A REVIEW OF COORDINATED ENERGY DISPATCH STRATEGY FOR HYBRID BATTERY- ULTRACAPACITOR STORAGE MODULES IN AUTONOMOUS MICROGRID ENVIRONMENTS

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Abstract - *The increasing integration of renewable energy resources in microgrid systems has created significant challenges in maintaining power stability, reliability, and efficient energy management due to the intermittent and unpredictable nature of renewable generation. Energy storage systems play a critical role in mitigating these issues by balancing supply and demand and improving the dynamic performance of microgrids. Among various storage technologies, hybrid energy storage systems (HESS) that combine batteries and ultracapacitors have gained considerable attention because of their complementary characteristics. Batteries provide high energy density suitable for long-duration energy support, whereas ultracapacitors offer high power density and rapid charge–discharge capability, making them effective for handling short-term power fluctuations. In autonomous microgrid environments, coordinated energy dispatch strategies are essential to optimally allocate power between these storage components, enhance system efficiency, reduce battery stress, and extend the operational lifetime of storage devices. This review paper presents a comprehensive overview of coordinated energy dispatch strategies for hybrid battery–ultracapacitor storage modules in autonomous microgrids. Various energy management approaches, including rule-based control, filter-based power allocation, optimization-based dispatch methods, and emerging data-driven techniques, are critically analyzed and compared. Furthermore, the paper discusses the architectural configurations of hybrid storage systems, their operational roles in microgrid stability, and the major technical challenges associated with their deployment. Finally, key research gaps and potential future directions are identified to support the development of more intelligent and efficient coordinated dispatch strategies for next-generation autonomous microgrid systems.*

Key Words: Autonomous Microgrid; Hybrid Energy Storage System; Battery–Ultracapacitor; Energy Dispatch Strategy; Energy Management System; Renewable Energy Integration; Power System Stability.

1. INTRODUCTION

1.1 Background

The rapid growth of renewable energy technologies has significantly transformed modern power systems. Distributed renewable energy sources such as solar photovoltaic (PV) and wind power are increasingly integrated into microgrid infrastructures to reduce greenhouse gas emissions, improve energy efficiency, and support sustainable electricity generation. Autonomous microgrids, particularly those operating in islanded or remote environments, rely heavily on renewable resources to supply electricity to local loads. However, the inherent intermittency and variability of renewable energy generation create several operational challenges, including power imbalance, voltage fluctuations, and frequency instability. These issues become more critical in autonomous microgrids where the absence of a main grid limits the ability to absorb fluctuations in generation or demand (Lasseter, 2002; Hatziargyriou et al., 2007).

Energy storage systems (ESS) have emerged as an effective solution to address these challenges by providing flexibility in energy management. By storing excess energy during periods of high generation and supplying power during deficits, ESS enables stable operation of microgrids with high renewable penetration. Furthermore, energy storage technologies contribute to power quality improvement, peak load shaving, and frequency regulation within autonomous microgrid environments (Divya and Østergaard, 2009). As renewable penetration continues to increase, the need for advanced energy storage integration and management strategies has become a key research focus in modern power system engineering.

1.1.1 Role of Energy Storage Systems in Microgrids

Energy storage systems play a fundamental role in ensuring reliable and efficient microgrid operation. In renewable-based microgrids, generation patterns often do not align with load demand due to variations in weather conditions and daily consumption cycles. Energy storage systems act as buffers that absorb surplus energy and release it when generation is insufficient, thereby maintaining the balance between supply and demand. In addition to energy balancing, ESS technologies provide ancillary services such as voltage support, frequency regulation, and mitigation of transient disturbances (Akhil et al., 2013).

Another important function of energy storage systems is improving system resilience. During sudden disturbances or load changes, storage devices can rapidly respond to stabilize the system and prevent power outages. In autonomous microgrids, where grid support is unavailable, the presence of reliable storage infrastructure becomes even more critical for maintaining continuous electricity supply and operational stability.

1.2 Hybrid Battery–Ultracapacitor Energy Storage Systems (HESS)

Hybrid energy storage systems combine two or more energy storage technologies to exploit their complementary characteristics and overcome the limitations of individual storage devices. Among the various hybrid configurations, the combination of batteries and ultracapacitors has attracted significant attention in microgrid applications. Batteries, such as lithium-ion or lead-acid types, offer high energy density and are capable of storing large amounts of electrical energy over extended durations. However, they typically suffer from limited power density and reduced lifetime when subjected to frequent high-power cycling (Chen et al., 2009).

Ultracapacitors, also known as supercapacitors, possess extremely high power density and can charge or discharge rapidly with minimal degradation. These characteristics make them suitable for handling short-term power fluctuations and transient load variations. By integrating batteries and ultracapacitors into a unified hybrid storage system, it becomes possible to allocate long-duration energy supply to the battery while assigning rapid power variations to the ultracapacitor. This coordinated operation significantly improves system efficiency, reduces battery stress, and enhances overall microgrid reliability (Zhang et al., 2018).

1.2.1 Power Complementarity in Hybrid Storage

The effectiveness of hybrid battery–ultracapacitor systems is primarily derived from the complementary operational characteristics of the two technologies. Batteries are more suitable for low-frequency and long-duration energy demands, whereas ultracapacitors respond effectively to high-frequency power variations. When renewable generation fluctuates rapidly due to environmental conditions, ultracapacitors can absorb or supply power almost instantaneously, thereby preventing excessive cycling of the battery.

This complementary behavior enables hybrid energy storage systems to significantly extend battery lifespan while maintaining high power quality in microgrid operations. Additionally, hybrid systems improve overall energy efficiency and reduce operational costs associated with battery replacement and maintenance. Consequently, hybrid battery–ultracapacitor energy storage systems have become a promising solution for managing dynamic power flows in renewable-dominated microgrids.

1.3 Importance of Coordinated Energy Dispatch in Autonomous Microgrids

In autonomous microgrids, coordinated energy dispatch strategies play a crucial role in managing the interaction between distributed generation sources, loads, and hybrid energy storage systems. Coordinated dispatch refers to the systematic allocation of power among different components of the microgrid to achieve optimal performance under varying operating conditions. Without proper coordination, energy storage devices may operate inefficiently, leading to unnecessary energy losses, accelerated battery degradation, and unstable system performance.

Effective energy dispatch strategies ensure that power is distributed appropriately among renewable generators, storage devices, and loads. For example, during sudden increases in load demand or rapid decreases in renewable generation, ultracapacitors can immediately provide high-power support while batteries supply sustained energy over longer durations. By controlling the power flow between these storage components, coordinated dispatch strategies maintain power balance and prevent system instability (Guerrero et al., 2011).

Furthermore, advanced energy management algorithms can optimize operational costs by reducing reliance on expensive backup generators and minimizing energy losses. Coordinated dispatch also enhances system reliability by enabling real-time control of distributed energy resources and ensuring continuous power supply in isolated microgrid environments.

1.4 Objectives and Contributions of This Review

The rapid advancement of hybrid energy storage technologies and coordinated energy management strategies has generated a substantial body of research in recent years. However, existing studies are often fragmented across different control approaches, optimization techniques, and application scenarios. A comprehensive synthesis of these research efforts is necessary to provide a clear understanding of the current state of the art and to identify potential research opportunities in the field.

This review paper aims to present a systematic and critical survey of coordinated energy dispatch strategies for hybrid battery–ultracapacitor energy storage systems in autonomous microgrid environments. The study provides a detailed classification of existing energy management approaches, including rule-based methods, filter-based power allocation strategies, optimization-based dispatch algorithms, and emerging data-driven techniques. In addition, a comparative analysis of these methods is presented to highlight their advantages, limitations, and practical applicability in microgrid systems.

2. ARCHITECTURE OF AUTONOMOUS MICROGRIDS WITH HYBRID ENERGY STORAGE

2.1 Structure of Autonomous Microgrid Systems

Autonomous microgrids are localized power systems capable of operating independently from the main utility grid while supplying electricity to nearby loads. These systems typically integrate multiple distributed energy resources such as renewable generation units, distributed generators, energy storage systems, and controllable loads. Renewable energy sources, particularly solar photovoltaic (PV) panels and wind turbines, form the primary generation units in many modern microgrids because of their environmental benefits and decreasing installation costs. In addition to renewable sources, backup generators such as diesel generators or microturbines are often included to ensure power supply during periods of insufficient renewable generation (Lasseter, 2002).

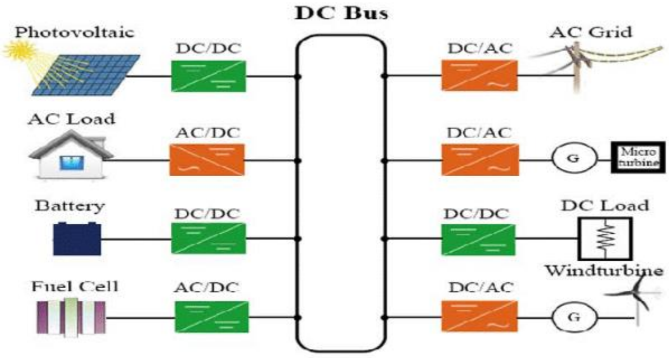

Figure-1: Architecture of Autonomous Hybrid Microgrid

2.1.1 Role of Distributed Energy Resources in Microgrid Architecture

Distributed energy resources (DERs) are essential elements in autonomous microgrid architecture because they provide localized electricity generation and enhance system flexibility. Renewable DERs such as PV arrays and wind turbines supply clean energy but are inherently intermittent due to environmental variability. To address this limitation, microgrids incorporate energy storage systems and controllable generators that balance the difference between energy supply and load demand.

Power electronic converters play a critical role in interfacing DERs with the microgrid network by regulating voltage, frequency, and power flow. Advanced control strategies allow these components to operate in a coordinated manner to maintain system stability under varying operating conditions. The integration of DERs, storage systems, and intelligent controllers creates a flexible energy infrastructure capable of supporting reliable electricity supply in remote or islanded regions.

2.2 Hybrid Battery–Ultracapacitor Storage Configuration

Hybrid battery–ultracapacitor energy storage systems combine the advantages of two complementary storage technologies to enhance microgrid performance. Batteries provide high energy density and are suitable for supplying sustained power over longer periods. In contrast, ultracapacitors possess very high power density and can respond rapidly to sudden power changes. Integrating these devices into a hybrid system enables efficient management of both long-term energy demands and short-term power fluctuations. To achieve effective coordination between these components, several hybrid storage configurations have been developed based on the arrangement of power converters and electrical connections (Chen et al., 2009).

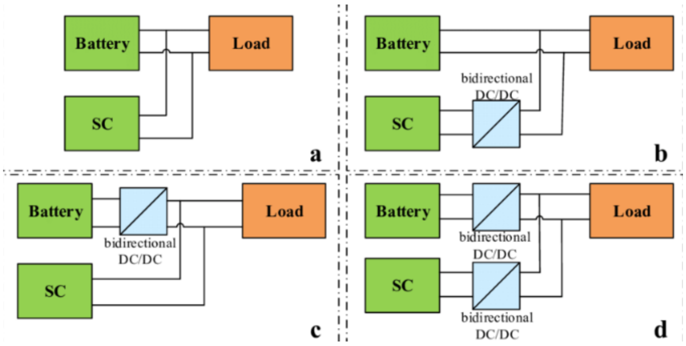

Figure-2: Hybrid Battery–Ultracapacitor Energy Storage Topologies

2.2.1 Passive Topology

In passive hybrid energy storage topology, the battery and ultracapacitor are directly connected in parallel without dedicated power converters for each storage component. The current distribution between the two devices depends primarily on their internal impedance characteristics. Because ultracapacitors have lower internal resistance, they naturally respond to rapid power variations, while batteries provide slower energy support.

The passive configuration offers advantages such as simple structure, low cost, and minimal control complexity. However, this topology lacks precise control over power sharing between storage devices. As a result, system efficiency may decrease and battery stress may increase under certain operating conditions. Consequently, passive hybrid storage is generally used in applications where cost and simplicity are prioritized over performance optimization.

2.2.2 Semi-Active Topology

Semi-active hybrid storage topology introduces a power electronic converter for either the battery or the ultracapacitor, allowing partial control over power flow. In many implementations, the ultracapacitor is connected through a bidirectional DC–DC converter, enabling it to regulate rapid power fluctuations while the battery remains directly connected to the DC bus.

This configuration provides improved flexibility compared to passive topology because the converter can regulate the ultracapacitor's charge and discharge behavior. As a result, the battery is protected from high-frequency power cycling, which helps extend its operational lifetime. However, semi-active topology still offers limited control compared to fully active systems, since only one storage component is actively regulated (Zhang et al., 2018).

2.2.3 Fully Active Topology

Fully active hybrid storage topology employs separate bidirectional converters for both the battery and the ultracapacitor. This configuration allows independent control of each storage device and enables precise power allocation according to system requirements. Through coordinated control algorithms, high-frequency power components can be assigned to the ultracapacitor while low-frequency energy demands are handled by the battery.

Although fully active topology provides the highest level of flexibility and operational efficiency, it also introduces higher system complexity, increased cost, and additional control requirements. Nevertheless, this configuration is widely adopted in advanced microgrid systems because it enables optimal energy management and enhances the reliability of hybrid storage integration.

2.3 Power Flow Characteristics in Hybrid Energy Storage Systems

The power flow characteristics of hybrid battery–ultracapacitor energy storage systems are primarily determined by the complementary dynamic properties of the two storage technologies. Batteries are designed to store large amounts of energy and therefore respond effectively to low-frequency power variations associated with gradual changes in load demand or renewable generation. However, frequent rapid charging and discharging cycles can accelerate battery degradation and reduce its operational lifetime.

Ultracapacitors, on the other hand, are capable of delivering high power almost instantaneously due to their electrostatic energy storage mechanism. This feature makes them particularly suitable for handling high-frequency power fluctuations, transient disturbances, and sudden load changes within microgrids. By distributing power components according to their frequency characteristics, hybrid energy storage systems ensure efficient energy utilization while minimizing stress on battery units (Divya and Østergaard, 2009).

2.4 Operational Challenges in Autonomous Microgrids

Despite their advantages, autonomous microgrids face several operational challenges that complicate system planning, control, and energy management. These challenges arise primarily from the stochastic nature of renewable generation, uncertainties in load demand, and the technical limitations of energy storage technologies. Addressing these issues requires advanced control strategies and intelligent energy management frameworks.

One of the major challenges is renewable energy intermittency. Solar and wind power outputs vary continuously due to weather conditions, leading to unpredictable fluctuations in power generation. These variations can cause voltage deviations, frequency instability, and power imbalance within microgrids. Another challenge is load uncertainty, where electricity demand changes dynamically depending on consumer behavior and environmental conditions. Such variations increase the difficulty of maintaining real-time energy balance (Guerrero et al., 2011).

3. LITERATURE REVIEW OF COORDINATED ENERGY DISPATCH STRATEGIES

The increasing adoption of hybrid battery–ultracapacitor energy storage systems (HESS) in autonomous microgrids has led to extensive research on coordinated energy dispatch strategies. These strategies aim to optimally distribute power among storage components and distributed energy resources to ensure system stability, efficient energy utilization, and extended battery lifespan. Because batteries and ultracapacitors exhibit different dynamic characteristics, coordinated dispatch methods are essential to determine how power should be shared between them during various operating conditions. Over the past decade, several approaches have been proposed in the literature, ranging from simple rule-based control methods to advanced optimization and artificial intelligence-based algorithms. These approaches differ in complexity, computational requirements, and effectiveness in handling uncertainties associated with renewable generation and load demand (Guerrero et al., 2011).

3.1 Overview of Energy Management Strategies for HESS

Energy Management Systems (EMS) play a central role in controlling hybrid energy storage systems within autonomous microgrids. An EMS is responsible for monitoring system conditions, forecasting generation and load demand, and coordinating the operation of distributed energy resources and storage devices. In hybrid battery–ultracapacitor systems, the EMS determines how power is allocated between the battery and ultracapacitor based on system requirements, device characteristics, and operational constraints. Proper energy management ensures that high-frequency power fluctuations are handled by ultracapacitors while batteries supply long-duration energy support.

Effective EMS design also considers factors such as state-of-charge (SOC), system efficiency, battery degradation, and operational costs. Advanced EMS frameworks integrate real-time monitoring and predictive control techniques to improve dispatch accuracy and system reliability. By optimizing the interaction between storage components and renewable generation units, EMS-based dispatch strategies significantly enhance the operational performance of microgrids with hybrid energy storage (Akhil et al., 2013).

3.1.1 Objectives of Coordinated Energy Dispatch

The primary objective of coordinated energy dispatch is to ensure optimal power sharing among different energy storage components while maintaining stable microgrid operation. In hybrid storage systems, dispatch strategies must balance multiple objectives, including minimizing energy losses, reducing battery degradation, and improving system reliability. Coordinated dispatch algorithms typically analyze load demand, renewable generation output, and storage device conditions to determine the appropriate power allocation in real time.

Another important goal is to enhance the lifetime of battery systems by preventing excessive current peaks and deep discharge cycles. By assigning short-duration power fluctuations to ultracapacitors and maintaining moderate operating conditions for batteries, coordinated dispatch strategies can significantly improve the durability and economic viability of hybrid energy storage systems.

3.2 Rule-Based and Heuristic Dispatch Strategies

Rule-based and heuristic dispatch strategies are among the earliest approaches used for managing hybrid energy storage systems in microgrids. These methods rely on predefined control rules or decision logic that determine how power is distributed between batteries and ultracapacitors. One common technique is threshold-based control, where system parameters such as power demand or storage capacity are compared with predefined thresholds to trigger specific control actions. When the load demand exceeds a certain threshold, ultracapacitors may provide immediate power support, while batteries handle sustained energy delivery.

Another widely used method is state-of-charge (SOC) based control. In this approach, dispatch decisions are made according to the SOC levels of the battery and ultracapacitor. For instance, when the battery SOC is high, it may supply a greater share of the load demand, whereas the ultracapacitor handles transient fluctuations when its charge level is sufficient. Fuzzy logic-based control has also been applied to hybrid storage systems, where expert knowledge and linguistic rules are used to manage power distribution under uncertain conditions. Fuzzy controllers can handle nonlinear system behavior effectively and provide smoother control responses compared with conventional rule-based methods (Li et al., 2015).

3.3 Filter-Based Power Splitting Methods

Filter-based power splitting methods are widely used for coordinated energy management in hybrid battery–ultracapacitor systems due to their simplicity and effectiveness. These methods rely on signal processing techniques to separate the total power demand into low-frequency and high-frequency components. The low-frequency component, which represents gradual changes in power demand, is typically assigned to the battery because of its high energy capacity. In contrast, the high-frequency component representing rapid fluctuations is handled by the ultracapacitor due to its high power density and fast response capability.

High-pass and low-pass filters are commonly used to implement this power separation mechanism. A low-pass filter extracts the slow-changing power component that is delivered by the battery, while the remaining high-frequency component is directed to the ultracapacitor. This approach effectively reduces battery stress by preventing it from responding to rapid power fluctuations. Filter-based dispatch methods are computationally efficient and can be easily implemented in real-time control systems (Zhang et al., 2018).

3.4 Optimization-Based Dispatch Methods

Optimization-based dispatch strategies have been extensively studied to overcome the limitations of heuristic and filter-based approaches. These methods formulate the energy dispatch problem as an optimization task in which an objective function—such as minimizing operational cost, reducing energy losses, or extending battery life—is optimized subject to system constraints. Linear programming and nonlinear programming techniques are often used to determine optimal power allocation among storage devices and distributed generators.

Metaheuristic algorithms such as particle swarm optimization (PSO) and genetic algorithms (GA) have also been applied to energy management problems in hybrid storage systems. These algorithms are capable of exploring large search spaces and identifying near-optimal solutions for complex nonlinear systems. Another advanced method is model predictive control (MPC), which uses predictive models and real-time system data to optimize dispatch decisions over a future prediction horizon. MPC-based approaches are particularly effective in microgrid applications because they can handle system constraints and adapt to changing operating conditions (Camacho and Bordons, 2013).

Although optimization-based methods provide superior performance and flexibility, they often require significant computational resources and accurate system models. Implementing these algorithms in real-time microgrid control systems may therefore require advanced hardware and efficient computational frameworks.

3.5 Data-Driven and Artificial Intelligence-Based Dispatch Methods

Recent advancements in artificial intelligence and data analytics have led to the development of data-driven dispatch strategies for hybrid energy storage systems. These approaches leverage historical data, machine learning models, and adaptive control algorithms to improve energy management in microgrids. Unlike traditional model-based methods, data-driven approaches can learn system behavior directly from operational data, making them suitable for complex and nonlinear systems where accurate mathematical models are difficult to obtain (Zhao et al., 2020).

Machine learning techniques such as neural networks and support vector machines have been applied to forecast renewable generation and load demand, enabling more accurate dispatch decisions. Reinforcement learning algorithms have also gained attention for their ability to learn optimal control policies through interaction with the system environment. By continuously updating control strategies based on system feedback, reinforcement learning methods can improve dispatch performance over time.

4. COORDINATED ENERGY DISPATCH FRAMEWORK FOR HYBRID ENERGY STORAGE

4.1 Multi-Timescale Energy Dispatch

In autonomous microgrids, coordinated energy dispatch is typically implemented across multiple time horizons to effectively manage generation variability and load demand. Multi-timescale dispatch frameworks divide the energy management process into different operational layers, including day-ahead, hour-ahead, and real-time scheduling. Each timescale addresses different operational objectives and levels of uncertainty within the microgrid system. Day-ahead dispatch focuses on planning the operation of distributed generation units and energy storage resources based on forecasted renewable generation and predicted load demand. This stage helps determine the expected power contribution from batteries, ultracapacitors, and backup generators while minimizing operational costs and ensuring adequate energy reserves (Morais et al., 2010).

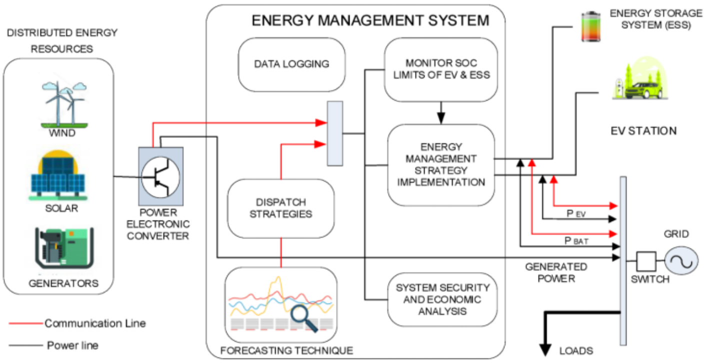

FIgure-3: Multi-Timescale Energy Management in Microgrids

Hour-ahead dispatch refines the day-ahead schedule by incorporating updated forecasts of renewable generation and load demand. Since renewable resources such as solar and wind are highly variable, hour-ahead optimization helps reduce forecast errors and improves system reliability. Real-time dispatch, on the other hand, addresses immediate fluctuations and disturbances within the microgrid. This stage involves rapid adjustments in power allocation between storage components and generation units to maintain voltage stability, frequency regulation, and power balance. Multi-timescale dispatch frameworks therefore enable microgrids to operate efficiently by combining long-term planning with real-time adaptive control strategies.

4.1.1 Importance of Hierarchical Dispatch Control

Hierarchical control structures are commonly used to implement multi-timescale energy dispatch in microgrids. In this framework, higher control layers handle long-term planning and economic optimization, while lower control layers manage real-time system dynamics. The hierarchical approach improves operational flexibility and enables coordinated control of distributed energy resources, storage devices, and loads.

At the upper level, the energy management system determines optimal schedules for storage devices and distributed generators based on forecast data. At the lower level, fast control loops regulate voltage, frequency, and power flow in real time. This layered architecture enhances system stability and allows microgrids to respond quickly to disturbances or sudden changes in renewable generation output (Olivares et al., 2014).

4.2 Power Allocation Between Battery and Ultracapacitor

Power allocation between battery and ultracapacitor units is a critical component of coordinated energy dispatch in hybrid energy storage systems. Because batteries are designed for high energy storage capacity but limited high-power cycling capability, excessive rapid charge–discharge cycles can accelerate battery degradation and reduce system reliability. Ultracapacitors, in contrast, are capable of delivering high power quickly and can withstand frequent cycling without significant degradation.

To maximize system efficiency and prolong battery lifetime, coordinated dispatch strategies allocate low-frequency energy variations to batteries and assign high-frequency power fluctuations to ultracapacitors. This approach ensures that the battery operates within moderate current ranges while ultracapacitors handle sudden power spikes caused by renewable intermittency or rapid load changes. Such coordinated power allocation reduces thermal stress on batteries and improves the overall durability of the hybrid energy storage system (Zhang et al., 2018).

4.2.1 Lifecycle Optimization of Hybrid Storage

Lifecycle optimization is a key objective in designing power allocation strategies for hybrid storage systems. Since battery replacement represents a significant portion of microgrid operating costs, reducing battery degradation is essential for improving economic performance. Advanced dispatch algorithms monitor parameters such as battery state-of-charge, state-of-health, and charge–discharge rates to determine appropriate power sharing between storage components.

By continuously adjusting the power contribution of ultracapacitors during transient conditions, coordinated dispatch frameworks reduce the depth of discharge and cycling frequency experienced by batteries. This approach significantly extends battery lifespan while maintaining stable power delivery in the microgrid. As a result, hybrid battery–ultracapacitor systems can provide reliable energy support while minimizing long-term maintenance and replacement costs.

4.3 Integration with Renewable Energy Sources

The integration of renewable energy sources such as photovoltaic (PV) systems and wind turbines introduces additional complexity into microgrid energy management due to the stochastic nature of these resources. Solar power output varies with solar irradiance and weather conditions, while wind generation depends on wind speed fluctuations. These variations can lead to sudden power imbalances within the microgrid, making coordinated dispatch strategies essential for maintaining stable operation.

Hybrid battery–ultracapacitor storage systems play a crucial role in mitigating renewable energy fluctuations. During periods of excess renewable generation, the battery can store surplus energy for later use, while ultracapacitors absorb rapid transient variations. Conversely, when renewable generation decreases or load demand increases suddenly, the hybrid storage system can supply the required power to maintain system stability. Coordinated dispatch frameworks therefore ensure that renewable energy sources are utilized efficiently while maintaining reliable power supply to microgrid loads (Lund et al., 2015).

4.3.1 Renewable Forecasting and Dispatch Coordination

Accurate forecasting of renewable generation is essential for effective energy dispatch in microgrids. Forecasting models use meteorological data and historical generation patterns to predict future solar and wind power output. These predictions enable the energy management system to plan energy storage utilization and adjust dispatch schedules accordingly.

By combining forecasting techniques with coordinated dispatch algorithms, microgrids can minimize energy curtailment, reduce reliance on backup generators, and improve renewable energy utilization. The integration of forecasting with hybrid storage control enhances the overall efficiency and sustainability of autonomous microgrid systems.

4.4 Real-Time Energy Management and Control

Real-time energy management is essential for maintaining stable operation in islanded microgrids where external grid support is unavailable. Real-time control systems continuously monitor system parameters such as voltage, frequency, power flow, and storage state-of-charge. Based on these measurements, control algorithms dynamically adjust the operation of distributed energy resources and storage devices to maintain power balance and system stability.

Advanced real-time scheduling algorithms are designed to respond rapidly to disturbances and sudden load changes. These algorithms determine optimal power allocation among batteries, ultracapacitors, and generation units while considering operational constraints such as storage capacity limits and converter ratings. Real-time control also ensures effective coordination between different components of the microgrid, allowing the system to maintain stable operation even under highly dynamic conditions (Guerrero et al., 2013).

4.4.1 Control Algorithms for Islanded Microgrid Operation

Various control algorithms have been developed for real-time energy management in islanded microgrids. These include droop control, predictive control strategies, and adaptive control methods. Droop control allows distributed generators and storage devices to share load changes proportionally without requiring centralized communication. Predictive control algorithms use system models to anticipate future disturbances and adjust control actions accordingly.

Adaptive control techniques further enhance microgrid performance by adjusting system parameters in response to changing operating conditions. When combined with hybrid energy storage systems, these control strategies enable rapid response to renewable fluctuations and load variations. As a result, coordinated real-time energy management ensures reliable and efficient operation of autonomous microgrids with high renewable energy penetration.

5. APPLICATIONS OF HYBRID ENERGY STORAGE IN AUTONOMOUS MICROGRIDS

Hybrid energy storage systems (HESS), particularly those combining batteries and ultracapacitors, have become an important component in modern autonomous microgrids. These systems enhance operational stability, improve power quality, and ensure reliable energy supply by addressing the limitations of renewable energy sources. Due to their complementary characteristics, hybrid storage systems are capable of handling both long-duration energy demands and short-term power fluctuations. As renewable penetration increases in microgrids, the role of HESS becomes increasingly significant in maintaining efficient and stable system operation (Luo et al., 2015).

5.1 Power Fluctuation Smoothing

One of the primary applications of hybrid energy storage systems in autonomous microgrids is smoothing power fluctuations caused by intermittent renewable energy sources. Renewable generation technologies such as solar photovoltaic and wind turbines produce variable output due to changing environmental conditions, including solar irradiance variations and wind speed fluctuations. These variations can lead to rapid changes in power output, which may cause instability in microgrid operation if not properly managed.

Hybrid battery–ultracapacitor storage systems effectively mitigate these fluctuations by distributing power variations according to the dynamic capabilities of each storage device. Ultracapacitors respond quickly to sudden changes in power output, absorbing or supplying high-frequency power components, while batteries manage slower variations in energy demand over longer durations. This coordinated operation ensures smoother power output from renewable energy systems and reduces stress on other microgrid components (Zhao et al., 2015).

5.1.1 Dynamic Response of Hybrid Storage Systems

The effectiveness of hybrid energy storage in fluctuation smoothing is largely attributed to its rapid dynamic response capability. Ultracapacitors can charge and discharge within milliseconds, allowing them to compensate for sudden variations in renewable generation or load demand. Batteries, although slower in response compared to ultracapacitors, provide sustained energy support when longer-duration power deficits occur.

By combining these technologies within a coordinated dispatch framework, hybrid storage systems maintain a stable power profile within the microgrid. This dynamic response capability is particularly valuable in microgrids with high renewable penetration, where rapid power fluctuations occur frequently.

5.2 Frequency and Voltage Regulation

Maintaining stable frequency and voltage levels is essential for reliable operation of autonomous microgrids. In islanded operation, microgrids cannot rely on the main grid for frequency and voltage support, making internal control mechanisms critical for system stability. Hybrid energy storage systems contribute significantly to frequency and voltage regulation by rapidly adjusting power output in response to system disturbances.

When a sudden imbalance occurs between generation and load demand, ultracapacitors can provide immediate power support to stabilize system frequency. Meanwhile, batteries supply sustained energy to maintain the balance over longer time periods. Coordinated dispatch strategies ensure that these storage components operate together to maintain stable voltage and frequency profiles throughout the microgrid (Guerrero et al., 2013).

5.2.1 Role of Storage in Ancillary Services

In addition to primary frequency regulation, hybrid energy storage systems can provide various ancillary services within microgrids. These services include voltage support, spinning reserve, and load-following capabilities. By rapidly adjusting their power output, storage devices help compensate for generation or load disturbances and maintain stable operating conditions.

The ability of HESS to deliver these ancillary services improves the resilience and operational flexibility of microgrids. As a result, hybrid storage systems are increasingly integrated into advanced microgrid control frameworks designed to enhance system stability and reliability.

5.3 Power Quality Improvement

Power quality is a critical concern in microgrid systems, particularly those with a high proportion of power electronic converters and distributed renewable resources. Disturbances such as voltage sags, harmonic distortion, and transient power fluctuations can negatively impact sensitive electrical equipment and reduce overall system performance. Hybrid energy storage systems play an important role in mitigating these issues by stabilizing voltage levels and compensating for transient disturbances.

Ultracapacitors are especially effective in responding to short-duration disturbances due to their high power density and rapid response time. When sudden voltage drops or spikes occur, ultracapacitors can quickly inject or absorb power to maintain stable voltage levels. Batteries complement this function by providing longer-term energy support when sustained disturbances occur (Divya and Østergaard, 2009).

5.3.1 Harmonic Mitigation and Transient Compensation

Hybrid energy storage systems also contribute to harmonic mitigation and transient compensation within microgrids. Power electronic converters associated with renewable energy sources can introduce harmonic distortion into the electrical network. By integrating advanced control algorithms with hybrid storage systems, it is possible to regulate power flow and reduce harmonic effects.

Furthermore, transient disturbances caused by sudden load switching or faults can be effectively compensated using the fast response capability of ultracapacitors. This coordinated response enhances power quality and protects sensitive electrical equipment connected to the microgrid.

5.4 Reliability Enhancement in Islanded Microgrids

Reliability is a major concern for autonomous microgrids, especially in remote or isolated regions where grid connectivity is unavailable. In such environments, uninterrupted power supply is essential for supporting residential, commercial, and critical infrastructure loads. Hybrid energy storage systems significantly enhance microgrid reliability by ensuring continuous power availability during periods of renewable energy shortage or unexpected system disturbances.

When renewable generation decreases due to unfavorable environmental conditions, the battery component of the hybrid storage system can provide sustained energy support to maintain load supply. At the same time, ultracapacitors handle rapid load variations and transient disturbances, ensuring stable operation during dynamic conditions. This coordinated operation reduces the risk of power outages and improves the overall reliability of microgrid systems (Lund et al., 2015).

5.4.1 Energy Security in Remote Microgrids

Hybrid energy storage systems also contribute to energy security in remote microgrids by reducing dependence on fossil fuel-based backup generators. In isolated regions where fuel transportation may be expensive or unreliable, hybrid storage systems enable greater utilization of locally available renewable resources. By storing excess renewable energy and supplying it when needed, these systems ensure a stable and sustainable energy supply.

6. CHALLENGES AND RESEARCH GAPS

Despite the significant progress in hybrid battery–ultracapacitor energy storage technologies and coordinated energy dispatch strategies, several technical challenges remain unresolved in autonomous microgrid environments. The integration of renewable energy sources, advanced control algorithms, and distributed storage systems introduces complex operational dynamics that require efficient and intelligent energy management frameworks. While many dispatch strategies have demonstrated promising results in simulations and small-scale implementations, their practical deployment often faces limitations related to battery degradation, system design optimization, computational requirements, and integration with modern smart grid infrastructures. Identifying these challenges and research gaps is essential for guiding future research toward the development of more reliable and scalable microgrid energy management systems (Olivares et al., 2014).

6.1 Battery Degradation and Lifecycle Management

One of the most critical challenges associated with hybrid energy storage systems is battery degradation caused by repeated charge–discharge cycles. In microgrid applications, batteries frequently experience variable operating conditions due to renewable energy fluctuations and dynamic load demands. Excessive cycling, high current peaks, and deep discharge events accelerate battery aging, leading to capacity loss and reduced operational lifetime. Since battery replacement represents a significant portion of microgrid maintenance costs, effective lifecycle management strategies are essential for improving the economic viability of hybrid energy storage systems.

Modern coordinated dispatch strategies increasingly incorporate battery health indicators such as state-of-health (SOH), depth of discharge, and temperature variations into the decision-making process. By monitoring these parameters, energy management systems can limit harmful operating conditions and distribute power more efficiently between batteries and ultracapacitors. However, accurately predicting battery degradation under varying operating conditions remains a complex research challenge that requires improved modeling techniques and real-time monitoring solutions (Berecibar et al., 2016).

6.1.1 Aging-Aware Dispatch Strategies

Aging-aware energy dispatch strategies represent an emerging research direction aimed at reducing battery degradation in hybrid storage systems. These approaches incorporate battery aging models into optimization algorithms to determine dispatch decisions that minimize long-term degradation effects. For instance, energy management systems may limit rapid charging cycles or adjust power allocation to ultracapacitors during transient events.

Although aging-aware dispatch strategies have shown promising results in simulation studies, practical implementation remains challenging due to the complexity of battery degradation mechanisms. Accurate aging models require detailed knowledge of electrochemical processes and environmental conditions, which are difficult to capture in real-time control systems. Consequently, further research is required to develop robust and computationally efficient aging-aware control frameworks.

6.2 Optimal Sizing and Configuration of HESS

Determining the optimal size and configuration of hybrid battery–ultracapacitor energy storage systems is another significant challenge in autonomous microgrid design. The capacity ratio between batteries and ultracapacitors directly influences system performance, cost efficiency, and operational reliability. If the battery capacity is oversized, system costs increase unnecessarily, whereas insufficient battery capacity may lead to frequent deep discharge cycles and accelerated degradation. Similarly, an inadequate ultracapacitor capacity may reduce the system's ability to handle high-frequency power fluctuations.

Optimal sizing involves analyzing several factors, including renewable generation variability, load demand patterns, storage device characteristics, and economic constraints. Researchers have proposed various analytical and optimization methods to determine appropriate capacity ratios for hybrid storage systems. However, the highly dynamic nature of microgrid environments makes it difficult to establish universally applicable design guidelines (Luo et al., 2015).

6.2.1 Multi-Objective Design Optimization

Recent research efforts have focused on multi-objective optimization techniques to determine the optimal configuration of hybrid energy storage systems. These methods simultaneously consider multiple design criteria such as system reliability, lifecycle cost, energy efficiency, and storage device lifespan. Optimization algorithms evaluate different combinations of battery and ultracapacitor capacities to identify the configuration that best satisfies system requirements.

Although multi-objective optimization provides valuable insights into system design, its effectiveness depends on accurate modeling of microgrid dynamics and renewable energy variability. Furthermore, real-world microgrid environments often experience unpredictable changes in load demand and environmental conditions, making it difficult to determine optimal configurations based solely on theoretical models.

6.3 Computational Complexity of Advanced Dispatch Algorithms

The development of advanced energy dispatch algorithms has significantly improved the efficiency of hybrid energy storage management in microgrids. However, many optimization-based and artificial intelligence-based dispatch strategies involve complex mathematical models and high computational requirements. These algorithms often require solving large-scale optimization problems or training machine learning models using extensive datasets.

In real-time microgrid operation, computational efficiency becomes a critical factor because dispatch decisions must be made rapidly to respond to system disturbances. High computational complexity may delay control actions and reduce system responsiveness, potentially affecting microgrid stability. Implementing advanced dispatch algorithms therefore requires efficient computational platforms and simplified models capable of delivering fast and reliable solutions (Camacho and Bordons, 2013).

6.3.1 Real-Time Implementation Challenges

Real-time implementation of complex dispatch algorithms presents several practical challenges. Microgrid controllers must process large volumes of operational data, including measurements from distributed sensors, renewable generation forecasts, and storage system parameters. Ensuring timely processing of this information requires high-performance computing resources and robust communication infrastructure.

Additionally, microgrid control systems must remain reliable even under communication delays or data uncertainties. Simplified control strategies and hybrid control frameworks that combine heuristic and optimization-based methods have been proposed to address these challenges. However, further research is necessary to develop scalable and computationally efficient dispatch algorithms suitable for practical microgrid deployment.

6.4 Integration with Smart Grid and IoT Technologies

The rapid development of smart grid and Internet of Things (IoT) technologies offers new opportunities for improving energy management in autonomous microgrids. Smart grid infrastructure enables advanced communication, monitoring, and control capabilities that facilitate coordinated operation of distributed energy resources and storage systems. IoT-enabled sensors can collect real-time data on system parameters such as power flow, voltage levels, and storage device conditions, providing valuable information for intelligent dispatch decisions.

By integrating IoT-based monitoring systems with hybrid energy storage management frameworks, microgrids can achieve higher levels of automation and operational efficiency. Data collected from distributed sensors can be analyzed using advanced analytics and machine learning techniques to predict system behavior and optimize energy dispatch strategies. This integration enables more accurate forecasting, improved fault detection, and adaptive control of microgrid components (Gungor et al., 2013).

6.4.1 Intelligent Energy Management Systems

Intelligent energy management systems represent the next generation of microgrid control architectures. These systems combine smart grid technologies, artificial intelligence, and hybrid energy storage to create self-adaptive energy networks capable of responding dynamically to changing operating conditions. Intelligent EMS platforms can analyze real-time system data, predict future energy demand, and automatically adjust dispatch strategies to maintain optimal performance.

7. CONCLUSION

The growing integration of renewable energy resources in modern power systems has accelerated the development of autonomous microgrids as a reliable and sustainable solution for decentralized electricity generation. However, the intermittent nature of renewable energy sources introduces significant challenges related to power stability, voltage regulation, and energy management. Hybrid energy storage systems (HESS), particularly those combining batteries and ultracapacitors, have emerged as an effective solution to address these challenges due to their complementary characteristics of high energy density and high power density.

This review has presented a comprehensive analysis of coordinated energy dispatch strategies for hybrid battery–ultracapacitor storage modules in autonomous microgrid environments. The study examined the architectural framework of microgrids integrated with hybrid energy storage and discussed the operational principles of different storage configurations. A detailed literature review highlighted various energy management approaches, including rule-based strategies, filter-based power allocation methods, optimization-based dispatch algorithms, and emerging artificial intelligence-driven techniques. Each approach was analyzed in terms of operational efficiency, computational requirements, and practical applicability in microgrid systems.

Furthermore, the review explored the major applications of hybrid energy storage systems, including power fluctuation smoothing, frequency and voltage regulation, power quality improvement, and reliability enhancement in islanded microgrids. Despite significant progress in this field, several challenges remain, such as battery degradation, optimal system sizing, computational complexity of advanced algorithms, and integration with smart grid technologies. Future research should focus on developing intelligent, scalable, and cost-effective energy management frameworks that integrate advanced optimization techniques, machine learning algorithms, and real-time monitoring technologies. Such advancements will enable more efficient utilization of hybrid energy storage systems and contribute to the reliable operation of next-generation autonomous microgrids.

8. LIMITATIONS OF THE REVIEW

Although this review provides a comprehensive overview of coordinated energy dispatch strategies for hybrid battery–ultracapacitor storage systems in autonomous microgrids, several limitations should be acknowledged. First, the review primarily focuses on conceptual frameworks, control strategies, and system architectures reported in the existing literature, while detailed experimental validations and large-scale real-world implementations are limited. Second, due to the rapid development of energy management technologies, some emerging approaches such as advanced deep learning-based control or blockchain-based energy management may not be fully represented. Additionally, the review emphasizes electrical and operational aspects of hybrid storage systems but provides limited discussion on economic analysis, lifecycle assessment, and environmental impacts. Finally, variations in microgrid configurations, renewable energy penetration levels, and geographical conditions may influence the applicability of the discussed dispatch strategies. Therefore, further studies incorporating practical case studies, techno-economic evaluations, and real-time implementation analyses are required to provide a more comprehensive understanding of hybrid energy storage management in autonomous microgrid systems.

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