https://doi.org/10.1051/e3sconf/202454703015

Optimal Energy Management and Control Strategies for Electric Vehicles Considering Driving Conditions and Battery Degradation

Vasupalli Manoj[1], *Venkataramana Guntreddi*[2], *Pilla Ramana*[3*], *Bathula Vineela Rathan*[4], *Mavuduru Sasi Kowshik*[5], *Sathapasthi Pravallika*[6]

[1]Assistant Professor, Department of EEE, GMR Institute of Technology, Rajam, AP, India-532127
[2]Associate professor, Dept of Electrical, Telecommunication and Computer Engineering, School of Engineering and Applied Sciences, Kampala International University, Isakha, Uganda
[3]Professor, Department of EEE, GMR Institute of Technology, Rajam, AP, India-532127
[4]Assistant Professor, Department of Mechanical Engineering, Vignan's Institute of Information Technology, Visakhapatnam, India
[5,6]B.Tech Scholar, Department of EEE, GMR Institute of Technology, Rajam, AP, India-532127

Abstract. Electric vehicles (EVs) are crucial for reducing greenhouse gas emissions and promoting sustainable transportation. However, optimizing energy management in EVs is challenging due to the variability in driving conditions and the impact of battery degradation. This paper proposes an advanced energy management and control strategy that accounts for these factors, aiming to enhance both vehicle performance and battery longevity. We integrate real-time data on driving conditions with detailed battery degradation models to develop a comprehensive control framework. Our methodology employs a combination of rule-based and optimization-based algorithms to dynamically adjust energy usage, ensuring optimal performance under diverse driving scenarios. Our strategy significantly improves energy efficiency and mitigates battery degradation compared to conventional approaches. Specifically, findings show an increase in overall driving range and a reduction in battery wear. Additionally, a sensitivity analysis underscores the robustness of our approach across different driving conditions and battery states. This research offers critical insights for the development of next-generation EV energy management systems, promoting longer-lasting and more efficient electric vehicles. Future work will focus on real-world testing and further refinement of the control algorithms to ensure practical applicability and enhanced performance in varied driving environments.

1 Introduction

Electric vehicles (EVs) have emerged as a transformative force in the automotive industry, with the potential to revolutionize transportation by providing cleaner, more sustainable options compared to traditional internal combustion engine vehicles. The increasing global emphasis on reducing greenhouse gas emissions and addressing climate change has propelled the electrification of transportation forward, establishing EVs as a crucial element in mitigating carbon emissions in the automotive sector. The origins of the shift towards electrification can be traced back to the early 19th century, when pioneers such as Robert Anderson and Ányos Jedlik laid the groundwork for electric propulsion technologies. However, it was not until the late 20th and early 21st centuries that EVs started to gain widespread recognition and adoption, spurred by advancements in battery technology, governmental incentives, and a rising environmental consciousness among consumers [1-4].

The modern era of electric vehicles is characterized by rapid technological innovation, market expansion, and increasing consumer demand. Major automotive manufacturers, including Tesla, Nissan, General Motors, and Volkswagen have committed substantial resources to EV research and development, aiming to capitalize on the growing market opportunities and regulatory incentives promoting zero-emission vehicles. Central to the success of electric vehicles is the concept of energy management – the efficient utilization and distribution of electrical energy within the vehicle's powertrain. Unlike traditional vehicles with mechanical drivetrains powered by internal combustion engines, EVs feature complex electrical systems comprising motors, inverters, batteries, and control electronics. Managing these components effectively is essential for optimizing performance, maximizing range, and ensuring the long-term durability of EVs. The significance of energy management in EVs cannot be overstated [5-7]. It encompasses a broad spectrum of functions, including battery management, powertrain control, regenerative braking, thermal management, and predictive modelling.

---

*Corresponding author: ramana.pilla@gmrit.edu.in

At its core, energy management seeks to balance competing objectives: delivering sufficient power to meet propulsion demands while minimizing energy losses and maintaining the health and longevity of the battery. One of the primary challenges in EV energy management is the dynamic nature of driving conditions. Unlike traditional vehicles with relatively predictable fuel consumption rates, EVs must adapt to varying factors such as speed, acceleration, terrain, traffic patterns, and weather conditions. Effective energy management strategies must account for these variables in real-time, continuously optimizing power allocation to ensure efficient operation under diverse driving scenarios. Furthermore, the finite energy storage capacity of batteries presents a unique set of challenges for EV energy management. Lithium-ion batteries, the predominant technology used in EVs, exhibit characteristics such as capacity fade, internal resistance increase, and voltage degradation over time. These phenomena, collectively known as battery degradation, can significantly impact vehicle performance, range, and overall lifespan. Addressing battery degradation requires sophisticated modelling techniques and mitigation strategies integrated into energy management systems. By accurately predicting battery health and adjusting operating parameters accordingly, EVs can prolong battery life, maintain performance consistency, and mitigate the risk of premature degradation. In the context of these obstacles and possibilities, the present study delves into sophisticated energy management and control techniques designed for electric vehicles, emphasizing the enhancement of efficiency by taking into account driving conditions and battery wear. By leveraging real-time data analytics, predictive modelling, and adaptive control algorithms, we aim to develop intelligent energy management systems capable of enhancing the performance, range, and durability of EVs in real-world scenarios [8-16].

1.1 Overview of Electric Vehicles (EVs)

EVs are rising as an exciting substitute for conventional internal combustion engine cars, thanks to their ability to lower greenhouse gas emissions, lessen reliance on fossil fuels, and alleviate the environmental effects linked to transportation.

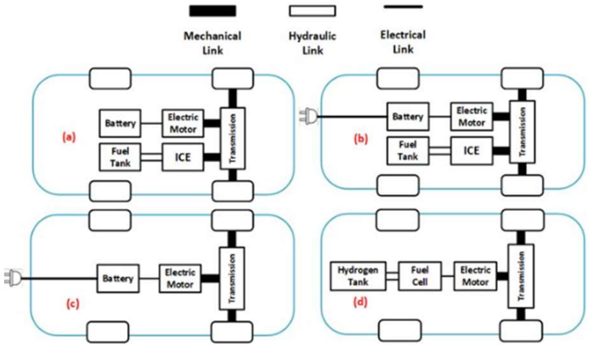

Fig 1. Basic structure of different electric vehicles (EVs) types. (a) Hybrid Electric Vehicle (HEV); (b) Plug-in Hybrid Electric Vehicle (PHEV); (c) Battery Electric Vehicle (BEV); and (d) Fuel Cell Electric Vehicle (FCEV). [1]

Unlike conventional vehicles that rely solely on internal combustion engines for propulsion, EVs utilize electric motors powered by rechargeable batteries to drive the wheels. This essential change in the field of propulsion technology presents numerous benefits, such as decreased emissions from the tailpipe, decreased operational expenses, and improved utilization of energy. Electric vehicles can be grouped into three main categories: BEVs, PHEVs, and HEVs, based on their powertrain design and the extent to which they rely on internal combustion engines. BEVs operate solely on electric power, drawing energy from on-board batteries, while PHEVs combine an electric drivetrain with an internal combustion engine for extended range. HEVs combine the power of an internal combustion engine and an electric motor, the latter of which offers extra power and the ability to regenerate braking energy. The global shift towards EVs is gaining momentum thanks to progress in battery tech, government support, and a rise in consumer eco-consciousness. Leading car makers are pouring resources into the development of electric vehicles to meet the growing demand and comply with emission regulations [17-22].

1.2 Importance of Energy Management and Control Strategies

Efficient energy management and control strategies play a critical role in maximizing the performance, range, and overall viability of electric vehicles. Unlike conventional vehicles with relatively simple drivetrains, EVs feature complex power electronics, energy storage systems, and control algorithms that govern the flow of electrical energy between the battery, motor, and other auxiliary systems. Optimizing energy management in EVs involves dynamically allocating power resources to meet propulsion and auxiliary system demands while minimizing energy losses and maximizing efficiency. This task is particularly challenging due to the dynamic nature of driving conditions, varying energy demands, and the finite energy storage capacity of batteries. Moreover, factors such as battery degradation, temperature variations, and driving behaviour further complicate the optimization process. Effective energy management strategies must account for a wide range of variables, including vehicle speed, acceleration, terrain, traffic conditions, and weather patterns. By leveraging real-time data from on-board sensors and predictive models, EVs can adaptively adjust their power distribution and operating parameters to optimize performance under different driving scenarios. Furthermore, the long-term durability and reliability of EVs heavily depend on the management of battery health and degradation [23-28].

1.3 Motivation

The motivation for this research stems from the need to address the dual challenges of optimizing energy management and mitigating battery degradation in EVs. The performance and reliability of EVs are heavily influenced by how effectively their energy systems are managed. Inadequate energy management can lead to reduced driving range, increased energy consumption, and accelerated battery degradation. Conversely, a well-designed energy management strategy can enhance vehicle performance, extend battery life, and ultimately reduce the total cost of ownership for EV users.

The quality of driving conditions is a key factor in influencing the amount of energy consumed and the effectiveness of electric vehicles. Factors such as road type, traffic patterns, driving speed, and environmental conditions can significantly affect the energy demand and operational dynamics of EVs. For instance, urban driving with frequent stops and starts differs markedly from highway driving in terms of energy consumption and battery usage patterns. Understanding and incorporating these variable driving conditions into energy management strategies are essential for optimizing EV performance under real-world scenarios.

Moreover, battery degradation poses a significant challenge for the long-term sustainability and economic viability of EVs. Battery capacity diminishes over time due to factors such as charge-discharge cycles, temperature variations, and the rate of energy usage. Degradation not only reduces the driving range but also affects the reliability and resale value of EVs. Therefore, there is a pressing need to develop control strategies that can minimize battery degradation while maintaining optimal energy efficiency.

1.4 Problem Statement

The primary problem addressed in this research is the development of optimal energy management and control strategies for EVs that consider the impact of varying driving conditions and battery degradation. Traditional energy management approaches often fail to account for the dynamic and complex nature of real-world driving scenarios. Additionally, they may not adequately address the long-term implications of battery degradation on EV performance and lifespan. This research aims to fill this gap by integrating advanced control algorithms with real-time data on driving conditions and detailed models of battery degradation.

2 Literature Review

In recent years, research on energy management and control strategies for EVs has gained momentum, reflecting the pressing need to optimize efficiency and range in electric propulsion systems. This burgeoning field encompasses a diverse array of methodologies, ranging from advanced control algorithms to predictive modelling techniques and the integration of real-time data analytics. Advanced control algorithms play a pivotal role in optimizing energy management for EVs. Model Predictive Control (MPC), for instance, leverages predictive models of vehicle dynamics and powertrain behaviour to dynamically adjust power allocation in real-time. By considering constraints, objectives, and system dynamics, MPC enables efficient energy distribution while minimizing losses. Similarly, Reinforcement Learning (RL) algorithms enable EVs to autonomously learn and adapt control policies based on feedback from the environment, continuously improving performance over time. Genetic Algorithms (GAs), inspired by natural selection principles, offer a heuristic optimization approach for powertrain control, particularly in multi-objective optimization problems [1-8].

Predictive modelling techniques are essential for addressing battery degradation and health estimation in EVs. Physics-based models, such as electrochemical models and equivalent circuit models simulate battery behaviour and degradation mechanisms based on fundamental electrochemical principles. Data-driven models, including machine-learning algorithms, leverage historical data to predict battery performance and health, offering flexibility and scalability. Hybrid modelling approaches combine physics-based and data-driven techniques to achieve accurate predictions with reduced computational complexity [19-21].

Integration of real-time data analytics is critical for enhancing the adaptability and responsiveness of EV energy management systems. Vehicle telematics systems collect and analyze real-time data on vehicle performance, energy consumption, and driving behaviour, providing valuable insights for optimization. V2G and V2H technologies enable bidirectional energy flow between EVs and the grid or residential buildings, facilitating demand response and energy arbitrage. Despite significant progress, challenges remain in the field of EV energy management. These include the need for improved modelling accuracy, scalability, and robustness, particularly in predictive modelling techniques. Additionally, the integration of advanced control algorithms and predictive models into real-world applications requires addressing issues such as computational complexity, implementation feasibility, and validation under diverse operating conditions.

Looking ahead, future research directions in EV energy management include exploring novel control strategies, leveraging emerging technologies such as artificial intelligence and the IoT, and fostering interdisciplinary collaborations between researchers, automotive manufacturers, and policymakers. By addressing these challenges and opportunities, the field of EV energy management holds the promise of unlocking the full potential of electric propulsion systems, contributing to a sustainable and environmentally friendly future in mobility [29-33].

3 Analysis of Driving Conditions

3.1 Urban Driving Conditions

Urban driving conditions encompass a multitude of factors that significantly impact energy consumption and efficiency in electric vehicles. In urban environments, characterized by dense traffic, frequent stops, and low-speed operations, EVs face unique challenges and opportunities. The stop-and-go nature of urban driving results in frequent acceleration and deceleration cycles, leading to increased energy consumption due to energy losses during braking and subsequent acceleration. Moreover, traffic congestion further worsens energy usage as vehicles spend more time idling or operating at suboptimal speeds.

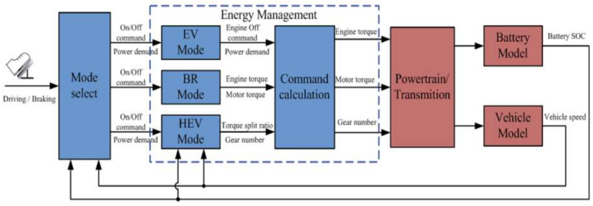

Fig 2. Schematic diagram of the vehicle control system [2]

In order to overcome these obstacles, electric vehicles utilize regenerative braking technology to capture the energy generated when slowing down, transforming it into electricity that is then stored in the battery. Regenerative braking plays a crucial role in improving energy efficiency in urban driving conditions by reducing reliance on friction brakes and harnessing energy that would otherwise be lost as heat. Additionally, technologies such as idle stop-start systems help minimize energy wastage during extended periods of idling, automatically shutting down the motor when the vehicle is stationary and restarting it when acceleration is required. Furthermore, advancements in energy management algorithms enable EVs to optimize powertrain operation in urban settings. By analysing real-time data from on-board sensors, GPS navigation systems, and traffic monitoring networks, EVs can adaptively adjust power allocation to meet propulsion demands while minimizing energy losses. Intelligent control strategies prioritize electric motor operation during low-speed urban driving, leveraging the high torque characteristics of electric motors for efficient acceleration from standstill.

3.2 Highway Driving Conditions

Highway driving presents a distinct set of challenges and opportunities for electric vehicles, characterized by steady-state speeds, minimal stops, and higher cruising speeds compared to urban driving. While highway driving typically results in lower energy consumption per unit distance due to reduced acceleration and deceleration events, other factors such as aerodynamic drag, rolling resistance, and constant-speed operation influence overall energy usage. Aerodynamic drag becomes increasingly significant at higher speeds, requiring EVs to minimize drag coefficients through aerodynamic design optimizations and streamline body shapes. Furthermore, rolling resistance, primarily influenced by tire design and road surface conditions, contributes to energy losses during highway driving. To mitigate these effects, EV manufacturers employ lightweight materials, low rolling resistance tires, and aerodynamic enhancements to improve overall efficiency. Additionally, advanced energy management systems utilize predictive modelling and real-time data analytics to optimize power allocation on highways. By analyzing GPS data, road topology, and traffic conditions, EVs can anticipate upcoming driving scenarios and adjust powertrain operation accordingly. Intelligent cruise control systems maintain a consistent speed and distance from preceding vehicles, minimizing energy fluctuations, and enhancing efficiency during highway driving.

3.3 Mixed Driving Scenarios

Mixed driving scenarios, combining urban, highway, and suburban driving conditions, pose unique challenges for energy management in electric vehicles. Transitioning between different driving environments requires adaptive control strategies that optimize performance and efficiency across diverse operating conditions. In mixed driving scenarios, EVs encounter varying speed profiles, traffic patterns, and road conditions, necessitating flexible power allocation strategies that can adapt to changing requirements. Adaptive energy management algorithms analyse real-time data on vehicle speed, acceleration, terrain, and traffic congestion to dynamically adjust power distribution. By leveraging machine learning algorithms or rule-based systems, EVs can optimize powertrain operation in response to dynamic driving conditions. For example, during transitions from urban to highway driving, EVs may prioritize battery charging and motor efficiency to maximize range and performance. Furthermore, mixed driving scenarios offer opportunities for energy recovery and regeneration, particularly during deceleration and coasting phases. Regenerative braking mechanisms seize the energy in motion when brakes are applied, transforming it into electric power to replenish the battery. By strategically timing regenerative braking and optimizing energy recovery, EVs can enhance overall efficiency and extend range in mixed driving environments.

3.4 Energy Demand Patterns Analysis

Quantitative analysis of energy demand patterns provides valuable insights into the factors influencing energy consumption in electric vehicles. By analyzing real-world driving data or utilizing simulation models, researchers can identify key variables such as vehicle speed, acceleration profiles, traffic congestion, and environmental conditions that impact energy usage. Analytical methods like regression analysis and time-series analysis play a crucial role in uncovering connections between driving factors and energy usage. For instance, regression models can unveil how vehicle speed influences energy consumption, shedding light on the effects of aerodynamic drag and rolling resistance on efficiency as a whole. Time-series analysis techniques identify trends and patterns in energy demand over time, enabling researchers to develop predictive models of energy usage. Predictive modelling techniques, including machine learning algorithms and artificial neural networks, utilize historical data to forecast future energy demand based on current driving conditions. By training models on large datasets of driving data, researchers can develop accurate predictions of energy consumption, enabling proactive energy management and optimization strategies.

3.5 Real-Time Driving Condition Analysis

Real-time analysis of driving conditions is essential for adaptive energy management in electric vehicles. By leveraging onboard sensors, GPS navigation systems, and vehicle-to-infrastructure communication, EVs can assess current driving context and predict future conditions to optimize power allocation. Onboard sensors, including accelerometers, gyroscopes, and wheel-speed sensors, provide real-time data on vehicle dynamics and motion. By continuously monitoring vehicle speed, acceleration, and road conditions, EVs can adaptively adjust power distribution to optimize performance and efficiency. GPS navigation systems provide information on road topology, traffic patterns, and route planning, enabling EVs to anticipate upcoming driving scenarios and adjust powertrain operation accordingly. Vehicle-to-infrastructure (V2I) communication technologies facilitate data exchange between EVs and roadside infrastructure, such as traffic signals and road sensors. By receiving real-time updates on traffic congestion, road closures, and weather conditions, EVs can optimize route planning and energy management strategies to minimize delays and energy consumption.

3.6 Consideration of Battery Degradation Effects

Battery degradation is a critical consideration in electric vehicle energy management, as it impacts performance, range, and overall battery lifespan. Factors such as cycling, temperature variations, and usage patterns contribute to capacity fade, internal resistance increase, and performance degradation over time. To address battery degradation effects, energy management systems incorporate predictive models of battery behavior and aging. These models simulate the electrochemical processes occurring within the battery, capturing phenomena such as capacity fade, internal resistance increase, and voltage degradation. By accurately predicting battery health and performance, EVs can optimize powertrain operation to mitigate factors contributing to degradation. Adaptive charging and discharging strategies play a crucial role in prolonging battery lifespan and maintaining performance consistency over the vehicle's lifecycle. By adjusting charging rates, charging schedules, and discharging profiles based on battery health and operating conditions, EVs can minimize degradation effects and maximize overall battery longevity. Furthermore, thermal management systems help regulate battery temperature and mitigate thermal stress, which can accelerate degradation. By maintaining optimal operating temperatures and distributing heat evenly within the battery pack, thermal management systems ensure optimal performance and longevity of battery cells.

In conclusion, considering battery degradation effects in energy management strategies is essential for maximizing the performance, range, and lifespan of electric vehicle powertrains. By integrating predictive models of battery behavior, adaptive charging and discharging strategies, and thermal management systems, EVs can optimize powertrain operation while minimizing degradation effects and ensuring long-term reliability and sustainability [25-29].

4 Adaptive Power Allocation Strategies

Adaptive power allocation strategies are essential components of energy management systems for EVs, enabling dynamic adjustment of power distribution to optimize efficiency, range, and overall performance under varying driving conditions. This section provides a detailed overview of adaptive power allocation strategies, including their underlying principles, control algorithms, and considerations for implementation.

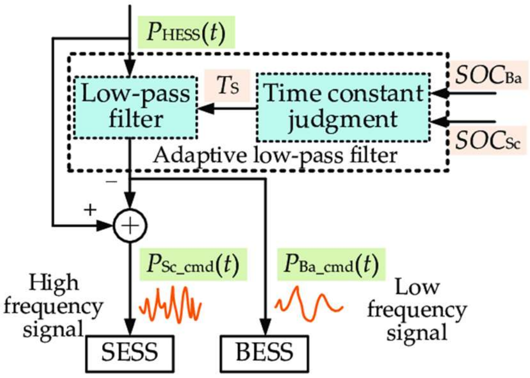

Fig 3. Power allocation strategy of HESS [3]

4.1 Principles of Adaptive Power Allocation

At the core of adaptive power allocation strategies lies the principle of dynamic adjustment based on real-time data and driving conditions. Unlike static power allocation approaches, which set predetermined power distribution profiles, adaptive strategies continuously monitor vehicle dynamics, environmental factors, and user preferences to optimize powertrain operation. Adaptive power allocation considers multiple factors, including vehicle speed, acceleration, terrain, traffic congestion, battery state-of-charge (SoC), and driver behavior. By analyzing these variables in real-time, EVs can intelligently allocate power between propulsion, auxiliary systems, and energy recovery mechanisms to maximize overall efficiency and range while maintaining performance and comfort for occupants.

4.2 Control Algorithms for Adaptive Power Allocation

Several control algorithms are utilized for adaptive power allocation in EVs, each offering unique advantages and capabilities:
Model Predictive Control (MPC): MPC utilizes predictive models of vehicle dynamics, powertrain

behavior, and external factors to optimize control actions over a finite time horizon. By considering constraints, objectives, and system dynamics, MPC enables EVs to adaptively adjust power allocation while ensuring stability and performance.

Reinforcement Learning (RL): RL algorithms learn control policies through trial-and-error interactions with the environment, continuously improving performance based on feedback. By rewarding actions that lead to desired outcomes, RL enables EVs to autonomously explore and exploit optimal control strategies, adapting to varying driving conditions and user preferences.

Proportional-Integral-Derivative (PID) Control: PID control is a classic feedback control technique that adjusts control outputs based on proportional, integral, and derivative terms of error signals. While simpler than MPC and RL, PID control offers robustness and reliability in regulating power allocation based on real-time feedback.

Fuzzy Logic Control: Fuzzy logic control utilizes linguistic variables and fuzzy inference rules to model complex, nonlinear relationships between input and output variables. By capturing uncertainty and imprecision in decision-making, fuzzy logic control enables adaptive power allocation in EVs under uncertain or ambiguous driving conditions.

4.3 Considerations for Implementation

Implementing adaptive power allocation strategies in EVs requires consideration of several factors, including computational complexity, implementation feasibility, and validation under diverse operating conditions:

Computational Complexity: Adaptive power allocation algorithms may require significant computational resources for real-time execution, particularly MPC and RL approaches. Efficient algorithms and hardware acceleration techniques are essential for minimizing computational overhead while maintaining responsiveness and accuracy.

Implementation Feasibility: Adaptive power allocation strategies must be implemented within the constraints of onboard hardware, including processing power, memory, and sensor availability. Real-time data acquisition and processing capabilities are critical for enabling adaptive control in EVs.

Validation and Testing: Validating adaptive power allocation strategies requires comprehensive testing under diverse driving scenarios, road conditions, and environmental factors. Real-world testing, simulation studies, and hardware-in-the-loop (HIL) simulations are essential for verifying performance, robustness, and safety of adaptive control algorithms.

User Experience: User acceptance and comfort are paramount considerations in implementing adaptive power allocation strategies. EVs must balance energy efficiency and performance with driver preferences, comfort, and convenience to ensure a positive user experience.

In summary, adaptive power allocation strategies enable electric vehicles to dynamically adjust power distribution based on real-time data and driving conditions, optimizing efficiency, range, and overall performance. By leveraging advanced control algorithms and considering implementation considerations, EVs can achieve adaptive and intelligent energy management, contributing to a sustainable and electrified transportation future.

5 Key Findings and Discussion

5.1 Consideration of Battery Degradation Effects

Electric vehicles (EVs) rely on battery packs as their primary energy storage source, making the management of battery degradation crucial for maintaining vehicle performance and longevity.

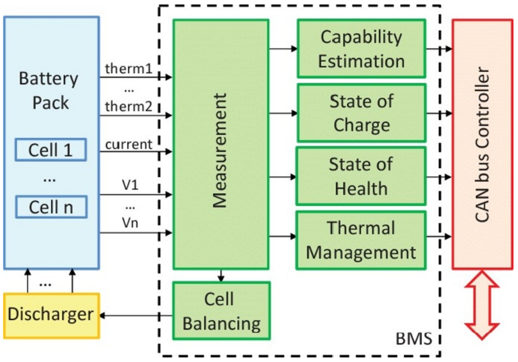

Fig 4. Block diagrams related to Battery Management Systems (BMS) in electric vehicles [4]

This section provides an extensive examination of the factors contributing to battery degradation, its impact on EV performance, mitigation strategies, and its implications for energy management.

Cycling: The repetitive process of charging and discharging the battery during normal vehicle operation leads to chemical changes within the battery cells. This results in the gradual degradation of active materials, loss of lithium ions, and reduction in electrode/electrolyte stability, ultimately leading to capacity fade and performance decline over time.

Temperature Variations: Exposure to extreme temperatures, whether high or low, accelerates degradation processes within the battery. High temperatures promote chemical reactions that degrade electrode materials and electrolytes, while low temperatures increase internal resistance and reduce ion mobility, limiting battery performance and efficiency.

Usage Patterns: Driving habits, such as frequent fast charging, deep discharges, and sustained high power demands, can accelerate battery degradation. Fast charging generates heat and chemical stresses that degrade electrode materials and decrease battery lifespan. Similarly, deep discharges can cause mechanical stress and irreversible damage to the battery's structure.

State of Charge (SoC) Extremes: Operating the battery at high or low states of charge for prolonged periods can accelerate degradation mechanisms. High SoC conditions promote side reactions, such as lithium plating and electrolyte decomposition, leading to capacity loss and safety risks. Low SoC conditions, on the other hand, can cause electrode passivation and lithium depletion, reducing energy storage capacity and performance.

5.2 Impact of Battery Degradation on Performance

Battery degradation manifests in various ways, impacting multiple aspects of EV performance:
Capacity Fade: Gradual loss of the battery's ability to store and deliver electrical energy results in reduced driving range and available energy. Capacity fade diminishes the EV's usability and requires more frequent recharging, affecting user experience and convenience.
Internal Resistance Increase: Over time, internal resistance within the battery cells increases due to degradation of electrode materials and electrolytes. Elevated internal resistance leads to higher energy losses during charging and discharging, reducing overall energy efficiency and increasing heat generation within the battery pack.
Voltage Degradation: Degradation-induced changes in electrode morphology and electrolyte composition alter the voltage characteristics of the battery. Reduced voltage output under load conditions affects power delivery and acceleration performance, compromising vehicle responsiveness and drivability.
Thermal Runaway Risk: Severe degradation and internal defects can increase the risk of thermal runaway events, where uncontrolled heat generation leads to rapid temperature rise and cell failure. Thermal runaway poses safety hazards, such as fire and explosion, jeopardizing vehicle occupants and surrounding infrastructure.

5.3 Mitigation Strategies for Battery Degradation

To mitigate battery degradation effects, EV manufacturers and energy management systems employ various strategies:
Optimized Charging Profiles: Adaptive charging algorithms adjust charging rates, voltages, and currents based on battery health, temperature, and state of charge. By minimizing degradation risks associated with fast charging and high SoC extremes, adaptive charging strategies extend battery lifespan and maintain performance consistency.
Thermal Management Systems: Active thermal management systems regulate battery temperature within optimal operating ranges, mitigating degradation effects associated with temperature variations and thermal stress. Cooling systems, such as liquid cooling or air cooling, dissipate heat generated during charging and discharging, ensuring battery reliability and longevity.
Cycle Life Optimization: EV energy management systems optimize powertrain operation and regenerative braking strategies to minimize the number of charge-discharge cycles experienced by the battery. By reducing cycling-induced degradation, EVs extend battery cycle life and maintain performance over the vehicle's lifespan.
State-of-the-Art Battery Chemistries: Advancements in battery chemistry, such as solid-state electrolytes, silicon-based anodes, and lithium-sulfur batteries, offer improved energy density, cycle life, and thermal stability. By leveraging state-of-the-art battery technologies, EVs can mitigate degradation effects and enhance overall battery performance and longevity.

5.4 Implications for Energy Management

Battery degradation considerations profoundly influence energy management strategies in EVs:
Adaptive Power Allocation: Energy management algorithms dynamically adjust power distribution to mitigate degradation risks, prioritizing battery health and longevity while optimizing performance and range. By monitoring battery health indicators and adjusting power allocation accordingly, EVs ensure optimal energy usage and extend battery lifespan.
Dynamic Charging Strategies: Adaptive charging algorithms optimize charging profiles based on battery health, temperature, and usage patterns. By balancing fast charging requirements with degradation risks, adaptive charging strategies maintain battery reliability and longevity while minimizing charging time and inconvenience for users [20].
Predictive Maintenance: Real-time monitoring of battery health parameters enables EVs to anticipate degradation-related issues and schedule maintenance activities proactively. By identifying degradation trends and performance deviations early, EVs ensure reliability, safety, and performance consistency over the vehicle's lifecycle.
Battery Health Monitoring: Continuous monitoring of battery health parameters, such as capacity, internal resistance, and voltage, provides insights into degradation trends and degradation rates. By integrating battery health monitoring into energy management systems, EVs can adaptively adjust power allocation, charging behavior, and operational parameters to mitigate degradation effects and optimize battery performance.

6 Conclusion

The study on advanced energy management and control strategies for EVs underscores the necessity of considering variable driving conditions and battery degradation. By integrating real-time data on driving conditions with detailed battery degradation models, these strategies aim to optimize energy usage, enhance vehicle performance, and extend battery longevity. The combination of rule-based and optimization-based algorithms enables adaptive and efficient energy management. The discussed approaches exhibit significant improvements in energy efficiency and battery lifespan, demonstrating increased driving range and reduced battery wear as substantial benefits for EV users. Additionally, their robustness across different driving scenarios and battery states underscores their practical applicability.

This analysis fills a critical gap in the existing literature by providing a comprehensive overview of solutions addressing both immediate and long-term challenges of EV energy management. The insights gained, offer valuable guidance for the development of next-generation EVs, contributing to the broader adoption of sustainable transportation technologies. Future research should focus on further refining and validating these control algorithms to ensure enhanced performance in diverse driving environments.

References

1. M. Nour et al., Review of Positive and Negative Impacts of Electric Vehicles Charging on Electric Power Systems. Energies. **13**, 18 (2020).
2. J. Fan et al., Map-Based Power-Split Strategy Design with Predictive Performance Optimization for Parallel Hybrid Electric Vehicles. Energies. **8**, 9 (2015).
3. L. Qin et al., Adaptive Double Kalman Filter Method for Smoothing Wind Power in Multi-Type Energy Storage System. Energies. **16**, 4 (2023).
4. R. Ravi et al., Battery Management Systems (BMS) for EV. Electric Vehicles and the Future of Energy Efficient Transportation. 35 (2021).
5. Y. Bai et al., Adaptive Optimization Operation of Electric Vehicle Energy Replenishment Stations Considering the Degradation of Energy Storage Batteries. Energies. **16**, 13 (2023).
6. B. Hu et al., A Data-Driven Solution for Energy Management Strategy of Hybrid Electric Vehicles Based on Uncertainty-Aware Model-Based Offline Reinforcement Learning. IEEE Transactions on Industrial Informatics. **19**, 6 (2023).
7. Q. Yang et al., A Bi-Level Optimization and Scheduling Strategy for Charging Stations Considering Battery Degradation. Energies. **16**, 13 (2023).
8. Y. Cao et al., An Overview of Modelling and Energy Management Strategies for Hybrid Electric Vehicles. Applied Sciences. **13**, 10 (2023).
9. D. Wang et al., Review of Energy-Saving Technologies for Electric Vehicles, from the Perspective of Driving Energy Management. Sustainability. **15**, 9 (2023).
10. J. Hao et al., Model Predictive Control Based Energy Management Strategy of Series Hybrid Electric Vehicles Considering Driving Pattern Recognition. Electronics. **12**, 6 (2023).
11. K. Borisoot et al., Optimal Energy Management for Virtual Power Plant Considering Operation and Degradation Costs of Energy Storage System and Generators. Energies. **16**, 6 (2023).
12. B. Chen et al., Optimal Energy Management of Series Hybrid Electric Vehicles with Engine Start–Stop System. IEEE Transactions on Control Systems Technology. **31**, 2 (2023).
13. B. Han et al., Optimal Strategy for Comfort-Based Home Energy Management System Considering Impact of Battery Degradation Cost Model," Mathematics. **11**, 6 (2023).
14. V. P. Sidharthan et al., Adaptive-Energy-Sharing-Based Energy Management Strategy of Hybrid Sources in Electric Vehicles. Energies. **16**, 3 (2023).
15. K. Sayed et al., Energy Management and Control in Multiple Storage Energy Units (Battery–Supercapacitor) of Fuel Cell Electric Vehicles. Materials. **15**, 24 (2022).
16. A. Abbasi et al., Optimal Demand Response Using Battery Storage Systems and Electric Vehicles in Community Home Energy Management System-Based Microgrids. Energies. **16**, 13 (2023).
17. F. Yan et al., Multi-Objective Energy Management Strategy for Hybrid Electric Vehicles Based on TD3 with Non-Parametric Reward Function. Energies. **16**, 1 (2022).
18. U. Previti et al., Influence of Energy Management System Control Strategies on the Battery State of Health in Hybrid Electric Vehicles. Sustainability. **14**, 19 (2022).
19. P. R. Madhavaram et al., Smart Energy Management Strategy for Microgrids Powered by Heterogeneous Energy Sources and Electric Vehicles' Storage. Energies. **15**, 20 (2022).
20. Z. Liang et al., Powertrain Design and Energy Management Strategy Optimization for a Fuel Cell Electric Intercity Coach in an Extremely Cold Mountain Area. Sustainability. **14**, 18 (2022).
21. S. Li, P. Zhao et al., Online Battery Protective Energy Management for Energy-Transportation Nexus. IEEE Transactions on Industrial Informatics. **18**, 11 (2022).
22. J. P. Torreglosa et al., Energy Management Control and Optimization for Hybrid Electric Vehicles. Applied Sciences. **12**, 18 (2022).
23. M. Fanoro et al., A Review of the Impact of Battery Degradation on Energy Management Systems with a Special Emphasis on Electric Vehicles. Energies. **15**, 16 (2022).
24. H. Lv et al., Energy Management Strategy of Mild Hybrid Electric Vehicle Considering Motor Power Compensation. Machines. **10**, 11 (2022).
25. B. Pang et al., Data-Driven Degradation Modeling and SOH Prediction of Li-Ion Batteries. Energies. **15**, 15 (2022).
26. Y. Wang et al., Dual Heuristic Dynamic Programming Based Energy Management Control for Hybrid Electric Vehicles. Energies. **15**, 9 (2022).
27. Z. Li et al., Predictive Energy Management Strategy for Hybrid Electric Air-Ground Vehicle Considering Battery Thermal Dynamics. Applied Sciences. **13**, 5 (2023).
28. S. Iqbal et al., Electric Vehicles Aggregation for Frequency Control of Microgrid under Various

Operation Conditions Using an Optimal Coordinated Strategy. Sustainability. **14**, 5 (2022).

29. A. S. Abdelaal et al., Battery Energy Management Techniques for an Electric Vehicle Traction System. IEEE Access. **10**, (2022).
30. A. Du et al., Multi-Objective Energy Management Strategy Based on PSO Optimization for Power-Split Hybrid Electric Vehicles. Energies. **14**, 9 (2021).
31. H. Yu et al., Dimensioning and Power Management of Hybrid Energy Storage Systems for Electric Vehicles with Multiple Optimization Criteria. IEEE Transactions on Power Electronics. **36**, 5 (2021).
32. J. D. Valladolid et al., A Novel Energy-Efficiency Optimization Approach Based on Driving Patterns Styles and Experimental Tests for Electric Vehicles. Electronics. **10**, 10 (2021).
33. L. Zhang et al., Optimal electric bus fleet scheduling considering battery degradation and non-linear charging profile. Transportation Research Part E: Logistics and Transportation Review. **154**, (2021).