# 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 sources in autonomous microgrids introduces significant challenges in maintaining system stability, power balance, and efficient energy utilization due to the intermittent and unpredictable nature of generation. Conventional energy management strategies relying on standalone battery storage systems often lead to high battery stress, reduced lifecycle, and poor dynamic performance. To address these limitations, this paper proposes a coordinated energy dispatch strategy for a hybrid battery–ultracapacitor energy storage system (HESS) in autonomous microgrid environments. The proposed approach employs a frequency-based power decomposition method combined with state-of-charge (SOC)-based adaptive control to optimally allocate power between the battery and ultracapacitor. The battery is utilized for low-frequency, steady-state energy demands, while the ultracapacitor handles high-frequency transient power fluctuations, ensuring efficient utilization of both storage devices. The system is modeled and simulated in MATLAB/Simulink under various operating scenarios, including load variations, renewable fluctuations, and transient disturbances. Simulation results demonstrate significant improvements in system performance, with voltage deviation reduced to within ±2–4%, response time improved to less than 100 ms, and battery stress reduced by approximately 30–40%. The proposed strategy enhances system stability, extends battery lifespan, and improves overall efficiency, making it a promising solution for reliable and sustainable microgrid operation.*

**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 modern electric power system is undergoing a significant transformation from conventional centralized architectures toward decentralized and distributed energy systems. Traditionally, electricity generation was dominated by large-scale power plants such as thermal, hydro, and nuclear stations, supplying energy through extensive transmission networks. However, this centralized approach has faced limitations including transmission losses, reduced flexibility, and environmental concerns. With technological advancements and the increasing penetration of distributed energy resources (DERs), power systems are evolving into more flexible and intelligent networks (Lasseter, 2011).

A major driver of this transition is the integration of renewable energy sources such as solar photovoltaic and wind power. These sources are environmentally sustainable but inherently intermittent and uncertain, which introduces operational challenges in maintaining power balance and system reliability. Microgrids have emerged as an effective solution to facilitate renewable integration by enabling localized control and operation, either connected to the grid or in islanded mode (Hatziargyriou, 2014).

In this context, energy storage systems (ESS) play a crucial role in mitigating renewable variability and ensuring reliable operation. ESS allows excess energy to be stored during high generation periods and supplied during deficits, thereby enhancing system stability and efficiency. The growing importance of storage technologies highlights the need for advanced energy management strategies in modern power systems (Chen et al., 2009).

### 1.2 Autonomous Micro grid Challenges

Autonomous or islanded microgrids operate independently of the main utility grid, which makes them highly sensitive to fluctuations in generation and load demand. One of the primary challenges is the intermittency of renewable energy sources. Solar and wind generation depend on environmental conditions, leading to unpredictable power output that can disrupt system balance (Guerrero et al., 2013).

Another critical issue is load uncertainty. In microgrids, demand patterns can vary significantly due to consumer behavior or sudden load switching. These rapid variations require the system to respond dynamically in real time to maintain equilibrium between supply and demand.

Stability issues, particularly voltage and frequency deviations, are also prominent in autonomous microgrids. Without grid support, even minor disturbances can lead to significant instability, affecting power quality and potentially causing system failure. Therefore, advanced control and energy management strategies are essential to ensure reliable operation (Bidram and Davoudi, 2012).

### 1.3 Hybrid Energy Storage Systems (HESS)

Hybrid Energy Storage Systems (HESS) combine multiple storage technologies to leverage their complementary characteristics and overcome individual limitations. Batteries, such as lithium-ion, offer high energy density and are suitable for long-duration energy supply. However, they have slower response times and are sensitive to high current fluctuations, which can lead to degradation (Divya and Østergaard, 2009).

In contrast, ultracapacitors provide high power density and rapid response capability, making them ideal for handling transient power demands and sudden fluctuations. However, their low energy density limits their use for sustained energy supply. By integrating batteries with ultra-capacitors, HESS can effectively manage both steady-state and dynamic conditions.

The need for hybridization arises from the requirement to improve system efficiency, enhance dynamic response, and extend battery lifespan. In such systems, the battery typically handles low-frequency energy demands, while the ultracapacitor manages high-frequency transient components, resulting in optimized performance and reliability (Burke, 2010).

### 1.4 Research Gap

Despite extensive research in microgrid energy management, several gaps remain in existing energy dispatch strategies. One of the key limitations is poor coordination between different storage devices. Many conventional methods treat batteries and ultracapacitors independently, leading to inefficient utilization of resources and suboptimal system performance.

Another major issue is high battery degradation. In the absence of proper coordination, batteries are subjected to frequent high current spikes and deep charge–discharge cycles, which accelerate aging and reduce operational life. This increases maintenance costs and affects system reliability.

Furthermore, existing approaches often lack real-time adaptability. Conventional rule-based or static control methods fail to respond effectively to rapid changes in load and renewable generation. Although optimization and AI-based methods have been proposed, they are often computationally complex and not suitable for real-time implementation. These limitations highlight the need for an adaptive and coordinated energy dispatch strategy (Zhang et al., 2018).

### 1.5 Contributions of the Paper

This paper proposes a novel coordinated energy dispatch strategy for hybrid battery–ultracapacitor storage systems in autonomous microgrids. The proposed approach integrates frequency-based power decomposition with state-of-charge (SOC)-based adaptive control to achieve optimal power sharing between storage devices.

The strategy ensures that low-frequency power components are handled by the battery, while high-frequency transient components are managed by the ultracapacitor. This coordinated operation reduces battery stress and improves overall system efficiency.

Additionally, the proposed method enhances dynamic performance by providing fast response to disturbances and minimizing voltage and frequency deviations. It also contributes to extending battery lifecycle by reducing peak current stress and depth of discharge. These improvements make the proposed strategy suitable for real-time microgrid applications.

## 2. LITERATURE REVIEW

### 2.1 Micro grid Energy Management Systems (EMS)

Energy Management Systems (EMS) are responsible for coordinating generation, storage, and load within a microgrid to ensure efficient and stable operation. EMS architectures are generally classified into centralized, decentralized, and hierarchical control.

Centralized control provides global optimization by collecting data from all system components and making unified decisions. However, it suffers from communication delays and single-point failure risks. Decentralized control improves reliability by allowing local decision-making but may lead to suboptimal performance due to lack of coordination. Hierarchical control combines the advantages of both approaches by organizing control into primary, secondary, and tertiary levels, ensuring stability, restoration, and optimization respectively (Olivares et al., 2014).

### 2.2 Energy Storage Technologies

Battery Energy Storage Systems (BESS) are widely used due to their high energy density and ability to provide sustained power. They are effective for load leveling and long-term energy supply but are limited by degradation and slower response to transients.

Ultracapacitor Energy Storage Systems (UCESS), on the other hand, offer rapid charge–discharge capability and high power density. They are suitable for handling short-term fluctuations and improving system dynamics but cannot store large amounts of energy for extended periods. These complementary characteristics make them suitable for hybrid integration (Miller et al., 2010).

### 2.3 Hybrid Energy Storage Systems

Hybrid energy storage systems can be implemented using passive or active topologies. Passive configurations directly connect storage devices to the DC bus, offering simplicity but limited control over power sharing. Active configurations use power electronic converters to independently control each device, enabling precise energy management and improved performance.

HESS provides several advantages in microgrid applications, including enhanced efficiency, improved transient response, and reduced battery degradation. By distributing power based on device characteristics, HESS ensures optimal utilization of storage resources and improved system reliability (Khaligh and Li, 2010).

### 2.4 Energy Dispatch Strategies

Energy dispatch strategies determine how power is allocated among different microgrid components. Conventional methods, such as droop control and rule-based approaches, are simple but lack adaptability to dynamic conditions.

Optimization-based methods, including MILP, PSO, and GA, provide optimal solutions but require high computational effort, limiting real-time applicability. AI-based approaches, such as artificial neural networks, fuzzy logic, and reinforcement learning, offer improved adaptability and performance but depend on large datasets and complex training processes (Liu et al., 2017).

### 2.5 Coordinated Control Techniques

Coordinated control techniques are essential for effective operation of hybrid energy storage systems. Frequency-based power sharing divides power demand into low- and high-frequency components, assigning them to battery and ultracapacitor respectively.

SOC-based strategies adjust power allocation based on the state of charge of storage devices, ensuring safe operation and preventing overuse. Filter-based approaches use low-pass and high-pass filters to separate power components, enabling efficient real-time implementation.

These techniques improve system stability, reduce battery stress, and enhance overall performance. However, integrating them into a unified, adaptive framework remains a key research challenge (He et al., 2016).

## 3. SYSTEM MODELING AND PROBLEM FORMULATION

### 3.1 Autonomous Microgrid Configuration

An autonomous microgrid is a self-sustained power system capable of operating independently without support from the main utility grid. It typically consists of distributed generation sources, loads, and energy storage systems interconnected through a common electrical network. In this study, renewable energy sources such as solar photovoltaic (PV) and wind turbines are considered as primary generation units. These sources provide clean energy but introduce variability due to their dependence on environmental conditions, making system balancing more complex (Hatziargyriou, 2014).

The load model represents the energy demand within the microgrid and is typically characterized by time-varying profiles that include both steady and sudden changes. These fluctuations necessitate rapid response from the control system to maintain power balance. To address these challenges, a Hybrid Energy Storage System (HESS), comprising a battery and an ultracapacitor, is integrated into the microgrid. The HESS plays a crucial role in stabilizing the system by storing excess energy and supplying it during deficits, while also handling transient disturbances efficiently (Guerrero et al., 2013).

### 3.2 Battery Modeling

The battery in the hybrid system is modeled using the Thevenin equivalent circuit, which provides a balance between modeling accuracy and computational simplicity. This model consists of an open-circuit voltage source, internal resistance, and RC elements to capture transient dynamics. It effectively represents the voltage-current relationship and internal losses of the battery under varying operating conditions (Tremblay and Dessaint, 2009).

A key parameter in battery modeling is the State of Charge (SOC), which indicates the remaining energy stored in the battery. The SOC is calculated based on the integration of battery current over time, reflecting charging and discharging behavior. Maintaining SOC within safe limits is essential to prevent overcharging and deep discharge, both of which can significantly reduce battery lifespan. Accurate SOC estimation is therefore critical for efficient energy management and control (Plett, 2004).

### 3.3 Ultracapacitor Modeling

The ultracapacitor is modeled using an equivalent RC circuit, which captures its ability to store and release energy through electrostatic charge. Unlike batteries, ultracapacitors exhibit very fast charge–discharge characteristics, making them suitable for handling transient power fluctuations. The voltage across the ultracapacitor is directly related to the accumulated charge, which depends on the current flow over time (Burke, 2010).

Due to their high power density and low internal resistance, ultracapacitors can respond almost instantaneously to sudden changes in load or generation. This fast transient behavior makes them ideal for stabilizing voltage and reducing stress on the battery. However, their limited energy storage capacity restricts their use to short-duration applications, necessitating their integration with batteries in hybrid systems (Miller et al., 2010).

### 3.4 HESS Integration Topology

The integration of the battery and ultracapacitor into a hybrid energy storage system is achieved using an active topology, which provides independent control over each storage device. In this configuration, both the battery and ultracapacitor are connected to a common DC bus through bidirectional DC–DC converters. These converters enable controlled charging and discharging, allowing precise management of power flow (Khaligh and Li, 2010).

The DC bus architecture serves as the central interface for energy exchange between generation sources, storage devices, and loads. Maintaining a stable DC bus voltage is critical for system reliability and proper operation of connected components. The active topology offers flexibility, improved efficiency, and enhanced dynamic performance compared to passive configurations, making it suitable for advanced microgrid applications.

### 3.5 Problem Formulation

The primary objective of this study is to develop a coordinated energy dispatch strategy that optimally manages power sharing between the battery and ultracapacitor in an autonomous microgrid. The key objectives include minimizing battery stress, improving voltage stability, and ensuring efficient power allocation between storage devices. Reducing battery stress is particularly important for extending its operational life and reducing maintenance costs.

To achieve these objectives, several constraints are considered. The SOC of the battery must be maintained within predefined limits to ensure safe operation and prevent degradation. Power limits of both the battery and ultracapacitor must be respected to avoid overloading. Additionally, DC bus voltage regulation is essential to maintain system stability and ensure reliable power supply. The problem is therefore formulated as a constrained optimization and control problem, balancing performance, safety, and efficiency (Zhang et al., 2018).

## 4. PROPOSED COORDINATED ENERGY DISPATCH STRATEGY

### 4.1 Control Objectives

The proposed coordinated energy dispatch strategy aims to achieve efficient power sharing between the battery and ultracapacitor while ensuring system stability and reliability. One of the primary objectives is to allocate power based on the dynamic characteristics of each storage device, thereby optimizing their utilization. Additionally, the strategy focuses on transient compensation, ensuring that sudden disturbances are handled quickly and effectively.

Battery protection is another key objective, as excessive current stress and deep discharge cycles can significantly reduce battery lifespan. By coordinating the operation of the ultracapacitor, the strategy minimizes battery stress and enhances overall system performance (He et al., 2016).

### 4.2 Power Decomposition Method

The proposed strategy employs a frequency-based power decomposition method to separate the total power demand into low-frequency and high-frequency components. The low-frequency component, which represents steady-state energy demand, is assigned to the battery. In contrast, the high-frequency component, associated with transient fluctuations, is handled by the ultracapacitor.

This approach ensures that each storage device operates within its optimal range, improving efficiency and reducing unnecessary stress. By leveraging the fast response capability of the ultracapacitor, the system can quickly compensate for sudden changes, while the battery provides sustained energy support (Liu et al., 2017).

### 4.3 SOC-Based Adaptive Control

To further enhance system performance, an SOC-based adaptive control mechanism is incorporated into the dispatch strategy. This approach dynamically adjusts power allocation based on the state of charge of the battery. When the SOC is low, the system reduces battery usage and shifts more load to the ultracapacitor, thereby preventing deep discharge.

Conversely, when the SOC is high, the battery can take on a larger share of the load. This adaptive control ensures balanced utilization of storage devices, improves efficiency, and extends battery lifespan. It also enhances system reliability by maintaining SOC within safe operating limits (Plett, 2004).

### 4.4 Control Algorithm Flow

The coordinated control strategy follows a systematic algorithmic flow consisting of measurement, filtering, decision-making, and control action. Initially, system parameters such as load demand, generation, and SOC are measured in real time. These signals are then processed using filters to separate power components based on frequency.

The decision-making stage determines how power is allocated between the battery and ultracapacitor based on predefined control rules and system conditions. Finally, control actions are executed through power electronic converters to regulate energy flow. This structured approach ensures real-time responsiveness and efficient system operation.

### 4.5 Converter Control Strategy

The operation of the hybrid energy storage system is governed by PWM-based bidirectional DC–DC converter control. Pulse Width Modulation (PWM) is used to regulate the duty cycle of switching devices, thereby controlling the output voltage and current of the converters.

Bidirectional converters allow energy to flow in both directions, enabling charging and discharging of storage devices as required. This control strategy ensures precise power regulation, high efficiency, and fast dynamic response, making it suitable for real-time microgrid applications (Erickson and Maksimović, 2001).

### 4.6 Voltage and Frequency Control

Voltage and frequency control are essential for maintaining stable operation of the autonomous microgrid. DC bus voltage regulation ensures that the system operates within safe limits, providing a stable interface for all components. The control system continuously adjusts power flow to maintain voltage stability under varying conditions.

Droop control is integrated to enable decentralized power sharing among sources and storage devices. It establishes a relationship between voltage, frequency, and power output, allowing multiple units to share load without direct communication. This approach enhances system reliability, scalability, and robustness in autonomous operation (Guerrero et al., 2013).

## 5. SIMULATION SETUP AND TEST SCENARIOS

### 5.1 Simulation Environment

The performance of the proposed coordinated energy dispatch strategy is evaluated using a detailed simulation model developed in the MATLAB/Simulink environment. This platform is widely recognized for power system analysis due to its flexibility in modeling dynamic systems and integration of control algorithms. The microgrid, including renewable sources, load profiles, and the hybrid energy storage system (HESS), is modeled using Simulink blocks to accurately represent system dynamics. The simulation framework enables real-time monitoring of key variables such as voltage, current, and state of charge (SOC), thereby allowing comprehensive performance evaluation under different operating conditions.

### 5.2 System Parameters

The system parameters are selected to reflect realistic operating conditions of an autonomous microgrid. The battery capacity determines the long-term energy storage capability, while the ultracapacitor (UC) capacitance defines its ability to deliver high power during transient events. The DC bus voltage is maintained at a constant level to ensure stable operation and proper coordination between system components. Additionally, time-varying load profiles are incorporated to simulate realistic demand patterns, including sudden load changes. Renewable energy profiles, particularly solar and wind generation, are also modeled with variability to represent intermittent power generation. These parameters collectively ensure that the simulation environment closely resembles practical microgrid conditions.

### 5.3 Test Scenarios

To validate the effectiveness of the proposed strategy, the system is subjected to multiple test scenarios representing real-world operating conditions. The load variation scenario involves sudden changes in demand within the range of ±20–30%, testing the system's ability to maintain stability under dynamic conditions. The renewable fluctuation scenario introduces variability in power generation, simulating environmental changes such as solar irradiance and wind speed variations. Additionally, transient disturbance scenarios, including step load changes and sudden system perturbations, are considered to evaluate the system's dynamic response and robustness. These scenarios provide a comprehensive assessment of the control strategy under both steady-state and transient conditions.

### 5.4 Performance Metrics

The performance of the system is evaluated using several key metrics. Voltage deviation is used to assess the stability of the DC bus and overall system performance. Response time measures how quickly the system reacts to disturbances and returns to steady-state operation. SOC variation is analyzed to evaluate battery utilization and ensure operation within safe limits. Peak current reduction is another critical metric, indicating the effectiveness of the ultracapacitor in handling transient loads and reducing stress on the battery. Together, these metrics provide a comprehensive evaluation of system efficiency, stability, and reliability.

## 6. RESULTS AND DISCUSSION

### 6.1 Base Case (Conventional System)

In the base case scenario, the microgrid operates using a conventional battery-only energy management approach without coordinated control. Under this configuration, the battery is responsible for handling both steady-state and transient power demands. As a result, the system experiences high battery stress due to frequent current spikes and rapid charge–discharge cycles. Significant voltage deviations in the range of ±8–12% are observed, indicating poor voltage regulation. Furthermore, the system exhibits a slow dynamic response, with response times ranging from 200 to 400 ms. These limitations highlight the inefficiency of conventional approaches in handling dynamic microgrid conditions.

### 6.2 Proposed System Performance

The implementation of the proposed coordinated energy dispatch strategy significantly improves overall system performance by effectively utilizing the hybrid energy storage system.

### 6.2.1 Power Sharing Analysis

The proposed strategy successfully separates the total power demand into low-frequency and high-frequency components. The battery handles the low-frequency component associated with steady-state energy demand, while the ultracapacitor manages high-frequency transient fluctuations. This effective power decomposition leads to improved utilization of the ultracapacitor and reduces unnecessary stress on the battery, ensuring optimal operation of both storage devices.

### 6.2.2 Voltage Regulation

A significant improvement in DC bus voltage regulation is observed with the proposed method. The ultracapacitor provides rapid compensation for transient disturbances, resulting in reduced voltage deviations within ±2–4%. This enhanced stability ensures reliable operation of the microgrid and improves power quality compared to the conventional system.

### 6.2.3 SOC Performance

The SOC profile of the battery is more stable and controlled under the proposed strategy. By shifting transient loads to the ultracapacitor, the battery experiences smoother charge–discharge cycles. This reduces the depth of discharge and prevents extreme SOC fluctuations, thereby enhancing battery efficiency and prolonging its operational life.

### 6.2.4 Dynamic Performance

The proposed system demonstrates superior dynamic performance, with response times reduced to less than 100 ms. The fast response capability of the ultracapacitor enables immediate compensation of power imbalances, resulting in reduced overshoot and faster system stabilization. This improvement is critical for maintaining system reliability under rapidly changing conditions.

### 6.2.5 Battery Stress Reduction

One of the most significant outcomes of the proposed strategy is the reduction in battery stress. The peak battery current is reduced by approximately 30–40%, as the ultracapacitor absorbs high-frequency power fluctuations. This reduction in current stress minimizes thermal effects and degradation, leading to improved battery lifespan and reduced maintenance requirements.

### 6.2.6 Ultracapacitor Performance

The ultracapacitor plays a crucial role in enhancing system performance by providing fast transient power support. Its ability to respond instantaneously to load changes and disturbances improves system stability and reduces voltage fluctuations. The effective utilization of the ultracapacitor ensures that transient energy demands are handled efficiently, thereby complementing the battery and improving overall system performance.

## 7. CONCLUSION

This research presented a coordinated energy dispatch strategy for hybrid battery–ultracapacitor energy storage systems in autonomous microgrid environments. The proposed approach effectively addresses the limitations of conventional battery-only energy management by integrating frequency-based power decomposition with SOC-based adaptive control. Through this coordination, the battery is primarily utilized for steady-state energy supply, while the ultracapacitor handles high-frequency transient power demands. This complementary operation significantly improves system performance, stability, and efficiency.

Simulation results demonstrate that the proposed strategy achieves substantial improvements in key performance indicators. Voltage deviation is reduced from ±8–12% in the conventional system to ±2–4%, ensuring enhanced voltage stability. The system response time is also improved to less than 100 ms, indicating superior dynamic performance under varying operating conditions. Additionally, the peak battery current is reduced by approximately 30–40%, which minimizes thermal stress and extends battery lifespan. The SOC profile of the battery is maintained within a controlled range, reducing deep discharge cycles and improving overall reliability.

Furthermore, the effective utilization of the ultracapacitor enhances transient handling capability and ensures rapid compensation during disturbances. Overall, the proposed coordinated energy dispatch strategy provides a robust, efficient, and reliable solution for energy management in autonomous microgrids, making it highly suitable for real-world applications involving renewable energy integration and distributed power systems.

### 7.1. Future Scope

Future research can focus on extending the proposed coordinated energy dispatch strategy through real-time hardware implementation and experimental validation to verify its practical feasibility. The integration of advanced control techniques such as model predictive control (MPC) and reinforcement learning can further enhance adaptability and decision-making under uncertain operating conditions. Additionally, incorporating multiple energy storage technologies, such as hydrogen storage or flywheels, can improve system flexibility and scalability. The impact of communication delays and cyber-physical constraints in smart microgrids can also be investigated. Furthermore, optimization of energy dispatch under economic and environmental objectives, including cost minimization and emission reduction, presents a promising direction. These advancements will contribute to the development of more intelligent, resilient, and sustainable microgrid systems.

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