

# Mitigating GFM-Induced Battery Stress with a VDCM-Controlled Hybrid Energy Storage

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**Abstract**—In a power system dominated by inverter-based resources (IBRs), maintaining system stability is challenging without the support of an energy storage system. This study proposes a degradation-aware voltage-dependent current management (VDCM) battery-supercapacitor hybrid energy storage system (HESS). The hybrid configuration leverages the high energy density of batteries and the fast response and high-power density of supercapacitors to manage both moderate and rapid power fluctuations. By shifting fast charge–discharge activities to the supercapacitor, the system reduces stress on the battery and improves its ability to withstand abrupt frequency fluctuations. Simulation results demonstrate that the proposed control strategy not only effectively regulates voltage and frequency variations in the power system but also minimizes battery degradation while enabling grid-forming capabilities.

**Index Terms**—Inverter-Based Resources, Battery-Supercapacitor Hybrid Energy Storage, Grid-Forming Converter, Battery Degradation.

**I. INTRODUCTON** The penetration of IBRs, such as solar photovoltaic (PV) and wind energy, has been increasing rapidly in recent years. This trend has significantly increased the demand for grid-forming inverters in modern power systems, as IBR-dominated networks lack inherent inertia and are unable to provide adequate grid support during disturbances. Grid-forming (GFM) converters are capable of independently establishing voltage and frequency references. However, they face limitations in handling rapid voltage and frequency variations without the integration of appropriate energy storage systems (ESS) [1, 2]. Among various ESS technologies, battery energy storage systems (BESS) play a critical role in enhancing grid reliability, flexibility, and resilience by providing both primary and ancillary services. As a primary service, BESS supports energy arbitrage, peak shaving, and renewable energy integration by storing excess generation during low demand periods and discharging during

peak loads or generation shortfalls. Beyond these primary functions, BESS also delivers a range of ancillary services essential for stable grid operation, including frequency regulation, voltage support, spinning reserve, and black start capability [3]. While BESS can respond rapidly to frequency deviations, its ability to handle very short-duration, high-magnitude frequency excursions is limited by factors such as inverter ramp rates, state-of-charge constraints, and the risk of overloading. These constraints reduce its effectiveness during extreme transient events unless supplemented with advanced control algorithms and coordinated with other fast-responding resources [4].

HESS, which integrate two or more storage technologies, offer a promising solution by leveraging the complementary characteristics of each component. This improves overall system performance, reliability, and lifespan in a variety of power system applications. Common HESS configurations include battery-supercapacitor, battery-flywheel, and battery-hydrogen/fuel cell combinations [5, 6]. Comparative studies show that supercapacitors offer power response times nearly half that of flywheels and significantly faster than battery-only systems [7].

HESS technology is already widely adopted in the electric vehicle (EV) industry, where combining batteries with other storage devices enhances acceleration, improves regenerative braking efficiency, and extends battery lifespan [8–11]. Beyond transportation, HESS is increasingly employed in renewable energy applications—such as solar PV and wind systems—to smooth output fluctuations, support grid stability, and deliver fast frequency response, particularly in microgrid and islanded operations [12, 13].

HESSs combine the high energy density of batteries with the high-power density and rapid response capability of supercapacitors, creating a versatile and efficient solution for modern power systems. This functional division enhances the system’s overall dynamic response while significantly reducing

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the stress on batteries caused by high charge and discharge rates (C-rates). As a result, battery lifespan is extended, and operational reliability is improved. However, its application in power systems remains limited, with only a few studies [12] exploring its potential for grid stability and frequency support. Furthermore, few [14] studies have considered grid-forming HESSs and the impact of GFM behavior on battery degradation

In this study, a battery-supercapacitor HESS is proposed and interfaced with the grid through a grid-forming converter. This configuration enables the system to enhance grid stability by contributing to frequency regulation, improving damping, and maintaining voltage control during dynamic events. The main contributions of this paper are twofold:

- 1) A comprehensive assessment of the impact of grid-forming converters on battery degradation, with a particular focus on how virtual inertia and damping responses influence battery stress and lifespan.
- 2) The development of a VDCM strategy that dynamically allocates power between the battery and supercapacitor based on real-time operating conditions, thereby mitigating battery wear.

The remaining part of the paper is structured as follows. Section II provides a concise overview of HESS design and sizing. Section III details the system description and control implementation. Section IV presents and analyses the simulation results. Finally, Section V concludes the paper.

## I. HYBRID ENERGY STORAGE SYSTEM

The proposed HESS architecture is illustrated in Fig. 1. In this configuration, the BESS is connected to the DC bus via a bidirectional DC-DC converter, while the supercapacitor is directly coupled to the same DC bus. The DC bus supplies power to the grid-forming converter, which serves as the interface between the HESS and the AC power grid. This design is intentionally structured to manage rapid frequency variations in the power system, while reducing stress on the battery by offloading fast charge-discharge demands to the supercapacitor.

The C-rate defines the rate at which a battery charges or discharges relative to its nominal capacity and is a critical parameter for evaluating battery suitability in dynamic applications such as frequency regulation and grid stabilization [15]. degradation of lithium-ion batteries by increasing internal resistance, which leads to heat generation, mechanical stress on electrode materials, and adverse effects such as lithium plating and microcracking. These degradation mechanisms collectively reduce battery capacity, efficiency, and lifespan. For instance, increasing the charge rate from 1C to 1.5C can reduce battery life by up to 50%, while operating at 2C can cause a lifespan reduction of approximately 70% [14].

Moreover, the rapid current fluctuations commonly encountered in grid frequency support applications impose severe electrical and thermal stresses on batteries, further accelerating capacity fade and internal resistance growth. Pulsed and fluctuating currents—especially under high C-rate conditions and

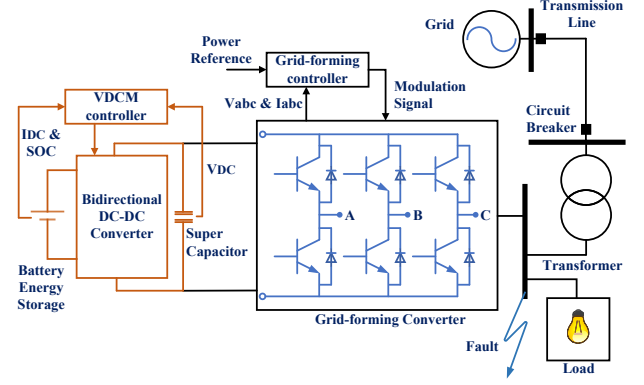


Fig. 1. System of the Study

partial state-of-charge (SoC) cycling—exacerbate degradation through localized heating and lithium plating [16].

The proposed HESS effectively mitigates these degradation challenges by utilizing supercapacitors to absorb and deliver rapid power fluctuations. By handling high-frequency transients and fast power demands, the supercapacitor significantly reduces the instantaneous current variations experienced by the battery. As a result, the battery operates under smoother, lower-stress conditions, thereby extending its operational lifespan and enhancing overall system reliability.

## II. SYSTEM DESCRIPTION AND CONTROL IMPLEMENTATION

The experimental platform features a 500 kVA, 415 V, 50 Hz three-phase grid-forming converter connected via a 415 V/11 kV step-up transformer to an 11 kV network. The grid is modeled under weak conditions with a short-circuit ratio (SCR) of 1.0 and an X/R ratio of 10.0.

### A. Grid-Forming Converter System Architecture

Virtual Synchronous Machine (VSM) control emulates the swing dynamics of a conventional synchronous generator [17]:

$$J \frac{d\omega}{dt} = P_m - P_e - D(\omega - \omega_{\text{ref}}) \quad (1)$$

where  $J$  is the virtual inertia constant,  $\omega$  is the converter angular frequency,  $P_m$  and  $P_e$  are the mechanical input and electrical output powers, and  $D$  is the damping coefficient. The power components generated by the VSM control are:

$$P_{\text{in}} = J \cdot \frac{df}{dt} \cdot 2\pi, \quad P_d = D(\omega_g - \omega_{\text{ref}}) \quad (2)$$

where  $P_{\text{in}}$  represents the virtual inertia power response and  $P_d$  is the damping power component. Here,  $\omega_g$  is the measured grid frequency and  $\omega_{\text{ref}}$  is the reference frequency.

The system also incorporates virtual impedance fault ride-through, following the adaptive approach discussed in [18],

which dynamically adjusts the converter's apparent impedance during fault conditions:

$$Z_v = R_v + jX_v \quad (3)$$

where

$$\begin{cases} R_v = K_R \cdot \max(0, |I| - I_r) \\ X_v = K_X \cdot \max(0, |I| - I_r) \end{cases} \quad (4)$$

In this formulation,  $Z_v$  is the virtual impedance,  $R_v$  and  $X_v$  are the virtual resistance and reactance,  $K_R$  and  $K_X$  are control gains,  $I$  is the measured converter current, and  $I_r$  is the rated current.

### B. Sizing of Hybrid Energy Storage

The nominal DC bus voltage is 1300 V. For a 500 kW inverter and a four-hour discharge, the commonly adopted duration for grid-scale Li-ion BESS deployments [19], the energy requirement is 2 MWh. This translates into 1538 Ah of the capacity of the battery. Allowing design margin, we sized the battery at 2000 Ah, with an internal resistance of 0.02  $\Omega$ . Moreover, To limit depth-of-discharge to 80 % and thereby maximize cycle life, only 1600 Ah of that capacity is usable.

The supercapacitor sizing is based on the most critical grid condition, which occurs when a sudden large load change causes the system frequency to drop to 47 Hz. During this event, the frequency remains low until the secondary control system activates, which is assumed to take at least 30 seconds [20]. To prevent system instability, the supercapacitor must sustain high power delivery throughout this period to support the virtual inertia response.

The energy required to support this event is calculated based on delivering 500 kW of power for 30 seconds, resulting in an energy requirement of approximately 15 MJ:

$$E_{\text{req}} = P \times t = 500 \text{ kW} \times 30 \text{ s} = 15 \text{ MJ} \quad (5)$$

The usable energy from the supercapacitor bank is:

$$E_{\text{sc}} = \frac{1}{2} C_{\text{tot}} (V_{\text{max}}^2 - V_{\text{min}}^2) \quad (6)$$

Solving for the required capacitance:

$$C_{\text{tot}} = \frac{2E_{\text{req}}}{V_{\text{max}}^2 - V_{\text{min}}^2} = \frac{30 \times 10^6}{1300^2 - 900^2} \approx 35 \text{ F} \quad (7)$$

To achieve the required system voltage, 482 supercapacitor cells, each rated at 2.7 V, are connected in series. This means that the ESR of a single string reaches to 0.482  $\Omega$ . To reduce to below 0.01  $\Omega$ —50 parallel strings are used. With 50 parallel strings and total required capacitance of 35 F each supercapacitor has 337 F capacity.

### C. degradation-aware voltage-dependent current management

The bidirectional DC–DC converter interfacing the hybrid storage system is governed by a two-layer hierarchical control scheme, referred to as VDCM. The primary control layer

provides fast, bidirectional current regulation using a PI-based current loop to track the reference current  $I_{\text{ref}}$ :

$$e(t) = I_{\text{ref}}(t) - I_L(t), \quad D(t) = K_p \cdot e(t) + K_i \int e(t) dt \quad (8)$$

where  $I_L$  is the inductor current and  $D(t)$  is the converter duty cycle. This control ensures stable, precise current tracking in both charging and discharging modes.

The secondary control layer dynamically generates  $I_{\text{ref}}$  based on real-time supercapacitor and battery conditions. It activates when the supercapacitor voltage drops below 1 p.u.. To prevent excessive thermal and aging stress, the reference current is limited using a degradation-aware scheduling algorithm that constrains charge/discharge rates and the instantaneous C-rate.

The battery current reference is smoothly ramped and continuously adjusted according to battery C-rate, temperature, and state-of-charge. As the battery approaches its operational limits, its power contribution is automatically reduced.

Power sharing between the battery and supercapacitor is defined by:

$$P_{\text{bat}}(s) = \frac{P_{\text{tot}}(s) \cdot K_{\text{bat}}(C_r)}{1 + s\tau_{\text{ad}}} \quad (9)$$

$$P_{\text{sc}}(s) = P_{\text{tot}}(s) - P_{\text{bat}}(s) \quad (10)$$

where  $K_{\text{bat}}(C_r)$  dynamically reduces battery participation as C-rate increases:

$$K_{\text{bat}}(C_r) = \begin{cases} 1.0 & \text{if } C_r < 0.5C \\ 1.0 - \frac{C_r - 0.5}{1.5} & \text{if } 0.5C \leq C_r \leq 2.0C \\ 0.0 & \text{if } C_r > 2.0C \end{cases} \quad (11)$$

The adaptive time constant  $\tau_{\text{ad}} = \tau_{\text{base}} \cdot f(\text{SOC}_{\text{bat}}, T_{\text{bat}}, C_r)$  ensures the response dynamically respects battery health constraints.

The VDCM strategy prioritizes supercapacitor support for fast transients while safely managing battery participation to mitigate degradation, maintain system reliability, and meet the grid-forming converter's dynamic performance requirements.

## III. RESULTS AND DISCUSSION

To demonstrate the necessity of the HESS approach, two critical stress scenarios that expose fundamental battery limitations in grid-forming applications are analyzed.

### A. Scenario 1: Temporary Three-Phase Fault Response Analysis

This scenario evaluates the system's response to a temporary three-phase balanced fault applied at the point of common coupling (PCC) from 3s to 5s. Grid-forming converters must provide reactive current injection within 5 milliseconds when voltage falls below 90% according to GC0137 [21]. This will create extreme current demands on energy storage systems.

Fig. 2 shows the frequency response, which drops to 47 Hz during the fault and returns to 50 Hz following fault clearance. The RMS current and voltage measurements in Fig. 3 indicate that the system remains stable throughout the fault period. The

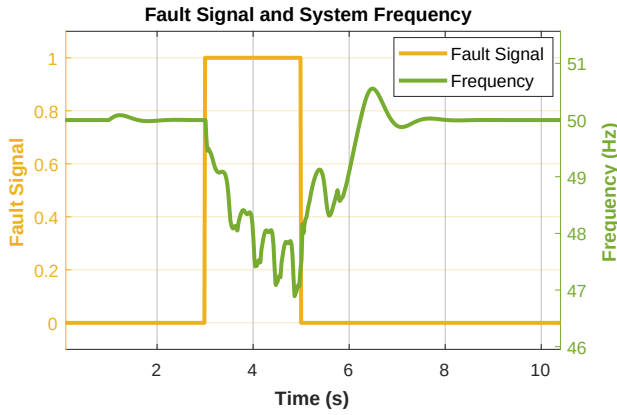


Fig. 2. Grid Frequency and Fault Trigger Signal in the First Scenario

inverter current demand presented in Fig. 4 (blue trace) reveals the high current requirements imposed on the energy storage system, resulting in instantaneous current transitions that stress conventional battery systems.

The proposed HESS, in Fig. 4 (orange trace), effectively manages these demands by utilizing the supercapacitor's current fluctuation capability to handle initial fault injection and clearing transients, while the battery provides sustained energy at controlled rates. This approach ensures adequate fault current magnitude while protecting the battery from degradation-inducing current spikes.

1) *Scenario 2: Dynamic Frequency Ramp Response (C-Rate Stress)*: This scenario evaluates the system's response to sustained frequency deviations that stress battery C-rate limits. During severe frequency events, grid frequency can change at rates of 1-2 Hz/s and remain deviated until secondary control restores nominal conditions, typically within 30 seconds.

The test profile, shown in Fig. 5, consists of frequency ramping from 50 Hz to 52 Hz over 1 second, maintaining 52 Hz for 5 seconds, then dropping to 47 Hz for 20 seconds. The corresponding voltage drops from 1.0 p.u. to 0.88 p.u., while grid current increases to 1.3 p.u. during the low frequency period.

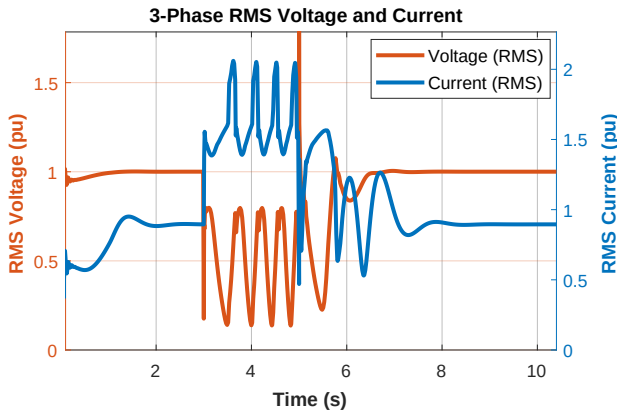


Fig. 3. Grid Voltage and Current Changes in the First Scenario

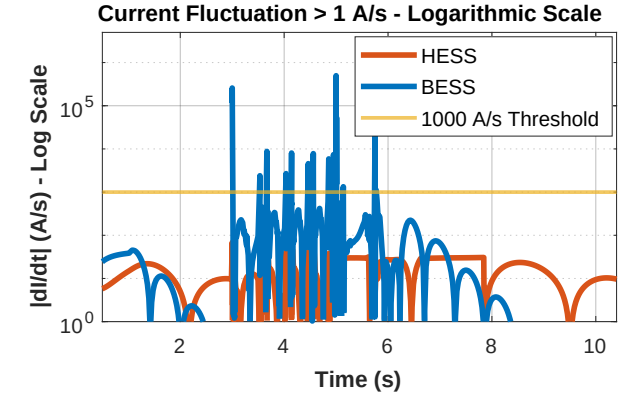
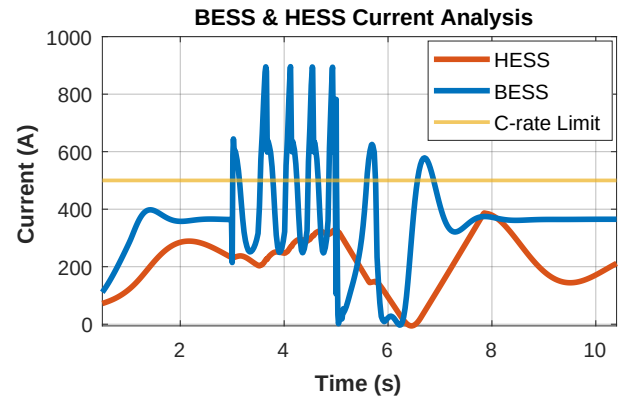


Fig. 4. Battery and SuperCap Current Changes in the First Scenario

The virtual inertia response to frequency deviations and demands high current from the energy storage system. Fig. 6 (blue trace) shows that conventional battery systems would operate well above safe C-rate limits during the low frequency period, potentially causing lithium plating and electrode damage.

The proposed HESS addresses this challenge by providing immediate high-power response through the supercapacitor during frequency transients, 6 (blue line) while limiting battery C-rates below 1C. The adaptive control algorithm monitors

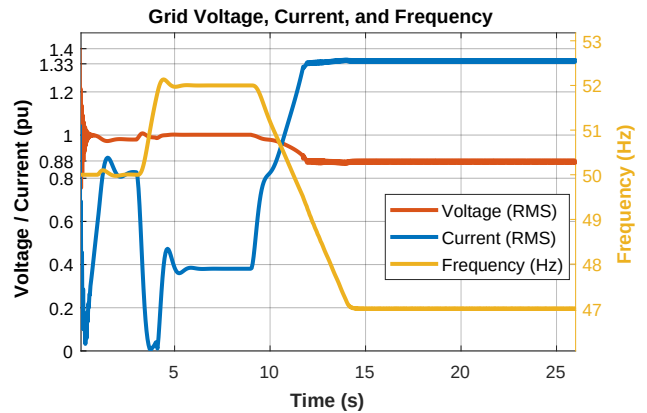


Fig. 5. Grid Frequency and Voltage and Current Changes in the Second Scenario

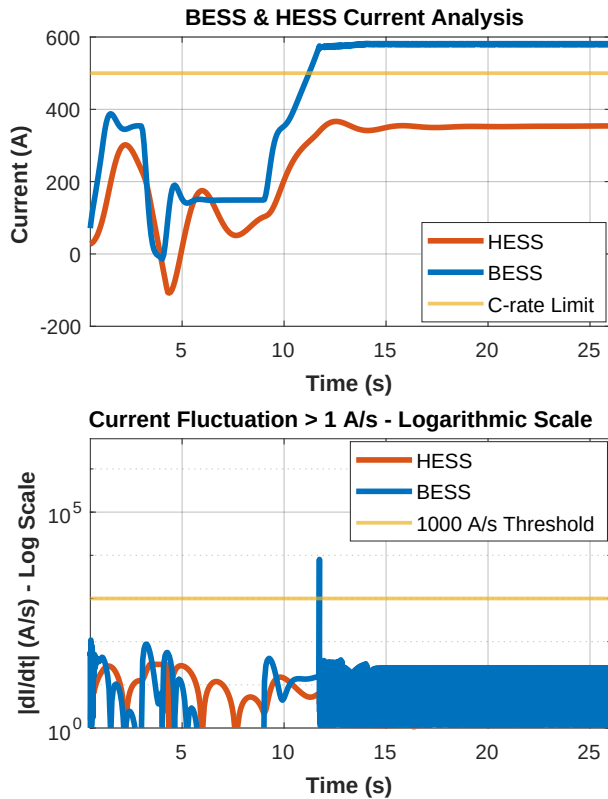


Fig. 6. Battery and SuperCap Current Changes in the Second Scenario

battery stress indicators and dynamically shifts power demand to the supercapacitor when C-rate limits are approached, maintaining grid support performance while preserving battery health.

## CONCLUSION

This study demonstrates that GFM technology can pose significant challenges to connected batteries, contributing to accelerated degradation and reduced lifespan. These issues are primarily associated with high C-rates and severe current fluctuation stresses. Based on two scenarios examined in this paper—a short-circuit fault and a sudden load change—the impact of the GFM controller on the battery was evaluated. In both cases, the battery experienced violations of its recommended C-rate and exposure to extreme current fluctuations.

To address these challenges, this study proposes a VDCM control strategy integrated with a HESS). The proposed approach effectively mitigates battery stress by offloading rapid transients to the supercapacitor. As a result, both C-rate violations and current fluctuation impacts on the battery are significantly reduced. Additionally, the performance of the GFM converter is slightly improved, owing to the lower equivalent series resistance (ESR) of the supercapacitor.

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