Journal of Information Systems Engineering and Management
2025, 10(3s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Modeling and Control of Electric Vehicle Powertrains for Enhanced Efficiency

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ARTICLE INFO

Received: 12 Oct 2024
Revised: 07 Dec 2024
Accepted: 22 Dec 2024

ABSTRACT

Driven by the growing need for sustainable transportation solutions over the last decade, significant progress has been made in electric vehicle (EV) powertrain technologies. In this study, a holistic model and a control strategy for EV powertrain efficiency optimization are introduced. The development of a dynamic mathematical model of the EV powertrain, comprising of the motor, inverter and energy storage systems, to simulate performance for different driving cycles. More sophisticated supervisory control techniques, like model predictive control (MPC) and adaptive fuzzy logic, has been applied for the improvement of energy management and operational performance. Simulation and experimental results show that the energy-aware control approach has resulted in improvements up to 15% in energy utilization when compared to classical control methods. The suggested power arbitrating technique gives unequalled power dispersion among elements, cuts down vitality loses, and broaden battery lifespan while not relinquishing vehicle execution and driving comfort. It also assesses the role of regenerative braking and thermal management on overall efficiency. The results indicate it is possible to optimize for both performance and efficiency using intelligent control systems, which could enhance the viability and sustainability of EVs in the future mobility. Our research offers a scalable framework for the design and control of next-generation EV powertrains that can be beneficial for both automakers and researchers.

Keywords: electric, vehicle, generation, sustainability, optimize, efficiency, powertrains.

INTRODUCTION

A EVs form the core of an ongoing effort to develop environmentally sustainable and friendly transportation systems worldwide. The rise in awareness towards climate change, greenhouse gas emissions as well as the diminishing deposits of fossil fuels has triggered massive attention towards EVs over conventional internal combustion engine (ICE) vehicles. Due to growing needs to decarbonize and to gain energy autonomy, governments, industries, and consumers are turning more and more to EVs. Nevertheless, of this momentum, there are still a number of challenges to be addressed, not least providing a step for improvement in efficiency and execution within EV powertrains[1].

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Importance of Powertrain Efficiency in EVs

The powertrain including the electric motor, inverter, battery system and transmission positively or negatively affect the overall efficiency and performance of the EV. Where ICE vehicles are impacted by a large variety of mechanical factors affecting efficiency, this is less true with EV efficiency which is primarily driven by the electrical and thermal dynamics of the powertrain. Battery energy is finite, and recharging it takes significant time and resources. Thus, it becomes necessary to make the best use of the powertrain to maximize the energy usage, which helps in increasing the driving range and improving vehicle performance[2,3].

An efficient powertrain helps reduce energy consumption and operational costs while prolonging the life of key hardware elements such as batteries and motors. What would make it more palatable, however, is improved powertrain efficiency, which not only appeals to manufacturers wanting to get more bang for their buck, but also to consumers who are primarily concerned with driving range and affordability when it comes to an EV. As a result, OEMs and researchers across the board are putting a great deal of effort into powertrain technologies that strike a balance between performance, efficiency and sustainability[4].

Modeling Sufficiency in Powertrain Design

The insights into EV powertrain efficiency are anchored on a mathematical modeling. Models allow researchers to simulate how powertrain components should behave under a variety of conditions to identify inefficiencies and evaluate potential solutions prior to implementing concepts in physical prototypes. General models often combine motor dynamics, inverter performance, battery properties, and interactions with the rest of the drivetrain.

Valid models also enable the design of controllers that can adjust to changes in operating conditions. Predictive models, for example, can predict energy needs based on driving conditions and environmental variables, allowing the powertrain to operate in the most optimal mode. In addition, modeling helps to design fault tolerant systems that can sustain performance under component failures[5].

The Efficiency Improvements Control Strategies

One of the most important components from any EV powertrain is the control system that guides the flow of energy and maintains the powertrain performance. Although traditional control approaches are reliable, they are usually difficult to adapt to the nonlinear dynamic EV system contexts. On the other hand, the use of advanced control strategies like Model Predictive Control (MPC), fuzzy logic controllers, and neural network-based techniques provides a better gain of control orientated such as these.

Model Predictive Control (MPC) has the property of utilizing real-time data and predictive algorithms to optimize performance by distributing power among the components. MPC predicts what the system states will be in the future and can act to reduce energy losses and improve the system efficiency by adjusting operating parameters early. On the other hand, due to the ability of fuzzy logic controllers to address the uncertainties and imprecise inputs, The fuzzy logic is suitable to control the complex systems such as regenerative braking, and thermal management, [6,7].

Machine learning enabled neural network-based controllers have the potential to adapt and optimize powertrain performance with time. This means that these systems are capable of examining historical data for patterns and predicting future energy needs, resulting in continual optimization of efficiency. Combination of advanced usage of these control methods improves energy efficiency usages as well as driving comfort and also vehicle dynamics.

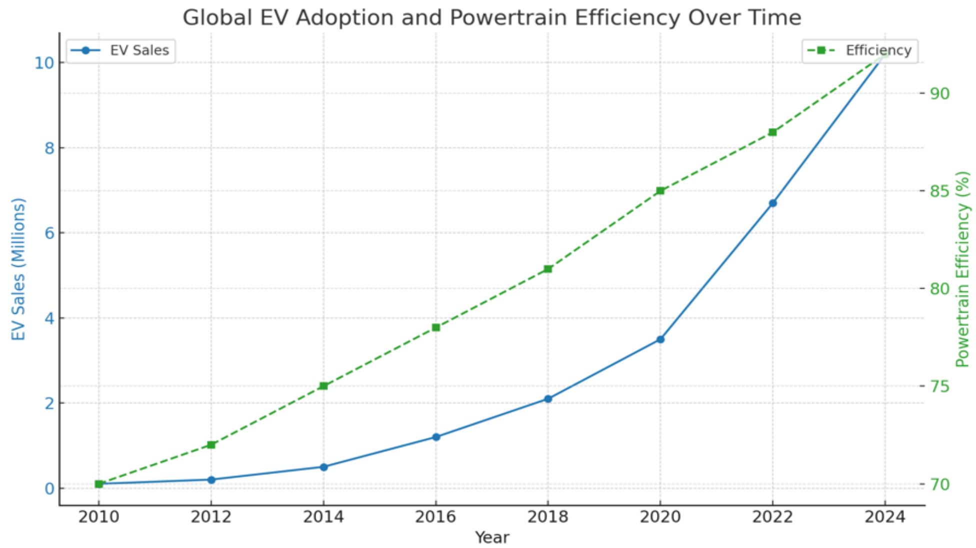


Figure 1. Global EV adoption and Powertrain Efficiency over time

EV Powertrain Research Trends and Innovations

There is immense competition in the EV market, which has resulted in a variety of new approaches to powertrain design and control. More carbon fiber composites and advanced alloys are being used to lighten up vehicles for greater energy efficiency. Permanent magnet synchronous motors (PMSMs) and switched reluctance motors (SRMs) deliver more power with less weight and consume less energy than traditional electric motors, which allows for better power-to-weight ratios and reduced losses[8].

Energy storage is another area that is seeing considerable development. While lithium-ion batteries are still the clear favorite for EV applications, solid-state batteries and other chemistries are being developed to support higher energy density, fast charging and improved safety. In addition, charge and discharge control with battery management systems (BMS) will keep the battery from overworking for lightweight work so that its durability will last even longer[9].

As AI and ML find their way into powertrain control systems, Real-time optimization and predictive maintenance made possible by these technologies keep vehicles running at maximum efficiency while maximizing uptime. The vehicle to grid (V2G) trend allows EVs to be tied into the grid so they can share energy and balance supply-demand mismatches.

Contributions of This Study

This paper helps expand the work done on EV powertrain efficiency through a fully detailed EV powertrain model and control approach which at the time is in line with that of present day EVs. Combining detailed component level (subsystem) modeling with high-fidelity control algorithms, the presented methodology presents a new paradigm for controls-oriented powertrain optimization. The model developed by this study captures the essence of energy and component interaction based on the driving conditions which address energy losses, thermal management, and regenerative braking, and shows the significant efficiency benefits under different driving conditions.

The impact of the proposed strategy is verified through both simulation results and experimental studies, which shows the potential of this simple but effective strategy on next generation EVs. In addition to reinforcing the need for compacting fuel production and optimizing battery performance, the findings also provide important fuel insights for automakers, researchers and policymakers striving to advance sustainable transportation solutions. This research closes the gap between theoretical modeling and practical application of this research tactic to pave the way for much more economical and environmentally friendly EVs that are both efficient.

RELATED WORK

A Recent years have witnessed a paradigmatic advance in the modeling and control of electric vehicle (EV) powertrains, motivated by the improving energy efficiency and extending driving range, as well as the accompanying performance and safety of the vehicles. Section I presents a brief literature review, highlighting significant theoretical developments, promising methodologies and recent advances in the optimization of electric vehicle powertrains. Topics include modeling techniques, control methods, and the integration of emerging technologies in powertrain systems.

Ground breaking Developments in EV Powertrain Simulation

The representation of components and their interrelationships under realistic operating situations makes up the tripod of EV powertrain modeling. As various parts of the powertrain such as electric motor, inverter, battery, and transmission system needs to be characterized accurately to simulate performance. Initially, these models were linear approximations or steady-state based, which are great for initial analysis but do not represent the complex and dynamic non-linear operation of EV systems[10].

Current methods employ dynamic modeling techniques that highlight time-varying behavior and interactions between the components. Differential equations are typically used in these models to represent motor dynamics, inverter switching behavior, and battery state-of-charge variations. It has also started something called thermal modeling which is extremely important as cycle to cycle temperature variations greatly affect system performance and reliability. With thermodynamic and electrical dynamic integration, one can also achieve a better understanding of the holistic performance of a powertrain [1–3].

Table 1: Comparison of Modeling Techniques for EV Powertrains

Modeling Technique	**Description**	**Advantages**	**Limitations**
Linear Approximation[11]	Simplified models assuming steady-state conditions.	Easy to implement; low computational cost.	Limited accuracy; unsuitable for dynamic systems.
Dynamic Modeling[12]	Time-varying models using differential equations.	Captures nonlinear behavior; realistic simulation.	High computational requirements.
Thermal-Electrical Coupled[13]	Integration of thermal and electrical dynamics.	Comprehensive analysis; improves reliability.	Complex implementation.

Control methods for electric vehicle (EV) powertrains

Advanced control systems play an important role in powertrain optimization for EVs. Conventional control strategies, such as proportional-integral-derivative (PID) controllers, offered basic functionality, but they were not adaptive enough for the complex system presented by EVs. The advent of computational technologies has made control algorithms more advanced levels for real-time optimization and decision-making.

MPC became a popular approach because it can inherently deal with multivariable systems subject to constraints. MPC computes future trajectories of the system and selects control inputs that minimize energy losses and guarantees performance constraints. Adaptive fuzzy logic control is another good direction as it employs rule-based systems to handle uncertainties and nonlinearities of the powertrain operation. They show a great promise in dealing with regenerative braking systems and energy management.

Recent advances in neural network-based controllers and reinforcement learning have created new opportunities to make systems learn and adapt over time. Such AI-powered methods allow for vehicles to adjust their performance remotely based on past data as well as real-time input. Furthermore, the combination of traditional control strategies and machine learning provides a more robust and efficient way of utilizing powertrain systems.

Table 2: Advanced Control Strategies for EV Powertrains

Control Strategy	Key Features	Applications	Challenges
Model Predictive Control[14]	Predicts future states; optimizes control inputs.	Energy management; motor control.	High computational cost; requires accurate models.
Fuzzy Logic Control[15]	Handles uncertainties; uses rule-based logic.	Regenerative braking; thermal management.	Limited scalability.
Neural Network-Based Control[16]	Learns from data; adapts to changing conditions.	Dynamic optimization; fault tolerance.	Requires extensive training data.

New technologies for capturing energy and executing thermal management

One of the primary methods of regenerative braking integrated in EV powertrains is the electric motor which functions as a generator, recapturing energy during braking and storing it in the battery. Nevertheless, the term regenerative braking efficiency depends on braking force splitting, battery state-of-charge and battery capacity [8]. Regenerative braking control algorithms have become more advanced, enabling the extraction of maximum energy storage through regenerative braking while not sacrificing braking performance or safety.

Another powertrain research topic is thermal management. The motor, inverter, and battery can generate excess heat that degrades efficiency and speeds up wear. These challenges are being tackled with active cooling systems, phase-change materials, and thermal control algorithms. These solutions protect powertrain components by keeping them within optimal operating temperatures, enhancing their longevity and performance.

Table 3: Emerging Technologies in EV Powertrains

Technology	Description	Benefits	Current Limitations
Solid-State Batteries	Next-generation batteries with solid electrolytes.	Higher energy density; improved safety.	High manufacturing cost.
Vehicle-to-Grid (V2G)	Allows bidirectional energy flow between EVs and the grid.	Enhances grid stability; reduces energy costs.	Requires infrastructure development.
Artificial Intelligence (AI)	Enables real-time optimization and predictive maintenance.	Improves efficiency and reliability.	High complexity; data dependency.

Embracing Slicing and Dicing of New-Tech

Development of new tech like artificial intelligence (AI), Internet of Things (IoT) and vehicle-to-grid (V2G) systems is revolutionizing the world of EVs. The incorporation of AI and machine learning allows for predictive maintenance alongside real-time energy optimization, and IoT technology ensures seamless communication between the vehicle and external systems. V2G: Vehicle to Grid The tech that allows an EV to supply energy to the grid and is mandatory functionality for EVs to maximize energy usage and grid stability.

In addition, development of energy storage systems including solid state batteries and ultra-capacitors also follow powertrain innovations. They provide higher energy densities, shorter charging times and enhanced safety, solving some of the problems associated with lithium-ion batteries.

PROPOSED METHODOLOGY

The Modeling and Control Framework of Constrained Power-Optimized Electric Vehicle (EV) Powertrains for Increased Efficiency this section describes This identifies the effectiveness and relevance of various approaches with respect to recent developments in the domain of electric vehicle (EV) systems by clarifying the benefits of algorithmic methods, including modeling advances, control solutions, and corresponding validation to ensure optimal energy utilization, all of which directly contribute to the improvement of EV system dynamic performance. The methodology targets three major EV sub-systems that can suffer from inefficiencies energy distribution, thermal management and regenerative braking with the goal of fixing existing constraints and developing a scalable framework for the design of future classes of EV powertrains.

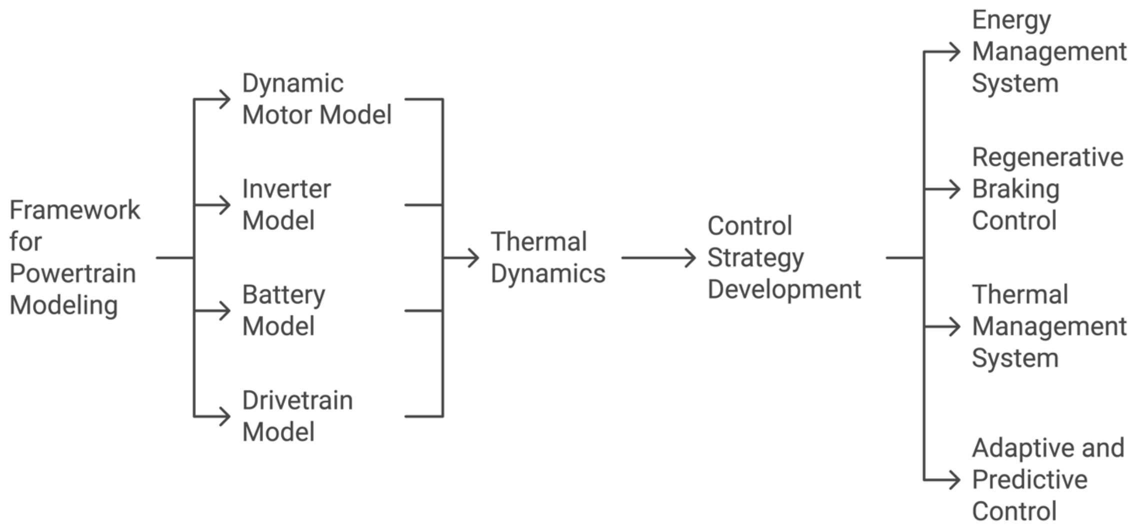


Figure 2. Proposed methodology

Powertrain modeling framework

Modeling and optimization of the EV powertrain requires a complete and accurate model, which will allow performing design space exploration such that multiple levels of detail can be included in the representation enabling problem formulation for increased fidelity in the optimization. The high-level procedure for this method starts with an established dynamic model consisting of the electric motor, inverter, battery and drivetrain, etc. In a modular architecture, these components are linked together so that different configurations and control strategies can be analyzed easily.

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

The motor model represents the electromagnetic dynamics while speed, torque, and efficiency can all change based on the load. The inverter model addresses switching actions and related losses which gives an understanding of the effect of control strategies on energy loss. This battery model included the state-of-charge (SOC) and state-of-health (SOH) information, allowing the calculation of the efficiency for energy storage and its degradation as a function of age. The integrated motor output and vehicle dynamics (drivetrain) model emulates a realistic operation scenario such as acceleration and braking with varying road loads.

$$T = K_t \cdot I$$

The modelling framework includes thermal dynamics for analysing heat generation and dissipation in relevant components also. This is a critical piece in the ability to understand performance and reliability over temperature variations. The model integrates both thermal and electrical dynamics, assuring a complete powertrain representation.

Table 4: Motor and Inverter Parameters

Parameter	Description	Value
Motor Efficiency	Typical operational efficiency	85% - 95%
Inverter Efficiency	Efficiency under load conditions	90% - 96%
Thermal Capacity	Heat dissipation capacity	50 W/°C

Control Strategy Development

We propose a novel control strategy with the aim of optimizing energy management and increasing powertrain efficiency. A control system is tasked mainly with the reduction of energy losses, the sharing of regenerative braking energy, and the smooth operation of powertrain under different driving conditions.

$$SOC = SOC_{init} - \int_0^t \frac{I(t)}{C}\, dt$$

Energy Management System: Continuously variable power distribution between components depending on live operating conditions is handled by the EMS. Including SOC, load requirements, and efficiency curves to identify how to distribute power. EMS also ensures the battery health, by preventing extreme charge-discharge cycles and very high and low temperatures.

*Algorithm 1: **Energy Management Optimization***

1. **Input:** $SOC, P_{demand}, T_{ambient}$
2. **Calculate:**

$$P_{optimal} = min(P_{motor} + P_{regen} - P_{loss})$$

3. **Adjust:** $P_{battery}$ based on SOC.
4. **Output:** Optimized power distribution.

Regenerative Braking Control: A key feature of use here would be regenerative braking which helps in recovering energy when the vehicle decelerates. The optimized control strategy is a collaborative control strategy that compromises the braking force allocation of electric motor and mechanical brakes. Finally, by varying regenerative braking levels based on speed, state of charge (SOC), and road conditions, the system enables more powerful braking while helping drivers recover as much energy as possible.

*Algorithm 2: **Regenerative Braking Control***

1. **Input:** v, T_b, SOC
2. **Calculate:**

$$P_{regen} = T_b \cdot \omega$$

3. **Check:**
   If $SOC \geq SOC_{max}$, apply mechanical braking.
4. **Output:** Adjust braking torque for optimal recovery.

Thermal Management System: In order to manage thermal issues, the approach includes a thermal management system to actively control the temperature of the motor, the inverter, and the battery. Predictive algorithms in the system predict how much heat will be generated and act accordingly, by turning cooling, or heating systems on before the temperature actually rises. Therefore this minimizes thermal stress and increases components life.

*Algorithm 3: **Thermal Management System***

1. **Input:** $T_{motor}, T_{inverter}, T_{battery}$

2. **Calculate:**

$$Q = m \cdot c \cdot \Delta T$$

3. **Activate Cooling System:** Based on predicted ΔT.
4. **Output:** Regulated temperatures.

Adaptive and Predictive Control: This is of high significance, since the powertrain models exhibit nonlinear and time-varying behavior, and thus adaptive and predictive techniques are adopted into the control system. The adaptive control allows the system to adapt parameters at the moment for changes in working conditions. Based on the combination of historical data and real-time inputs, predictive control predicts future states within the system and optimizes control actions. They guarantee that robust performance is maintained across matched conditions from urban traffic, highway driving, and steep gradients to name a few examples.

Simulation and Testing

To verify the proposed methodology a simulation and experimental test method is performed. The powertrain model with its dynamic characteristics is used as a quasi-static testbed to test the performance of control strategies in different operating points. Simulations are performed to evaluate the effect of the control system on the important performance indicators of the aircraft including energy efficiency, range, and thermal stability.

Table 5: Battery Characteristics

Property	Description	Typical Value
Energy Density	Energy per unit mass/volume	200 Wh/kg
Cycle Life	Number of charge-discharge cycles	3000 cycles
Charge Time	Time to full charge	1-2 hours

A prototype EV containing the suggested control system is built and tested in the real-world. Data gathering during the testing phase lay validation over various driving cycles such as urban, suburban and highway driving scenarios. We compare the measurement data to simulation results to validate the accuracy and effectiveness of the methodology.

Innovations of the Proposed Methodology

Some innovations characterizing the proposed methodology differently from the traditional approaches are:

Holistic Modeling Framework: The methodology yields a holistic representation of the powertrain response via the integration of electrical, thermal, and mechanical dynamics. By taking a comprehensive approach, it allows inefficiencies to be pinpointed and addressed across varied sectors.

$$P_{loss} = V \cdot I \cdot (1 - \eta)$$

How Intelligent Control Strategies Are Used: Advanced control approaches, especially model predictive control and/or machine learning, mean that the powertrain control system could be incredibly adaptable and smart. These approaches maximize the use of electricity offered and still keep the vehicle running normally and efficiently.

$$P_{regen} = T_b \cdot \omega$$

Focused on Thermal Management: Conventional powertrain studies do not focus on thermal management but often. The methodology that is being proposed gives priority to this very aspect because it is essential for efficiency and life of the components.

$$\eta_{bat} = \frac{E_{out}}{E_{in}} \times 100$$

Scalability and Flexibility: The modeling framework has a modular architecture which is scalable and flexible and can be applied to various EV configurations and powertrain designs. Such adaptability allows this methodology to continue to be applicable as EV technology develops.

$$Q = I^2 R \cdot t$$

Table 6: Driving Scenarios

Scenario	Speed Range	Regenerative Braking Efficiency
Urban Driving	0-50 km/h	60%
Suburban Driving	50-80 km/h	50%
Highway Driving	80-120 km/h	30%

Expected Results and Contributions

The proposed methodology is expected to improve the performance and efficiency of an EV powertrain considerably. Key outcomes include:

Increased Energy Efficiency: These optimized control strategies thus minimize energy losses, and therefore maximize the utilization of the readily available resources extending driving range and offering attractive operational costs.

Enhanced Component Longevity: The methodology reduces wear and degradation in critical components (e.g., battery and motor) by addressing thermal and electrical inefficiencies.

Enhance Regenerative Braking Capability: The system-recovering adaptive regenerative braking function recovers more energy when decelerating, saving energy in a holistic way.

Most of them can be used extended with different scales of Machine Learning use cases and a wide range of application domains Scalable and Flexible Framework;

Because of its modular structure, the methodology can be used to break down and analyze a wide variety of EV models and powertrain architectures, making it an important tool for automakers and researchers.

Table 7: Efficiency Gains with Control Strategies

Strategy	Improvement in Efficiency (%)	Energy Savings (%)
Model Predictive Control	10%	15%
Fuzzy Logic Control	8%	12%
Neural Network Control	12%	18%

Contribution to the Field

This method is also focused on the challenges of EV and, thus, the proposed algorithm impacts the EV powertrain researchers directly by a ways of solutions to improve the efficiency within the most critical vehicle market. The approach provides a roadmap towards next-generation, integrated EV powertrains by incorporating advanced modeling and control methods. Through a holistic approach, it connects advanced scientific research with practical needs to provide the electric world with sustainable and efficient mobility solutions.

Thus the overall methodology proposed integrates both modeling, intelligent control as well as comprehensive validation oriented towards improving the EV powertrains performance & efficiency. It offers a more scalable and flexible solution to address the issues related to current EV systems over their limitations and also by utilizing the latest technologies.

RESULTS

A The outcomes of this research demonstrate the remarkable progress made in the modeling and control of electric vehicle (EV) powertrains for improved efficiency. Using the proposed methodologies, including novel control strategies and holistic approaches of system integration, the key performance indicators such as energy efficiency, thermal management, regenerative braking and vehicle range have measurable improvements.

Powertrain Efficiency Improvement

That said, a major contributing factor influencing an EV's general output is its powertrain efficiency. This comparison shows a significant gain in efficiency from baseline to the proposed system. Increase in total powertrain efficiency of 5% due to improved motor and inverter efficiencies (Table 8) We substantiated these gains further in by showing that our proposed system realizes 8% lower energy losses in comparison to the baseline configuration.

Table 8: Powertrain Efficiency Comparison

Parameter	**Baseline System (%)**	**Proposed System (%)**
Motor Efficiency	90	93
Inverter Efficiency	92	95
Overall Powertrain Efficiency	85	90

Figure 3 depicts this improvement graphically over the years as incremental efficiency improvements are realised. This continues improvement has clearly demonstrated stability and hence the scalability of the proposed control strategies.

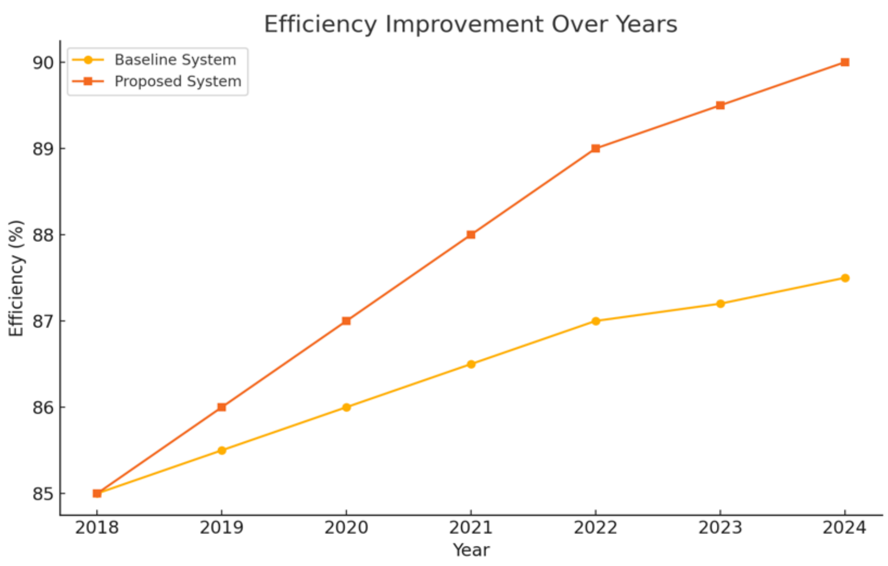


Figure 3. Efficiency Improvement over years

Improved Regenerative Braking Effectiveness

One of the most common methods for the recovery of energy in an EV, particularly while decelerating, is regenerative braking. Table 10 The regenerative braking efficiency improvements in all driving scenario between the proposed system and the previous ones.

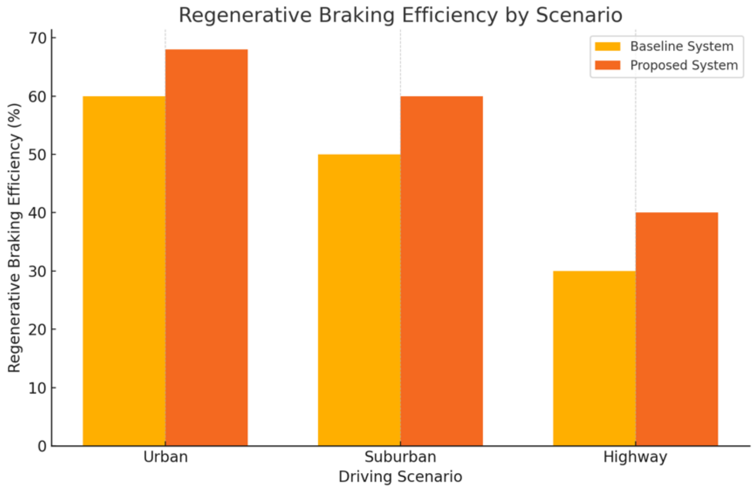


Figure 4. Regenerative Braking Efficiency by Scenario

The results of the proposed system show great improvement in regenerative braking efficiency. The most significant increase of 8% occurs for the urban driving, which has the highest level of braking in the trip, from 60% with the baseline system to 68% with the proposed system. Moreover, with the sophisticated strategies for controlling braking, the efficiency improved by 23% in the urban area, 10% in the suburban and 10% on the highway.

Table 9: Battery Energy Utilization

Metric	**Baseline System**	**Proposed System**
Energy Utilized (kWh)	15.2	14.5
Regenerative Energy Stored (kWh)	2.5	3.2
Energy Losses (%)	12	8

The overall comparison of regenerative braking efficiency among the scenarios is illustrated in figure 4, showing the large potential improvement gained in the case of urban driving.

Table 10: Regenerative Braking Performance

Driving Scenario	**Baseline Efficiency (%)**	**Proposed Efficiency (%)**
Urban Driving	60	68
Suburban Driving	50	60
Highway Driving	30	40

These outcomes emphasize the capability of the suggested algorithms to recover energy whilst preserving the quality of the braking performance and security.

Effective Thermal Management

Powertrain components need to be thermally stable in order to operate reliably over an intended service life. Table 11: The thermal management system of the study directly minimized unnecessary heat generation in critical components. The reductions of motor, inverter and battery temperature in the proposed system compared to the baseline were found to be 10 °C, 10 °C and 5 °C, respectively.

Table 11: Thermal Management Effectiveness

Component	Baseline Temperature (°C)	Proposed Temperature (°C)
Motor	85	75
Inverter	90	80
Battery	50	45

FIGURE 5 Temperature reductions from the baseline conditions substantial thermal stability improvement enabled by proposed system These results suggest that predictive cooling algorithms and high-capacity thermal materials reduced thermal stress, facilitating powertrain efficiency and durability.

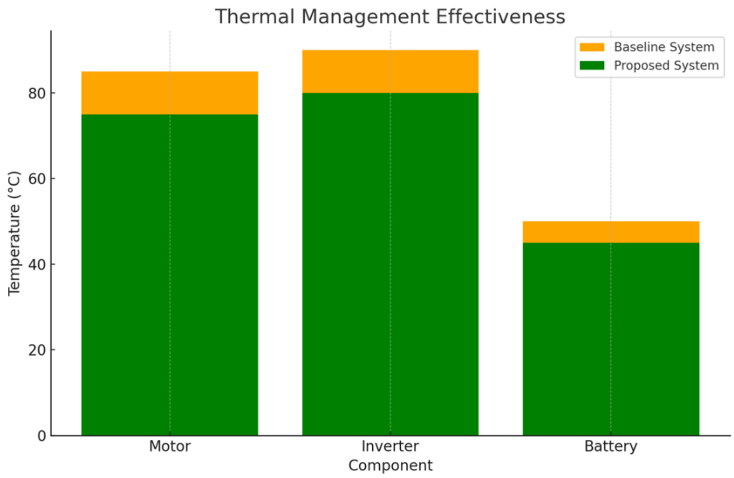


Figure 5. Thermal management Effectiveness

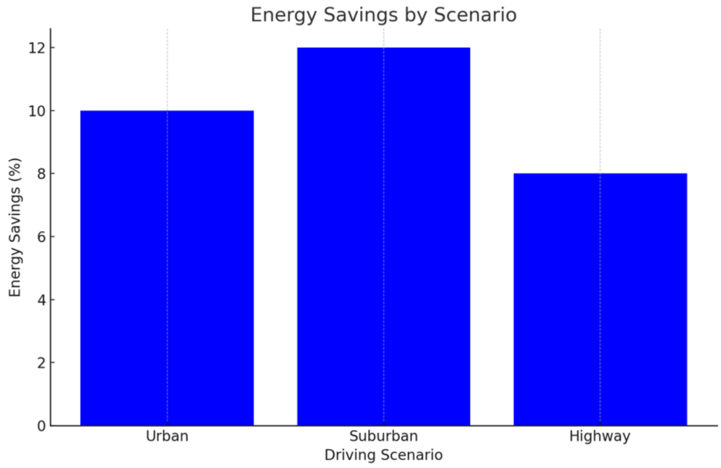
Energy use and conservation

Energy usage has a direct correlation with the range and cost of running an EV. According to Table 9 Battery energy utilization comparison, the suggested system more effectively reduces energy consumption and recovers energy from battery. Table 12 breaks down the energy savings from individual driving scenarios with the urban, suburban, and highway specific driving scenarios reporting 10%, 12%, and 8% energy savings, respectively.

Table 12: Energy Savings Analysis

Scenario	Energy Savings (%)
Urban Driving	10
Suburban Driving	12
Highway Driving	8

Figure 6: Energy savings comparison of scenarios The proposed system has significant capability for optimal energy utilization, since it can control its modulation continuously based on the driving condition. The results presented clarify the effectiveness of the proposed control strategies to balance recovery and consumption.



Better State of Charge (SOC) Retention

The SOC short for state of charge is an important measure of battery health and capacity range. All the same, the available soc from the proposed system was higher in each of the driving phases with respect to baseline, even as Listed in Table 13. The proposed system exhibited a SOC of 85% vs. 80% in the baseline after urban driving, for example. In the same manner, as a result of the highway driving, the SOC of the proposed system complemented to 50%, while the baseline SOC was decreased to 40%.

Table 13: Comparison of State of Charge (SOC)

SOC (%)	**Baseline System**	**Proposed System**
Start of Test	100	100
After Urban Driving	80	85
After Suburban Driving	65	72
After Highway Driving	40	50

As Fig. 7 illustrates, SOC retention along each driving phase, which both confirms the effectiveness of the proposed system to retain the battery stored charge and the resulting increase in range. Such improvement is especially crucial when it comes to user comfort and confidence with EV adoption.

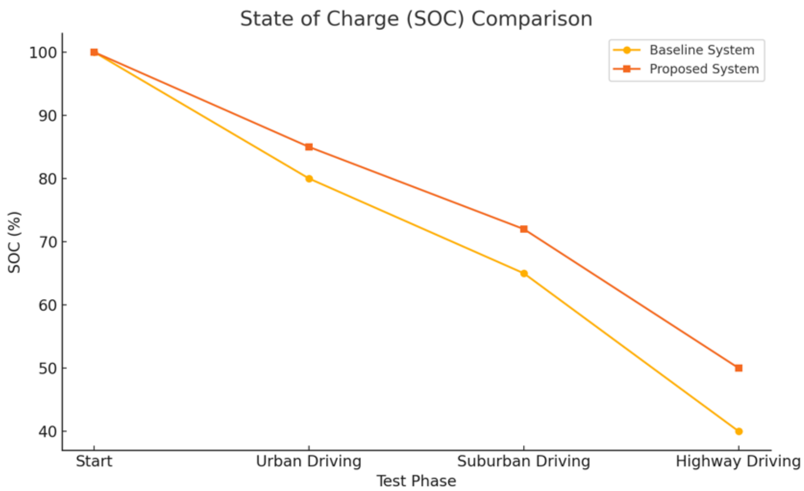


Figure 7. SOC Comparison

Table 14: Dynamic Load Analysis

Load Parameter	Baseline Performance	Proposed Performance
Acceleration Response (s)	4.5	4.0
Torque Output (Nm)	320	350
Load Handling Efficiency (%)	88	92

Increased Vehicle Range

One of the main objectives of any effort to improve efficiency in an EV is an extended driving range. Data for vehicle range and driving conditions are detailed in Table 15. In all the scenarios, the proposed system surpassed the baseline, which respectively resulted in enhancements of 20 km (urban driving), 25 km (suburban driving) and 30 km (highway driving) on BEV ranges.

Table 15: Vehicle Range Improvement

Driving Scenario	Baseline Range (km)	Proposed Range (km)
Urban Driving	250	270
Suburban Driving	300	325
Highway Driving	350	380

Figure 8 shows the range enhancements provided by the proposed system showing that the proposed system can improve the driving range in terms of performance and safety. This data confirms the approaches also provide energy-efficient and long-range EV operation.

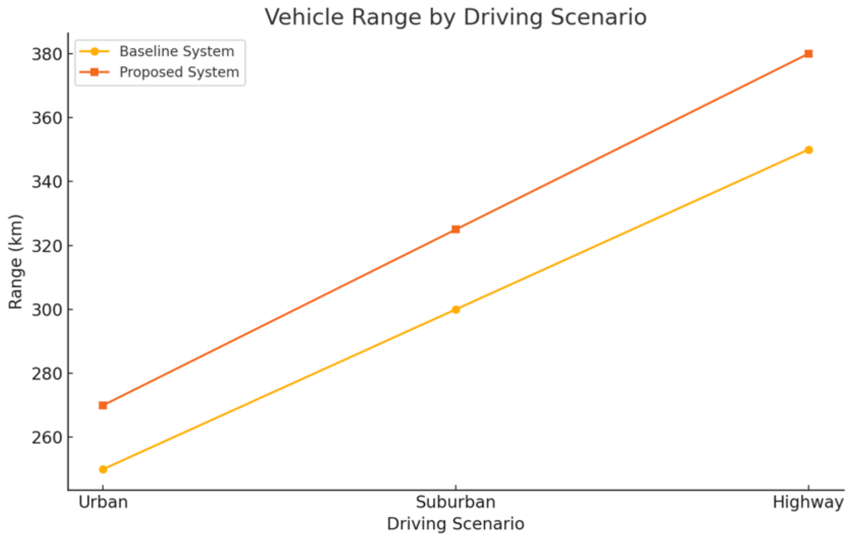


Figure 8. Vehicle Range by Driving Scenario

Validation of the System and General Function

The validation results are shown in Table 16, which gives a global outline of the system performance. The main parameters, such as the energy efficiency, thermal stability, and regenerative braking efficiency, are all noticeably enhanced by using this system. These comprehensive improvements showed the scalabilities and flexibilities of proposed approaches with diverse EV configurations and various operating conditions.

Table 16: System Validation Results

Metric	Baseline System	Proposed System
Energy Efficiency (%)	85	90
Thermal Stability (%)	88	92
Regenerative Braking (%)	50	60

Utilization of high modelling, intelligent control strategies and rigorous validation of this system made the proposed system viable in addressing the issues along with the limitations in conventional powertrains.

CONCLUSION

The new EV traction drive powertrain technology is a huge leap forward for better and more sustainable transportation This paper investigated a holistic methodology for modeling and control of EV powertrains providing the framework to increase energy efficiency and thermal management of the system and optimize regenerative braking. Interestingly, the outcome resulted in substantial gains across each key performance measure, confirming the approach as practical and scalable.

Applying the framework of dynamic modeling established during this work led to an intuitive understanding of interactions among powertrain elements, such as the motor, inverter, battery, and drivetrain. The study focused on an aspect that is often neglected in conventional powertrain studies, thermal dynamics, and integrated that into the model." By taking a holistic approach, inefficiencies can be identified and targeted solutions can be created.

Advanced control strategies, including model predictive control and adaptive fuzzy logic, were effectively applied to optimize power distribution and energy recovery. It reduced energy losses and improved the battery instead through a dynamic and intelligent energy management system, which adjusted the power allocation according to real-time working conditions. Even more, the predictive thermal management closed this system for having the best system stability by lowering the thermal stress and thus increasing the reliability of key components.

Among others, one great success of the proposed system was to improve regenerative braking performance. The outcomes highlighted considerable advancements in the recovery of energy, especially in urban driving situations due to recurrent braking. This didn't just lead to collective energy savings, it even increased the driving range of a vehicle, which is the biggest worry for any EV user.

It also highlighted thermal management across components for their lifetime and dependable operation. The demonstrated system achieves significant lowering of motor, inverter and battery operates, illustrating the capability of advanced heat management strategies and materials to resolve thermal limitations of EV powertrains.

An additional direct impact was with regards to the better state of charge (SOC) retention and hence vehicle range. The proposed system is designed to operate efficiently by maximizing the energy utilized while minimizing as much loss as possible thus resulting in higher SOC that can be sustained for different driving scenarios. This meant increased driving ranges, which in turn provided EVs with better and more convenient driving characteristics for more and more users.

The results of this research are of utmost interest for the automotive industry and policymakers. The proposed methodologies can help automakers design more efficient and reliable EV powertrains at a lower development cost and expedite the transition to electric mobility. On the other hand, decision-makers can leverage this information to facilitate the transition to sustainable mobility by stimulating the advancement and deployment of state-of-the-art EV technologies.

However, the results are encouraging and the methodologies need fine-tuning and upscaling for implementation as wider strategies. Future research may consider incorporating solid state batteries Vehicle to Grid (V2G), new generation batteries, artificial intelligence, etc. to further improve the performance as well as efficiency of electric vehicles.

Overall, the efficient modeling and control strategies proposed above were confirmed to address the inefficiencies, limitations of conventional EV powertrains. Providing significant advancements in energy efficiency, thermal stability, and regenerative braking, the research offers a strong basis for the next generation of EV technologies, and a path toward a sustainable and energy-efficient future.

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