.

#### 4. Model of battery degradation

##### 4.1. Degradation pathways

We distinguish calendar ageing, driven by time, temperature, and SOC, from cycling-induced ageing, driven by energy throughput, cycle depth, C-rate, and temperature. Final parameterization must reflect the specific BESS chemistry and rely on manufacturer data or validated sources for the technology under study.<sup>[18]</sup>

##### 4.2. Representation of cycling-induced ageing

$$\Delta E_{\text{through}} = \int |\text{PBESS}(t)| dt \quad (15)$$

$$\text{EFCE} = \Delta E_{\text{through}} / (2 \text{ EB}) \quad (16)$$

$$\Delta \text{SOH}_{\text{cycle}} = \Phi(\text{DoD}, \text{C-rate}, T, \text{SOC}_{\text{mean}}, \text{EFCE}) \quad (17)$$

$$\text{SOH}_{k+1} = \text{SOH}_k - \Delta \text{SOH}_{\text{calendar}} - \Delta \text{SOH}_{\text{cycle}} \quad (18)$$

For long-duration datasets, rainflow counting converts SOC trajectories into cycles of varying depth. For a single dynamic event, we estimate incremental ageing using energy throughput, thus avoiding the illusion of high lifetime accuracy inferred from a disturbance that only spans a few seconds.<sup>[18]</sup>

##### 4.3. Cost of degradation

$$\text{Cdeg} = \text{Creplacement} \cdot \Delta \text{SOH}_{\text{event}} \quad (19)$$

Cdeg monetizes the fraction of service life consumed by dynamic support. Sensitivity analysis is essential because ageing coefficients and future replacement costs are uncertain.

#### 5. Degradation-aware adaptive GFM control

The supervisory layer adapts the GFM parameter vector:  $\theta_{\text{GFM}} = [\text{Hvirt}, \text{mp}, \text{KD}, \text{nq}, \text{Preserve}]$  (20) as a function of the system and asset state.

$z = [\text{Heq}, \text{SCR}, \text{SOC}, \text{SOH}, \Delta \text{P}_{\text{event}}, \text{interconnection status}, \text{converter headroom}]$  (21)

##### 5.1. Multi-objective performance criterion

$$\min \text{JGFM} = w_1 \cdot |\text{RoCoF}|_{\text{max}} + w_2 \cdot |f_0 - f_{\text{adir}}| + w_3 \cdot \text{trec} + w_4 \cdot V_{\text{severity}} + w_5 \cdot \text{Cdeg} + w_6 \cdot \text{Isat} \quad (22)$$

Alternatively, security requirements can be imposed as hard constraints. The optimizer then seeks the minimum degradation consistent with the prescribed dynamic-security thresholds, which clarifies the trade-off.

##### 5.2. Adaptive operating policy

- During normal conditions with high inertia, apply a low virtual inertia gain and minimize battery intervention.
- Under low-inertia yet secure conditions, provide moderate GFM support while maintaining sufficient SOC headroom.
- In the event of a severe contingency, temporarily increase virtual inertia, damping, and active power response, subject to current and SOC constraints.

#### Adaptive decisions: dynamic security and battery lifetime

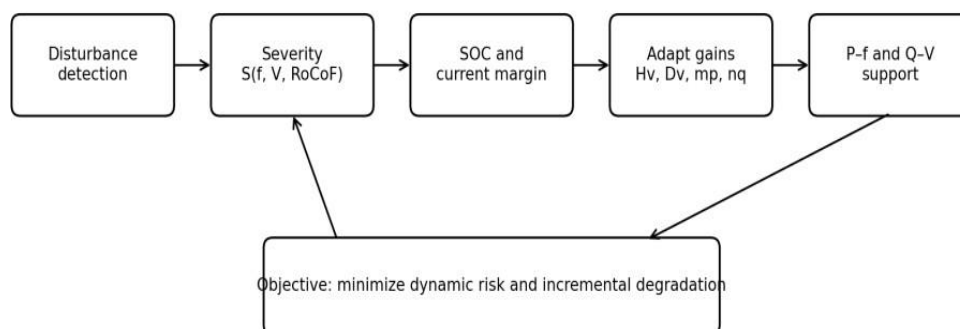


**Figure 2. Joint adaptation of GFM gains and battery response to severity, SOC, and converter constraints (author's illustration).**

- Weak-grid operation: ensure coordinated delivery of active-power and frequency support together with reactive-power and voltage regulation, all within the converter's apparent-power and current ratings.
- Low state of charge or battery degradation: prioritize security-critical services and curtail nonessential cycling.

#### 6. Comparison of control strategies

Table 1: consolidates five schemes, C0 to C4. A staged comparison is used to disentangle the incremental effects of fast-response capability, grid-forming behavior, adaptive parameterization, and explicit ageing-aware control.

**Table 1: Control strategies compared in the GFM-BEeSS evaluation.**

| Strategy | Mode                           | Parameters                 | Ageing accounted for | Purpose                    |
|----------|--------------------------------|----------------------------|----------------------|----------------------------|
| C0       | No BESS frequency support      | —                          | No                   | System benchmark           |
| C1       | Grid following FFR             | Fixed                      | No                   | Fast response benchmark    |
| C2       | Grid forming                   | Fixed Hvirt/droop          | No                   | Conventional GFM benchmark |
| C3       | Adaptive GFM                   | System dependent           | No                   | Value of adaptation        |
| C4       | Degradation aware adaptive GFM | System dependent + SOC/SOH | Yes                  | Proposed strategy          |

### 7. Scenarios and dynamic contingencies

Table 2 defines cases D1–D8 that span the principal sources of system imbalance and vulnerability: loss of generation or interconnection, variability in renewable

output, fault events, weak-grid operation, and recurrent support interventions. To enable a rigorous comparison across strategies, all simulations commence from identical initial conditions.

**Table 2: Dynamic contingencies and validation scenarios D1–D8.**

| Case | Disturbance                                          | Stressed dimension                | Main metrics                  |
|------|------------------------------------------------------|-----------------------------------|-------------------------------|
| D1   | Loss of largest online synchronous generator         | Frequency deficit                 | RoCoF, nadir, reserve         |
| D2   | Loss of major interconnection                        | Loss of external support          | RoCoF, nadir, recovery        |
| D3   | Large PV power reduction / cloud ramp                | Renewable variability             | $\Delta f$ , PBESS, SOC       |
| D4   | Load step                                            | Demand disturbance                | $\Delta f$ , damping          |
| D5   | Critical transmission fault cleared normally         | Voltage and transient constraints | Vmin, current, recovery       |
| D6   | Weak grid / SCR sensitivity                          | Grid strength                     | Stability, current saturation |
| D7   | High PV penetration / minimal synchronous commitment | Low local inertia                 | RoCoF, nadir                  |
| D8   | Repeated daily support events                        | Lifetime constraint               | SOH loss, throughput, EFCE    |

### 8. Senegal specific validation

Table 3 summarizes the empirical and historical

benchmarks used to parameterize the Senegalese cases and check their consistency.

**Table 3: Empirical and historical benchmarks for validating the GFM-BESS framework in Senegal.**

| Benchmark                   | Value          | Period          | Role in Article 4                                        |
|-----------------------------|----------------|-----------------|----------------------------------------------------------|
| Walo Storage                | 10 MW / 20 MWh | 2025            | Existing BESS reference; GFM capability not demonstrated |
| National peak               | 1,261 MW       | 4 Nov. 2025     | System scale                                             |
| Magal spinning reserve      | $\geq 50$ MW   | 12–14 Aug. 2025 | Reserve calibration                                      |
| Time within [49.7, 50.3] Hz | 95.73–99.62%   | 12–14 Aug. 2025 | Frequency consistency target                             |
| PATRP solar fluctuation     | 41 MW          | Historical      | Ramp scenario                                            |
| PATRP wind fluctuation      | 54 MW          | Historical      | Ramp scenario                                            |
| PATRP Sendou outage         | 115 MW         | Historical      | Generation contingency                                   |

The case study will be grounded in an SPS-2025 dynamic model derived by updating the legacy PATRP/Senelec representations with the most recent operational measurements. Baseline models for synchronous machines, excitation systems, turbine governors, photovoltaic converters, and wind plant controllers will be adopted, but their parameter sets will be rigorously validated before being retained for the 2025 network representation.

Disturbance scenarios are chosen for their direct operational salience in Senegal. They include the tripping of a large generating unit, the loss of an interconnection, rapid fluctuations in renewable production, and faults affecting a critical 225/90 kV corridor. For each scenario, all disturbance magnitudes, timings, and model

inputs will be explicitly recorded.

Regional interconnections will not be idealized as providing unlimited inertial support. To isolate the intrinsic contribution of the GFM-BESS, simulations will compare cases with strong support, weak support, and no support from the interconnection.

### 9. Specifies the performance metrics

- Frequency quality will be assessed through the maximum absolute RoCoF, the frequency nadir and zenith, the maximum frequency deviation, and the associated recovery or settling time.
- Voltage performance will be quantified by the minimum and maximum bus voltages and the voltage recovery time.

- Converter- and storage-related indicators will include peak BESS active and reactive power, the converter current peak and the duration spent in current saturation, and the energy delivered or absorbed per disturbance.
- State-of-charge dynamics will be characterized by the SOC excursion and the remaining upward and downward headroom.
- Degradation will be tracked via equivalent full-cycle count, incremental SOH loss, and the resulting degradation cost per event as well as per unit of frequency security improvement.
- Where applicable, stability margins such as critical clearing time and other stability indicators will be reported. Sensitivity analyses will cover local synchronous inertia, short-circuit ratio (SCR), and interconnection status.

### 10. Proposed decision metrics

Introduces two decision metrics that relate frequency security gains to the battery wear incurred. We use the labels FSDC and DNFS for convenience within this protocol without asserting priority for the terminology.

The Frequency Support Degradation Cost is defined as  $FSDC = C_{deg,event} / \Delta SecurityBenefit^{[23]}$ , and the Degradation Normalized Frequency Support is  $DNFS = \Delta SecurityBenefit / \Delta SOH_{event}^{[24]}$ .

The security benefit can be quantified as an avoided threshold violation, an improvement in the nadir, a reduction in RoCoF, or a clearly specified composite index. Together, FSDC and DNFS indicate whether additional GFM response yields a commensurate security enhancement relative to the incremental degradation.

### 11. Lists the hypotheses to be tested

- H1. A high, fixed virtual inertia setting does not always deliver the optimal security-degradation

tradeoff across operating conditions.

- H2. Adaptive GFM control can match or surpass frequency security while incurring lower energy throughput and battery degradation than an aggressive fixed GFM setting.
- H3. The marginal benefit of a GFM-BESS increases as local synchronous inertia and grid strength decline, but current-limited converter operation constrains that benefit during severe disturbances.
- H4. Regional interconnection support reduces the dynamic energy the BESS must supply for frequency control, whereas loss of the interconnection raises the value of local GFM capability.
- H5. Adequate SOC headroom is as important as installed BESS power for dependable frequency support under repeated disturbances.

### 12. Outlines empirical benchmarks and the validation protocol

#### 12.1. operating evidence from August 2025

provides a frequency benchmark without isolating any effect of GFM control. From 12 to 14 August, the daily frequency minima were 49.277, 49.297, and 49.331 Hz, and the maxima were 50.565, 50.602, and 50.775 Hz. Frequency remained within the [49.7, 50.3] Hz band for 95.73%, 99.62%, and 96.23% of those days, respectively. The contemporaneous report indicates that at least 50 MW of spinning reserve was maintained. These observations will serve to check the plausibility and consistency of the simulations rather than to demonstrate outcomes attributable to the proposed controller.<sup>[8]</sup>

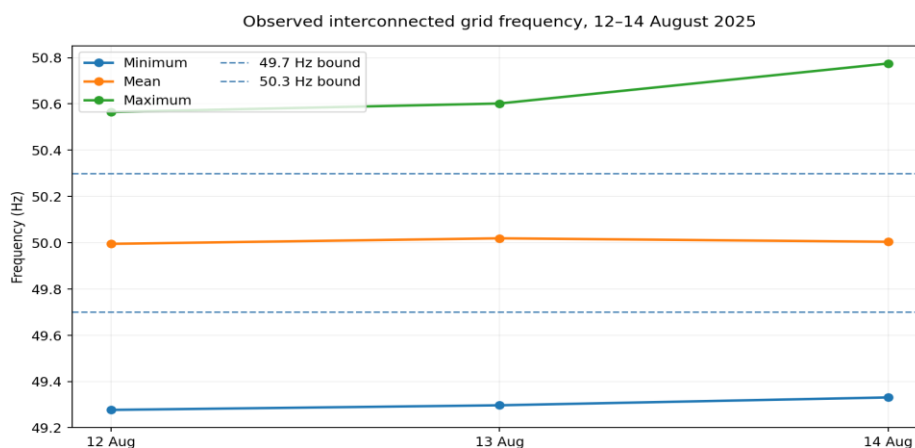


**Figure 3: Daily frequency statistics observed from 12 to 14 August 2025. (Data source: Senelec, 2025 Annual Energy Movements Report).**

#### 12.2. Historical benchmarks for frequency security

The PATRP assessment covering 2017 to 2035 concludes

that spinning reserves must be sized to withstand the tripping of the largest single unit as well as variability

from wind and photovoltaic generation. For the 2022 horizon, it analyzes an outage at Sendou of 115 MW, a wind maximum of 72 MW, and representative variability of 41 MW for solar and 54 MW for wind. It further demonstrates that support from OMVS and OMVG alters the local reserve requirement. In this study, these values are used as historical stressors and sensitivity references rather than as assumptions for 2025 operating practice.<sup>[9]</sup>

### 12.3. Comparative validation matrix

We will assess five control strategies under identical operating conditions and contingency sets: C0 is operation without BESS support; C1 is grid-following fast frequency response; C2 is grid-forming control with fixed parameters; C3 is adaptive grid-forming control without an explicit ageing cost; and C4 is degradation-aware adaptive grid-forming control. For each pairing of strategy and contingency, we will record rate of change

of frequency, frequency nadir, recovery characteristics, voltage, peak current, exchanged energy, state-of-charge excursion, and estimated degradation. Any incremental effects specific to C4 cannot be quantified until all cases are executed on a validated dynamic model.

The planned figures are aligned with this analysis: frequency trajectories for C0 to C4 following D1; a comparative view of RoCoF, nadir, and recovery time; time series of active and reactive power, SOC, and converter current during a severe event; sensitivity to inertia and short-circuit ratio; security benefit as a function of ageing cost; and, for D8, accumulated throughput, EFCE, and SOH loss. Each figure will be fully traceable to the exact parameters of its underlying simulation.

### 12.4. Hypothesis assessment criteria

**Table 4: Hypothesis testing matrix for Article 4.**

| Hypothesis | Main comparison                  | Metrics                                                     | Interpretation criterion                                                                   |
|------------|----------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| H1         | C2 vs C3/C4                      | RoCoF, nadir, Cdeg                                          | Supported if aggressive fixed settings do not dominate on both security and degradation.   |
| H2         | C2 vs C4                         | Security, $\Delta E_{\text{through}}$ , $\Delta \text{SOH}$ | Supported if C4 maintains/improves security with less battery stress.                      |
| H3         | Heq/SCR sensitivity              | RoCoF, nadir, I <sub>max</sub>                              | Supported if GFM benefit grows as grid strength falls until limited by current saturation. |
| H4         | Strong/weak/lost interconnection | BESS energy, nadir, recovery                                | Supported if regional support lowers the dynamic effort required from the BESS.            |
| H5         | Initial SOC / headroom           | Saturation, reserve, security                               | Supported if SOC headroom determines actual availability of frequency support.             |

### 12.5. Reproducibility requirements

Ensuring reproducibility requires that each simulation archive the software and version used, the numerical integration step, the total run time, the machine and governor models, and the adopted GFM control structure. The record must also include all filters and delays, the controller gains  $H_{\text{virt}}/\text{mp}/\text{KD}/\text{nq}$ , current and power limits, initial SOC and SOH, the battery chemistry with its ageing parameters, the operating point, the interconnection status, and the contingency clearing time. Results will be distributed together with post-processing scripts and any parameters that can be shared, in compliance with operator confidentiality constraints.

## 13. DISCUSSION

The central aim is to quantify the trade-off between gains in system security and the battery life expended. A high virtual inertia can strengthen the initial frequency response, yet it may not be the most effective configuration across all operating conditions. Insights from multiscale adaptation<sup>[2]</sup> and severity-dependent control<sup>[3]</sup> motivate this comparative assessment. An adaptive strategy will be judged beneficial only when improvements in RoCoF, nadir, or recovery are not achieved by displacing undue stress onto converter current, SOC, or battery ageing.

Disentangling local inertia from external support is particularly important in Senegal. Historical PATRP analyses connect reserve requirements to regional contributions, and the 2025 measurements show that the frequency of the interconnected grid depends on operating conditions. Interconnection status will therefore be treated as an explicit input to the supervisory controller and to sensitivity analyses, rather than being subsumed into a single, fixed inertia assumption.<sup>[8,9]</sup>

The definition of ageing cost is inherently time-scale dependent. A single disturbance generally imposes a small burden on the battery, whereas lifetime degradation is driven by the accumulated sequence of events, temperature profile, and SOC history. Prior work on ageing-aware voltage and frequency support<sup>[4]</sup> and on energy-aware GFM control<sup>[2]</sup> supports this distinction. We will use  $\Delta \text{SOH}_{\text{event}}$  primarily to compare controller settings within the same event. Any annualized evaluation must rely on a representative distribution of disturbances and operating conditions.

The simulated response must remain achievable by the converter. During faults, current limiting can modify transient stability and reduce the delivered support.<sup>[6,7,13,14,16,17,20]</sup> Accordingly, we will track peak current and the duration of saturation alongside

frequency metrics, to avoid conclusions that would follow from an idealized voltage source that neglects equipment protection.

#### 14. CONCLUSION

This work proposes coordinated tuning of virtual inertia, droop, damping, and Q-V support in a GFM-BESS as a function of disturbance severity, grid strength, and battery state. The framework incorporates converter limits, SOC headroom, and an incremental ageing cost, enabling frequency security to be assessed jointly with battery lifetime. Validation cases are informed by 2025 observations from Senegal and by historical PATRP benchmarks; these references serve to frame and check the studies, not to claim that adaptive GFM control has already delivered measurable grid benefits. The C0-C4 and D1-D8 protocol specifies how RoCoF, nadir, recovery, converter stress, and degradation are to be compared once the dynamic model is validated. Quantitative performance will be established by those simulations.

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