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Review of Hybrid Energy Management Scheduling Techniques for Electric Vehicles

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***Abstract*— This review examines the various hybrid energy management scheduling techniques used in electric vehicles to enhance efficiency, reliability, and overall performance. By integrating multiple energy sources such as batteries, supercapacitors, and renewable inputs, hybrid systems require intelligent scheduling strategies to balance power flow, reduce energy losses, and extend component lifespan. The paper explores key scheduling methods, including rule-based approaches, optimization algorithms, machine learning models, and predictive control techniques, highlighting their strengths and limitations. Through a detailed comparison of recent advancements, the review provides insights into how effective scheduling can improve energy utilization, support dynamic driving conditions, and contribute to the development of more sustainable and high-performing electric vehicle technologies.**

Keywords—DC, Microgrid, Renewable, Energy, Photovoltaic, Solar.

I. Introduction

Hybrid energy management has emerged as a key solution in modern power systems as the world shifts toward cleaner, smarter, and more efficient energy technologies. Traditional single-source systems—such as battery-only storage or stand-alone renewable setups—often struggle to meet the growing demands for reliability, stability, and high performance. Hybrid energy management addresses these challenges by integrating multiple energy sources and storage technologies into one coordinated system [1]. These sources may include batteries, supercapacitors, fuel cells, and renewable inputs like solar or wind power. Each source has its own strengths and limitations, and hybrid energy management ensures that they work together in a complementary manner to provide a more efficient and resilient energy supply[2].

The need for hybrid systems has increased significantly with the expansion of electric vehicles, microgrids, smart homes, and industrial automation. Batteries alone cannot always handle sudden increases in load or frequent charge–discharge cycles, which can lead to faster degradation and reduced lifespan. Supercapacitors, on the other hand, are capable of delivering high bursts of power but cannot store energy for long periods[3]. Renewable sources are sustainable but unpredictable due to weather variations. Hybrid energy management intelligently coordinates these diverse sources, preventing overload, reducing stress on components, and ensuring continuous and balanced power flow[4].

A Hybrid Energy Management System (HEMS) uses both hardware and software strategies to optimize energy distribution. Advanced control algorithms, predictive models, and real-time monitoring help determine which source should supply power at any given moment[5]. For example, during high acceleration in electric vehicles, the supercapacitor may supply quick energy, while the battery provides steady power for long-distance travel. In renewable-powered microgrids, solar energy may be prioritized during daytime, with the battery supplying power when sunlight is insufficient. By dynamically shifting energy flows, hybrid management achieves better performance, improves efficiency, and maximizes the use of clean energy[6].

In addition to improving operational stability, hybrid energy management promotes sustainability by reducing dependence on fossil-fuel-based backup systems. It minimizes energy waste, enhances the lifespan of storage devices, and supports grid stability—especially in environments with high renewable penetration. The use of intelligent energy management also opens opportunities for smart scheduling, demand-response planning, and predictive maintenance. These innovations are crucial for building advanced smart grids and highly efficient electric mobility systems[7].

Overall, hybrid energy management represents a major advancement in the energy sector by combining multiple sources, improving flexibility, and enabling optimized power delivery. As global energy needs continue to rise, the importance of hybrid systems will only grow. With ongoing developments in control technologies, artificial intelligence, and energy storage, hybrid energy management will play an essential role in developing the next generation of sustainable, reliable, and intelligent power systems[8].

As the complexity of energy systems increases, hybrid energy management also plays a critical role in maintaining safety and protecting key components from excessive stress. Batteries, for example, are sensitive to deep discharges, high currents, and temperature variations, all of which can shorten their lifespan. Supercapacitors, while highly durable, require proper voltage balancing to prevent damage. Hybrid energy management ensures that each component operates within safe limits by intelligently distributing the load and preventing unnecessary strain[9]. This leads to long-term cost savings by reducing maintenance requirements and minimizing the need for frequent component replacement. In electric vehicles, this safety-oriented management translates into better reliability, improved driving comfort, and enhanced user confidence. The ability to maintain stable power under different driving conditions—such as city traffic, highway cruising, or sudden braking—demonstrates the importance of coordinated control among multiple energy sources[10].

II. LITERATURE SURVEY

A. Kumar et al. [1] highlight that alternative energy sources such as solar chargers and batteries help electrical engineers monitor power systems more effectively and meet rising energy demands. They emphasize that combining renewable energy resources with intelligent control strategies can significantly improve energy productivity. This approach not only supports growing electricity needs but also reduces greenhouse gas emissions, leading to a more efficient, sustainable, and environmentally friendly smart grid environment.

According to Z. Zhang [2], a three-port smart converter that links electric vehicles (EVs) and photovoltaic (PV) panels to the electrical grid offers a flexible and adaptive solution for future smart grids. This architecture relies on a large DC-link capacitor to manage the interaction of AC, DC, and multi-energy flows. However, the use of bulky capacitors limits the system's ability to achieve high power density and reliability. To overcome this issue, the study proposes a dynamic power decoupling control method for a single-stage three-port converter, improving overall system performance.

A. M. Mahfuz-Ur-Rahman et al. [3] present an advanced control-based energy management system (EMS) validated through MATLAB/Simulink simulations and laboratory experiments. Their work introduces a seven-level multilevel converter integrated with a PV inverter and a full-bridge inverter using a sophisticated pulse-width modulation method for the battery energy storage system (BESS). Traditional commercial inverters require heavy and costly power transformers, and the proposed design aims to offer a more efficient and lightweight solution for integrating renewable energy into the grid.

R. Ando et al. [4] focus on improving the operation of battery energy storage systems (BESS) to compensate for discrepancies between predicted and actual PV power generation. Due to the high cost of BESS, it is not feasible to eliminate all mismatches solely through storage. Moreover, conventional power generators react too slowly to handle rapid fluctuations caused by renewable energy. The paper proposes a new power generation strategy known as “imbalance smoothing” combined with optimal BESS scheduling based on short-term PV forecasting. Using a Japanese frequency control model, the researchers demonstrate that their method significantly reduces the burden on conventional generators.

A. A. A. Alahmadi et al. [5] emphasize the need for an intelligent control strategy for DC microgrids. They propose a smart energy management system using a fractional-order PID controller integrated with fuzzy logic. The hybrid DC microgrid incorporates a battery bank, wind turbine, and PV panels. The advanced controller optimizes the performance of source-side converters to extract maximum renewable energy and improve overall power quality. The study focuses on maximizing the contribution of wind and solar energy to the microgrid.

In a forward-looking study, Sorour et al. [6] develop an EMS for residential PV–battery systems aimed at increasing self-consumption and reducing energy exchange with the utility grid. Their algorithm lowers electricity costs, minimizes transmission losses, and reduces dependence on centralized generation. The EMS combines fuzzy logic with a rule-based approach while considering day-ahead energy forecasting errors and battery state of health (SOH). By intelligently controlling battery charging and discharging, the system extends battery life and enhances operational efficiency.

R. K. Sharma et al. [7] propose a coordinated control strategy for a standalone AC/DC hybrid system consisting of PV, battery energy storage (BES), and a diesel generator (DG). Since PV penetration in DG-based systems is

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typically limited due to synchronization and reliability issues, the study introduces a DC–bus-based multi-level control framework. This method simplifies coordination, improves stability, and allows more precise control of the hybrid architecture. An additional optimal controller is proposed to ensure effective power sharing between the DG and BES.

Q. Li et al. [8] improve distributed power supply performance by coordinating energy from batteries, fuel cells, electrolyzers, and the external grid. Their approach uses short-term forecasting to estimate PV generation and load demand. Instead of traditional offline optimization, they apply a continuous rolling optimization strategy that updates power distribution in real time. The method outperforms standard techniques like dynamic programming, MILP-MPC, and rule-based control.

S. S. Ahmad et al. [9] design an EMS using model predictive control (MPC) to manage power dispatch and address rapid changes associated with solar PV penetration, particularly the "duck curve" slope. Their system effectively controls sudden power ramps using battery storage, load shedding, and PV curtailment. The proposed solution is validated using a 24-bus RTS test system, demonstrating its ability to stabilize grid operations under high PV penetration.

To reduce fossil-fuel emissions, increase renewable energy usage, and optimize residential energy consumption, A. Imran et al. [10] introduce a heuristic programmable energy management controller (HPEMC). They develop a hybrid genetic–particle swarm optimization (HGPO) technique and compare it with existing algorithms such as GA, BPSO, ACO, WDO, and BFA. The proposed method schedules smart home appliances efficiently while utilizing rooftop solar energy from microgrids, ultimately improving cost savings and operational reliability.

III. Existing Approaches

1. Rule-Based Energy Management Approaches

Rule-based methods are among the earliest and most widely used techniques for hybrid energy management. These approaches rely on predefined rules, thresholds, or conditions that determine when each energy source should be charged or discharged. For example, if battery SOC is low, the system prioritizes charging; if the load demand suddenly increases, the supercapacitor provides quick power support. These systems are easy to implement and computationally light, but their performance depends heavily on the quality of the rules and they are not very efficient under unpredictable or rapidly changing operating conditions.

2. Optimization-Based Approaches

Optimization techniques use mathematical models to achieve the best balance between energy supply, demand, efficiency, and cost. Common methods include linear programming (LP), nonlinear programming (NLP), mixed-integer optimization (MILP), and dynamic programming (DP). These approaches aim to minimize losses, maximize battery life, or reduce operating cost. Although optimization techniques provide high performance and precise control, they often require high computational power and may not be suitable for real-time applications without simplification.

3. Model Predictive Control (MPC) Approaches

Model Predictive Control (MPC) predicts future system behavior and optimizes energy flow accordingly. It uses real-time feedback and forecast data—such as renewable generation prediction and load demand—to make decisions for the next time interval. MPC is highly effective in managing systems with fluctuating renewable energy like solar PV. It also handles constraints, such as battery limits or converter efficiency. However, its performance strongly depends on accurate prediction models and requires powerful processors for continuous optimization.

4. Machine Learning and Artificial Intelligence Approaches

AI-based methods use machine learning, deep learning, and reinforcement learning to improve decision-making in hybrid energy systems. These techniques learn from past data—such as driving behavior, solar patterns, load profiles, and environmental conditions—to optimize energy distribution. Reinforcement learning (RL) is particularly useful because it learns optimal strategies by interacting with the environment. AI-driven methods offer adaptability and improved accuracy, but they require large datasets, training time, and careful tuning.

5. Fuzzy Logic–Based Approaches

Fuzzy logic controllers manage energy flow using linguistic rules rather than strict mathematical equations. They handle uncertainties effectively, such as unpredictable solar generation or fluctuating load demand. Fuzzy systems decide how much power should come from the battery, supercapacitor, or renewable source by evaluating conditions like SOC, power variations, and system temperature.

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Their main advantage is flexibility and robustness; however, designing fuzzy rules and membership functions requires expert knowledge and can become complex for large systems.

6. Hybrid Approaches (Combined Methods)

Many modern systems combine two or more techniques to achieve better performance. For instance, rule-based control may be integrated with fuzzy logic to improve adaptability, or MPC may be combined with machine learning to enhance prediction accuracy. Hybrid approaches take advantage of the strengths of each technique while minimizing their individual limitations. These methods offer higher efficiency, better stability, and improved reliability, but they are often more complex and require advanced hardware and control algorithms.

IV. CHALLENGES

- **Complex Coordination of Multiple Energy Sources** Managing batteries, supercapacitors, and renewable sources together is difficult because each behaves differently. Ensuring smooth power flow and avoiding conflicts between sources requires sophisticated control strategies.
- **Unpredictability of Renewable Energy** Solar and wind energy depend on weather, time, and environmental conditions. Sudden drops or spikes in energy generation make it challenging to maintain stability, especially in electric vehicles and microgrids.
- **High Complexity in Power Converter Design** Bidirectional converters must operate efficiently in both charging and discharging modes. Designing converters that are fast, reliable, and energy-efficient under dynamic conditions is a major technical challenge.
- **Battery Degradation and Safety Issues** Batteries deteriorate faster when exposed to frequent charge–discharge cycles, high currents, or temperature variations. Protecting batteries while still meeting power demands is a critical challenge in hybrid systems.
- **High Implementation and Maintenance Costs** A hybrid system requires additional components such as sensors, controllers, communication units, and multiple storage devices. These increase installation costs and make long-term maintenance more expensive.
- **Lack of Standardization and Interoperability** Hybrid energy systems often use components from different manufacturers, which may not communicate or operate seamlessly together. The absence of common standards makes integration, scaling, and reliability more difficult.

V. CONCLUSION

Hybrid energy management plays a crucial role in improving the efficiency, reliability, and sustainability of modern power and electric vehicle systems by intelligently coordinating multiple energy sources such as batteries, supercapacitors, and renewable energy. While the integration of diverse storage units and renewable inputs offers significant benefits in terms of performance, cost savings, and reduced emissions, it also introduces challenges related to system complexity, accurate forecasting, converter design, safety, and standardization. Despite these obstacles, advancements in control technologies, artificial intelligence, and power electronics continue to strengthen hybrid systems, making them more adaptive and efficient. Overall, hybrid energy management represents a promising pathway toward cleaner, smarter, and more resilient energy infrastructures for the future.

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