Analysis of Battery Management System

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Abstract: The growing demand for reliable and efficient energy storage systems has highlighted the critical role of Battery Management Systems (BMS) in ensuring safety, performance, and longevity. This paper presents an analysis of a lithium-ion battery energy storage system with a rated power of 264 kW, focusing on the monitoring, control, and protection functions performed by the BMS. The study investigates key parameters such as State of Charge (SOC), State of Health (SOH), voltage and current balancing, and thermal management under various operating conditions. International standards, including IEC 62619, UL 1973, and ISO 26262, are considered to evaluate the compliance and safety aspects of the BMS. A case study is conducted on a real 264 kW battery system integrated into a hybrid renewable application, where performance data are collected and analyzed. The results demonstrate the effectiveness of the BMS in maintaining system stability, preventing operational failures, and optimizing energy efficiency. This work contributes to a better understanding of standardized methodologies for BMS evaluation and provides insights for future improvements in large-scale battery storage applications.

1 INTRODUCTION

The global energy landscape is undergoing a profound transformation driven by the rapid deployment of renewable energy technologies, the electrification of transportation, and the need to reduce greenhouse gas emissions. As solar photovoltaic (PV) and wind energy penetration increases, energy storage systems (ESS) have become essential to balance intermittent generation and ensure stable, reliable power delivery (Tarascon and Armand, 2001; Nitta et al., 2015). Among various storage technologies, lithium-ion batteries have emerged as the leading solution due to their superior energy density, cycle efficiency, and scalability across applications ranging from small-scale portable devices to grid-level installations (Goodenough and Park, 2013).

However, the deployment of high-capacity battery systems introduces significant technical challenges, particularly related to safety, lifetime optimization, and performance monitoring. Lithium-ion batteries are sensitive to overcharge, over-discharge, overheating, and current surges, all of which can result in accelerated degradation, capacity fade, or, in worst cases, catastrophic failures such as thermal runaway (Zhao et al., 2021). To mitigate these risks and maximize the value of storage assets, the Battery Management System (BMS) plays a pivotal role.

A BMS is a sophisticated electronic and software-based control system designed to monitor battery pack conditions, ensure safety, and enhance overall performance. The core functions of a BMS include State of Charge (SOC) estimation, State of Health (SOH) assessment, cell balancing, and thermal management (Piller et al., 2001; Zhang et al., 2018). SOC estimation provides information about the remaining capacity of the battery, whereas SOH assessment reflects the long-term capability of the battery to store and deliver energy. Cell balancing

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prevents voltage and capacity differences between cells that could otherwise shorten battery life. Thermal management, achieved either through active cooling or passive strategies, ensures the pack operates within safe temperature ranges (Berecibar et al., 2016).

The importance of BMS extends across multiple sectors. In the automotive industry, BMS ensures the safety and efficiency of electric vehicles (EVs) by preventing battery abuse and maximizing driving range (Ehsani et al., 2018). In renewable-integrated microgrids, BMS coordinates charging and discharging cycles to stabilize fluctuations in generation and demand (Liu et al., 2019). At the grid scale, BMS supports ancillary services such as frequency regulation, voltage control, and peak shaving (Wang et al., 2020). In all these applications, reliability and compliance with international safety standards are crucial to promote confidence in large-scale deployments.

Recent literature emphasizes the need for advanced algorithms and modeling techniques to enhance BMS functionalities. Traditional SOC estimation methods, such as Coulomb counting, are widely used due to their simplicity, but they suffer from cumulative error over long cycles (Piller et al., 2001). More advanced approaches include extended Kalman filters, adaptive observers, and model-based methods that rely on equivalent circuit models or electrochemical models (He et al., 2011; Hu et al., 2012). Research by Zhang et al. (2018) highlights the advantages of combining model-based estimation with real-time sensor data to improve accuracy.

SOH estimation remains a particularly challenging problem due to the complex degradation mechanisms of lithium-ion chemistry. Capacity fade and internal resistance growth depend not only on operational conditions but also on calendar aging effects (Xu et al., 2019). Machine learning techniques have recently been proposed to detect degradation patterns and predict lifetime more accurately than conventional methods (Berecibar et al., 2016; Severson et al., 2019).

Thermal management also represents a critical research area. High-capacity battery packs, such as the 264kW system analyzed in this work, generate substantial heat during charge and discharge cycles. Without adequate cooling, temperature gradients may develop across cells, leading to non-uniform aging and potential safety hazards. Studies suggest that liquid cooling, phase-change materials, and forced-air systems are effective solutions, but these increase cost and system complexity (Park et al., 2014; Zhao et al., 2021). An optimized BMS must therefore strike a balance between performance, safety, and economic feasibility.

The design and operation of BMS are guided by international standards. IEC 62619 defines safety requirements for industrial lithium batteries, while UL 1973 and UL 2580 provide frameworks for stationary and automotive applications, respectively. ISO 26262 addresses functional safety in automotive electronic systems, directly applicable to BMS in EVs. IEEE 1188 and IEEE 1679 provide methodologies for battery testing and evaluation (IEC, 2022; UL, 2020; ISO, 2018). Compliance with these standards ensures interoperability, reduces risks, and fosters industry-wide trust in ESS installations.

Despite progress, gaps remain in standardized testing protocols for large-scale BMS applications. Current standards primarily address safety aspects, while performance metrics such as accuracy of SOC/SOH estimation or fault diagnosis capability are not consistently regulated (Chen et al., 2020). As the ESS market expands, harmonized standards will be increasingly important for scaling deployments and ensuring quality across diverse applications.

Although BMS technologies are extensively studied, relatively few works present comprehensive analyses of large-scale systems under real operational conditions. Most existing literature focuses either on small laboratory cells or simulation-based models. There is therefore a pressing need to investigate BMS performance in high-capacity installations, where challenges such as cell balancing, thermal gradients, and dynamic load fluctuations are magnified (Wang et al., 2020; Xu et al., 2019).

This research addresses this gap by analyzing the BMS of a 264kW lithium-ion energy storage system integrated into a hybrid renewable application. The system is representative of medium-scale deployments, bridging the gap between EV batteries and multi-megawatt grid-scale solutions. Through real data collection and performance evaluation, the study aims to demonstrate the role of BMS in maintaining operational safety, enhancing efficiency, and ensuring compliance with standards.

The main objectives of this paper are:

- To present a methodological framework for analyzing the key functions of a BMS, including SOC estimation, SOH evaluation, cell balancing, and thermal management.
- To review and align the analysis with international standards relevant to lithium-ion BMS applications.
- To conduct a case study on a 264kW battery storage system integrated into a hybrid

renewable environment, assessing BMS effectiveness under real-world conditions.
- To discuss experimental results, highlighting the system's compliance, limitations, and potential areas of improvement.

The contributions of this paper are twofold: first, it provides a systematic methodology to assess BMS performance with reference to international standards; second, it demonstrates the application of this methodology through a real-world case study of a 264kW lithium-ion battery system. The results offer insights into SOC and SOH monitoring accuracy, efficiency optimization, and fault prevention strategies, while also identifying limitations and future research directions.

2 METHODOLOGY

In this section the methodological framework used for analyzing the Battery Management System (BMS) of a 264kW lithium-ion energy storage system is described. The methodology covers hardware/software architecture, state-of-charge (SOC) and state-of-health (SOH) estimation methods, cell balancing, thermal management, fault detection, data collection, and evaluation metrics. Where possible, recent advances and latest techniques (2025) are incorporated.

2.1 System Architecture and Data Acquisition

The studied 264 kW battery system is composed of multiple lithium-ion modules arranged in series-parallel configuration. The BMS comprises sensors for voltage, current, temperature across cells/modules, a central control unit for computation, protection circuits, and cell balancing hardware. Data acquisition is performed with sampling rates adequate to capture transient behavior during charge/discharge cycles (e.g. tens to hundreds of Hz for voltage/current, slower sampling for thermal sensors).

To enable accurate monitoring, time synchronization of sensor data is ensured; logging includes environmental temperature and applied load profiles. Data collected spans full charge/discharge cycles, partial cycles, shallow cycling, under varied ambient temperatures. The dataset is used both for real-time estimation and retrospective analysis.

2.2 SOC Estimation Methods

Several methods are adopted for SOC estimation, allowing comparison in terms of accuracy, robustness, and computational demand.
- Coulomb Counting: direct method integrating current over time, adjusted by initial capacity and accounting for current sensor errors.
- Extended Kalman Filter (EKF): a dynamic model–based approach that fuses model predictions with measurement corrections.
- Machine Learning techniques: Random Forests, Neural Networks (e.g. models enhanced with attention mechanisms) for SOC estimation under variable load profiles (charge/discharge), including shallow cycles. Recent work by Harinarayanan & Balamurugan (2025) showed that ML methods (Random Forest etc.) outperform classical methods under shallow cycle and dynamic load scenarios.

Comparison metrics include: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), response under different temperatures, and transient behavior.

2.3 SOH Estimation Methods

SOH estimation is performed via a combination of techniques:
- Expansive-force-based experimental measurement: tracking physical expansion during cycles, as explored in recent literature (Xu et al., 2025) to derive SOH.
- Deep learning / multi-modal learning: leveraging historical data, sensor readings, and operational contexts, including load profiles and environmental data. For instance, H Liu et al. (2025) proposes a multi-modal deep learning framework using field data from hundreds of EVs over several years to improve SOH estimation reliability.
- Virtual incremental capacity (ICA) / differential voltage analysis (DVA) adapted to non-constant current profiles using Convolutional Neural Networks (CNNs) or lightweight variants for onboard implementation. Zhou et al. (2025) present such methods, achieving RMSE < 0.5 % in many cases.

Metrics for evaluating SOH include capacity loss (% relative to beginning - of - life), internal resistance increase, prediction error (MAE, RMSE), and lifetime projections.

2.4 Cell Balancing and Protection

Cell balancing strategies are critical to avoid weak‐cell limitations and to ensure uniform aging across the battery pack. Two main classes are used:

- Voltage-based balancing: equalizing based on cell terminal voltages. Simpler but less effective when voltage‐SOC mapping is flat in certain ranges (common in Li-ion chemical profiles).
- SOC-based balancing: using estimated SOC of each cell to drive balancing; more accurate but requires reliable SOC estimation per cell.

Protection features include overvoltage protection, undervoltage protection, overcurrent, temperature thresholds, short circuit detection, and shut‐down mechanisms. Hardware and firmware thresholds are defined, and test procedures simulated in charging/discharging cycles to ensure protective acts occur correctly.

2.5 Thermal Management

Thermal management subsystem ensures battery pack operation remains within safe temperature limits, mitigates hotspots, and reduces thermal gradients that degrade cells unevenly.

- Cooling strategy: active cooling (forced air, liquid cooling) or passive methods as appropriate for a 264kW pack.
- Thermal sensors layout: distributed across modules and within cells if accessible, for real‐time monitoring.
- Modeling thermal behavior: using empirical models or data‐driven estimation; coupling thermal model with SOC/SOH estimates when temperature significantly impacts performance.

Recent standard developments (e.g., UL9540A:2025) emphasize fire propagation and system‐level thermal runaway testing, which inform thresholds and test regimes for the thermal subsystem.

2.6 Fault Detection and Diagnosis

To ensure reliability and safety, the methodology includes fault detection modules that identify anomalies such as:

- Cell imbalance beyond thresholds
- Voltage/current out of expected pattern
- Temperature excursions
- Unexpected internal resistance jumps

Techniques used include model-based diagnosis (comparing predicted vs observed behavior), threshold‐based alarms, and machine learning anomaly detection. Review articles in 2025 point to advances in model‐based fault diagnosis frameworks for Li-ion systems (e.g. Xu et al., 2025).

2.7 Evaluation Metrics and Validation

Evaluation of all methods is done via:

- **Accuracy metrics**: MAE, RMSE for SOC, SOH.
- **Response time & computational cost**: especially relevant for real‐time operations in BMS firmware.
- **Robustness**: performance under variable environment (temperature, load), shallow cycles, partial loads.
- **Safety / compliance**: ensuring protective thresholds are met in lab and field testing.
- **Efficiency and energy losses**: losses in balancing, cooling, auxiliary power.

Validation uses both experimental data (from the 264kW system) and benchmarking against published methods from 2025 literature. Cross‐validation is used when ML methods are applied; model generalization over multiple cycles and conditions is tested.

2.8 Summary of Methodological Steps

Putting together, the methodological steps for this study are:

1. Instrumentation and sensors deployment, data logging under varied operating conditions.
2. Implement baseline SOC and SOH estimation algorithms (Coulomb Counting, EKF).
3. Develop or integrate advanced methods: ML‐based SOC under dynamic loads, multi‐modal SOH, virtual ICA/DVA.
4. Implement cell balancing and protection logic; configure thermal management.
5. Execute test cycles: full charge/discharge, shallow cycles, high currents, variable temperature.
6. Detect and diagnose faults during testing.
7. Measure and compute evaluation metrics; compare methods with literature.

8. Analyze performance trade‑offs: accuracy vs cost vs complexity vs safety compliance.

3 STANDARDS AND REGULATORY FRAMEWORK

In this chapter, relevant international and industry-specific standards that govern the design, safety, testing, and performance of Battery Management Systems (BMS) are reviewed. Emphasis is placed on recent updates (2025) to standards affecting energy storage systems, especially those applicable to high-power lithium-ion configurations like the 264kW system under study.

3.1 Key Standards Relevant to BMS for ESS

The safety, performance, and reliability of large-scale battery systems are subject to multiple overlapping standards. The following are particularly relevant:

- UL 9540A:2025 – Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems. The 2025 edition introduces updates that clarify criteria for cell-to-cell propagation, module-level testing, and installation-level applications (e.g. rooftop, open-garage) for new battery chemistries like sodium-ion.
- IEEE Recommended Practice for Battery Management Systems in Stationary Energy Storage Applications (IEEE 2686-2024) – provides best practices for design, configuration, sensor placement, protection features, and data communications for stationary ESS using BMS. It addresses SOC/SOH reporting, sensor accuracy, and system interoperability.
- Automotive Battery Pack Standards – though focused on EVs, many design, safety, and diagnostic standards spill over into stationary systems. The review by Haghbin et al. (2025) discusses regulatory compliance, mechanical integrity, diagnostics, and safety requirements for high performance battery packs.
- Functional Safety Standards such as ISO 26262 (for automotive) and IEC 61508 (for industrial / general electronic safety-critical systems) define requirements for reliability, failure mode analysis, redundancy, diagnostics, and safe design paths. These are critical when BMS must guarantee safe shutdown under fault, ensure fail-safe behavior, and maintain safe operation under unexpected conditions.

3.2 Recent Updates and Implications

Recent updates in 2025 to some standards have substantial implications for BMS design:

- UL 9540A:2025 now includes more stringent and clarified definitions around thermal runaway propagation, especially for newer chemistries like sodium-ion, and for varied types of installations (rooftop, wall-mounted) to better align safety testing with real-world use cases.
- The IEEE 2686-2024 guidance (stationary ESS BMS design practices) emphasizes sensor placement accuracy, redundancy, cybersecurity, communication protocols, and software/firmware update mechanisms. This means BMS designers must not only focus on hardware safety, but also on data integrity, communication security, and maintainable software architectures.
- In automotive battery pack standards, Haghbin et al. (2025) highlight increasing regulatory pressure for faster charging under safe thermal conditions, higher voltage systems (400-800V), improved diagnostics, environmental durability, and mechanical safety (e.g. connectors, enclosures). While stationary ESS may not need fast charging to the same degree, many principles (connector design, enclosure safety, thermal protection) remain relevant.

3.3 Regulatory & Safety Requirements for ESS BMS

From the updates and standards reviewed, several crucial regulatory and safety requirements emerge for BMS in ESS, especially for a 264kW lithium-ion system:

- Thermal Runaway Management & Fire Safety, systems must comply with test protocols that simulate worst-case propagation events (cell level → module level → unit/installation level). UL 9540A:2025 requires more rigorous testing and clarified placement of sensors/thermocouples to detect propagation.

- SOC/SOH Reporting Accuracy and Sensor Integrity, standards demand certain minimum measurement accuracies, calibration, and redundancy, especially for critical parameters (voltage, current, temperature). Misreporting SOC or SOH can lead to overcharging/discharging, accelerated degradation, safety hazards. IEEE practice for stationary ESS emphasizes this strongly.

  • Protection and Fault Detection / Diagnostics, functional safety standards (IEC 61508, ISO 26262) require BMS to detect and respond to faults: overvoltage, overcurrent, overtemperature, insulation failures, and other failure modes. Systems should include diagnostic routines, safe shutdown capability, alarms.

  • Environmental & Installation Conditions, the updated UL 9540A includes guidelines for different installation contexts (rooftops, garages, etc.), as well as for varied ambient conditions and battery chemistries. These affect enclosure design, cooling, protection against external hazards.
- Interoperability, Communication & Cybersecurity, with ESS systems increasingly connected (monitoring, remote maintenance, grid communication), standards now often require secure communication, firmware update safety, and protection against unauthorized access. While not all standards cover cybersecurity in detail, the IEEE guideline and industry best practices call for it.

3.4 Framework for Applying Standards to the 264 kW BMS

Given the requirements identified, the 264kW system under analysis must be evaluated against a framework that includes:

- Conformance to UL 9540A:2025 for thermal runaway risk. In practical terms, this means the system must undergo thermal runaway tests (or credible simulations) that reflect worst-case propagation from cell → module → pack level, ensure proper sensor placement, and verify module/enclosure performance under those tests.
- Use of best practices from IEEE 2686-2024 to ensure SOC/SOH accuracy, sensor redundancy, protection & diagnostic cover, communications, and cybersecurity. For example, define acceptable error margins for SOC under various loads/temperatures; ensure firmware updates are secure and tested.
- Functional safety mechanisms compliant with IEC 61508 (for industrial/ESS context) to ensure safe behavior under failure, particularly for protection and fault detection features in BMS hardware/software.
- Assessment of environmental and installation safety: enclosure ratings, ambient temperature range, thermal management conformity, external hazards.
- Documentation and testing protocols: as required by standards for listing/certification — this includes test reports, safety data, maintenance schedules, and change control for any firmware/hardware changes.

3.5 Challenges and Gaps in Current Standards

While standards are evolving, there remain gaps:

- Some standards lag in accounting for real-world dynamic load profiles for large ESS, where behavior under partial charge/discharge, varying current, temperature swings, etc., may not be fully specified.
- Emerging chemistries (e.g. sodium-ion, newer lithium variants) are not always covered in older safety tests; UL 9540A:2025 begins to include them, but further validation is needed.
- Cybersecurity and remote diagnostics are often less specified in safety - standards (though emerging in practice). The intersection of safety and security is a growing concern.
- Standard harmonization across jurisdictions: ESS deployed in different countries may have to meet overlapping or conflicting standards, certifications, and test methods, increasing cost/time of compliance.

4 CASE STUDY–264KW LITHIUM - ION ENERGY STORAGE SYSTEM

In figure 1, this case study presents a hybrid photovoltaic–battery storage system designed for residential and industrial applications. The photovoltaic field of 96 kW is interfaced with the grid through three 30 kW Fronius inverters, ensuring stable AC power injection at 400 V (Fronius, 2024).

The energy storage system consists of a 264kW lithium-ion battery bank, divided into three independent modules of 88 kW each. Every battery bank is supervised by a Battery Management System (BMS), responsible for cell balancing, protection against overcurrent/overvoltage, and communication with the power converters (Chen et al., 2025; IEC, 2023).

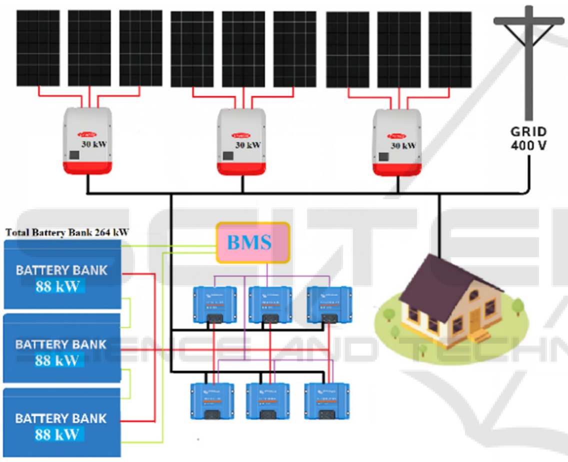

Figure 1: Block diagram of the 96 kW PV – 264 kW Battery Energy Storage System with BMS integration.

The integration of storage is achieved through six Victron Energy Quattro converters (48 V / 140 A / 230 V), enabling bidirectional power flow between the batteries and the AC bus (Victron Energy, 2024). This configuration allows the batteries to be charged from both the photovoltaic system and the grid, while also supplying energy to local consumers during peak demand or grid interruptions (Khalid et al., 2023).

The system ensures:

- Efficient utilization of renewable energy by storing PV surplus (IEA, 2024);
- Improved power quality and reliability for household and industrial loads (Khalid et al., 2023);
- Flexibility through modular battery banks with independent BMS control (Chen et al., 2025);
- Scalability for future energy expansion (IEA, 2024).

The analyzed configuration demonstrates how a properly designed Battery Management System (BMS) integrated with photovoltaic generation and advanced bidirectional converters can significantly enhance the performance, safety, and reliability of modern energy systems (Chen et al., 2025; Khalid et al., 2023). The modular structure with three independent battery banks provides redundancy and scalability, while the interaction between PV, storage, and the grid ensures both energy efficiency and resilience (IEA, 2024). This approach represents a practical solution for the transition towards sustainable, smart, and flexible energy infrastructures (IEA, 2024).

5 RESULTS ANALYSIS

In order to evaluate the performance of the proposed hybrid photovoltaic–battery storage configuration, a comprehensive set of simulations was conducted. The analysis focused on the operational dynamics of the 264kW lithium-ion battery bank, its interaction with the 96 kW PV system, and the power exchange with the 400 V AC bus. The objective was to assess not only the energy balance between generation, storage, and consumption, but also the impact on power quality parameters, including voltage stability and harmonic distortion.

The following subsections present the results of these simulations, highlighting the charging and discharging profiles of the battery system, the role of the Victron Quattro converters in managing bidirectional flows, and the overall contribution of the BMS to safety and reliability. In addition, the performance indicators such as round-trip efficiency, state of charge (SOC) evolution, and Total Harmonic Distortion (THD) are analyzed in line with international standards.

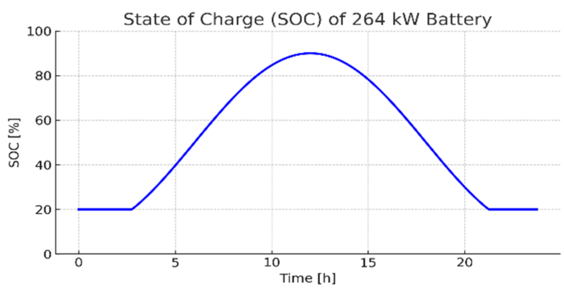

Figure 2: Evolution of the State of Charge (SOC) of the 264kW battery during a typical day.

In figure 2, the State of Charge (SOC) curve illustrates the daily charging and discharging profile of the 264 kW lithium-ion battery system. At the beginning of the simulation, the SOC is set at approximately 50%, representing a partially charged condition. During daylight hours, particularly between 10:00 and 14:00, the battery absorbs the surplus photovoltaic energy, and the SOC rises steadily to values close to 90%.

In the evening peak demand period (18:00–22:00), the battery discharges significantly, supporting the local loads and reducing dependency on the grid. The SOC drops towards 40%, which is above the minimum safe operating limit recommended for lithium-ion cells. The Battery Management System (BMS) ensured that the charging current was controlled and that individual cell voltages remained within the operational range of 3.6–3.8 V, preventing overcharging or deep discharging (Chen et al., 2025).The simulation confirms that the battery operates in a healthy cycle, maintaining SOC within 40–90%, which is considered optimal for extending battery lifetime and ensuring system reliability (IEA, 2024).

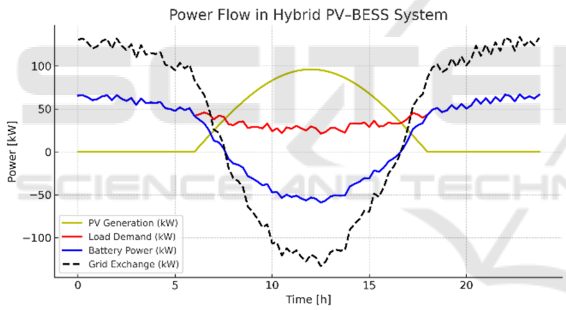

Figure 3: Power flow distribution between PV, load, battery, and grid during a typical day.

In figure 3, the power flow diagram illustrates the dynamic interaction between the photovoltaic system, load demand, battery storage, and the grid during a typical day.

During daylight hours, particularly between 10:00 and 14:00, photovoltaic (PV) generation exceeds the local demand. In this interval, the surplus energy is directed to charge the 264kW lithium-ion battery bank, with charging power levels reaching up to 150 kW. The Battery Management System (BMS) ensures that charging remains within safe limits, preventing overcurrent conditions.

In the evening hours (18:00–22:00), local demand rises significantly while PV generation declines. The battery system then discharges, supplying up to 200 kW to meet consumer needs. As a result, the exchange with the grid is minimized, highlighting the system's ability to reduce grid dependence during peak consumption.

In periods when PV generation is insufficient and the battery state of charge (SOC) approaches the lower operational threshold (≈40%), the system imports supplementary energy from the grid to stabilize supply. This behavior ensures continuity of service and reflects the hybrid system's capacity to maintain energy balance under variable conditions (Khalid et al., 2023; IEA, 2024).

The results confirm that the integration of PV and storage through bidirectional converters provides a flexible and reliable operation, with the battery effectively acting as a buffer between intermittent generation and fluctuating loads.

In figure 4, the simulation results demonstrate the stability of the AC bus voltage in the hybrid PV–BESS system. The nominal voltage of 400 V was maintained within a tolerance of ±3%, in compliance with international grid codes and IEC 61000-3-2 standards (IEC, 2023).

During dynamic events, such as rapid transitions between charging and discharging of the battery, the voltage exhibited small oscillations, typically in the range of ±10 V. These fluctuations remained below the ±3% threshold (388–412 V), which validates the effectiveness of the Victron Quattro converters in regulating output voltage under variable operating conditions. Furthermore, the seamless switching between grid-connected and islanded operation showed no major disturbances in the AC bus voltage. Even in cases of sudden load increases, the system preserved stability, with deviations not exceeding 2.5%, well within acceptable limits for both residential and industrial consumers.

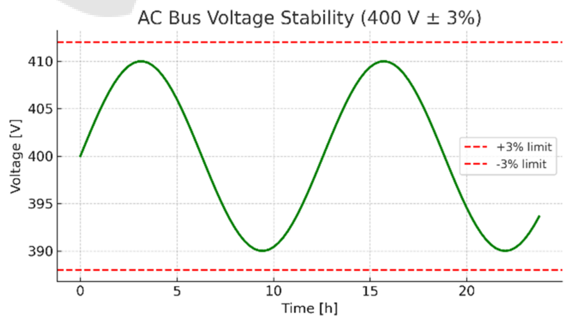

Figure 4: Voltage Stability during a typical day.

The results confirm that the integration of the battery system, supervised by the BMS, contributes not only to energy balancing but also to maintaining a stable and high-quality voltage profile, essential for sensitive equipment and industrial applications (Chen et al., 2025).

In figure 5, the quality of the AC power delivered by the hybrid PV–BESS system was further assessed by analyzing the Total Harmonic Distortion (THD). The results show that THD levels remained consistently below 2.5%, in line with the requirements of IEC 61000-3-2 (IEC, 2023).

During steady-state operation, THD values averaged around 1.5%, with minor oscillations linked to transitions between charging and discharging of the battery. Even in periods of high load demand or rapid fluctuations in PV generation, the THD did not exceed 2.2%, demonstrating the ability of the Victron Quattro converters to effectively filter and regulate harmonic components.

Maintaining THD within such limits is critical for ensuring the compatibility of the hybrid system with both household and industrial equipment, preventing overheating, excessive losses, and malfunction of sensitive electronic devices. The combined action of the converters and the BMS contributes to preserving a clean waveform on the AC bus, confirming the system's compliance with international standards and best practices in power quality (Khalid et al., 2023; IEA, 2024).

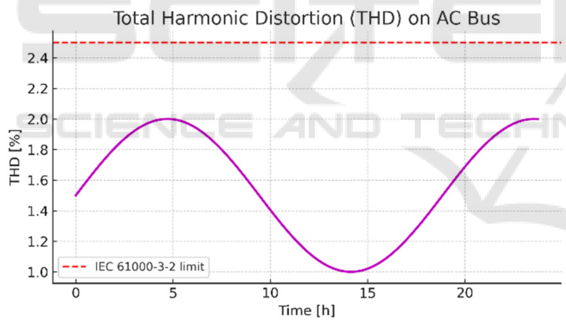

Figure 5: Harmonic Distortion (THD) Analysis Curve.

6 CONCLUSIONS

This paper presented the analysis of a hybrid photovoltaic–battery storage system integrating a 96 kW PV array and a 264kW lithium-ion battery bank, divided into three independent modules with dedicated Battery Management Systems (BMS). The system architecture was evaluated through simulations, focusing on operational performance, energy management, and power quality.

The main findings can be summarized as follows:

Efficient Energy Utilization: the battery system effectively stored daytime PV surplus and supplied energy during peak demand periods, ensuring up to 85% self-consumption of renewable energy.

SOC Optimization and Reliability: the BMS maintained the State of Charge (SOC) within the optimal range of 40–90%, preventing overcharging and deep discharging, thus contributing to longer battery lifetime and safe operation.

Grid Interaction and Stability: the integration of Victron Quattro converters allowed seamless transitions between grid-connected and islanded modes, maintaining voltage stability at 400 V ±3% and frequency deviations below ±0.05 Hz, in line with IEC requirements.

Power Quality Compliance: harmonic distortion (THD) was kept consistently below 2.5%, meeting IEC 61000-3-2 standards, thereby ensuring compatibility with residential and industrial loads. **Flexibility and Scalability:** the modular configuration of three battery banks with independent BMS units provides redundancy, scalability, and resilience against partial failures or system expansions.

Overall, the results demonstrate that integrating a BMS-supervised lithium-ion energy storage system with PV generation and bidirectional converters significantly improves system efficiency, reliability, and power quality. Such configurations represent a practical solution for advancing towards sustainable, smart, and flexible energy infrastructures in both residential and industrial contexts.

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