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A COMPREHENSIVE REVIEW ON ENERGY STORAGE TECHNOLOGIES FOR GRID INTERACTIVE

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ABSTRACT

This paper reviews the growing importance of energy storage technologies in modern power systems driven by the rapid expansion of renewable energy sources such as solar PV and wind. The inherent variability and intermittency of renewables create challenges in maintaining grid stability, power quality, and reliability. To address these issues, several energy storage elements—batteries, ultra-capacitors, flywheels, and fuel cells—are increasingly integrated into grid-connected and islanded systems. The review covers their operating principles, performance characteristics, and suitability for AC and DC microgrid environments. Special attention is given to battery charging and discharging strategies, as they significantly influence system efficiency and lifetime. The survey further examines the impacts of renewable energy integration on the main grid and highlights how microgrids and Building-to-Grid (B2G) concepts enhance flexibility, controllability, and energy management. Key findings indicate that hybrid storage systems and coordinated control methods are critical for future smart grids, while gaps remain in multi-storage optimization and standardized frameworks for AC/DC microgrids and B2G interaction.

Keywords: Energy storage, batteries, ultra-capacitors, flywheels, microgrids, building-to-grid, fuel cells.

1. INTRODUCTION

The increasing penetration of renewable energy sources such as solar photovoltaic (PV) and wind power has transformed modern electric networks. While these resources are environmentally sustainable and economically attractive, their inherent intermittency and variability introduce significant challenges to grid stability, power quality, and reliable energy supply. To overcome these issues, flexible energy storage systems have become essential components of both centralized and distributed power systems. Storage technologies such as batteries, ultra-capacitors, flywheels, and fuel cells provide critical functions including energy buffering, peak load management, voltage/frequency regulation, and renewable power smoothing. Energy storage plays a particularly important role in the development of AC and DC microgrids, which serve as localized, controllable power networks capable of operating in both grid-connected and islanded modes. In addition, the emerging Building-to-Grid (B2G) concept enables residential and commercial buildings to act as active participants in energy transactions, leveraging on-site storage and smart energy management systems to support

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grid flexibility. These developments highlight the growing demand for effective storage technologies and intelligent control methods.

This literature survey provides a comprehensive review of major energy storage technologies—batteries, ultra-capacitors, flywheels, and fuel cells—along with their characteristics and roles in modern microgrids and Building-to-Grid (B2G) systems. It further examines battery charging and discharging strategies, highlighting the control requirements necessary for reliable operation. The survey also analyzes the technical challenges associated with integrating high levels of renewable energy into the main grid and explains how AC and DC microgrid architectures can help mitigate these issues through flexible, decentralized control. Additionally, the review outlines key research gaps in areas such as hybrid storage coordination, microgrid optimization, and building-level energy interaction, emphasizing the need for advanced control frameworks and standardized operational strategies in future smart grid environments.

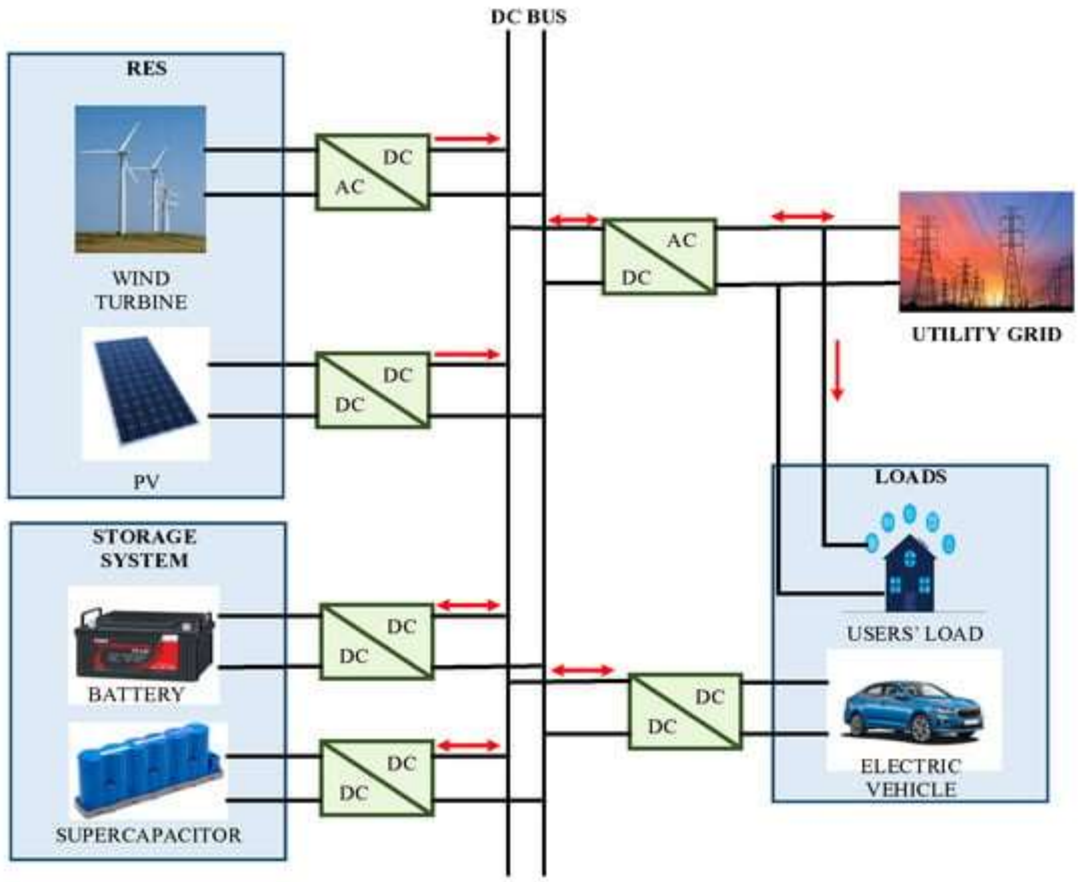

Fig 1 Power Management Strategies in a Hybrid Energy Storage System Integrated AC/DC Microgrid

II. Energy Storage Elements for Grid Applications

Energy storage systems (ESS) serve as the backbone of flexible and resilient power networks. They help manage fluctuations caused by renewable energy sources and improve overall system performance by providing fast response, high reliability, and localized energy balancing. This section reviews four major categories of storage technologies widely used in microgrids, distribution networks, and B2G environments. Batteries are the most commonly deployed form of electrical energy storage due to their high energy density, modularity, and ease of integration with both AC and DC systems. Common battery technologies include Lithium-ion (Li-ion), Lead–acid, Sodium–sulfur (NaS), and Flow batteries. Li-ion batteries dominate modern energy storage applications because of their high efficiency, long cycle life, and decreasing cost, making them ideal for residential storage systems, electric vehicles (EVs), and utility-scale battery energy storage systems (BESS). Lead–acid batteries, while lower in cost, suffer from shorter cycle life and lower depth of discharge, limiting their use to cost-sensitive applications. Key performance metrics include energy density, power density, round-trip efficiency, cycle life, safety characteristics, and cost per kWh. Batteries support a wide range of grid services such as peak shaving, load shifting, energy arbitrage, backup power, and renewable energy smoothing. Their ability to charge and discharge as needed makes them essential in microgrid energy management strategies.

Ultra-capacitors are electrochemical storage devices characterized by extremely high power density and rapid charge–discharge capability. Although they have low energy density compared to batteries, their fast response time and long cycle life make them highly suitable for short-duration, high-power applications. In microgrids, ultra-capacitors are used for power smoothing, mitigating sudden load or generation fluctuations, and providing bridging power during transient disturbances. Ultra-capacitors are often combined with batteries to form hybrid energy storage systems (HESS), where the ultra-capacitor handles fast dynamics while the battery provides long-term energy support. This combination improves system stability and prolongs battery life by reducing stress during high-power events.

Flywheel energy storage systems (FESS) store energy mechanically by accelerating a rotating mass. They offer high cycle life, fast response, and excellent power handling. Although flywheels have relatively low energy density, they excel in applications requiring frequent charge–discharge cycles, such as frequency regulation, voltage support, and stabilization of microgrids with high renewable penetration. Their robustness and minimal maintenance make them attractive for power quality applications and short-term energy backup. A comparative evaluation of batteries, ultra-capacitors, and flywheels highlights their complementary strengths. Batteries provide high energy capacity but limited power response compared to ultra-capacitors and flywheels. Ultra-capacitors deliver very high power density but store energy for only short durations. Flywheels offer mechanical robustness and fast dynamics, making them suitable for grid stability and frequency support. A summary comparison typically includes parameters such as energy density, power density, response time, lifetime, cost, and common applications. This comparison forms the foundation for selecting appropriate storage technology for AC/DC microgrids, hybrid systems, and B2G environments.

IV Fuel Cells in Distributed and Building-Scale Systems

Proton Exchange Membrane Fuel Cells (PEMFCs) are among the most widely used types for distributed generation and residential applications due to their low operating temperature (60–80°C), rapid start-up, and compact structure. They use a solid polymer electrolyte and hydrogen as the primary fuel, producing electricity, heat, and water. Their efficiency and controllability make them suitable for microgrid environments where quick load-following capability is essential. However, PEMFCs require high-purity hydrogen, and their durability is affected by membrane dehydration and catalyst degradation. Solid Oxide Fuel Cells (SOFCs) operate at significantly higher temperatures (600–1000°C), allowing internal

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reforming of fuels such as natural gas, biogas, and hydrogen. Their high efficiency, excellent fuel flexibility, and suitability for combined heat-and-power (CHP) applications make them attractive for building-level energy systems. SOFCs provide stable, continuous power, but challenges include long start-up times, thermal stress, and material stability issues under cycling conditions. These limitations restrict their use in fast-response scenarios but make them ideal for steady-state distributed generation. Molten Carbonate Fuel Cells (MCFCs) and Phosphoric Acid Fuel Cells (PAFCs) are also utilized in larger distributed power installations. MCFCs operate at intermediate temperatures (600–700°C) and can handle various hydrocarbon fuels. They are used in medium-scale commercial power systems due to their high efficiency and capability for CO_2 capture. PAFCs operate at around 200°C and are employed in CHP systems, offering moderate efficiency and good reliability. Their advantages include fuel tolerance and long operational life, whereas disadvantages include lower power density and higher cost compared to PEMFCs.

Alkaline Fuel Cells (AFCs), although less common in commercial distributed generation, offer high efficiency and low weight. They operate using potassium hydroxide as the electrolyte and are very efficient at converting hydrogen and oxygen into electricity and water. Historically used in spacecraft applications, AFCs are sensitive to CO_2 contamination, making them impractical for widespread deployment without advanced purification systems. Their relevance in microgrids is limited, but ongoing research into membrane materials and CO_2-resistant electrolytes may expand their future applicability. Fuel cells are widely recognized as stable, continuous power sources for distributed generation due to their ability to deliver high-quality, low-emission electricity. Numerous studies highlight their role in microgrids as base-load generators that complement intermittent renewable sources such as solar and wind. Because fuel cells provide steady output, they improve voltage regulation and reduce the variability associated with renewables. Research also emphasizes their integration in islanded microgrids, where they enhance reliability and provide long-duration backup. Hybrid systems combining fuel cells with batteries have been extensively reported in literature as a strategy for balancing slow dynamic response of fuel cells with the fast response of batteries. Representative studies demonstrate that hybrid fuel cell–battery systems offer smoother power output, better transient performance, and increased operational flexibility. The battery absorbs rapid load fluctuations while the fuel cell supplies sustained energy, improving overall system efficiency and extending fuel cell life by reducing load oscillations.

Similarly, hybrid fuel cell–ultra-capacitor systems are used to achieve fast dynamic response in high-power applications such as DC microgrids and electric vehicle charging stations. Ultra-capacitors manage sudden load spikes, providing instantaneous power support, while the fuel cell maintains steady energy supply. Research papers describe various power-sharing strategies, including rule-based control, fuzzy logic control, and model-predictive control, to optimize hybrid operation and safeguard fuel cell durability. Control strategies for coordinating hybrid systems remain a major topic in recent literature. Droop control, hierarchical microgrid control, and advanced energy management systems have been used to ensure balanced power sharing between fuel cells and storage elements. Studies also highlight the importance of efficiency optimization, fuel consumption minimization, and enhanced transient stability. These works collectively demonstrate that hybrid systems combining fuel cells with fast-response storage offer superior performance compared to standalone fuel cell units in distributed energy applications.

Fuel cells are increasingly deployed in buildings as part of Combined Heat and Power (CHP) systems, where they simultaneously generate electricity and recover waste heat for space heating or water heating. This efficient utilization of energy makes fuel cell CHP systems highly attractive for residential and commercial applications. Their ability to supply both electrical and thermal loads positions them as key technologies for future smart buildings equipped with B2G capabilities. In a B2G environment, fuel cell systems interact with building loads through advanced energy management controllers that schedule their operation based on demand profiles, electricity prices, and thermal load requirements. When building load is low and fuel cell generation exceeds internal demand, excess power can be exported to the grid or stored in local batteries. Conversely, during high demand, the building can supplement fuel cell output with battery discharge or grid import. This flexible interaction enhances building autonomy and grid stability.

Fuel cell-based building systems also contribute to grid-level ancillary services such as peak load reduction, voltage support, and reduced dependence on conventional power plants. Literature shows that coordinated operation of fuel cells with batteries or ultra-capacitors allows buildings to participate in demand response programs and frequency regulation markets. These capabilities turn buildings into active grid participants rather than passive consumers.

A typical configuration includes a fuel cell stack connected to a DC bus through a DC–DC converter, operating alongside batteries and ultra-capacitors. An inverter links the DC microgrid to the building's AC loads and the distribution grid. This block diagram illustrates the coordinated operation of distributed generation and storage within a building-to-grid framework, enabling optimized power flow between renewable sources, building loads, and the main grid.

V. Impact of Grid Integration of Renewable Sources

High penetration of renewable energy sources introduces several technical challenges in conventional distribution networks. Voltage fluctuations occur due to rapid changes in solar irradiance or wind speed, disrupting voltage stability across feeders. Frequency deviations arise when renewable output does not match load demand, causing imbalances between supply and demand. Reverse power flow can occur when distributed generation exceeds local consumption, creating operational issues for transformers and protection devices. Furthermore, power quality issues—including harmonics, flicker, and phase imbalance—become more pronounced in networks lacking proper regulation or storage support. Energy storage systems play a vital role in mitigating renewable-induced disturbances. Batteries, ultra-capacitors, and flywheels provide fast frequency regulation by injecting or absorbing power within milliseconds. These storage systems also supply reactive and active power support, helping maintain voltage stability under high renewable penetration. Batteries smooth short-term variations in solar and wind output, reducing ramping stress on conventional generators. Flywheels and supercapacitors offer fast transient support and contribute to enhanced system inertia, improving system reliability. Storage units also contribute to black start capabilities in microgrids by supplying stable power during startup.

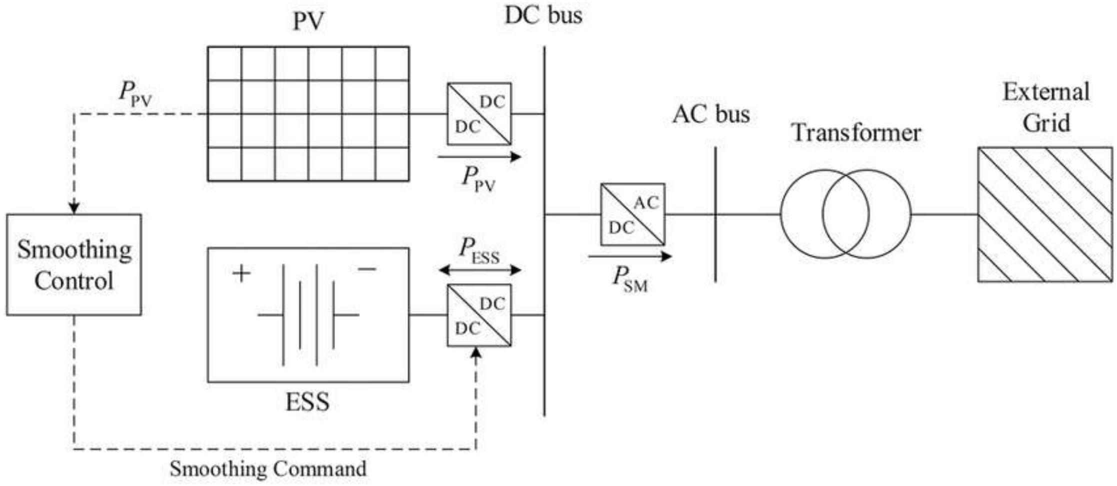

Fig 2: Architecture of microgrid with PV and ESS for PV power smoothing

Recent studies highlight that the integration of storage significantly enhances renewable-rich grid performance. Various control techniques—such as droop control, model-predictive control (MPC), and hierarchical energy management systems—have been proposed to coordinate renewable sources and storage units. Case studies demonstrate improvements in reliability, reduced curtailment of renewable energy, and enhanced power quality when hybrid storage systems are used. Microgrid simulations further show that coordinated storage dispatch reduces frequency excursions, mitigates voltage dips, and optimizes power-sharing between sources. A summary of studies typically lists details such as renewable type, storage technology used, and major contributions to system stability.

VI. Introduction to AC and DC Microgrids

AC microgrids consist of distributed energy resources (DERs), loads, protection systems, and a point of common coupling (PCC) connecting them to the utility grid. Their control hierarchy includes primary control for voltage/frequency regulation, secondary control for restoring deviations, and tertiary control for economic optimization and power flow management. AC microgrids remain dominant due to their compatibility with existing AC infrastructure and ease of integrating conventional loads and generators. DC microgrids are gaining prominence because many renewable sources (PV), storage devices (batteries), and loads (electronics, EVs) inherently operate on DC. DC microgrids eliminate multiple conversion stages, thereby improving efficiency and reducing conversion losses. However, protection challenges such as fault detection and coordination, as well as lack of standardized DC voltage levels, continue to limit widespread deployment. Despite these challenges, they offer simple power flow control and high efficiency. Hybrid AC/DC microgrids combine both AC and DC buses interconnected by bidirectional converters. These architectures leverage the strengths of both systems, enabling flexible integration of diverse DERs. Energy storage systems are commonly placed on the DC bus for ease of control. Hybrid microgrids support efficient EV charging, renewable integration, and multi-directional power exchange between AC and DC subsystems.

CONCLUSION

This literature survey has reviewed major energy storage technologies—including batteries, ultra-capacitors, flywheels, and fuel cells—highlighting their key characteristics, performance metrics, and suitability for microgrid and building-level applications. Battery

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charging and discharging strategies such as CC, CV, and CC–CV methods were discussed, along with SOC/SOH estimation and the essential protective role of the Battery Management System. The survey also examined the technical impacts of renewable energy integration, emphasizing challenges such as voltage instability, frequency deviations, and power quality issues that arise without adequate storage. AC and DC microgrid architectures were shown to play a critical role in mitigating these impacts by enabling flexible, autonomous, and efficient coordination of distributed resources. Furthermore, Building-to-Grid (B2G) frameworks were identified as a promising direction for future smart energy systems, enabling buildings to act as responsive, grid-supportive entities through intelligent storage scheduling and multi-energy management. Future research should focus on optimal sizing and coordination of hybrid storage systems, advanced control and optimization techniques for B2G participation, and standardized communication and interoperability frameworks for DC and hybrid microgrids. These advancements will be essential for achieving stable, resilient, and highly renewable energy networks.

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