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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Coordinated Inertia Supervision for Grid-Forming BESS: A Headroom Aware Approach

TESI MAGISTRALE IN Electrical ENGINEERING – INGEGNERIA Elettrica

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1 Introduction

The global energy sector is undergoing a paradigm shift driven by the imperative to decarbonize power generation. By the end of 2024, renewable energy sources (RES) accounted for nearly half of the global installed electricity capacity, with solar and wind power comprising the vast majority of new additions [1]. While this transition is essential for climate mitigation, the displacement of synchronous generators with Inverter-Based Resources (IBRs) fundamentally alters the dynamic characteristics of the power system. Traditional generators possess large rotating masses that provide inherent physical inertia, naturally resisting changes in grid frequency. In contrast, standard IBRs are decoupled from the grid frequency via power electronics, leading to a system with lower total inertia. In such low-inertia grids, power imbalances result in rapid frequency deviations and a high Rate of Change of Frequency (RoCoF), significantly increasing the risk of under-frequency load shedding (UFLS) or cascading system failures [2]. To restore stability, the industry is increasingly deploying Battery Energy Storage Systems (BESS) equipped with Grid-Forming (GFM) control. Unlike Grid-Following (GFL) inverters that merely track the grid's angle, GFM inverters act as voltage sources, autonomously establishing the frequency and voltage at the Point of Connection (POC). Central to this capability is the Virtual Synchronous Machine (VSM) algorithm, which emulates the swing equation of a traditional generator. By monitoring the RoCoF, the VSM calculates a specific active power injection to oppose frequency drifts, providing "synthetic inertia" [3].

1.1 Literature Review

Considerable research has been dedicated to optimizing the coordination of multiple BESS units to ensure efficient power sharing and stability. Early approaches primarily utilized fixed weighting factors based on the nominal capacity of each inverter. In this "current-weighting" scheme, a central controller distributes the total active power reference proportional to each unit's rating, ensuring balanced current sharing under steady-state conditions. However, this method is rigid and fails to account for varying State-of-Charge (SOC) levels among heterogeneous units [4]. To address this, more advanced adaptive strategies were introduced, such as SOC-based droop control. These methods dynamically adjust the participation factors so that units with higher SOC contribute more power, thereby balancing the energy levels across the plant. Other studies have explored hierarchical Model Predictive Control (MPC) frameworks to optimize dispatch profiles over a future time horizon [4].

Despite these advancements, a significant limitation persists in how these strategies handle dynamic frequency events. Literature underscores that synthetic inertia is strictly bounded by the instantaneous current and power ratings of the semiconductor components, unlike the thermal overload capability of synchronous machines. The ability to provide inertial support is heavily dependent on the "headroom"—the difference between the inverter's maximum rating and its pre-disturbance operating point. If a BESS is already discharging at a high power level to serve energy markets, its available headroom may be insufficient to accommodate the massive power surge required during a high-RoCoF event [5].

Existing Power Plant Controllers (PPCs), including those using adaptive SOC-based or droop-based logic, typically suffer from "Headroom Blindness." They treat the BESS primarily as an energy reservoir for steady-state balancing without explicitly reserving the dynamic power margin required for frequency stability. When a multi-unit BESS plant operates near its rated capacity, these conventional strategies may unknowingly push individual inverters to their thermal limits. In the event of a sudden frequency disturbance, these saturated units cannot provide the necessary inertial response, leading to "Inertia-Saturation." This phenomenon results in the clipping of output power or the disconnection of the inverter exactly when grid support is most critical, effectively nullifying the benefits of GFM control. This thesis addresses this specific deficiency by proposing a coordinated supervision logic that explicitly reserves active power headroom, ensuring that synthetic inertia provision remains reliable and compliant with grid codes even under high-stress operating conditions.

2 Methodology

The study models a heterogeneous BESS plant connected to the medium voltage (MV) grid. The system consists of two parallel battery units connected to a common Point of Connection (POC) through separate inverters and transformers, as shown in Figure 2.1.

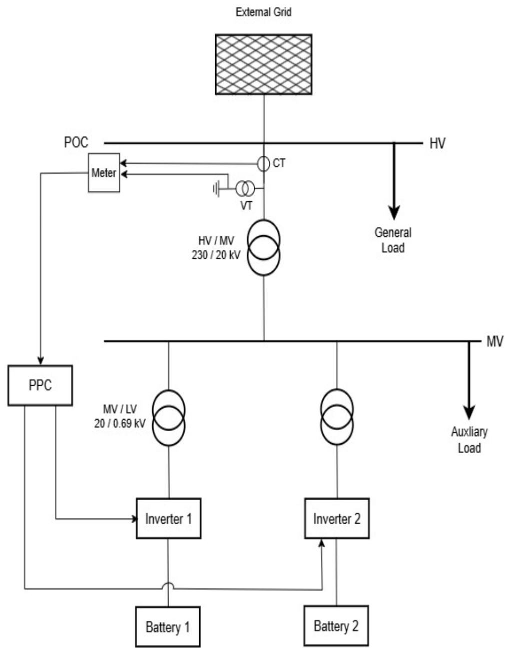

Figure 1.1, Single line diagram of the BESS.

2.1 Battery Model

Instead of a complex electrochemical model, the batteries are modeled as controlled voltage sources in series with internal resistance, as shown in Figure 2.2. A linear relationship between the SOC and the open-circuit voltage is assumed. This simplification is chosen because frequency events occur over short timeframes (seconds), where the primary impact is the power injection capability rather than long-term chemical degradation.

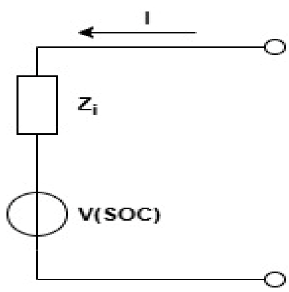

Figure 2.1, Equivalent Circuit Model of the implemented batteries.

2.2 GFM

The inverters employ a VSM control strategy to provide grid-forming capabilities. The VSM mimics the swing equation of a synchronous generator, as presented in Equation 2.1, calculating a virtual rotor speed (ω_r) based on the power imbalance between the setpoint (P_{set}) and measured output (P_{mea}). The core control law governing this synthetic inertia provision is:

$$T_a \cdot s \cdot \omega = P_{set} - P_{mea} - D_p(\omega_r - \omega_{set}) \qquad (2\text{-}1)$$

Where T_a is the mechanical time constant (related to inertia constant H) and D_p is the damping coefficient. This control structure enables the BESS to instantaneously inject active power to oppose frequency deviations.

2.3 PPC Architecture

The central coordination of the plant is managed by the PPC. As shown in Figure 2.3, the PPC architecture is designed for both high speed and high accuracy.

- **Reference Computation:** This block processes external TSO commands and applies ramp-rate limiters to ensure the battery is not subjected to instantaneous stress that could damage the cells or violate thermal limits.
- **Control Loop (PI + FF):** The PPC employs a Proportional-Integral (PI) controller to eliminate steady-state error at the POC. To handle the rigid limits of power electronics, the PI includes an Anti-Windup mechanism. This ensures that if the inverters saturate, the controller "freezes" its integral action, preventing overshoots and ensuring a rapid return to stable operation once the disturbance passes. A Feed-Forward (FF) path is added to bypass the PI for immediate setpoint tracking.
- **Limiter and Redispatching Block:** If a unit's local capacity is reached (e.g., due to a low SOC or thermal limit), this block detects the "unserved" power and automatically shifts that demand to the other parallel units. This ensures the plant always meets the TSO's total power request at the POC, maximizing the reliability of the BESS plant as a single virtual power plant.

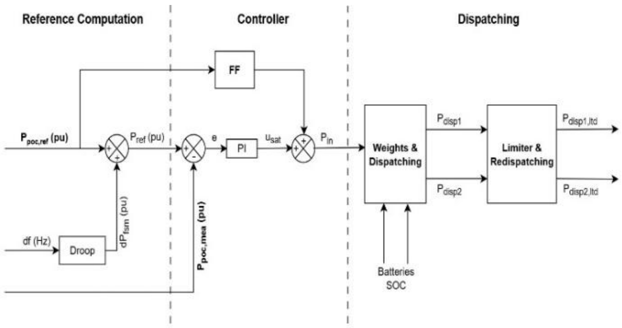

Figure 2.2, Block diagram structure of PPC

A core requirement of this methodology is the reservation of a specific power margin, or "headroom." This thesis adopts a 0.2 p.u. headroom criteria based on the GBGF-I (Great Britain Grid Forming) grid code requirements. The code mandates that GFM inverters must be able to respond to a RoCoF of 1 Hz/s. For a system with an inertia constant of $H = 5s$, the power surge required to oppose such a deviation is:

$$\Delta P = \frac{2 \cdot H \cdot RoCoF}{f_0} = \frac{2 \cdot 5 \cdot 1}{50} = 0.2\ p.u. \qquad (2\text{-}2)$$

By reserving this 20% of capacity, the PPC ensures the inverter always has the "breathing room" to provide synthetic inertia, even when it is already discharging for energy arbitrage.

2.4 Proposed Supervision Logic

The aim of the thesis is the logic that prevents "Inertia-Saturation." Conventionally, BESS units are dispatched based on their SOC (W_{SOC}). However, if one battery is much fuller than the other, the SOC-based logic might push that inverter to 0.9 p.u. power, leaving only 0.1 p.u. for inertia, violating the safety criteria.

The proposed logic introduces a Convergence Mode using Equation (2-3) to calculate an adaptive weight (W):

$$W = \frac{E_i \cdot SOC_i}{\sum_{i=1}^{m} E_i \cdot SOC_i} + \beta \cdot \left(W_{avg} - \frac{E_i \cdot SOC_i}{\sum_{i=1}^{n} E_i \cdot SOC_i} \right) \qquad (2\text{-}3)$$

As the power output of the units ($P_{ref,i}$) crosses a lower threshold ($P_{th,low} = 0.7\ p.u.$), the factor begins to increase linearly from 0 to 1, as shown in Figure 2.4. This forces the dispatch weights of both units to converge toward an average value (W_{avg}), regardless of their SOC. This transition ensures that all units reach the 0.8 p.u. limit simultaneously, preventing one unit from saturating early and failing to provide its share of grid support.

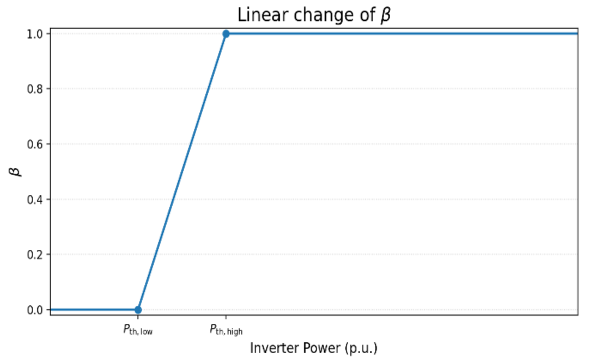

Figure 2.1, Value of β as a function of the inverter output power

3 Results and Discussion

The effectiveness of the proposed supervisory logic was validated through time-domain simulations in DIgSILENT PowerFactory. The performance was assessed using two distinct scenarios: a simplified Single-Machine model for control validation and a modified IEEE 9-Bus system to test network-level robustness.

3.1 Single-Machine Case Validation

The system was subjected to a sequence of events, shown in Figure 3.1, designed to force operation near the inverter thermal limits, testing the controller's ability to maintain the 0.2 p.u. headroom required for GBGF-I compliance. First, it will be subjected to an increase in the power reference to 180 MW (1 p.u), then another decrease to 135 MW (0.75 p.u.). After that a RoCoF event of 1 Hz/s is applied. The proposed approach will be compared to two another approaches: Nominal Energy-Based and SOC-Based Weight dispatching.

- **Steady-State and SOC Balancing:**
  Initially, the weights are distributed based on the SOC. As shown in **Figure 3.2**, the unit with higher capacity (Inverter 2) dispatches more power, ensuring that the SOC of both batteries decreases at the same rate, maintaining plant equilibrium.
- **Weight Convergence During Loading:**
  In the SOC-based and Nominal Energy-based approaches, both inverters increase their power at the same rate, as shown in Figure 3.3. This leads to Inverter 2 reaching its maximum 1.0 p.u. capacity earlier than Inverter 1, forcing the latter to compensate for the remaining load ramp. Conversely, in the proposed "Headroom-Aware" logic, the dispatching rates are coordinated differently, Inverter 2 increases at a lower rate than Inverter 1. This ensures both units converge toward the 0.8 p.u. threshold, effectively sharing the load while preserving the plant-wide headroom.
- **Headroom Restoration in Deloading:**
  A significant advantage of the proposed logic is observed during the power reference decrease (from 1.0 p.u. back to 0.75 p.u.). In standard approaches, Inverter 2 remains saturated at 1.0 p.u. while only Inverter 1 reduces its output to meet the new setpoint. In contrast, with the proposed logic, Inverter 2's power output successfully decreases to the 0.8 p.u. safety limit. This action restores the critical 0.2 p.u. headroom required for frequency support, whereas standard methods leave the unit in a vulnerable, saturated state.

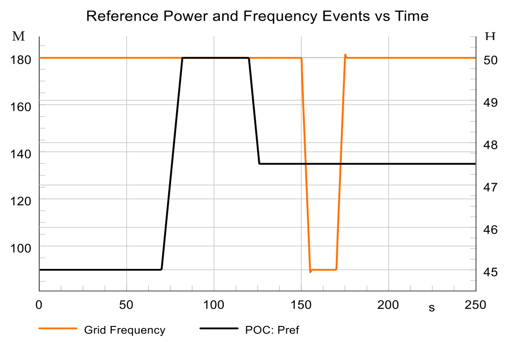

Figure 3.2, Applied events to the external power reference and grid frequency

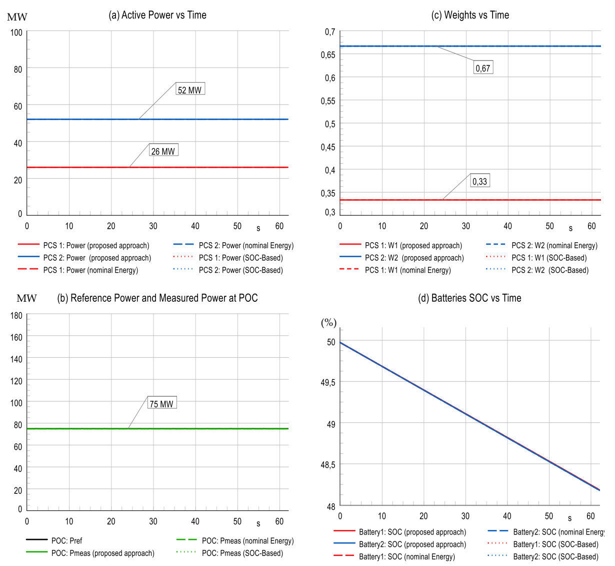

Figure 3.3, Dynamic response of metrices (a) inverter power (b) POC reference power and measured (c) weights (d) SOC before applying any events.

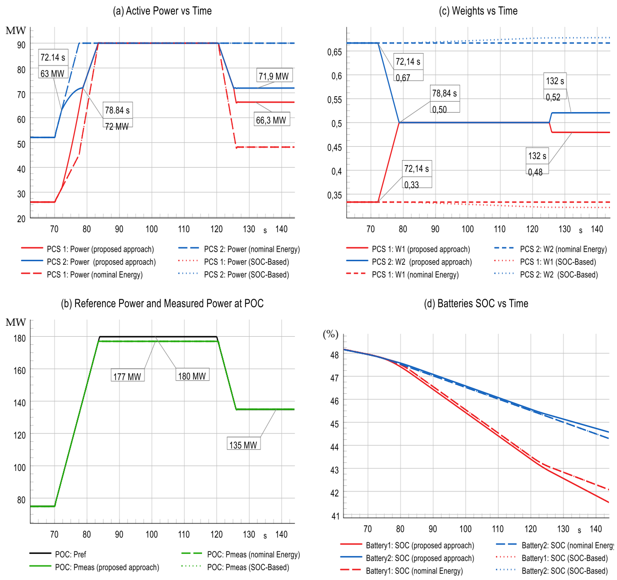

Figure 3.5, Dynamic response of metrices during ramp changing the external reference power.

- **Response to Severe RoCoF:**
  Standard controllers, being "headroom-blind," attempt to provide a full inertial response that pushes the inverters beyond their 1.0 p.u. rating. However, they fail to provide full inertia support in this scenario because Inverter 2 is already saturated, leaving only Inverter 1 capable of supporting the grid. Consequently, only half of the required inertia is provided, as illustrated in Figure 3.4.
  Unlike the standard approaches, he proposed logic intelligently monitors and manages available headroom across the system to ensure that the required inertia is fully supported. By preventing individual inverter saturation while still meeting the grid's demand, the BESS remains online and

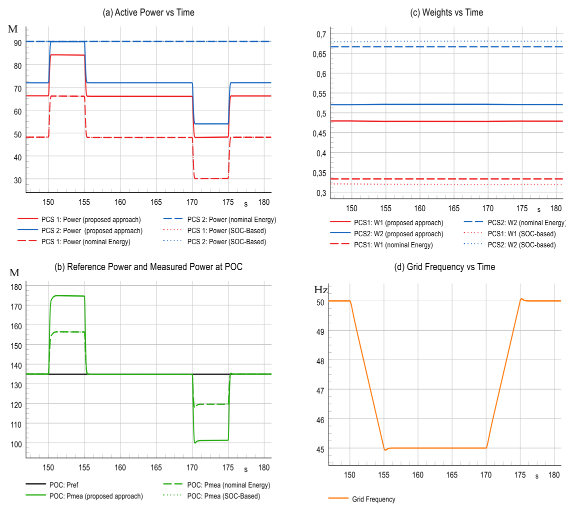

Figure 3.4, Dynamic response of metrices to a RoCoF event of 1 Hz/s

provides a full, unclipped inertial response. This allows the system to remain stable and effectively fulfill GBGF-I requirements even under extreme stress.

3.2 IEEE 9-Bus Study Validation

To confirm that the logic holds true in complex environments, it was integrated into a modified IEEE 9-Bus network featuring transmission impedances and multiple generation sources.

- **Network Interactions:**

The results in Figures 3.5 and 3.6 confirm that the supervision logic remains effective even with network-coupled impedances. While the response exhibits slightly higher oscillatory behavior due to physical reactances, the fundamental protection mechanism—reserving 0.2 p.u. headroom—prevents inverter saturation across the network.

- **Reliability:**
  Even under high-stress conditions, the proposed PPC ensures that the BESS plant behaves as a single, dependable grid-forming asset, fulfilling the TSO requirements without triggering local overcurrent protections.

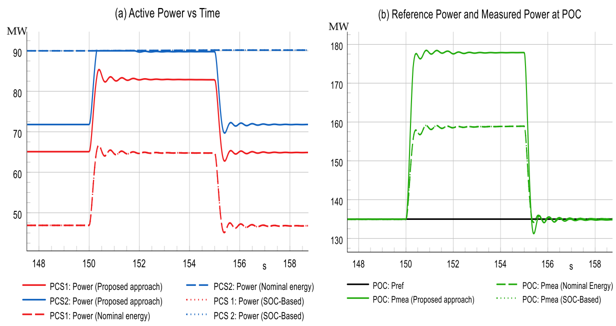

Figure 3.5, BESS response to a RoCoF of -1 Hz/s in IEEE study case

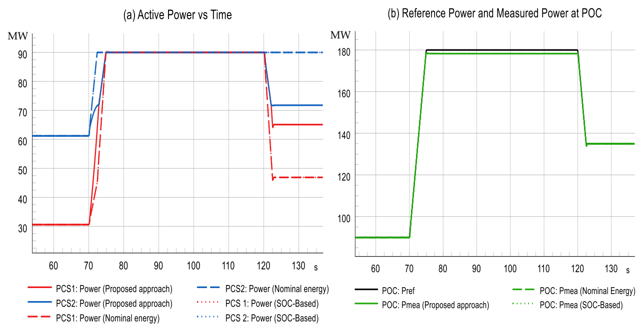

Figure 3.6, BESS response to a change in power reference in IEEE study case

4 Conclusion

The global energy landscape is undergoing a rapid transition driven by the urgent need to decarbonize, leading to a significant increase in RES such as wind and solar PV. The increasing number of IBRs causes the power systems worldwide are facing a critical reduction in physical inertia. This decline makes the grid frequency highly sensitive to imbalances, resulting in faster and steeper RoCoF events that jeopardize system stability.

While BESS equipped with VSM control offers a promising solution to restore this missing inertia, they are fundamentally constrained by the rigid current limits of their power electronics. A major vulnerability identified in this thesis is "Headroom Blindness", a flaw in standard control strategies where the pursuit of inertial support ignores these physical limits.

This research addresses the "Headroom Blindness" inherent in conventional BESS control strategies, which often causes inverters to saturate or trip during critical frequency events. The key findings are:

- **Failure of Standard Approaches:** Traditional SOC-based and energy-based weighting methods fail to account for the physical power limits of individual inverters. During severe disturbances, such as a -1.0 Hz/s RoCoF, these systems push units into saturation, leading to inadequate grid support.
- **Proposed Supervisory Logic:** The thesis introduces a coordinated inertia supervision logic integrated into the PPC. This logic dynamically estimates available headroom and adjusts the synthetic inertia response to keep operations within the Safe Operating Area (SOA).
- **Performance Validation:** Simulations using a modified IEEE 9-Bus network confirm that the proposed logic prevents inverter saturation even in complex topologies. It ensures the BESS remains a reliable source of inertial support while maintaining hardware safety.

4.1 Future Developments

The following points are suggested to expand the scope and robustness of the proposed control strategy:

- **Reactive Power and Voltage Control:** The current logic focuses primarily on active power and inertia; integrating a coordinated reactive power control or voltage control loop is essential to manage grid voltage stability and ensure the BESS remains within its full P-Q capability limits during disturbances.
- **Advanced Control Optimization:** Refining the tuning of the active power loop damping and virtual impedance to better manage oscillatory behaviors observed in complex network topologies.

5 Bibliography

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