

A COMPREHENSIVE STUDY ON HYBRID ENERGY STORAGE SYSTEMS FOR SUSTAINABLE HYBRID ELECTRIC VEHICLES

Mr. Kishor Dhore¹, Dr. Archana Shirbhate²

¹ PHD Scholar, PGTD Electronics and computer Engineering Department RTMNU Campus , RTMNU Nagpur.

² Associate Professor , Department of Electrical Engineering ,Anjuman college of Engineering Nagpur .

Abstract

The transition to sustainable transportation has driven the development energy storage plays a critical role in enhancing efficiency and performance. This study provides a comprehensive analysis of Hybrid Energy Storage Systems (HESS) designed to improve the reliability, lifespan, and energy management of HEVs. HESS integrates multiple energy storage technologies, such as batteries and super capacitors, leveraging their complementary characteristics to optimize power delivery and energy recuperation.

This research explores various HESS architectures, control strategies, and energy management techniques to achieve high efficiency and extended durability. The study highlights key performance parameters, including power density, energy density, and state-of-charge balancing, which influence system optimization. Additionally, a comparative analysis of different hybrid storage configurations is conducted to evaluate their effectiveness under dynamic driving conditions. Advances in power electronics and intelligent control algorithms, such as model predictive control and machine learning-based optimization, are also examined for their potential to enhance energy utilization.

Furthermore, the study assesses the environmental and economic impacts of HESS implementation in HEVs, considering lifecycle costs and sustainability factors. By integrating renewable energy sources and smart grid compatibility, HESS can contribute to reducing carbon emissions and promoting green mobility solutions. The findings of this research provide valuable insights for automotive manufacturers, policymakers, and researchers in advancing hybrid electric vehicle technology. Future prospects emphasize the development of next-generation materials, intelligent energy distribution networks, and enhanced integration with renewable energy systems to foster a more sustainable and energy-efficient transportation sector.

Keywords: Hybrid Energy Storage Systems, Hybrid Electric Vehicles, Energy Management, Power Electronics, Sustainable Mobility

Introduction

In recent years, Hybrid Electric Vehicles (HEVs) have emerged as a revolutionary advancement in the quest for sustainable and efficient transportation solutions. Defined by their integration of an internal combustion engine with an electric propulsion system, HEVs significantly reduce greenhouse gas emissions and fuel consumption compared to traditional vehicles. As global environmental concerns escalate and fossil fuel reserves dwindle, the significance of HEVs in modern transportation becomes ever more apparent. The growing demand for sustainable energy solutions drives the continuous innovation and development of HEVs, positioning them as a cornerstone of future mobility.

Central to the performance and efficiency of HEVs is the energy storage system (ESS). These systems are pivotal in storing and delivering the necessary energy to power the vehicle, directly influencing its range, power, and overall efficiency. Traditional ESSs, while effective, often face limitations in meeting the dynamic energy requirements of HEVs. This has led to the exploration and development of hybrid energy storage systems (HESS), which combine multiple types of energy storage technologies to optimize performance. By leveraging the strengths of different storage mechanisms, HESS can provide a more balanced, reliable, and efficient energy solution for HEVs.

This paper aims to provide a comprehensive study on hybrid energy storage systems for sustainable hybrid electric vehicles. The primary objective is to review the current state of HESS, exploring their design, functionality, and impact on the performance of HEVs. Key topics addressed include the various components and configurations of HESS, their operational principles, and the technological advancements driving their development. Through this review, we aim to highlight the critical role of HESS in the evolution of HEVs and their potential to revolutionize the future of sustainable transportation.

II. Background Information: A Comprehensive Study on Hybrid Energy Storage Systems for Sustainable Hybrid Electric Vehicles

1. ELECTRIC PROPULSION SYSTEM

The different types of topological architecture and configuration of HEV are shown in Figure 1 [8].

The energy source, power converters, and traction motor are the important prime parts of an EV. Energy sources comprise of a battery cell, SC, and fuel cell (FC). Electronic control unit (ECU) controls the power flow from source to the motor. According to the load demand, the power converter adjusts the voltage. Efficient operation of battery relies on its management system [9].

1.1. Cell technologies

Among many critical parameters, state of charge (SOC) of battery plays a crucial role. The direct measurement of battery SOC is impossible. It primarily trusts on chemical composition. Thus, for the accurate estimation of SOC, modeling of the battery cell is necessary. Analytical or stochastic model, electrical equivalent circuit, or electrochemical model are the present categories of battery models.

Batteries are subjected to high damages because of overcharging and over discharging characteristics. It must be prevented from those damages to improve their life cycle. Hence, optimization of the efficiency of energy utilization algorithms that incorporates battery terminal voltage and current is performed. for this analysis [10–12]. Some techniques are emerging for the estimation of battery SOC, and each technique has its own merits and demerits.

1.1.1. Battery modeling

1.1.1.1. Internal resistance model. The significance of internal resistance model is to describe the battery capacity regarding open-circuit voltage. Here, cell ohmic resistance is indicated by R_{Ω} .

1.1.1.2. Resistor–capacitor model. In resistor–capacitor model, C_n indicates nominal capacitance and $V_{oc}(SOC)$ represents open-circuit voltage as a function of SOC. Current discharge because of the effect of electrode

10.48047/jocaaa.2024.33.05.56

material is denoted as C_s , and V_{cs} is the surface capacitor voltage. The end, surface, and terminal resistance are represented as R_e , R_s , and R_t , respectively. A negative indication of current represents the discharging current.

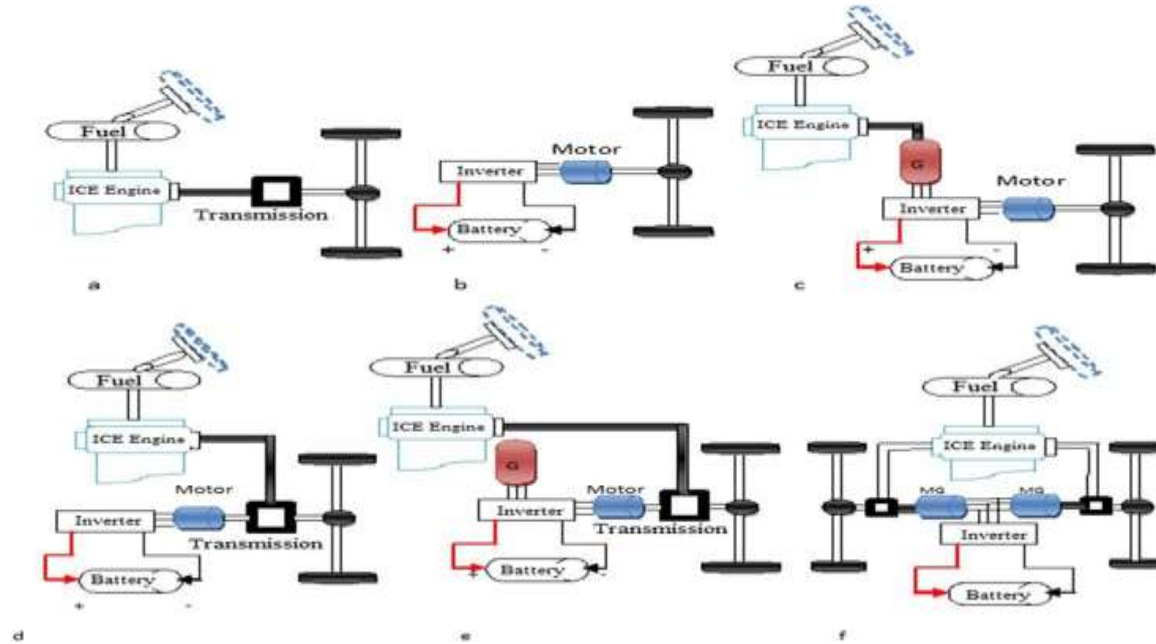


Figure 1. Architecture and configuration of different vehicles: (a) internal combustion engine (ICE) vehicle, (b) battery electric vehicle, (c) series hybrid vehicle, (d) parallel hybrid vehicle, (e) series-parallel hybrid vehicle, and (f) complex hybrid vehicle.

1.1.1.3 Thevenin battery model. Open-circuit voltage is the voltage across C_n that helps in SOC estimation. Electrochemical polarization capacitance of the model and its corresponding resistance is denoted as C_p and R_p . R_i is the input ohmic resistance. Figure 2 depicts the equivalent circuits of battery model [13–15].

1.1.2. Ultracapacitor

There are two types of electric double-layer capacitors present. When there is charge storage in the electronic interface material (or) electrical double layer (or) electrolyte, then the capacitor is termed as UC. When the atomic species underwent a transient reversible

10.48047/jocaaa.2024.33.05.56

absorption within the structure of a crystal, then it is named as SC. Figure 3a exhibits the different electrical properties of battery and UC [23]. UC can be utilized to supply very large currents, and at the same time, the change in voltage, which is a function of SOC of UC, is also very high. The SOC of UC is subjected to many quick changes [24].

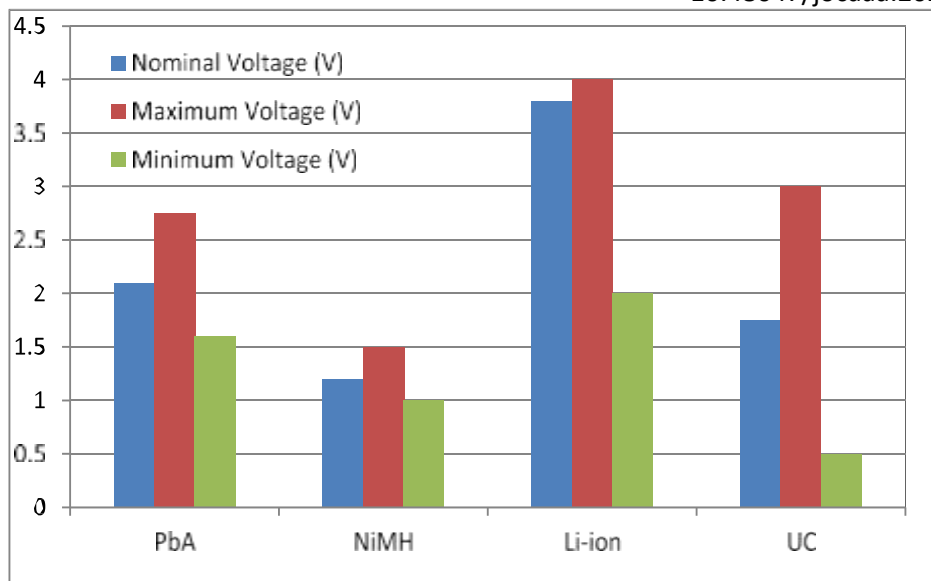
Because UC SOC is directly proportional to the square of UC cell voltage, SOC of UC can be determined accurately. Also, the operating temperature of UC ranges

between -40 and $+70$ °C, which seems to be greater than batteries. Hence, the hybridized UC–battery performance offers a best result in real-time applications. Figure 3a represents the electrical properties of different batteries and UC [25–28].

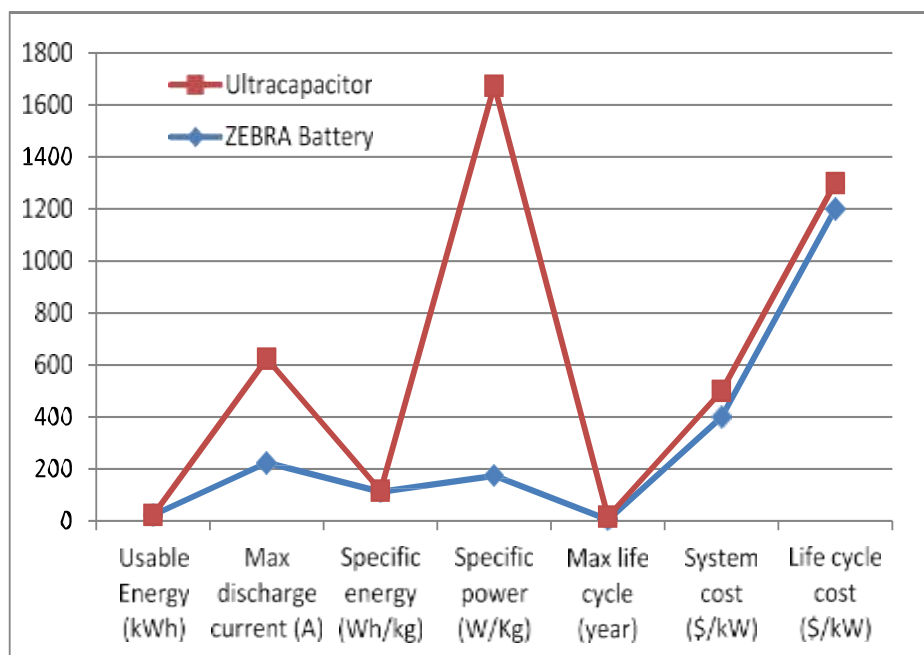
There are many starts, stop, and go driving condition in the urban driving cycle. The electricity generated because of regenerative braking is captured by UC, and the captured power can be immediately delivered power for acceleration. This is applicable in UC because of its fast charge and discharge rates. The design of carbon UC can help in the improvement of fuel economy under all driving cycles. Figure 3b compares the ZEBRA battery characteristics with UC [29].

1.2. Electric motors

In today's modern era, different types of electric motors are used in an EV application. In many conventional vehicles, direct current (DC) motors were highly used, but due to the recent technological developments, even alternating current (AC) electric motors are made more suitable [30].



a



b

Figure 3. (a) Electrical properties of batteries and ultracapacitors and (b) comparison of ZEBRA batteries and ultracapacitor. UC, ultracapacitor.

1.2.1. **Direct current motor**

Simple construction, control, and flux–torque decouple of DC motor pays more attention in the transportation sector in old times, but its maintenance problems due to brushes and rings pull down the DC motor [31]. Separately excited DC commutator motor has decoupled flux and torque characteristics; hence, it is highly recommended for field weakening operation. It requires more motor shaft torque because it supports low-speed and constant power operation. This drive is less suitable in the case of single gear transmission operation because of its weight and cost [32]. Brushed DC motor is less efficient, bulkier in construction, less reliable, and costlier, but it is well known for their high torque capability at low speed [33].

1.2.2. **Alternating current motor**

Direct current motor drives have some distinct disadvantages over AC counterparts, such as less efficiency, lower power density, inefficient regenerative braking, less reliable, and high maintenance. Fewer commutator and induction motors are accepted by the propulsion systems worldwide because of their reliability and free maintenance. Researchers work on vector control or field orientation control of the induction motor to offer a wide range of speed control and to improve its dynamic performance. It is noted that its efficiency is reduced considerable if it is operated at high speed. Field orientation control of the induction motor can decouple field and torque component. Flux-weakening control is meant for above-rated speed at rated power capability (constant power operation). The popularity of induction motor mainly depends on its ruggedness, reliable operation, and its improved dynamic performance [34,35].

1.2.3. **Synchronous reluctance motor**

Synchronous reluctance motors are developed by ABB that focuses on the improvement of system performance and efficiency. It is combined with frequency converter so as to tender service friendliness, cost effective of a simple induction motor. Revolutionary rotor constructions of induction motor contribute less loss and allow employing high power. Synchronous reluctance motor performances are similar to combined performance of induction motor and permanent magnet motors. The frame size is much

10.48047/jocaaa.2024.33.05.56

smaller when compared with induction motor for the same output [36,37]. By the utilization of current angle control, maximum torque can be achieved, which ensures that the motor is always operated at desirable efficiency for all values of load. The research Johan *et al.* performed is a simulation in which front drive is propelled by a petrol engine and back drive by 28-kW reluctance synchronous machine. They concluded that small synchronous reluctance motor could generate a peak torque of 150 Nm, 1480 kg vehicle accelerates from 0–60 km/h in 19 s. Also, it measures a maximum range of vehicle on a single battery charge as 90 km at 60 km/h [38].

1.1.1. Switched reluctance motor

Unlike other AC motors, switched reluctance motor (SRM) has only one magnetic field. The twisting force is generated based on the minimum reluctance position. SRM can replace permanent magnet synchronous motor desirably because it uses rare-earth magnet-free materials. Many researchers are focusing on the improvement of power/torque density and its efficiency. Selection of frame size and stator and rotor pole plays a major role in design procedure for SRM.

In the case of vehicle applications, 6/4, 8/6, 10/12, 8/12, 6/12, and 18/12 are used as stator/rotor pole numbers. The higher the number of poles, the lower the noises. This creates a major impact on power electronic converter configuration, stator phase current fundamental frequency, and changes in stator flux waveform. The main merits of SRM are its simple construction, cost, and robust operation. Despite of its merits, it has high acoustic noise level, and it is in need of a special converter [39–43].

Table I compares the different motor drives used in EV based on vehicle efficiency, maturity of the drive technology, reliability, power density, and cost factor [44]

1.3. Power electronic controller

In this section, interface required for the interconnection between the electrical system and the electrochemical energy storage systems is discussed. Power electronic converter acts as the interfacing unit. There are three different category- rise of power electronic converters: standard topologies, multiport topologies, and multilevel topologies. Standard topology or two-port converter is one in which input port is connected to source and output port to load.

10.48047/jocaaa.2024.33.05.56

It is further classified as single and double stage. In a single stage, the charge and discharge characteristic of storage system uses

	DC motor	Induction motor	Switched reluctance motor	Permanent magnet brushless DC motor
Efficiency	Low	Medium	Medium	High
Maturity	High	High	Medium	Medium
Reliability	Low	High	High	Medium
Power density	Low	Medium	Medium	High
Cost factor	Medium	Low	Medium	High

DC, direct current; EV, electric vehicle.

Table I. Comparison of different motor drive characteristics for EV application.

1. POWER MANAGEMENT CONTROL STRATEGY

There are many rule-based and optimization control studies that are used in the literatures. The general classification of control strategy is shown in Figure 6 [70–76].

topology. The charging and discharging current profiles of the battery are smooth because SOC depends on the voltage, it does not vary significantly as the power management is not active. The utilization of UC is poor in this topology [61,64–69]. The different HESS topologies' comparison is represented in Table III.

	Multiple converter configuration	UC/battery configuration	Battery/ UC configuration	Battery/UC passive parallel configuration
Efficiency	Low	Medium	Medium	High

10.48047/jocaaa.2024.33.05.56

Discharge and charge performance of battery pack	High	Medium	Medium	Low
Discharge and charge performance of UC pack	High	Medium	Medium	Lo
Converter efficiency	High	Medium	Medium	Low
Complexity	High	Medium	Medium	Low
Cost	High	Medium	Medium	Low
Semiconductor switches used	High	Medium	Medium	Low

UC, ultracapacitor.

Table III. Comparison of different hybrid energy storage system topologies.**A. Basics of Hybrid Electric Vehicles****Overview of HEV architecture and components**

A Hybrid Electric Vehicle (HEV) is a vehicle that combines a traditional internal combustion engine (ICE) with an electric motor. This combination aims to improve fuel efficiency, reduce emissions, and enhance performance. The key components of an HEV include:

- **Internal Combustion Engine (ICE):** Provides mechanical power to drive the wheels.
- **Electric Motor:** Generates electric power to assist the ICE or provide independent propulsion.
- **Battery Pack:** Stores electrical energy for the electric motor.
- **Power Electronics:** Controls the flow of electrical energy between the battery, motor, and generator.
- **Transmission:** Connects the ICE and electric motor to the wheels, allowing for various operating modes.

Types of HEVs (series, parallel, and series-parallel hybrids)

HEVs can be categorized into three main types based on how the ICE and electric motor interact:

1. **Series Hybrid:** The ICE generates electricity, which powers the electric motor, which in turn drives the wheels. This configuration is ideal for fuel efficiency but may have lower acceleration.
2. **Parallel Hybrid:** The ICE and electric motor can both drive the wheels directly, or the ICE can generate electricity to power the motor. This configuration offers a balance of performance and efficiency.
3. **Series-Parallel Hybrid:** Combines elements of both series and parallel configurations, allowing for greater flexibility in operating modes.

Hybrid Energy Storage Systems (HESS)

A Hybrid Energy Storage System (HESS) combines multiple energy storage technologies to leverage their respective strengths and mitigate their weaknesses. HESS typically consists of:

- **Battery Pack:** Provides the primary energy storage for the vehicle.
- **Super capacitor Bank:** Offers high power density for rapid charging/discharging and peak power delivery.
- **Fuel Cell Stack:** Generates electricity from a fuel source, such as hydrogen.

- **Power Management System:** Controls the energy flow between the different storage components.

Benefits of integrating multiple energy storage technologies

Integrating multiple energy storage technologies in HESS offers several advantages, including:

- **Improved overall performance:** HESS can provide a balance of energy density, power density, and charging/discharging capabilities.
- **Enhanced efficiency:** By optimizing the use of each storage technology, HESS can reduce energy losses and improve overall efficiency.
- **Extended battery life:** By sharing the load with other storage components, HESS can reduce the stress on the battery and prolong its lifespan.
- **Increased flexibility:** HESS can adapt to different driving conditions and operating modes, providing a more versatile and efficient solution.
- **Longer battery life:** Reduced battery stress from frequent deep discharge cycles.
- **Faster charging:** Super capacitors can handle high charging rates, enabling quicker refueling.

Limitations:

- **Higher cost:** Super capacitors generally have a higher cost per unit energy compared to batteries.
- **Size and weight:** The additional components can increase the overall size and weight of the vehicle.

III. Types of Hybrid Energy Storage Systems for Sustainable Hybrid Electric Vehicles

A. Battery-Super capacitor Hybrid Systems

Description and working principles:

- **Battery:** Provides high energy density, suitable for long-range driving.
- **Super capacitor:** Offers high power density, ideal for rapid charge/discharge and regenerative braking.
- **Hybrid:** Combines the strengths of both, delivering high energy and power capabilities.
- **Operation:** The battery stores energy during charging or regenerative braking, while the super capacitor handles rapid power surges for acceleration or peak loads.

Advantages:

- **Improved performance:** Enhanced acceleration, regenerative braking efficiency, and overall vehicle **Longer battery life:** Reduced battery stress from frequent deep discharge cycles.
- **Faster charging:** Super capacitors can handle high charging rates, enabling quicker refueling.

Limitations:

- **Higher cost:** Super capacitors generally have a higher cost per unit energy compared to batteries.
- **Size and weight:** The additional components can increase the overall size and weight of the vehicle.
- responsiveness.

B. Battery-Fuel Cell Hybrid Systems**Description and working principles:**

- **Battery:** Provides primary energy storage for initial acceleration and peak loads.
- **Fuel Cell:** Generates electricity through a chemical reaction between hydrogen and oxygen, offering a continuous power source.
- **Hybrid:** Combines the advantages of both for extended range and reduced emissions.
- **Operation:** The battery powers the vehicle initially, while the fuel cell takes over as the primary power source, replenishing the battery through regenerative braking.

Advantages:

- **Extended range:** Fuel cells can provide a continuous power supply, enabling longer driving distances.
- **Reduced emissions:** Fuel cells produce zero tailpipe emissions, making them more environmentally friendly.
- **Increased efficiency:** The combination of battery and fuel cell can optimize energy usage.

Limitations:

- **Higher cost:** Fuel cell technology is still relatively expensive.
- **Hydrogen infrastructure:** The availability of hydrogen refueling stations is limited in many regions.
- **Complexity:** Fuel cell systems are more complex and require careful management.

C. Other Hybrid Configurations**Emerging technologies and configurations:**

- **Flywheel energy storage:** Kinetic energy is stored in a rotating flywheel, offering high power density and fast response times.
- **Compressed air energy storage:** Air is compressed and stored in a tank, releasing energy upon expansion to power the vehicle.
- **Flow battery:** Electrolytes are circulated between two tanks, enabling energy storage and discharge.
- **Hybrid configurations:** Combining multiple technologies, such as battery-supercapacitor-flywheel or battery-fuel cell-compressed air, to optimize performance and address specific needs.

Potential benefits and challenges:

- **Enhanced performance:** These technologies can offer unique advantages, such as high power density, fast charging, or extended range.
- **Reduced environmental impact:** Some technologies, like compressed air energy storage, have a lower environmental footprint.
- **Cost and complexity:** Many of these technologies are still in development and may face challenges in terms of cost and complexity.

IV. Technical Considerations in HESS Design and Performance Analysis for HEVs

A. Energy Management Strategies

Importance of efficient energy management in HESS:

- Optimizes energy utilization, maximizing vehicle range and reducing fuel consumption.
- Ensures balanced state of charge (SOC) for both battery and ultra capacitor to prevent premature degradation.
- Minimizes power losses and maximizes system efficiency.

Common strategies and algorithms used:

- **Rule-based strategies:** Simple and easy to implement, but may not be optimal in all driving conditions.
- **Fuzzy logic:** Offers flexibility and adaptability to varying driving scenarios.
- **Predictive control:** Utilizes vehicle and road information to anticipate future energy needs.
- **Equivalent consumption minimization strategy (ECMS):** Balances energy consumption between the battery and ultra capacitor to minimize overall fuel consumption.

B. Power Electronics and Control Systems

Role of power electronics in HESS integration:

- Enables efficient power conversion and distribution between the battery, ultracapacitor, and electric motor.

- Provides isolation and protection for the components.
- Enables bidirectional power flow, allowing for regenerative braking.

Key control systems and their functionalities:

- **Battery management system (BMS):** Monitors battery SOC, temperature, voltage, and current to ensure safe and efficient operation.
- **Ultracapacitor management system (UCMS):** Similar to BMS, but specifically tailored for ultracapacitors.
- **DC-DC converter control:** Regulates voltage and current between the battery and ultracapacitor.
- **Motor control:** Controls the speed and torque of the electric motor based on driver inputs and energy management strategies.

C. Thermal Management**Importance of thermal management in HESS:**

- Prevents overheating or undercooling of battery and ultracapacitor cells, which can lead to performance degradation and safety hazards.

Techniques and technologies for effective thermal management:

- **Liquid cooling:** Circulates a coolant fluid around the battery and ultracapacitor cells to transfer heat.
- **Air cooling:** Uses fans to circulate air over the components to dissipate heat.
- **Phase change materials (PCMs):** Absorb and release heat during phase transitions (solid to liquid or liquid to solid).
- **Thermal management systems (TMS):** Integrated systems that combine various cooling techniques for optimal performance.

A. Efficiency and Range Improvement**Impact of HESS on vehicle efficiency and range:**

- **Improved efficiency:** Ultra capacitors can provide high-power bursts, reducing the load on the battery and improving overall system efficiency.
- **Increased range:** The combination of battery and ultra capacitor storage can extend the vehicle's range compared to using a battery alone.

Comparative analysis with traditional energy storage systems:

- **Compared to batteries:** HESS offers faster charging, higher power density, and longer cycle life.
- **Compared to fuel cells:** HESS provides higher power density and faster response times, but may have higher manufacturing costs.

Economic considerations in HESS deployment:

- **Initial cost:** HESS may have higher initial costs compared to traditional battery-only systems due to the inclusion of ultracapacitors and associated components.
- **Long-term cost:** HESS can offer lower long-term costs due to the extended lifespan of ultra capacitors and reduced battery degradation.

Long-term durability and reliability of HESS:

- **Ultra capacitor durability:** Ultra capacitors generally have longer cycle life and higher durability compared to batteries.
- **Battery management:** Proper battery management can significantly improve the lifespan of the battery component in HESS.

C. Environmental Impact

Environmental benefits of using HESS in HEVs:

- **Reduced emissions:** HEVs with HESS can significantly reduce greenhouse gas emissions compared to traditional internal combustion engine vehicles.
- **Improved energy efficiency:** The combination of battery and ultracapacitor storage can lead to higher energy efficiency and lower fuel consumption.

Analysis of lifecycle emissions and sustainability:

- **Lifecycle assessment:** Evaluating the environmental impact of HESS throughout its entire lifecycle, including manufacturing, operation, and end-of-life disposal.
- **Sustainability:** Assessing the long-term sustainability of HESS in terms of resource consumption, waste generation, and social impacts.

Review

Author [1] has described detailed reviews about energy storage systems for vehicles, focusing on technology, environmental impacts, and costs. It analyzes various vehicle types, including Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs). The study highlights the advantages and challenges of different energy storage solutions, such as lithium-ion and lithium-sulfur batteries, fuel cells, and super capacitors. It emphasizes the environmental benefits of electric vehicles (EVs), particularly in reducing greenhouse gas emissions, though limitations such as high costs, long charging times, and infrastructure challenges remain. The paper suggests that combining energy storage systems can optimize vehicle performance, proposing hydrogen fuel cells with auxiliary energy storage systems as a promising solution. It also notes that while current EV technologies are expensive, advancements are expected to make them competitive with internal combustion vehicles by 2050. The integration of renewable energy is crucial for maximizing environmental benefits.

The paper [2] discusses the transformation of the transportation sector towards electric vehicles (EVs) as a sustainable alternative to fossil fuel-powered vehicles. It highlights the advantages of EV technology, including eco-friendliness, reduced fuel costs, lower maintenance, and improved safety. The selection of an appropriate energy storage system is critical to the performance of EVs, with the paper emphasizing the importance of hybrid energy storage systems that combine batteries and ultra capacitors. Lithium-ion batteries are identified as the most suitable option due to their high specific energy and efficiency, while ultracapacitors address peak power demands during acceleration and other high-load situations. The paper outlines the basic configurations of battery and ultracapacitor hybrid systems, explaining

how they complement each other by delivering the average power and handling transient demands effectively. It also discusses the advantages of this hybrid system, such as extending battery life, reducing replacement costs, and improving overall vehicle performance. In conclusion, the paper underscores that the careful selection of energy storage systems plays a pivotal role in enhancing the functionality and driving performance of electric vehicles, making them a viable solution to reduce fossil fuel dependency and carbon emissions.

The paper [3] discusses the use of energy storage systems (ESS) in electric vehicles (EVs) and their role in the future electricity supply. Different types of energy storage devices (ESDs), such as batteries, super capacitors, and fuel cells, are used in EVs to meet the power

10.48047/jocaaa.2024.33.05.56

demand. Li-ion batteries are the most commonly used ESD in EVs due to their high capacity, energy density, and long cyclic life. The paper also highlights the importance of battery management systems (BMS) in ensuring the safety and longevity of ESDs in EVs. The BMS monitors and controls various parameters such as cell voltage, charge/discharge control, and cell balancing to optimize the performance of ESDs. The study also discusses the challenges and issues faced in the energy management system of EVs and provide some recommendations to overcome them. Overall, the paper provides an overview of EV systems, ESS technologies, and the importance of BMS in ensuring efficient and safe operation of EVs.

The article [4] "Design and Analysis of Hybrid Energy Storage System for Electric Vehicle Applications" discusses the development of a hybrid energy storage system (HESS) that integrates lithium-ion batteries and super capacitors for electric vehicles (EVs). The research addresses challenges such as limited driving range and long charging times associated with EVs. The proposed model utilizes solar panels for energy generation, employing Maximum Power Point Tracking (MPPT) to optimize energy extraction. The study includes simulations performed using MATLAB

Simulink, demonstrating improved performance metrics compared to previous models, such as increased battery voltage and current. The findings indicate significant potential for HESS in enhancing EV efficiency and operational flexibility. Future work will explore optimizing model accuracy and analyzing the impact of temperature on energy storage components.

The study reviews [5] the electric vehicle (EV) system and applicable energy storage system (ESS) technologies, focusing on the energy management system's challenges and issues. It highlights the increasing demand for EVs driven by factors such as cost, sustainable battery value, and e-commerce accessibility. The review methodology involved selecting 420 papers from various reputable sources, narrowing it down to 101 relevant studies, with over 90 published in the last three years. The output of the study is organized into five key steps: discussing different types of EVs, summarizing applicable ESS, analyzing energy management systems, highlighting issues and challenges, and proposing recommendations to address these problems. The study identifies critical challenges in energy management, including temperature control, safety, lifecycle management, environmental impact, and recycling of batteries. Lithium-ion batteries are identified as the preferred choice for EVs due to their high energy density. The study concludes by emphasizing the need for advancements in battery management systems and sustainable practices to enhance the overall efficiency

and safety of EV technology, ensuring a more reliable and environmentally friendly future for electric vehicles.

Systems (HESS) for Sustainable Hybrid Electric Vehicles (HEVs). We have explored the pivotal role of HESS in enhancing the efficiency, performance, and environmental impact of HEVs. Key findings include:

- The synergistic combination of different energy storage technologies in HESS offers a more effective solution compared to standalone batteries or super capacitors.
- HESS can significantly improve fuel economy, reduce emissions, and extend the driving range of HEVs.
- The optimal configuration of HESS depends on various factors, including vehicle application, driving conditions, and cost-benefit analysis.

Conclusion

This comprehensive study has delved into the intricacies of Hybrid Energy Storage. The future of HESS in the automotive industry is promising. As technology advances and costs decrease, HESS are likely to become a standard component in HEVs and electric vehicles (EVs). Further research and development are essential to address the challenges and limitations associated with HESS, such as energy density, power density, and durability. Advancing HESS technology is crucial for achieving sustainable transportation and reducing our reliance on fossil fuels. By combining the best aspects of different energy storage technologies, HESS offer a viable and promising solution for the future of automotive transportation. As we continue to invest in research and development, we can pave the way for a cleaner, more efficient and more sustainable transportation landscape.

References

1. Yasaman Balali, Sascha Stegen , Review of energy storage systems for vehicles based on technology, environmental impacts, and costs, Renewable and Sustainable Energy Reviews 135 (2021) 110185.
2. Umesh Mahapatra, Energy Storages and Technologies for Electric Vehicle, 2021 Innovations in Energy Management and Renewable Resources (IEMRE) | 978-1-6654-1259-9/20/\$31.00 ©2021 IEEE | DOI: 10.1109/IEMRE52042.2021.9386526.
3. Mohammad Kamrul Hasan a,*, Md Mahmud b,c,*, A.K.M. Ahasan Habib a,c, S.M.A. Motakabber d, Shayla Islam, Review of electric vehicle energy storage and

- management system: Standards, issues, and challenges, *Journal of Energy Storage* 41 (2021) 102940.
4. Himanshu Mishra, Shilpam Saxena, Design and Analysis of Hybrid Energy Storage System for Electric Vehicle Applications, *Journal of Information and Computational Science* ISSN: 1548-7741, Volume 12 Issue 10 – 2022.
 5. A.A. Habib, S.M.A. Motakabber, M.I. Ibrahimy, A.Z. Alam, A Single LC TankBased Active Voltage Balancing Circuit for Battery Management System, *IIUM Eng. J.* 19 (1) (2018) 158–167.
 6. N. Kittner, I. Tsiropoulos, D. Tarvydas, O. Schmidt, I. Staffell, D.M. Kammen, Electric vehicles. Technological Learning in the Transition to a Low-Carbon Energy System, Academic Press, 2020, pp. 145–163.
 7. K. Lim, J.J. Kim, J. Lee, Forecasting the future scale of vehicle to grid technology for electric vehicles and its economic value as future electric energy source: the case of South Korea, *Energy Environ.* (2020), 0958305x19898283.
 8. M.K. Hasan, M.M. Ahmed, A.H. Hashim, A. Razzaque, S. Islam, B. Pandey, A Novel Artificial Intelligence Based Timing Synchronization Scheme for Smart Grid Applications, *Wirel. Pers. Commun.* (2020 Apr 23) 1–8.
 9. X. Wang, Z. Wang, L. Wang, Z. Wang, H. Guo, Dependency analysis and degradation process-dependent modeling of lithium-ion battery packs, *J. Power Sources* 414 (2019) 318–326.
 10. M.K. Hasan, A.K.M. Habib, S. Islam, A.T.A. Ghani, E. Hossain, Resonant energycarrier base active charge-balancing algorithm, *Electronics (Basel)* 9 (12) (2020)2166.
 11. M.K. Hasan, M.M. Ahmed, S.S. Musa, S. Islam, S.N. Abdullah, E. Hossain, N.S. Nafi, N. Vo, An improved dynamic thermal current rating model for PMU-based wide area measurement framework for reliability analysis utilizing sensor cloud system, in: *IEEE Access*, 9, 2021 Jan 18, pp. 14446–14458.
 12. X. Lü, Y. Wu, J. Lian, Y. Zhang, C. Chen, P. Wang, L. Meng, Energy management of hybrid electric vehicles: a review of energy optimization of fuel cell hybrid power system based on genetic algorithm, *Energy Convers. Manage.* 205 (2020),112474.
 13. T. Wilberforce, A. Baroutaji, Z. El Hassan, J. Thompson, B. Soudan, A.G. Olabi, Prospects and challenges of concentrated solar photovoltaics and enhancedgeothermal energy technologies, *Sci. Total Environ.* 659 (2019) 851–861.

14. K. Schwalbe, A. Fischer, K. Wagner, K. Schmidt, K.H. Hoffmann, Recuperation gain for a hydraulic energy storage in automotive applications, *Appl. Therm. Eng.*(2020), 115275.
15. Muralidharan, R.S. Sreelekshmi, M.G. Nair, Cell Modelling for Battery Management System in Electric Vehicles, in: 2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT), IEEE, 2020, August, pp. 558–564. L. Kouchachvili, W. Yaïci, E. Entchev,
16. Hybrid battery/supercapacitor energy storage system for the electric vehicles, *J. Power Sources* 374 (2018) 237–248.
17. A.A. Habib, M.K. Hasan, M. Mahmud, S.M.A. Motakabber, M.I. Ibrahimya, S. Islam, A review: energy storage system and balancing circuits for electric vehicle application, *IET Power Electronics* 14 (1) (2021) 1–13.
18. Z.B. Omariba, L. Zhang, D. Sun, Review on health management system for lithium-ion batteries of electric vehicles, *Electronics (Basel)* 7 (5) (2018) 72.
19. J.I. Hidalgo-Reyes, J.F. G'omez-Aguilar, R.F. Escobar-Jim'enez, V.M. Alvarado-Martínez, M.G. L'opez-L'opez, Classical and fractional-order modeling of equivalent electrical circuits for supercapacitors and batteries, energy management strategies for hybrid systems and methods for the state of charge estimation: a state of the art review, *Microelectronics J.* 85 (2019) 109–128.
20. Z.B. Omariba, L. Zhang, D. Sun, Review of battery cell balancing methodologies for optimizing battery pack performance in electric vehicles, *IEEE Access* 7 (2019) 129335–129352.
21. J. Carter, Z. Fan, J. Cao, Cell equalisation circuits: a review, *J. Power Sources* 448 (2020), 227489.
22. A.K. Basu, S. Tatiya, S. Bhattacharya, Overview of Electric Vehicles (EVs) and EV Sensors. *Sensors for Automotive and Aerospace Applications*, Springer, Singapore, 2019, pp. 107–122.
23. S. Ajayan, A.I. Selvakumar, Implementation of Firefly Algorithm in Optimal Sizing of PEMFC-Battery Hybrid Locomotive, *Int. J. Renew. Energy Res. (IJRER)* 10 (2) (2020) 614–624.
24. Y. Qin, X. Tang, T. Jia, Z. Duan, J. Zhang, Y. Li, L. Zheng, Noise and vibration suppression in hybrid electric vehicles: state of the art and challenges, *Renewable Sustainable Energy Rev.* 124 (2020), 109782.

10.48047/jocaaa.2024.33.05.56

25. J.Y. Yong, V.K. Ramachandaramurthy, K.M. Tan, N. Mithulananthan, A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects, *Renewable Sustainable Energy Rev.* 49 (2015) 365–385.
26. M. Zweistra, S. Janssen, F. Geerts, Large scale smart charging of electric vehicles in practice, *Energies* 13 (2) (2020) 298.
27. M.M. Hoque, M.A. Hannan, A. Mohamed, A. Ayob, Battery charge equalization controller in electric vehicle applications: a review, *Renewable Sustainable Energy Rev.* 75 (2017) 1363–1385.
28. M. Frivaldsky, M. Pipiska, J. Sedo, M. Danko, Design of SOC evaluation unit for multi-cell traction battery system, in: 2020 ELEKTRO, IEEE, 2020, May, pp. 1–5.
29. S. Chakraborty, H.N. Vu, M.M. Hasan, D.D. Tran, M.E. Baghdadi, O. Hegazy, DC-DC converter topologies for electric vehicles, plug-in hybrid electric vehicles and fast charging stations: state of the art and future trends, *Energies* 12 (8) (2019)
30. M. Cipek, J. Kasa'c, D. Pavkovi'c, D. Zorc, A novel cascade approach to control variables optimisation for advanced series-parallel hybrid electric vehicle power-train, *Appl. Energy* 276 (2020), 115488.
31. Y. Qin, X. Tang, T. Jia, Z. Duan, J. Zhang, Y. Li, L. Zheng, Noise and vibration suppression in hybrid electric vehicles: state of the art and challenges, *Renewable Sustainable Energy Rev.* 124 (2020), 109782.
32. India energy outlook world energy outlook special report 2015 Jorgensen K. Technologies for electric, hybrid and hydrogen vehicles: electricity, renewable energy sources in transport. *Utilities Policy* 2008; 16:72–9.
33. Yi Z, Heping L, Wang H. Torque control strategy for parallel hybrid electric vehicles using fuzzy logic. *WSEAS Transactions on Systems* 2012; 10(4). Materials and Devices Conference, NMDC 2006. IEEE, Vol. 1, pp. 196–197, 22–25 Oct. 2006.
34. Grbovic P. *Energy Storage Technologies and Devices*. John Wiley & Sons, Ltd. Published, 2014.
35. Dustmann C-H. Advances in ZEBRA batteries. *Journal of Power Sources* 2004; 127:85–
36. Cunha Á, Martins J, Rodrigues N, Brito FP. Vanadium redox flow batteries: a technology review. *International Journal of Energy Research* June 2015; 39(7):889–918.

37. 35.Zhao P, Zhang H, Zhou H, Yi B. Nickel foam and carbon felt applications for sodium polysulfide/bromine redox flow battery electrodes. *Electrochimica Acta* 2005; 51:1091–8.
38. Koochi-Kamali S, Tyagi VV, Rahim NA, Panwar NL, Mokhlis H. Emergence of energy storage technologies as the solution for reliable operation of smart power systems: a review. *Renew. Sustain. Energy Rev.* 2013; 25:135–165.
39. 36.Srdjan M. Lukic, Sanjaka G. Wirasingha, Fernando Rodriguez, Jian Cao, and Ali Emadi, “Power management of an ultracapacitor/battery hybrid energy storage system in an HEV,” IEEE Vehicle Power and Propulsion Conference, pp. 1–6, 2006.
40. 37.Burke A. Ultracapacitors: why, how, and where is the technology. *Journal of Power Sources* 2000; 91(1):37–50..Burke A, Miller M. The power capability of ultracapacitors and lithium batteries for electric and hybrid vehicle applications. *Journal of Power Sources* 2011; 196(1):514–522 Thounthong P, Raël S, Davat B. Control strategy of fuel cell and supercapacitors Association for a distributed generation system. *IEEE*
41. 38..*Transactions on Industrial Electronics* Nov. 2007; 54(6):3225–3233.Sharma P, Bhatti T. A review on electrochemical double-layer capacitors. *Energy Conversion and Management* 2010; 51(12):2901–2912.
42. 39..Burke A. Ultracapacitor technologies and application in hybrid and electric vehicles. *International Journal of Energy Research* February 2010; 34(2):133–151.Nuno Grilo and Duarte M. Sousa, António Roque, “AC motors for application in a commercial electric vehicle: designing aspects,” 16th IEEE Mediterranean Electrotechnical Conference, pp.277–280, 25–28March 2012.
43. 40.Nasser Hashernnia and Behzad Asaei,“Comparative study of using different electric motors in the electric vehicles,” 18th International Conference on Electrical Machines, ICEM 2008, pp. 6–9 Sept. 2008.
44. 41..Khwaja M. Rahman, Mehrdad Ehsani, “Performance analysis of electric motor drives for electric and hybrid electric vehicle applications,” Published in: Power Electronics in Transportation, pp. 49–56, 24–25 Oct. 1996.
45. 42..X. D. Xue, K. W. E. Cheng, and N. C. Cheung, “Selection of electric motor drives for electric vehicles,” Power Engineering Conference, AUPEC '08. Australasian Universities, pp. 1–6, 14–17 Dec. 2008.

10.48047/jocaaa.2024.33.05.56

46. 43..Fan H, Dawson GE, Eastham TR. Model of electric vehicle induction motor drive system. In *Proc. of the Canadian Conf. on Elec. and Comp Engg*, Vol.2. 1993; 1045–1048.
47. 44.Saqib Rind, Yaxing Ren, Lin Jiang, “Traction motors and speed estimation techniques for sensorless control of electric vehicles: a review,” *Power Engineering Conference (UPEC)*, 2014 49th International Universities, pp. 1–6, 2–5 Sept. 2014.
48. 45..Matyska P. Advantages of synchronous reluctance motors. *Transactions on Electrical Engineering* 2014; 3(2).
49. 46..A. Vagati, “The synchronous reluctance solution: a new alternative in AC drives,” *Industrial Electronics, Control and Instrumentation*, 1994. *IECON '94*.,Vol. 1, pp. 1–13, 5–9 Sep 1994.
50. 47.Mdan J, Kamper MJ. Performance of a hybrid electric vehicle using reluctance synchronous machine technology. *IEEE Transactions on Industry Applications* Year: 2001; 37(5):1319–1324.
51. 48..Narayani Koirala, Fengxian He and Weixiang Shen, “Comparison of two battery
52. .equivalent circuit models for state of charge estimation in electric vehicles, I 10th Conference on Industrial Electronics and Applications (ICIEA), 2015.
53. 49..Wu T, Liu L, Xiao Q, Cao Q, Wang X. Research on SOC estimation based on second-order RC model. *TELKOMNIKA* November 2012; 10(7):1667–1672.
54. 50.Piao C, Liu M, Su L, Li Z, Cho C, Sheng L. Study on stable estimation method for lead-acid battery SOC by extended Kalman filter. *International Journal of Control and Automation* 2014; 7(4):429–438.
55. 51.Caumont O, Le Moigne P, Rombaut C, Muneret X, Lenain P. Energy gauge for lead-acid batteries in electric vehicles. *IEEE Transactions on Energy Conversion* Sep. 2000; 15(3):354–360.
56. 52..Boieca V. Energy storage technologies: the past and the present. *Proceedings of the IEEE* Oct 14, 2014; 102(11).
57. 53..Arun Patil, Ji-Won Choi and Seok-Jin Yoon, Review of issue and challenges facing rechargeable nano-structured lithium batteries, Nanot SaeidHagbhin, Ali Rabiei, Emma Grunditz, “Switched reluctance motor in electric or hybrid vehicle applications: a status review”, 2013 IEEE 8th Conference on Industrial Electronics and Applications (ICIEA), 2013, pp. 1017–1022.

58. 54..V. Petrus, A. Pop, C. Martis, J. Gyselinck, and V. Iancu, "Design and comparison of different switched reluctance machine topologies for electric vehicle propulsion," in *Electrical Machines (ICEM), 2010XIX International Conference on*, Sept. 2010, pp. 1–6.
59. 55..Takano Y, Takeno M, Hoshi N, Chiba A, Takemoto M, Ogasawara S, Rahman M. Design and analysis of a switched reluctance motor for next generation hybrid vehicle without pm materials. In *Power Electronics Conference IPEC '10*. Jun 2010; 1801–1806.
60. 56..Takeno M, Chiba A, Hoshi N, Ogasawara S, Takemoto M, Rahman M. Test results and torque improvement of the 50-kW switched reluctance motor Song Z, Hofmann H, Li J, Hou J, Han X, Ouyang M. Energy management strategies comparison for electric vehicles with hybrid energy storage system. *Applied Energy* 2014; 134:321–331.
61. 57.Kumar L, Jain S. Electric propulsion system for electric vehicular technology: a review. *Renewable and Sustainable Energy Reviews* 2014; 29:924–940.
62. 58.Ahmed A. Propulsion system design and sizing of an electric vehicle. *International Journal of Electronics and Electrical Engineering* February, 2015; 3(1).
63. 59..Hu XS, Sun FC, Zou Y. Comparison between two model based algorithms for Li-ion battery SOC estimation in electric vehicles. *Simulation Modelling Practice and Theory* 2013; 34(1).
64. 60.Chau KT, Wong YD, Chan CC. An overview of energy sources for electric vehicle. *Energy Conversion and Management* 1999; 40(10):1953–68.
65. 61..Piller S, Perrin M, Jossen A. Method for state of charge determination and their applications. *Journal of Power Sources* 2001; 96(1):113–120.Millo F, Rolando L, Fuso R, Mallamo F. Real CO₂ emissions benefits and end user's operating costs of a plug-in hybrid electric vehicle. *Applied Energy* 2014; 114:563–571.
66. 62..Warth M, Bassett M, Hall J, Korte V, Mahr B., "Design and development of the MAHLE range extender engine," paper presented at the Aachen Colloquia. Germany: Aachen; October 2011.
67. 63..Urquidi-Macdonald M, Bomberger NA. Predicting failure of secondary batteries. *Journal of Power Sources* 15 July 1998; 74(1):87–98.