Journal of Mines, Metals and Fuels, *73(8): 2439-2450; 2025. DOI: 10.18311/jmmf/2025/49311*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Modelling Techniques and Power Management Strategies for Dual Battery Systems in Electric Vehicles - A Review

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Abstract

Dual battery systems in Electric Vehicles (EVs) represent a significant advancement in optimising energy storage, power management, and vehicle performance. These systems combine two distinct batteries, often with different chemistries or capacities, to meet varying energy demands, improve efficiency, and extend battery lifespan. This review provides an in-depth analysis of the current modelling techniques and power management strategies used in dual battery systems. The modelling techniques explored include electrochemical models, Equivalent Circuit Models (ECM), data-driven models, and thermal models. Each modelling approach has distinct advantages and limitations depending on its application. For example, electrochemical models offer high accuracy in simulating battery behaviour but require substantial computational power, making them less suitable for real-time applications. In contrast, ECMs provide a simplified yet effective representation of battery performance, ideal for practical implementations in EVs. Power management strategies, including rule-based, optimisation-based, and predictive methods, are essential for managing the complexities of dual battery systems. Rule-based power management is cost-effective and simple but lacks the flexibility and efficiency of more advanced methods. Optimisation-based strategies use mathematical algorithms to dynamically distribute power between batteries, achieving higher efficiency. Predictive power management, such as Model Predictive Control (MPC), anticipates future driving conditions and adjusts battery usage in real-time, ensuring optimal performance and extended battery life. Additionally, the integration of energy harvesting systems, such as regenerative braking, further enhances the efficiency of dual battery configurations.

Major Findings: *The review highlights that dual battery systems, combining different chemistries, significantly enhance EV energy efficiency, power management, and battery life. Advanced modelling and predictive power management strategies are key to optimising performance, while integrating energy harvesting systems further boosts efficiency.*

Keywords: *Dual Battery Systems, Electric Vehicles, Electrochemical Models, Equivalent Circuit Models, Power Management*

1.0 Introduction

Electric vehicles (EV) are revolutionising the global transportation sector, offering a promising alternative to conventional Internal Combustion Engine (ICE) vehicles. With growing concerns over climate change and the depletion of fossil fuel resources, EVs have emerged as a sustainable solution that reduces greenhouse gas emissions and dependence on non-renewable energy sources[1]. Over the past decade, EV adoption has accelerated due to advancements in battery technology, government incentives, and an increasing awareness of

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environmental issues. The global EV market is projected to reach significant growth, with estimates suggesting that EV sales will constitute over 30% of total vehicle sales by 2030[2].

Several factors have contributed to the rise of EVs, including technological breakthroughs in battery performance, charging infrastructure expansion, and decreasing costs. Batteries are the core of EV powertrains, and their evolution has been pivotal in enhancing vehicle range, efficiency, and affordability. The shift towards electric mobility is also aligned with international policies aimed at achieving carbon neutrality by 2050, as outlined in the Paris Agreement. Consequently, automotive manufacturers are intensifying their research and development efforts to improve EV technologies, making electric mobility accessible to a broader population[1].

The battery system in EVs is fundamental to the vehicle's performance, acting as the primary source of energy for propulsion. In contrast to ICE vehicles, which rely on liquid fuels, EVs use electric batteries to store and deliver energy to the electric motor, driving the vehicle forward. The most widely used battery technology in modern EVs is Lithium-ion (Li-ion) batteries, known for their high energy density, longevity, and ability to undergo multiple charge and discharge cycles[3].

Battery performance directly impacts key EV characteristics such as range, charging time, and overall efficiency. To address the issue of range anxiety, the fear that an EV will run out of power before reaching a charging station, manufacturers are developing larger-capacity batteries with faster charging capabilities[4]. In addition, advancements in Battery Management Systems (BMS) ensure that the battery operates within optimal parameters, safeguarding against overcharging, overheating, and degradation.

However, relying solely on a single battery system can present limitations, especially when balancing energy demands and extending the vehicle's operational range. This has led to the exploration of dual battery systems, where multiple batteries with different chemistries or capacities are integrated to optimise performance. Dual battery systems provide opportunities for better energy utilisation, enhanced lifespan, and improved reliability[3].

Despite the advantages of dual battery systems, managing power distribution between two battery packs presents a set of complex challenges. One of the primary concerns is balancing the State of Charge (SOC) between the batteries, as the two systems may have different voltage levels, chemistries, and degradation rates[5]. An efficient power management strategy must be employed to determine how and when energy is drawn from each battery, ensuring that neither battery is over-stressed or prematurely degraded.

In a dual battery system, each battery typically serves a specific function. For instance, one battery may be optimised for high power output during acceleration, while the other is designed for energy storage over long durations. This differentiation necessitates a sophisticated Power Management System (PMS) capable of dynamically adjusting to driving conditions, user behaviour, and environmental factors[6].

Temperature control also poses a significant challenge in dual battery systems. Batteries are sensitive to extreme temperatures, and thermal management is crucial to prevent overheating and maintain performance. Poor thermal management can lead to reduced battery life, energy inefficiencies, and safety risks such as thermal runaway[4]. Integrating effective cooling and heating mechanisms into the PMS is essential for ensuring the longevity and reliability of the dual battery system.

1.1 Objectives

This review aims to explore and critically analyse the various modelling techniques and power management strategies used in dual battery systems for EVs. As EV adoption continues to rise, understanding the complexities of dual battery systems and their management is critical for advancing battery technology and improving vehicle performance. The objectives of this review are as follows:

- To provide an overview of different modelling techniques employed in dual battery systems, including electrochemical models, equivalent circuit models, and data-driven models.
- To examine the power management strategies used in dual battery systems, such as rule-based management, optimisation-based management, and predictive management strategies.
- To identify current gaps in research and propose future directions for improving battery modelling and power management in EVs.

2.0 Dual Battery Systems in Electric Vehicles

The evolution of EVs has led to innovative energy storage solutions, including the adoption of dual battery systems. A dual battery system comprises two separate batteries, often of different chemistries or capacities, designed to fulfil distinct energy needs within the vehicle. These systems are typically structured in two configurations: parallel and series. In parallel configurations, both batteries work together to provide power simultaneously, sharing the electrical load. This configuration allows for greater flexibility in power distribution and can reduce the strain on a single battery[7]. In a series configuration, the batteries provide power sequentially, which can enhance energy availability for specific driving modes, such as acceleration or regenerative braking[8].

Dual battery systems generally involve one high-energy battery, designed for prolonged driving ranges, and one high-power battery, optimised for rapid acceleration or other high-energy-demand scenarios. This architecture enhances overall system efficiency, as the power demand is distributed more effectively between the two batteries. Moreover, it allows for a more consistent State of Charge (SOC) between the batteries, improving performance and prolonging battery life. For instance, the high-power battery can handle peak loads during acceleration, while the high-energy battery is used for steady cruising, reducing the stress on both systems[9].

To ensure seamless operation, a Battery Management System (BMS) monitors the voltage, current, and temperature of each battery, dynamically adjusting power distribution according to driving conditions and the respective battery's State of Health (SOH). Additionally, the BMS plays a crucial role in protecting the batteries from overcharging or deep discharging, ensuring their longevity[10].

2.1 Types of Batteries Used in Dual Battery Systems

Dual battery systems in EVs commonly use a combination of different battery chemistries, each selected for specific performance characteristics. The most prevalent types of batteries include:

- Lithium-Ion (Li-ion) Batteries: Li-ion batteries are the most widely used in EVs due to their high energy density, long life cycle, and relatively lightweight structure. They are typically used as the main energy storage unit in dual battery systems, providing the necessary range for extended driving[11].
- Lead-Acid Batteries: Though less common in modern EVs, lead-acid batteries are occasionally used as secondary batteries in dual systems. Their low cost and robustness make them suitable for auxiliary functions such as powering onboard electronics and low-power applications (Wu *et al.*,)[12].
- Nickel-Metal Hydride (NiMH) Batteries: NiMH batteries offer higher energy density than lead-acid batteries but fall short compared to Li-ion batteries. However, they are known for their durability and are used in some hybrid vehicles as a secondary power source[13].

Table 1. Comparison of battery types in dual battery systems[11-14]

Battery Type	Energy Density (Wh/kg)	Cycle Life	Cost	Application in EVs
Lithium-Ion (Li-ion)	150-250	1000-2000	High	Main energy source
Lead-Acid	30-50	300-500	Low	Auxiliary power, low-power tasks
Nickel-Metal Hydride	60-120	500-1000	Moderate	Secondary battery in hybrids
Solid-State	400+ (est.)	2000+ (est.)	High (projected)	High-power applications (future tech)

- Solid-State Batteries: Solid-state batteries, although still in development, promise higher energy density and improved safety compared to Li-ion batteries. They have the potential to be used in future dual battery systems, particularly for high-power applications[14].

The selection of battery types for dual systems depends on the specific requirements of the vehicle, such as driving range, cost constraints, and power demands. In some configurations, hybrid chemistries (e.g., Li-ion and lead-acid) are used to optimise performance and extend the lifespan of the batteries by balancing power consumption between the two types[15].

2.2 Advantages of Using Dual Battery Systems Over Single Battery Systems

The integration of dual battery systems in EVs offers several advantages over traditional single battery configurations. These benefits address some of the key limitations of single battery systems, such as limited range, faster degradation, and reduced performance under high loads.

1. Improved Performance and Efficiency: One of the primary advantages of dual battery systems is the ability to optimise power distribution based on the specific driving conditions. For example, during high-energy-demand scenarios such as acceleration, the high-power battery can supply energy while the high-energy battery maintains the vehicle's range during normal cruising. This separation of functions reduces stress on the individual batteries, resulting in improved performance and efficiency[8].
2. Extended Battery Life: By distributing energy demands across two batteries, dual battery systems reduce the likelihood of overloading or deeply discharging either battery. This balanced approach helps to extend the lifespan of both batteries, which is particularly important for the cost-effectiveness and sustainability of EVs[13]. The reduced cycling stress on the main energy battery allows it to last longer without significant capacity loss, improving overall vehicle reliability.
3. Increased Range and Power Availability: Dual battery systems can provide a longer driving range by utilising the high-energy battery for normal operations while reserving the high-power battery for peak demands[9]. This setup ensures that the vehicle maintains a consistent range without compromising on power, offering a more balanced and predictable driving experience.
4. Enhanced Power Management: With a dual battery system, the BMS can more efficiently manage power flow, ensuring that the batteries operate within their optimal ranges. This capability reduces the likelihood of inefficiencies such as heat buildup or power loss, which are common issues in single battery systems[7].
5. Flexibility for Energy Recovery Systems: Dual battery systems are better suited for integrating regenerative braking and other energy recovery systems, as the secondary battery can store excess energy generated during deceleration. This flexibility enhances the overall energy efficiency of the EV, reducing the need for frequent recharging[14].

3.0 Modelling Techniques for Dual Battery Systems

In EVs, modelling the battery system is essential for optimising performance, ensuring reliability, and extending battery life. Battery modelling allows engineers and researchers to predict the behaviour of batteries under different conditions, making it crucial for effective energy management in dual battery systems. Various modelling techniques have been developed, each with its unique approach, strengths, and limitations. The primary types of models include electrochemical models, ECM, data-driven models, and thermal models.

Each of these techniques serves a specific purpose. Electrochemical models focus on the internal chemical reactions and dynamics within the battery, providing a detailed understanding of its physical processes. ECM simplifies the battery's behaviour using electrical components like resistors and capacitors, offering a balance between accuracy and computational efficiency. Data-driven models leverage machine learning and

Artificial Intelligence (AI) to analyse large datasets and predict battery performance under various conditions. Thermal models, on the other hand, focus on the impact of temperature on battery performance and safety, a critical aspect for EVs due to the potential risks of overheating.

3.1 Electrochemical Models

Electrochemical models are one of the most comprehensive methods for representing battery behaviour. These models simulate the electrochemical processes inside the battery, such as the movement of ions between the anode and cathode, the reaction kinetics, and the charge transfer at the electrolyte interfaces[16]. Electrochemical models can be categorised into two main types: empirical and physics-based models. Physics-based models are more common and rely on mathematical equations to represent the fundamental processes that govern battery behaviour.

Electrochemical models provide an in-depth look at the internal workings of batteries. These models account for the diffusion of lithium ions in the electrodes, electrolyte dynamics, and the impact of these factors on battery capacity, voltage, and SOC. They also capture degradation mechanisms, such as the formation of Solid Electrolyte Interphase (SEI) layers, which affect long-term performance[17]. By simulating these processes, electrochemical models allow for accurate predictions of battery performance under varying conditions.

3.1.1 Pros and Cons of Electrochemical Models

The primary advantage of electrochemical models is their high accuracy, especially in capturing the complex chemical reactions within batteries. This makes them ideal for research and development, particularly when investigating new battery chemistries or improving existing ones. However, the detailed nature of these models requires extensive computational resources and can be challenging to implement in real-time applications, such as EV power management systems[17].

Pros

- High accuracy and detail.
- Ability to simulate degradation mechanisms.
- Useful for research and design of new battery chemistries.

Cons

- Computationally intensive.
- Difficult to implement in real-time systems.

3.2 Equivalent Circuit Models (ECM)

Equivalent Circuit Models (ECM) simplify the complex electrochemical behaviour of batteries by representing them as electrical circuits composed of resistors, capacitors, and voltage sources. These models are widely used in EV battery management systems due to their balance of accuracy and computational simplicity. In an ECM, resistors model the internal resistance of the battery, while capacitors represent the dynamic response of the battery to charging and discharging[18].

The ECM approach involves creating a circuit that mimics the battery's behaviour in terms of voltage, current, and SOC. There are different types of ECMs, ranging from simple RC (resistor-capacitor) models to more complex ones that include multiple RC branches to capture different time constants of the battery's response. These models can be parameterised based on experimental data, allowing them to adapt to the specific characteristics of different battery types[18].

In dual battery systems, ECM is particularly useful because it allows for simplified control and management of the batteries. The model can dynamically adjust to the varying conditions of each battery, ensuring that energy is distributed efficiently between the two systems. For instance, ECMs can be used to monitor the SOC and voltage of each battery in real-time, enabling optimal power distribution and preventing over-discharge or overcharge conditions[19].

Pros

- Simple and efficient.
- Suitable for real-time applications.
- Easily adaptable to different battery types.

Cons

- Less accurate than electrochemical models.
- Limited ability to capture degradation mechanisms.

3.3 Data-Driven Models

Data-driven models leverage Machine Learning (ML) and Artificial Intelligence (AI) to predict battery performance based on historical data. These models use algorithms to analyse large datasets, such as charging/discharging cycles, temperature, and voltage readings, to make real-time predictions about battery health and SOC[20]. Data-driven models are particularly useful for dual battery systems, where they can optimise energy management by learning from past performance.

3.3.1 Use of Machine Learning and AI for Battery Modelling

Machine learning algorithms, such as neural networks and regression models, can predict battery behaviour without requiring detailed knowledge of the internal electrochemical processes. This approach allows data-driven models to adapt to various battery chemistries and configurations. AI can also be used to detect anomalies in battery performance, enabling predictive maintenance that reduces the risk of failure and extends battery life[21].

Data-driven models excel in scenarios where large amounts of data are available for training the model. They can provide real-time predictions with relatively low computational overhead, making them ideal for use in EVs. However, the accuracy of these models depends on the quality and quantity of the training data, and they may struggle to predict performance in scenarios that differ significantly from the data used for training.

Pros

- Adaptable to various battery types.
- Suitable for real-time predictions.
- Useful for predictive maintenance.

Cons

- Performance depends on data quality.
- Less effective in novel scenarios.

3.4 Thermal Models

Thermal models focus on the effect of temperature on battery performance, which is a critical factor in EV systems. Batteries generate heat during operation, and excessive heat can lead to performance degradation, safety hazards, or even thermal runaway. Thermal models simulate the heat generation within the battery and the impact of temperature on battery efficiency, safety, and lifespan[22].

3.4.1 Impact of Temperature on Battery Performance and Safety

Temperature plays a crucial role in battery performance. High temperatures can accelerate degradation, while low temperatures can reduce energy capacity and increase internal resistance. Thermal models help predict these effects, allowing engineers to design cooling systems that maintain optimal battery temperatures[23].

3.4.2 Incorporating Thermal Dynamics in Battery Models

Thermal models are often integrated with ECM or electrochemical models to create a comprehensive battery management strategy. These integrated models simulate both electrical and thermal behaviour, enabling real-time control of battery temperature through cooling systems or heat exchangers. Such models are essential for ensuring safety and maximising battery life, especially in high-performance EVs[24].

Pros

- Improves battery safety
- Extends battery lifespan by managing heat
- Essential for high-power applications

Cons

- Requires integration with other models for full accuracy
- Increased computational complexity

4.0 Power Management Strategies for Dual Battery Systems

Dual battery systems in EVs have the potential to improve energy efficiency, performance, and battery longevity. However, to achieve optimal functionality, an efficient

power management system is essential. The PMS must dynamically balance the power distribution between the two batteries, ensuring that energy is allocated based on demand while preventing overloading or excessive discharge of either battery. Efficient power management minimises energy losses, enhances range, and ensures the reliability of the system by maintaining battery health through proper charging and discharging cycles[25].

One of the key challenges in managing dual battery systems is the varying characteristics of the two batteries, such as different capacities, chemistries, or performance profiles. For instance, one battery might be optimised for high energy storage, while the other is designed for high power output. Without an intelligent PMS, the system could experience suboptimal performance or premature battery degradation. Additionally, the ability to incorporate regenerative braking and energy harvesting further highlights the need for sophisticated power management strategies that can handle these dynamic energy flows[26].

4.1 Rule-Based Power Management

Rule-based power management systems operate by following predefined rules or thresholds to control the power distribution between the two batteries. These rules are typically based on variables such as State of Charge (SOC), power demand, and battery voltage. The control logic determines when and how much power is drawn from each battery based on the system's current state[27].

Rule-based systems are designed to be straightforward to implement. The control rules are often based on simple if-then logic. For example, if the SOC of one battery drops below a certain threshold, the system may switch to using the second battery until the first battery is recharged. This approach provides a relatively simple and cost-effective way to manage the batteries without requiring complex computational resources[28].

Advantages

- Rule-based systems are easy to implement and require minimal computational overhead.
- These systems do not require advanced algorithms or high levels of customisation, making them more affordable.
- Rule-based systems can respond quickly to changes in battery SOC or load demand, ensuring reliable performance in most driving conditions.

Limitations

- Rule-based systems cannot adapt to varying driving conditions or optimise for long-term efficiency.
- The rigid nature of the rules may lead to suboptimal power distribution, resulting in higher energy consumption or reduced battery life[28].

4.2 Optimisation-Based Power Management

Optimisation-based power management systems use mathematical algorithms to find the best possible solution for power distribution between the two batteries. Unlike rule-based systems, which rely on fixed rules, optimisation-based systems dynamically adjust power distribution based on real-time data and computational models. These systems are designed to maximise energy efficiency, prolong battery life, and improve overall vehicle performance[29].

Several optimisation algorithms can be applied to power management in dual battery systems. Some of the most commonly used include linear programming, dynamic programming, and genetic algorithms. Linear programming involves solving a set of linear equations to optimise a given objective function, such as minimising energy consumption or maximising range. Genetic algorithms, on the other hand, are inspired by evolutionary biology and use iterative processes to evolve solutions over time[30].

4.2.1 Comparison of Different Optimisation Techniques

- Linear Programming: Efficient and well-suited for solving deterministic problems. However, it may not be ideal for systems with highly dynamic or nonlinear characteristics, such as dual battery systems that vary based on temperature, SOC, and load demand.
- Dynamic Programming: Offers greater flexibility and can handle complex, nonlinear systems. However, it is computationally intensive and may not be suitable for real-time applications in EVs.

- Genetic Algorithms: Provide a more adaptive and flexible approach, especially for complex and unpredictable systems. However, they can be slow to converge and require significant computational resources[26].

4.3 Predictive Power Management

Predictive power management systems rely on forecasting future conditions, such as driving patterns, battery behaviour, and energy demands, to optimise power distribution between the two batteries. One of the most advanced predictive techniques is Model Predictive Control (MPC), which uses a mathematical model of the system to predict future behaviour and adjust control actions accordingly[31].

MPC works by creating a dynamic model of the battery system that takes into account variables such as SOC, temperature, and power demand. The control system predicts how the system will behave over a set period (prediction horizon) and adjusts power distribution based on the predicted state. This allows the system to account for future changes in energy demand and driving conditions, optimising battery usage in real-time[32].

Predictive power management offers several advantages, including:

- By anticipating future power demands, MPC ensures that the battery system operates at optimal efficiency, reducing energy losses.
- MPC minimises the stress on the batteries by distributing power in a way that reduces deep discharges and overcharging, extending battery life[32].

Pros

- High efficiency.
- Prolongs battery life.
- Adapts to real-time conditions.

Cons

- High computational cost.
- Requires accurate system modelling.

4.4 Energy Harvesting and Regenerative Braking Systems

Energy harvesting and regenerative braking systems are critical for improving the overall energy efficiency of EVs. Regenerative braking allows EVs to recover energy that would otherwise be lost during braking and deceleration, storing it back in the batteries for later use. In dual battery systems, regenerative energy can be distributed between the two batteries based on their SOC and energy needs, further improving efficiency[33].

In a dual battery system, energy harvesting can be optimised by allocating regenerative energy to the battery that is best suited to store it. For example, the high-power battery could handle the rapid energy influx from braking,

Table 2. Comparison of power management strategies[28-35]

Strategy	Advantages	Limitations	Suitability
Rule-Based	Simple, low-cost, real-time	Limited flexibility, potential inefficiencies	Basic systems, cost-sensitive designs
Optimisation-Based	High efficiency, adaptable	Computationally intensive	Advanced EVs, performance-oriented systems
Predictive (MPC)	High efficiency, battery life extension	High computational cost, model-dependent	Cutting-edge EV designs
Energy Harvesting	Increases range, utilises lost energy	Requires sophisticated PMS	All EV systems with dual battery setups

while the high-energy battery could store excess energy for longer durations. This division of labour ensures that the energy recovery process is efficient and maximises the use of the harvested energy[34].

To manage power distribution during regenerative braking, the PMS must continuously monitor both batteries' SOC and determine which battery is most capable of absorbing the recovered energy. This requires a high level of coordination and control to ensure that energy is distributed efficiently and that neither battery is overcharged. A well-designed PMS can increase the range of the vehicle by as much as 20% by optimising regenerative braking[35].

5.0 Challenges and Future Directions

5.1 Challenges

While dual battery systems offer numerous advantages in EVs, their implementation presents several challenges, particularly in modelling and power management. These challenges stem from the complexity of managing two distinct battery systems with different characteristics, chemistries, and capacities. Some of the key challenges are:

5.1.1 Complexity of Modelling

The inherent complexity of dual battery systems makes accurate modelling difficult. Each battery may have different charge/discharge rates, degradation mechanisms, and thermal behaviours, which must be modelled accurately. Electrochemical models, though highly detailed, require significant computational resources, which are not feasible for real-time applications in EVs. ECMs simplify this complexity, but they often lack the precision necessary for long-term performance prediction and degradation analysis[19].

5.1.2 Power Management Complexity

Managing power distribution between two batteries introduces significant challenges. It is crucial to maintain an optimal balance of SOC between the batteries while considering their respective capacities and performance characteristics. Power management systems must account for varying loads, driving conditions, and battery health, which requires real-time monitoring and dynamic adjustments. This adds to the complexity of the Battery Management System (BMS), making it difficult to implement efficient algorithms that work in all scenarios[36].

5.1.3 Thermal Management

In a dual battery system, each battery generates heat during operation, which can lead to thermal imbalances. Batteries are highly sensitive to temperature fluctuations, and maintaining an optimal temperature range is crucial for preventing degradation and ensuring safety. However, integrating thermal management for two distinct battery systems in a compact EV architecture poses additional challenges. Effective cooling and heating solutions that cater to both batteries while optimising performance are still a challenge[23].

5.1.4 Cost and Scalability

Developing and implementing dual battery systems in EVs increases costs due to the need for additional components, such as extra batteries, more complex BMS, and advanced thermal management systems. Furthermore, scaling these systems to mass-market EVs is difficult due to cost constraints. This presents a barrier to the widespread adoption of dual battery systems[37].

5.2 Future Trends in EV Battery Systems and Power Management

Looking ahead, several key trends are expected to shape the future of dual battery systems and power management in EVs. These trends include the continued evolution of battery technologies, increased integration of AI and IoT, and the development of new power management strategies.

5.2.1 Hybrid Energy Storage Systems

Future dual battery systems may evolve into hybrid energy storage systems, where batteries are combined with other energy storage technologies, such as supercapacitors. Supercapacitors provide rapid bursts of power, making them ideal for applications such as regenerative braking. Integrating supercapacitors

with dual battery systems could improve energy recovery and efficiency while reducing the strain on the batteries[37].

5.2.2 *Wireless Charging and Vehicle-to-Grid (V2G) Integration*

Wireless charging technologies and Vehicle-to-Grid (V2G) capabilities are expected to become more prevalent in future EVs. Dual battery systems could be optimised for seamless integration with wireless charging infrastructure, allowing for more efficient charging without the need for physical connections. Additionally, V2G systems enable EVs to supply energy back to the grid, creating opportunities for load balancing and energy storage. Power management systems in dual battery configurations will need to adapt to these technologies, ensuring that energy is distributed efficiently between the grid and the vehicle[19].

5.2.3 *Enhanced Safety Features*

As battery technologies advance, safety will remain a top priority in EV development. Future dual battery systems will likely incorporate advanced safety features, such as real-time thermal monitoring, automatic shutdown mechanisms, and fire-resistant materials. The integration of AI and IoT will play a critical role in enhancing safety, enabling predictive monitoring of battery health and early detection of potential failures[38].

6.0 Conclusions

In this review, we have explored the various modelling techniques and power management strategies used for dual battery systems in EVs. Each modelling technique, from electrochemical models to equivalent circuit models and data-driven approaches, offers distinct advantages and limitations. Electrochemical models provide high accuracy in simulating battery behaviour but are computationally intensive and often unsuitable for real-time applications. Equivalent circuit models, while less detailed, offer a practical balance between accuracy and efficiency, making them ideal for many EV applications. Data-driven models, powered by AI and machine learning, present a flexible and adaptive approach but rely heavily on the availability of high-quality data.

Power management strategies, such as rule-based, optimisation-based, and predictive methods, are critical for ensuring that dual battery systems perform optimally. Rule-based strategies offer simplicity and low cost, making them suitable for basic applications, while optimisation-based and predictive strategies are more complex but offer higher efficiency and better long-term battery health. Each strategy must be carefully selected based on the specific requirements of the EV, whether it is cost-sensitivity, performance, or the need for real-time adjustments.

Choosing the appropriate modelling technique and power management strategy is essential for maximising the benefits of dual battery systems. The complexity of managing two batteries with different capacities, chemistries, or performance characteristics requires precise control and monitoring. Advanced modelling techniques can predict battery behaviour and degradation, while sophisticated power management systems can dynamically balance power distribution based on driving conditions, user preferences, and real-time battery health data. This dynamic balance ensures that the vehicle operates efficiently, with minimal energy loss and extended battery lifespan.

The findings from this review highlight the potential for dual battery systems to significantly improve the performance and efficiency of EVs. By leveraging the strengths of two different batteries, these systems can offer increased range, enhanced power delivery, and greater flexibility in managing energy demands. The integration of advanced power management strategies further ensures that the dual battery system operates at peak efficiency, adapting to the driving environment and maintaining battery health over time.

Looking to the future, dual battery systems hold significant potential for advancing electric vehicle technology. The continued development of advanced battery chemistries, such as solid-state batteries and lithium-sulfur batteries, along with innovations in AI-driven power management, will likely lead to even more efficient and powerful EVs. The integration of these technologies will enable EVs to meet the increasing demands for longer range, faster charging times, and improved safety features, making them more attractive to consumers and further accelerating the transition away from internal combustion engines.

7.0 Author Contributions

The authors declare that they have equal rights to this paper.

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