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Hybrid Energy Storage Systems for Microgrid Applications: Integration Architectures, Control Strategies, and Optimization Methods

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Abstract: The increasing penetration of renewable energy sources has made microgrids an important platform for local energy consumption, resilient power supply and flexible grid interaction. However, the variability of photovoltaic and wind generation, together with frequent changes in load demand and operating mode, places higher requirements on energy storage systems. A single storage technology usually cannot simultaneously provide long-duration energy support, fast transient response, long service life and acceptable economic performance. Hybrid energy storage systems (HESS), typically combining energy-type devices such as batteries or flow batteries with power-type devices such as supercapacitors or flywheels, provide a practical route for coordinating different time scales of power regulation. This review summarizes the functional complementarity of major storage technologies, compares common HESS integration architectures, and discusses hierarchical power allocation, source-storage-load scheduling, model predictive control and data-driven optimization methods for microgrid applications. Techno-economic and environmental evaluation indicators are also summarized to support engineering decision-making. Finally, representative application scenarios, current bottlenecks and future research directions are discussed. The review indicates that modular integration, adaptive control, life-cycle cost evaluation and standardized assessment frameworks will be key to the wider deployment of HESS in renewable microgrids.

1. Introduction

Microgrids are small-scale power systems that integrate distributed generation, energy storage, controllable loads and power electronic interfaces. They can operate either in grid-connected mode or in islanded mode, which makes them useful for improving renewable energy consumption, local power reliability and system resilience [1,2]. With the increasing penetration of photovoltaic and wind power, microgrid operation is increasingly affected by renewable intermittency, load uncertainty and converter-dominated dynamics [3-7].

Energy storage is one of the most important enabling technologies for stable microgrid operation.

It can absorb excess renewable power, supply energy during generation shortage, support voltage and frequency regulation, and smooth short-term power fluctuations [3,4,8,9]. However, no single energy storage technology can simultaneously provide high energy density, high power density, long cycle life, rapid response, low cost and high safety. This limitation has motivated the development of hybrid energy storage systems (HESS), in which batteries, flow batteries, supercapacitors, flywheels or other storage devices are combined according to their complementary characteristics [10-12].

Hybrid energy storage systems (HESS) address this problem by combining complementary storage devices. In a typical battery-supercapacitor HESS, the battery is responsible for low-frequency energy balancing and the supercapacitor is assigned high-frequency transient power components. This time-scale separation reduces unnecessary battery cycling and improves the dynamic response of the microgrid [13-16].

Although many studies have investigated HESS sizing, topology, control and economic evaluation, engineering application still faces several practical challenges. These include the trade-off between storage performance and cost, insufficient standardization of converter interfaces, limited robustness of control algorithms under extreme renewable fluctuations, and the lack of unified evaluation criteria covering technical, economic and environmental dimensions. To provide a concise and application-oriented summary, this review focuses on three questions: (i) which storage technologies are suitable for different microgrid tasks; (ii) how HESS can be integrated and controlled; and (iii) how its practical value can be evaluated in typical microgrid scenarios.

2. Energy Storage Technologies and Functional Complementarity

2.1 Energy-type storage devices

Energy-type storage devices are mainly used for energy shifting and long-duration power supply. Lithium-ion batteries are widely used because of their relatively high energy density, mature manufacturing chain and flexible modular design [10-11]. In microgrids, they are commonly applied for peak shaving, renewable energy shifting and backup power supply. Nevertheless, frequent high-rate charge-discharge cycles may accelerate degradation, which is one of the key motivations for combining batteries with power-type storage devices [17-18].

Flow batteries, especially vanadium redox flow batteries, separate power and energy capacity through stack and electrolyte design. This characteristic makes them attractive for long-duration microgrid storage and islanded renewable systems, although their balance-of-plant complexity and initial investment remain important engineering constraints [19-20]. Lead-carbon batteries and other low-cost electrochemical systems are also used in rural or small-scale microgrids where capital cost and maintenance simplicity are important.

2.2 Power-type storage devices

Power-type storage devices are designed for fast power exchange rather than long-term energy delivery. Supercapacitors have high power density, rapid response and excellent cycle life, making them suitable for suppressing high-frequency renewable fluctuations, stabilizing DC bus voltage and reducing battery stress [6,7,21]. Flywheels and superconducting magnetic energy storage can also provide fast transient support in specific applications, although cost, mechanical complexity or cryogenic requirements limit their broader use [22-23].

The key value of a power-type device in HESS is not to replace batteries but to protect them. By absorbing rapid power changes, the power-type branch reduces the number of high-rate battery cycles. This improves dynamic performance while delaying battery degradation. Therefore, the performance of HESS depends not only on the selected storage materials but also on sizing, converter design and power allocation strategy.

2.3 Rationale for hybridization

The basic principle of HESS is to divide microgrid power imbalance into different frequency or time-scale components. Slow and energy-intensive components are allocated to energy-type storage, while fast and power-intensive components are allocated to power-type storage. This principle has been implemented through low-pass filtering, wavelet decomposition, fuzzy control, droop-based coordination and optimization-based energy management [13,14,24,25] (Table 1).

Table 1. Comparison of representative storage technologies for microgrid HESS.

Storage type	Main strengths	Main limitations	Typical role in HESS
Lithium-ion battery	High energy density; mature technology; modular deployment	Aging under high-rate cycling; thermal management requirement	Low-frequency energy balancing, peak shaving and backup power
Flow battery	Long cycle life; independent power/energy sizing; high safety	Lower power density; higher system complexity	Long-duration stationary storage and islanded microgrid support
Lead-carbon battery	Relatively low cost; improved partial-state-of-charge tolerance	Lower energy density and shorter lifetime than advanced batteries	Cost-sensitive rural or small-scale microgrids
Supercapacitor	Very fast response; high power density; long cycle life	Low energy density; voltage varies with state of charge	High-frequency fluctuation suppression and DC bus stabilization
Flywheel	Fast response; high cycle life; low chemical pollution	Mechanical losses; safety and installation requirements	Short-duration frequency support and power-quality improvement
Hydrogen storage	Long-term and seasonal energy storage potential	Low round-trip efficiency; infrastructure complexity	Long-duration backup and multi-energy coupling

3. Integration Architectures of HESS in Microgrids

The integration architecture determines how storage units are connected to renewable sources, loads, converters and the main grid. It directly affects conversion efficiency, fault tolerance, scalability, protection design and control complexity. In engineering practice, centralized, distributed modular and AC/DC hybrid architectures are commonly discussed, and the selection of architecture should be matched with microgrid scale, renewable penetration, load sensitivity and maintenance capability.

From an engineering perspective, architecture design should not only consider the location of batteries and supercapacitors, but also the coupling form of converters, the bus structure and the information interface with the energy management system. A suitable architecture can reduce unnecessary power conversion, simplify protection coordination and provide a physical basis for hierarchical control and optimal scheduling.

3.1 Centralized architecture

A centralized HESS connects storage units to a common bus through a shared or coordinated converter system. Its structure is simple, the number of converters is limited, and operation and maintenance are relatively convenient. This architecture is suitable for small community microgrids or commercial microgrids with predictable load profiles. The main advantage is that storage sizing, SOC balancing and dispatch commands can be implemented in a unified platform. However, centralized systems have weaker fault tolerance. A converter failure or communication fault may affect the whole storage station, and system expansion is less flexible when renewable capacity or load demand increases.

3.2 Distributed modular architecture

Distributed modular HESS places storage modules at different points of the microgrid, such as the generation side, load side and point of common coupling. Each module can be sized according to local renewable output and load characteristics. This architecture improves scalability and fault tolerance because a single-module fault does not necessarily disable the whole system. It is also more suitable for industrial parks, campus microgrids and multi-area renewable microgrids. In addition, local power-type storage can suppress fast fluctuations near disturbance sources, while energy-type storage can be arranged at nodes with stronger energy-balancing requirements. The main challenge is the need for coordinated communication and distributed control, especially when modules are supplied by different manufacturers or operate under different SOC conditions.

3.3 AC/DC hybrid architecture

AC/DC hybrid microgrids are increasingly attractive because photovoltaic arrays, batteries and many electronic loads are naturally connected to DC buses, while conventional distribution networks and large loads usually operate on AC buses. A hybrid AC/DC architecture can reduce unnecessary conversion stages and improve the flexibility of renewable and storage integration [26]. In this structure, bidirectional DC/DC converters are usually used to manage the battery and supercapacitor branches, while interlinking converters coordinate the power exchange between AC and DC buses. However, it also introduces challenges in converter control, power sharing, protection coordination and stability during grid-connected/islanded switching.

Overall, architecture selection should follow a scenario-oriented logic. Centralized HESS emphasizes simplicity and unified dispatch, distributed modular HESS emphasizes scalability and resilience, and AC/DC hybrid HESS emphasizes conversion efficiency and multi-type equipment access. These architectural differences directly determine the feasible control strategy and economic performance of the microgrid (Table 2).

Table 2. Comparison of common HESS integration architectures.

Architecture	Advantages	Limitations	Suitable scenarios
Centralized HESS	Simple structure; convenient monitoring; lower communication burden	Limited scalability; weak fault tolerance; possible single-point failure	Small community or commercial microgrids

Distributed modular HESS	High flexibility; local power support; good fault tolerance	Higher coordination complexity; stronger communication requirement	Industrial parks, campuses and multi-area microgrids
AC/DC hybrid HESS	Reduced conversion stages; compatible with DC renewable sources and AC loads	Complex converter control; protection and stability challenges	High-renewable microgrids with diverse AC/DC equipment
Multi-energy HESS	Can combine electricity, heat and hydrogen storage; supports long-duration backup	High investment and planning complexity	Remote, islanded or integrated energy systems

4. Control and Optimization Strategies

A HESS can only release its complementary advantages when an appropriate control strategy is used. The control system should determine how much power each storage device should absorb or deliver, how to maintain SOC within a safe range, and how to coordinate storage operation with renewable forecasting and load demand. Therefore, HESS control is essentially a multi-time-scale decision problem that links fast converter control, medium-term SOC regulation and long-term economic scheduling.

In practical implementation, the control strategy must also consider measurement delay, converter power limits, battery aging, communication reliability and the switching between grid-connected and islanded modes. A strategy that performs well in simulation may not be robust in field operation if these constraints are ignored.

4.1 Frequency-based power allocation

Frequency-based allocation is one of the most widely used methods for battery-supercapacitor HESS. The net power imbalance of the microgrid is decomposed into low-frequency and high-frequency components. The battery follows the low-frequency part, while the supercapacitor or flywheel follows the high-frequency part. Filter-based methods are simple and effective, but their performance depends strongly on the cut-off frequency and SOC constraints; therefore, adaptive filtering, wavelet decomposition and fuzzy optimization have been proposed to improve operating robustness [15,16,24,25]. The key design problem is to avoid excessive battery cycling while preventing the power-type branch from reaching its energy limit during sustained fluctuations.

4.2 Hierarchical control

Hierarchical control usually includes primary, secondary and tertiary levels. Primary control provides fast local response, such as droop control and DC bus voltage regulation. Secondary control restores voltage and frequency deviations and coordinates different storage modules. Tertiary control optimizes power exchange with the main grid and economic dispatch. This layered structure is suitable for both grid-connected and islanded operation. In HESS, hierarchical control can also manage the state of charge of different storage branches to prevent overuse of a single device [27-28].

4.3 Source-storage-load scheduling

Microgrid operation is strongly affected by renewable generation forecasts, electricity price signals and load profiles. Source-storage-load scheduling uses these data to determine storage charge-discharge plans over different time horizons. In grid-connected mode, HESS may participate in peak shaving, valley filling, demand response and auxiliary services. In islanded mode, the priority shifts to energy adequacy, critical-load supply and power-quality maintenance. A practical scheduling strategy should balance immediate power stability with long-term SOC management and should reserve sufficient energy margin for renewable forecast errors or unexpected islanding events.

4.4 Model predictive and data-driven optimization

Model predictive control (MPC) is suitable for microgrids because it can handle constraints on power, voltage, SOC and converter capacity while considering forecasts over a rolling time horizon. MPC-based energy management has been widely studied for microgrids with batteries, supercapacitors and distributed storage units, and it is particularly useful when renewable generation and load demand are uncertain. Data-driven and machine-learning methods can further improve forecasting and parameter adaptation, but their engineering implementation still depends on data quality, communication reliability, interpretability and computational complexity [15,16,29].

A more realistic trend is to combine model-based control with data-driven correction. For example, physical models can define safety constraints and converter limits, while learning algorithms update forecasts or aging parameters using operating data. Such hybrid control may provide better robustness than purely rule-based or purely data-driven methods (Table 3).

Table 3. Summary of typical control and optimization methods for HESS.

Method	Core idea	Advantages	Limitations
Rule-based control	Assign storage power according to predefined thresholds	Simple and easy to implement	Poor adaptability under complex conditions
Filter-based allocation	Separate low- and high-frequency power components	Effective battery protection; low computational burden	Sensitive to filter parameter selection
Droop and hierarchical control	Coordinate local and system-level voltage/frequency regulation	Suitable for grid-connected and islanded operation	Requires careful parameter tuning
Model predictive control	Optimize future control actions under constraints	Handles multiple objectives and constraints	Depends on model accuracy and computational resources
Machine learning control	Use operating data for prediction or decision-making	Adaptive and suitable for complex nonlinear systems	Requires data quality, interpretability and safety validation
Multi-objective optimization	Optimize cost, degradation, power quality and emissions simultaneously	Supports planning and dispatch decisions	Results depend on weights and uncertainty modeling

5. Techno-economic and Environmental Evaluation

A comprehensive evaluation of HESS should not be limited to a single indicator such as energy capacity or initial cost. In microgrid applications, the value of HESS is reflected in technical performance, life-cycle economy and environmental benefits. These dimensions are interrelated. For example, a larger supercapacitor branch may increase initial investment but reduce battery degradation and replacement cost, while a long-duration storage branch may improve renewable energy consumption but may not be economical if it is rarely used.

Technical evaluation should be linked to the operating scenario. In islanded microgrids, frequency deviation, loss of load probability and energy adequacy are usually more important. In industrial park microgrids, power quality, demand-charge reduction and peak-valley arbitrage may dominate. In AC/DC hybrid microgrids, converter efficiency, bus-voltage stability and protection coordination should be considered together.

Technical indicators include voltage deviation, frequency deviation, renewable power curtailment, loss of load probability, converter efficiency, storage response time and battery degradation. Economic indicators usually include initial investment, replacement cost, operation and maintenance cost, electricity cost reduction, revenue from ancillary services and payback period [30,31]. Environmental indicators may include renewable energy utilization, carbon-emission reduction, material use, recycling potential and life-cycle environmental impacts [12,17,32]. Table 4 summarizes the key evaluation indicators discussed above across technical, economic, reliability, battery health and environmental dimensions.

For life-cycle economy, the initial cost of HESS should be evaluated together with degradation reduction and replacement delay. A storage configuration with a higher initial cost may still be attractive if it decreases battery cycling, extends service life and improves renewable self-consumption. Therefore, the economic comparison between single storage and HESS should be based on the whole project period rather than equipment cost alone.

Environmental assessment should also avoid overly simplified claims. Operational carbon reduction is important, but battery production, material consumption, transportation, recycling and second-life use may change the net environmental benefit. A credible evaluation framework should therefore combine operational performance with life-cycle assessment and end-of-life management (Table 4).

Table 4. Suggested evaluation indicators for microgrid HESS.

Dimension	Representative indicators	Engineering meaning
Technical performance	Voltage/frequency deviation; response time; power smoothing ratio; renewable curtailment rate	Reflects stability, dynamic response and renewable integration capability
Reliability and resilience	Loss of load probability; critical-load supply duration; islanded operation time	Measures the ability to maintain power supply under disturbances
Economic performance	Capital cost; replacement cost; operation and maintenance cost; payback period	Determines project feasibility over the full life cycle
Battery health	Depth of discharge; current peak; cycle aging; temperature rise	Evaluates degradation mitigation from HESS coordination
Environmental value	Avoided emissions; recycling potential; waste battery reduction	Supports low-carbon and sustainable microgrid design

6. Application Scenarios, Challenges and Concluding Remarks

6.1 Application scenarios and configuration logic

Application scenarios can be broadly divided into islanded or remote microgrids, industrial park microgrids and special-purpose microgrids. Islanded systems require reliable energy supply and fast disturbance suppression, industrial parks emphasize economic dispatch and power quality, while special-purpose systems such as shipboard microgrids need strong transient buffering for pulsed or highly variable loads [6,13,19,20,23].

The configuration should be determined by renewable resource characteristics, load profile, reliability requirement, electricity price and maintenance capability. In general, batteries or flow batteries provide energy adequacy, whereas supercapacitors or flywheels provide fast power support. Hydrogen storage, thermal storage and second-life batteries may be considered when long-duration backup, integrated energy supply or cost reduction is required [33,34] (Table 5).

Table 5. Typical application scenarios and compact HESS configuration logic.

Scenario	Main requirement	Typical HESS configuration	Key concern
Island/remote microgrid	Energy adequacy and renewable smoothing	Flow battery or battery + supercapacitor	Reliability, SOC reserve and maintenance
Industrial park microgrid	Peak shaving, power quality and economic dispatch	Lithium-ion battery + supercapacitor	Tariff structure, load peaks and battery degradation
Special-purpose microgrid	Fast buffering for pulsed or variable loads	Battery + supercapacitor/flywheel	Transient response and safety margin

6.2 Challenges and future directions

Current HESS development is still limited by the performance-cost trade-off of storage devices, insufficient standardization of converter interfaces and communication protocols, and incomplete life-cycle evaluation. Advanced storage devices and converters improve reliability but increase initial investment, whereas low-cost devices may suffer from limited cycle life, weaker dynamic response or safety concerns [10,17,30,31].

Future work should focus on modular hardware integration, degradation-aware sizing, adaptive control under uncertainty, and evaluation frameworks that combine technical, economic and environmental indicators. More field data, hardware-in-the-loop testing and long-term demonstration projects are needed to narrow the gap between simulation-based optimization and practical microgrid operation [15,24,35].

6.3 Concluding remarks

In summary, HESS provides an effective way to improve the flexibility, reliability and renewable energy utilization of microgrids by coordinating energy-type and power-type storage devices. Its practical value depends on appropriate architecture, power allocation, sizing and life-cycle assessment. Future research should shift from simply increasing storage capacity to scenario-oriented design, standardized integration and robust intelligent control.

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