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Optimizing Single-Inverter Electric Differential System for Electric Vehicle Propulsion Applications

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ABSTRACT

The increasing demand for electric vehicles (EVs) is driven by the urgent need for environmentally friendly transportation. This paper addresses the challenge of optimizing EV drivetrain efficiency by proposing a novel single-inverter electronic differential system for distributed EV drivetrains. The research focuses on reducing system cost and complexity while maintaining high performance. The methodology involves a detailed simulation using MATLAB/Simulink to validate the theoretical soundness of the proposed connection method. The results demonstrate that the proposed system achieves a minimum accuracy rate of 97.5%, marking a significant improvement over traditional dual-inverter systems. This approach not only enhances drivetrain efficiency but also contributes to more compact and cost-effective vehicle designs. Additionally, the findings underscore the potential for further refinement and exploration, suggesting that continued advancements in ED systems could lead to even greater performance gains in the future. This research lays the groundwork for future innovations in EV technology, particularly in the areas of cost reduction and system efficiency.

1. Introduction

Electric vehicles (EVs) represent a transformative shift in the automotive industry, offering a sustainable alternative to traditional fossil fuel-powered vehicles. By operating on rechargeable batteries and tapping into readily available electric energy through distribution systems, EVs not only reduce their dependency on finite fossil fuels but also align with global efforts toward renewable energy adoption, fostering a more sustainable energy ecosystem [1]. The design philosophy of EVs prioritizes environmental friendliness, safety, and seamless integration with electric infrastructure. Manufacturers have embraced innovation to deliver vehicles that not only minimize environmental impact but also prioritize driver comfort, convenience, and usability, ranging from sleek electric sedans to rugged electric SUVs [2].

However, despite these advancements, several critical gaps remain in current EV technology, particularly in the optimization of drivetrain efficiency and the reduction of system complexity. A key limitation is the reliance on multiple inverter systems for electronic differentials in distributed EV drivetrains. These systems, while effective, increase the overall cost and complexity, which may hinder their widespread adoption. Moreover, there is a notable lack of exploration into integrated electronic differential systems that can maintain high performance while minimizing both size and friction losses. This study seeks to address these specific gaps by proposing a novel single-inverter electronic differential system.

In recent years, significant attention has been directed toward enhancing the performance of electric vehicles, particularly focusing on refining traction drive systems [3]. A notable trend in this optimization journey is the incorporation of permanent magnet machines, reflecting the industry's broader focus on enhancing power and efficiency across traction drive systems [4]. To unlock the full potential of permanent magnet motors, various advanced control techniques have been employed. Direct torque control (DTC) [5], model predictive control (MPC) [6], sliding mode control (SMC) [7], fuzzy logic control (FLC) [8], and artificial neural networks (ANNs) [9] are among the methodologies utilized. These techniques offer a spectrum of benefits, including precise torque and speed control, reduced torque ripple, and overall improved performance. Comparative between control techniques shown in Table 1.

Table 1. Comparative between control techniques

Technique	Weaknesses	Ref.
DTC	1.Sensitivity to motor parameter variations, potentially leading to instability. 2.Complex implementation requiring real-time calculations. 3.Limited effectiveness at low speeds, resulting in torque ripple.	[5]
MPC	1. High computational complexity 2. High implementation cost 3. Dependence to cost function	[6]
SMC	1.Chattering phenomenon, causing high-frequency oscillations and potential mechanical stress. 2.Sensitivity to uncertainties and disturbances, impacting performance. 3.Complexity in parameter tuning, requiring expertise and experimentation.	[7]
FLC	1.Heavy time complexity for large scale systems 2.Absence of interpretability: There is no standardized methodology for rule design, contributing to difficulties in understanding and interpreting the system's behavior. 3.Total reliance on human knowledge and expertise: The system heavily depends on human understanding and expertise for rule formulation and adjustment, which can introduce subjectivity and biases.	[8]
ANN	1.Data dependency, requiring extensive training datasets for accurate modeling. 2.Black-box nature, making it challenging to interpret decision-making processes. 3.Computational complexity during training and inference phases, affecting real-time applicability	[9]

In this comparative analysis, we observed distinct weaknesses associated with each advanced control technique [5]-[7]. Direct torque control (DTC) exhibits challenges related to parameter sensitivity and implementation complexity, particularly at low speeds [5]. Model predictive control (MPC) faces issues regarding computational complexity and sensitivity to modeling inaccuracies. Sliding mode control (SMC) encounters difficulties with chattering phenomena and sensitivity to uncertainties, necessitating careful parameter tuning [7]. Understanding these weaknesses is essential for devising strategies to mitigate their impact and enhance the robustness and reliability of electric vehicle traction drive systems. Further research and development efforts should focus on addressing these weaknesses to unlock the full potential of advanced control techniques in advancing electric vehicle technology. These methods, present significant challenges when applied to EV traction systems, such as sensitivity to motor parameter variations, high computational complexity, and issues with real-time applicability. These weaknesses directly impact the performance and reliability of EVs, particularly in terms of torque control, efficiency, and stability under varying driving conditions.

In [10], the researchers introduce a traction control model tailored for electric vehicles, employing an electric differential mechanism grounded on the Ackermann steering model. This innovative model is designed to enhance the maneuverability and stability of electric vehicles, particularly by accurately controlling the power distribution between the wheels. The Ackermann steering model ensures that the wheels turn at appropriate angles to maintain optimal contact with the road surface, thereby improving vehicle handling and safety. While the proposed system demonstrates considerable efficacy at lower speeds, providing smooth and precise control over vehicle dynamics, it encounters significant challenges when operating at higher speeds. These challenges include maintaining stability and ensuring consistent performance under varying driving conditions. Additionally, the system's implementation incurs notable cost implications, primarily due to the necessity of individual inverters for each motor. This requirement increases the overall complexity and expense of the traction control system, making it less economically viable for widespread adoption. The study underscores the need for further research and development to address these high-speed operational challenges and to explore cost-reduction strategies, potentially through the integration of more advanced inverter technologies or alternative design approaches that could mitigate the financial and technical limitations identified. In [11], [12], the authors explore the utilization of a different inverter variant known as the nine-switch inverter. This alternative demonstrates cost reduction benefits in comparison to employing two separate inverters. The nine-switch inverter achieves this by reducing the number of components required, which in turn lowers the material costs and simplifies the overall system design. Additionally, this configuration minimizes the need for additional circuitry and control mechanisms, further contributing to its cost-effectiveness. The study underscores the nine-switch inverter's potential to deliver efficient performance while offering significant economic advantages, making it a promising option for applications where reducing costs is a priority.

A critical gap in the existing literature is the lack of a unified approach that addresses the optimization of the electrical connectivity of differentials in distributed EV drivetrains using a single inverter. Existing solutions, such as using multiple inverters, increase system complexity and cost, which may limit the widespread adoption of these advanced technologies. Furthermore, the literature has not adequately explored the potential of reducing system size and friction losses through an integrated electronic differential system that maintains high performance while minimizing costs [13], [14].

This paper aims to fill this research gap by developing and analyzing an innovative approach for optimizing the electrical connectivity of differentials in EVs using a single inverter. The objectives of this research are to:

- Design a simplified electrical differential system that reduces the need for multiple inverters, thereby lowering the overall system cost and complexity.
- Analyze the performance of the proposed system in terms of drivetrain efficiency, friction reduction.
- Validate the theoretical model through simulation and compare its performance against traditional systems.

In our study, we seek to develop an innovative and alternative connection approach for electric vehicles, emphasizing strong control functionality while also reducing connection costs compared to the use of two individual inverters. This approach focuses on leveraging a more integrated and streamlined system design that combines the functionalities of multiple inverters into a single, cohesive unit. By doing so, we aim to minimize the number of necessary components, which not only reduces the overall material costs but also simplifies the manufacturing and assembly processes. Additionally, this novel connection strategy is intended to enhance the efficiency and reliability of the control mechanisms, ensuring that the electric vehicles operate smoothly and effectively. Our research highlights the potential for this integrated approach to offer substantial economic and operational benefits, making it a viable and attractive option for advancing the technology and affordability of electric vehicles. Through rigorous testing and validation, we aim to demonstrate that this innovative connection method can meet or exceed the performance standards of traditional dual-inverter systems, thereby providing a robust and cost-effective solution for the future of electric vehicle design.

The research contributions of this paper are twofold:

- The development of a novel connection approach for electric differentials that utilizes a single inverter to control multiple motors, significantly reducing system cost and complexity.
- The demonstration of enhanced drivetrain efficiency and reduced friction losses in a distributed EV system, thereby contributing to the advancement of EV technology and laying the groundwork for future innovations.

The paper is structured as follows: Section 3 explains the advantages of an electrical differential over a mechanical one. Section 4 outlines the basic architecture of the electrical differential. Section 5 aims to enhance the connection of the electrical differential using mathematical equations. Finally, Section 6 presents and discusses the results, comparing the new control systems to classical ones.

2. Methodology

The proposed research methodology follows a structured approach to ensure a thorough exploration and validation of the single-inverter electric differential system. The process begins with problem identification, which establishes the necessity for optimizing electric differential systems to reduce complexity and costs while maintaining high performance. This initial step provides a clear rationale for the research, setting the stage for a focused investigation.

Following this, a comprehensive literature review is conducted to assess existing technologies and methodologies related to electric differentials and inverter systems. This step is essential for identifying gaps in the current knowledge and ensuring that the research contributes novel insights to the field. The system design phase involves the development of the theoretical framework and mathematical models for the proposed single-inverter system. This stage is crucial for laying the groundwork for the simulations and analyses that follow.

The simulation and testing phase is where the theoretical models are put to the test. By simulating various conditions using MATLAB/Simulink, the research ensures that the proposed system is robust, efficient, and viable for practical applications. This step is key to validating the design and identifying any potential areas for improvement.

Results analysis involves a detailed evaluation of the simulation data to assess the system's performance. This stage is critical for interpreting the outcomes and understanding how well the system achieves the research objectives.

In the Discussion phase, the findings are contextualized within the broader field of electric vehicle technology. Comparisons with existing systems are made, and the implications of the research are explored, providing a deeper understanding of the system's potential impact.

Finally, the methodology concludes with the Conclusion, where the key findings are summarized, and the contributions to the field are highlighted. This final step reinforces the significance of the research and suggests avenues for future work.the following Fig. 1 illustrates the flowchart of the research methodology.

3. Implementation of an ED in Evs

Fig. 2 illustrates the classic EV drivetrain, which features a single electric motor powering the wheels through a reduction gear and a mechanical differential (MD). The MD plays a crucial role in cornering, managing the speed differences between the inner and outer wheels. Traditionally, a complex arrangement of spur gears in various configurations achieved this function. Over time, various MD designs have emerged, ranging from open differentials to limited-slip options, each offering specific advantages for different driving scenarios [12]. However, conventional MDs have several drawbacks for EVs [15], [16]:

- Bulk and weight: Their intricate mechanical design adds unwanted mass, hindering the quest for lightweight EVs.
- Friction losses: The gears in MDs cause significant energy dissipation, reducing the effective driving range of EVs.
- Limited control: MDs offer passive speed adjustments, leaving room for improvement in handling and safety.

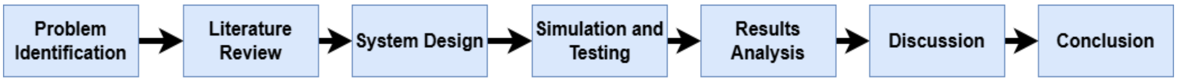

Fig. 1. Methodology flowchart

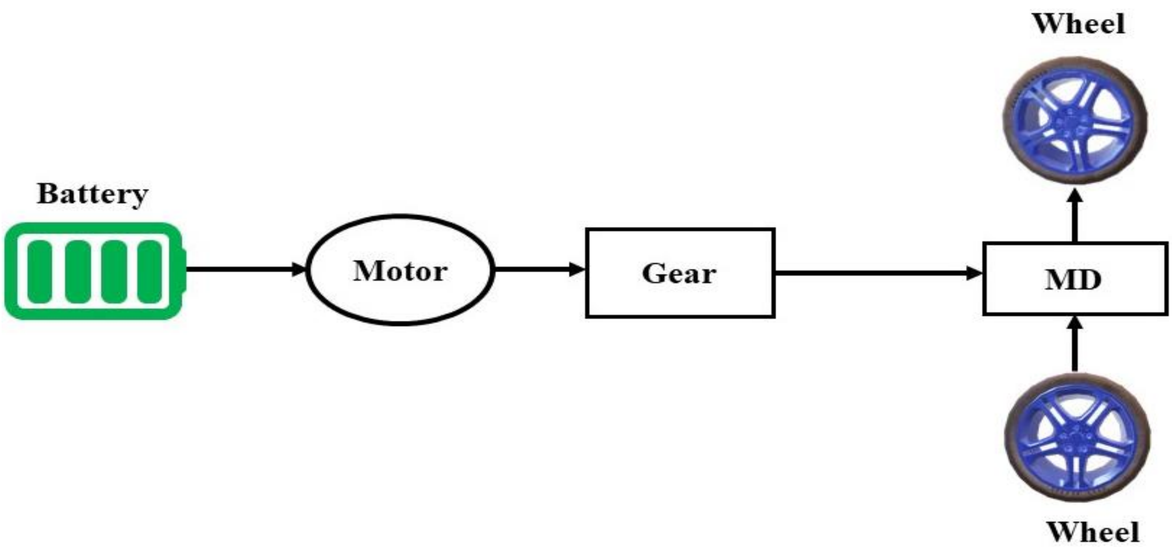

Fig. 2. EV powertrain with MD and centralized motor

Recognizing these limitations, EV engineers embarked on a drivetrain upgrade: replacing the MD with an electronic differential (ED). This innovation aimed to overcome the previous hurdles by [17], [18]:

- Embracing digital control: EDs utilize precise electronic algorithms to manage wheel speeds, leading to enhanced responsiveness and agility.
- Streamlining the drivetrain: By eliminating bulky gears, EDs contribute to a lighter and more compact overall system.
- Boosting efficiency: EDs minimize friction losses, translating into an extended driving range for EVs.

In essence, the shift from MDs to EDs marked a significant advancement in EV drivetrain technology, promoting better efficiency, agility, and driving range for electric vehicles. Recent improvements in motor technology have paved the way for exploring alternative EV drivetrains beyond traditional MDs. Among these, Wellington Adams's wheel-hub motor design, also called an in-wheel motor drivetrain, stands out as an innovative and potentially viable option [18], [19]. This ingenious concept does away with the conventional gearbox, clutch, driveshaft, and differential by integrating the motor directly within the wheel hub. This translates to a remarkable reduction in overall bulk and mechanical complexity, a major advantage for lightweight and efficient EVs. However, while this technology is simple, it is not without its drawbacks. The heavy weight of motor-laden tires can significantly impact vehicle performance. This can manifest as [19], [20]:

- Uncomfortable driving at high speeds: An increase in the unsprung mass of the wheels can lead to a rougher ride, especially on uneven surfaces.
- Compromised handling: A heavier wheel may reduce responsiveness and agility, particularly during cornering maneuvers. Therefore, while wheel-hub motors offer an intriguing proposition for future EV drivetrains, addressing the weight issue remains crucial for maximizing their potential and delivering a truly smooth and enjoyable driving experience.

A revolutionary approach in EV technology is the distributed drivetrain architecture, which has given rise to a new breed of vehicles called distributed drive EVs (DDEVs). The defining feature of DDEVs is the individual connection between each motor and its corresponding driving wheel, This Fig. 3 shows the distributed drive electric vehicle (DDEV) configuration with an electronic differential (ED). It emphasizes the reduced weight, enhanced flexibility, and superior controllability offered by DDEVs. [21], [22].

This setup allows for diverse configurations, including front-wheel, rear-wheel, and even all-wheel drive options [23], [24].

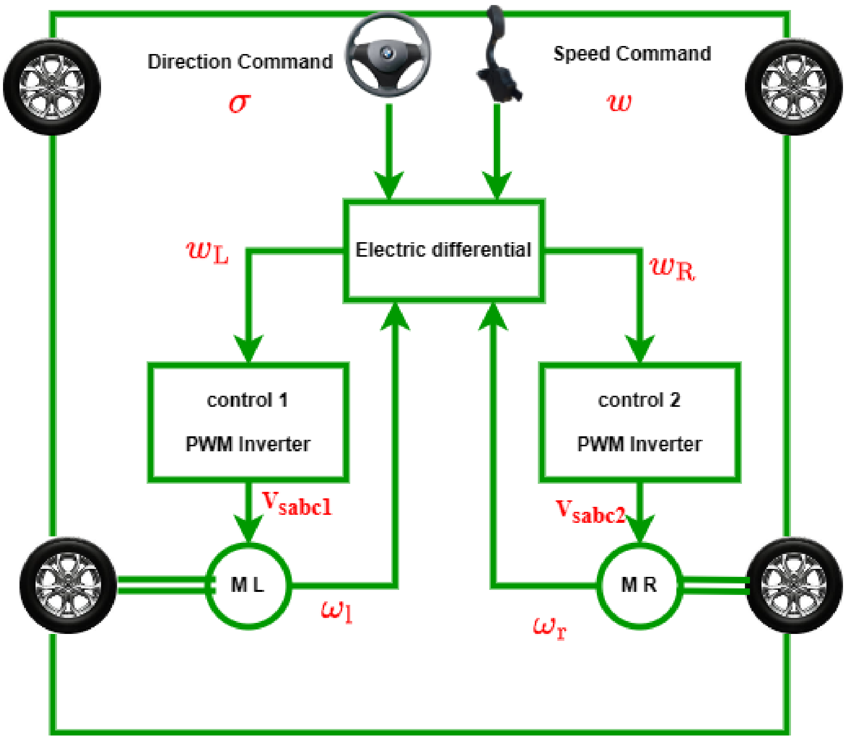

Fig. 3. The DDEV configuration with an ED system

DDEVs have many advantages over traditional transmissions:

- Reduced weight: Ditching the heavy driveshaft and gearboxes makes DDEVs inherently lighter, boosting efficiency and range.
- Enhanced flexibility: Individual wheel control opens up exciting possibilities for maneuverability and dynamic adjustments.
- Superior controllability: Precise, real-time control over each wheel translates to exceptional responsiveness and handling.

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- Rapid reaction: DDEVs boast swift torque delivery, leading to sharper acceleration and improved agility.
- Elevated safety: The independent control system enhances traction and stability, contributing to a safer driving experience.
- Cutting-edge control integration: DDEVs effortlessly embrace advanced features such as ESP, ADAS, and ASR, further improving their safety and performance. Ford's Ecostar powertrain marked the first real-world adoption of the distributed drivetrain, with Nissan's future concept car following suit [25], [26]. These pioneering examples showcase the immense potential of DDEVs to reshape the landscape of electric mobility [27], [28].

Distributed drive electric vehicles (DDEVs) represent a significant breakthrough with the introduction of electronic differentials (EDs). Unlike traditional mechanical differentials (MDs), which rely on mechanical gear linkages, EDs electronically coordinate the motors at each wheel, guaranteeing synchronized speeds, especially during turns. This advancement contributes to unmatched stability, responsiveness, and efficiency in DDEVs [29], [30].

However, the magic of EDs lies not only in their hardware but also in the art of torque distribution. This emerging research area aims to provide the precise commands that unlock the full potential of DDEVs. Think of it as a high-wire act, balancing agility with safety and maximizing efficiency through precise torque allocation [31], [32].

The challenge lies in the reliance on various sensor readings, creating a symphony of information that needs the right conductor. Inadequate control strategies can lead to system falters, jeopardizing the very benefits that EDs offer [33], [34].

Therefore, mastering the art of torque distribution is key to unlocking the true potential of DDEVs. New research avenues are actively being explored, focusing on the following:

- Advanced algorithms: These algorithms interpret sensor data and calculate the optimal torque distribution based on driving conditions.
- Robustness under extreme scenarios: Ensuring that the system functions flawlessly even during complex maneuvers and challenging terrains.
- Efficiency optimization: Balancing agility with minimal energy consumption, maximizing the driving range of DDEVs.

By conquering these challenges, the future of DDEVs, powered by intelligent torque distribution, promises enhanced driving experiences, increased safety, and ultimately, a smoother ride toward a cleaner, more efficient future of mobility. smoother ride toward a cleaner, more efficient future of mobility [35], [36].

The selection of the Ackermann steering geometry for this study is driven by several compelling reasons that align with the goals of optimizing electric vehicle (EV) performance, particularly in urban driving conditions. Firstly, the Ackermann system ensures optimal wheel path alignment during turns, which is crucial for maintaining stability and reducing tire wear, especially at lower speeds. This is particularly beneficial for EVs that frequently operate in urban environments. Additionally, the Ackermann system enhances vehicle stability and safety by minimizing the risk of skidding or loss of control during turning maneuvers. Its simplicity and proven reliability make it an attractive choice, as it is easier to implement and maintain compared to more complex steering systems, thereby contributing to cost-effectiveness. Furthermore, the Ackermann geometry integrates seamlessly with electronic differential systems, providing precise control over wheel speeds and reducing energy consumption by minimizing friction during turns. These factors, combined with the system's scalability and adaptability to different vehicle configurations, make the Ackermann steering geometry a well-rounded solution for improving the efficiency and safety of EVs.

4. ED Architecture

Fig. 3 illustrates the core architecture of an ED system in a distributed drive EV (DDEV). Each traction motor independently connects to its respective wheel, eliminating the need for a traditional driveshaft and gearbox. However, each motor relies on precise speed references from the central electronic differential (ED) block. This unit analyzes data from multiple sensors, including the steering angle, wheel speed and vehicle acceleration, to determine the optimal torque distribution for each wheel while ensuring the safety and comfort of the driver and passengers.

This arrangement of linkages physically steers the wheels during a turn, ensuring that they follow paths with different radii (inner and outer wheels). The most common method for implementing ED action electronically is the Ackermann–Jeantand steering geometry. This arrangement of linkages physically steers the wheels during a turn, ensuring that they follow paths with different radii (inner and outer wheels) [37]. While Ackermann-Jeantand excels in low-speed cornering scenarios, it becomes less accurate at higher speeds [38]. During faster turns, the relationship between the steering angle and wheel speed becomes more complex and is influenced by factors such as vehicle dynamics and tire slip [39]. To address this, the ED relies on additional sensor data, such as driver throttle input, to estimate the inner and outer wheel speeds more accurately. For example, during a right turn, the ED would command that the left wheel spin faster than the right wheel to maintain the stability and control of the vehicle.

4.1. Calculating Wheel Speeds

Each driving wheel's linear speed can be expressed as a function of the steering angle (δ) and the vehicle speed (v). This formula, which is typically used for low-speed scenarios, helps the ED determine the ideal speed differential between the inner and outer wheels. This Fig. 4 demonstrates the core architecture of an ED system in a DDEV. It explains how the system utilizes the Ackermann–Jeantand steering geometry for precise wheel speed control during turns.

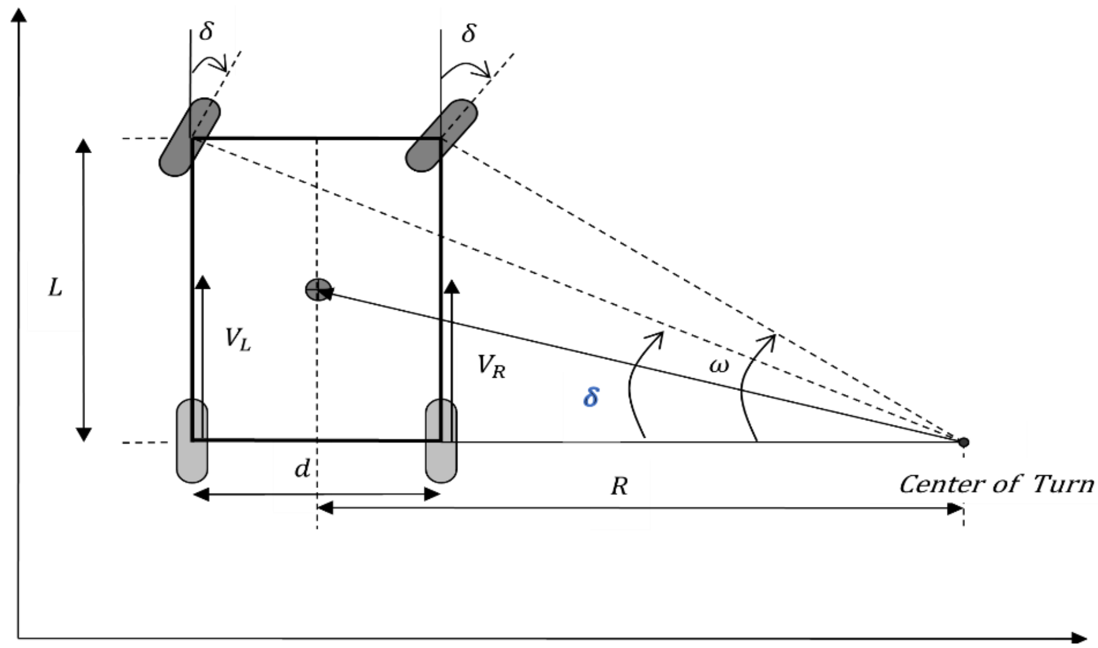

Fig. 4. The Ackermann–Jeant and steering geometry used in an ED system

From this model, the following characteristics can be calculated.

$$R = \frac{L}{tg(\delta)} \tag{1}$$

where δ is the steering angle. Therefore, the linear speed of each wheel drive is given by:

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$$V_R = (R - (\frac{d}{2}))\omega$$
$$V_L = (R + \left(\frac{d}{2}\right))\omega \tag{2}$$

And the angular speed is given by:

$$\omega_R = \frac{L - (\frac{d}{2})\text{tg}\,(\delta)}{L}\omega$$
$$\omega_L = \frac{L + (\frac{d}{2})\text{tg}\,(\delta)}{L}\omega \tag{3}$$

Where ω is the vehicle angular speed of the vehicle from the center of the turn. and the speed difference is:

$$\Delta\omega = \omega_L - \omega_R = \frac{-d\omega\, tg(\delta)}{L} \tag{4}$$

The turning direction can be determined by the polarity of the steering angle: specifically, d > 0 denotes a right turn, d < 0 indicates a left turn, and d = 0 signifies straight ahead. The electronic differential (ED) adjusts the speed of the inner wheel downward while boosting the speed of the outer wheel to ensure equilibrium in the vehicle's motion. The adjusted speeds resulting from the ED can be expressed as follows:

$$\omega_L = \omega + \frac{\Delta\omega}{2} \tag{5}$$

$$\omega_R = \omega - \frac{\Delta\omega}{2} \tag{6}$$

According to equation (3), the steering angle is directly correlated with the angular velocity of the wheels. Consequently, the electronic differential (ED) computes the requisite speed adjustments for each driving wheel during cornering maneuvers based on the inputs of the steering angle and velocity.

According to the above equations, Fig. 5 this block diagram represents the electric differential system used in the simulations, showing the relationship between the vehicle's steering angle, wheel speeds, with K1 = 1/2 and K2 = – 1/2, where K1 and K2 are the speed difference coefficients in Eqs. (5), (6):

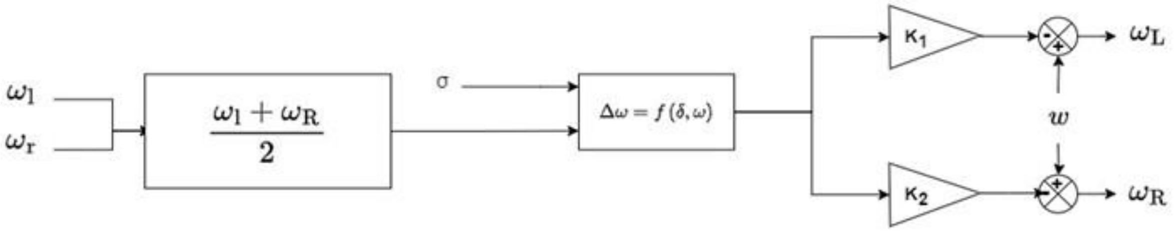

Fig. 5. Electric differential system block diagram

By combining the Ackermann-Jeantand geometry with advanced control techniques and sensor data, DDEVs achieve unparalleled stability, responsiveness, and efficiency in both low- and high-speed driving situations.

The mathematical models utilized in this study, while valuable for optimizing the electric differential system, inherently include several assumptions that may limit their accuracy in real-world applications.

- First, these models often assume uniform and idealized conditions, such as perfectly smooth road surfaces, equal traction across all wheels, and evenly distributed vehicle loads. In reality, road surfaces can be uneven, traction can vary, and load distribution can change, leading to potential inaccuracies.
- The models simplify complex, non-linear dynamics by linearizing them, which can overlook significant factors like tire slip and suspension effects, especially under extreme driving conditions.
- The accuracy of the model's predictions is heavily dependent on the precision of input parameters, such as vehicle mass and road friction coefficients, which can vary in practice and introduce errors. Additionally, the models assume ideal system behavior, neglecting external disturbances like wind or road grade, and do not account for the inherent delays and limitations of control systems.
- The models may over-simplify vehicle dynamics by ignoring the effects of pitch, roll, and yaw, which are critical during aggressive maneuvers. These limitations could lead to potential inaccuracies in the predicted wheel speeds and torque distribution, impacting vehicle performance and efficiency.

It is essential to complement these models with experimental validation to ensure their reliability and accuracy in practical applications.

4.2. Optimized electrical differential

While differential control represents a significant advancement in the realm of electric vehicles, it does indeed face a notable challenge and cost. This stems from the necessity of an inverter for each motor, as the speed of each wheel varies independently from the others. As a result, the requirement for multiple inverters adds to the overall expense of implementing this technology in EVs. From the preceding equations, it becomes evident that there exists a correlation between the velocity of each wheel and the angular velocity of the vehicle, as seen in relation to the center of turn equation (7).

$$\omega_L = \frac{-d\omega\, tg(\delta)}{L} + \omega_R \tag{7}$$

A mathematical correlation exists that allows for the calculation of the coefficient between the speeds of the two motors. It is inevitable that a correlation exists between the torques of the two motors, indicating a connection between the supply currents and both motors. Therefore, we suggest the following model:

This schematic diagram Fig. 6 illustrates the proposed model where a single inverter powers two motors, each operating at different speeds, to reduce costs and simplify control.

This model offers the advantage of utilizing a single inverter to power two motors, each operating at a different speed. This feature helps reduce the cost of electric cars while also simplifying the control process, thus enhancing overall simplicity.

4.3. Safety Considerations

Addressing safety considerations in the development and implementation of an electronic differential (ED) system and a distributed drivetrain is crucial, as these systems directly impact the vehicle's stability, control, and overall safety. Here are some important points to consider:

4.3.1. System Redundancy and Fault Tolerance

Handling Sensor Malfunctions: The ED system relies heavily on various sensors (e.g., wheel speed sensors, steering angle sensors, and accelerometers) to make real-time adjustments to torque distribution and wheel speed. If one or more sensors fail, the system could misinterpret the vehicle's dynamics, leading to unsafe driving conditions. To mitigate this risk, the system should incorporate redundancy, such as backup sensors or fault-tolerant algorithms that can estimate the missing data based on available inputs. Additionally, the system should be designed to detect sensor malfunctions quickly and switch to a safe mode, where the vehicle can still operate safely, albeit with reduced performance.

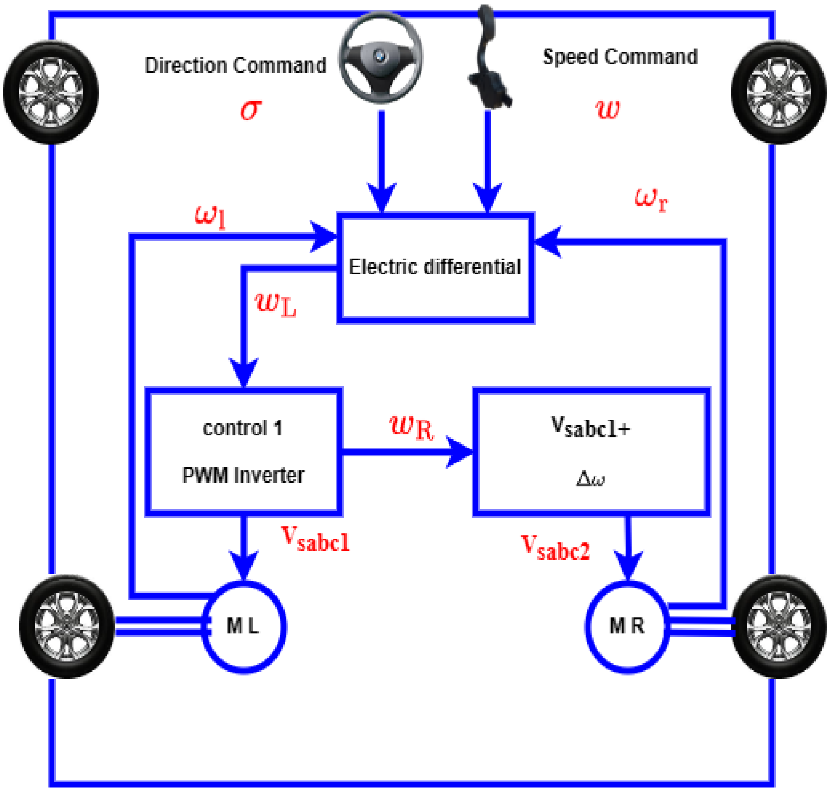

Fig. 6. EV propulsion schematic diagram

4.3.2. Emergency Response Mechanisms

Safe Degradation and Fail-Safe Modes: In the event of a critical system failure, such as a loss of communication between the ED system and the vehicle's control unit, the system should be able to degrade gracefully. This means implementing fail-safe modes where the vehicle can continue to operate in a limited capacity, allowing the driver to safely stop or drive to a service center. For example, the system could lock the differential to a default state that balances the torque equally between wheels, thereby preventing sudden loss of control.

4.3.3. Robustness to Sudden Changes in Driving Conditions

Adapting to Environmental and Road Conditions: The ED system should be designed to adapt to sudden changes in driving conditions, such as rapid changes in road friction (e.g., icy patches, wet roads) or sudden maneuvers (e.g., evasive steering). This requires the system to be robust enough to quickly and accurately adjust torque distribution and wheel speeds to maintain vehicle stability. Incorporating predictive algorithms that use real-time data to anticipate and react to these changes can enhance safety.

4.3.4. Real-Time Monitoring and Diagnostics

Continuous Health Monitoring: The system should include real-time monitoring of its components to ensure they are functioning correctly. This includes continuous diagnostics of the ED system, drivetrain components, and sensor array. If any abnormalities are detected, the system should alert the driver and, if necessary, adjust its operation to maintain safety.

4.3.5. Driver Interaction and Alerts

Providing Feedback and Warnings: It's important that the ED system communicates effectively with the driver. If the system detects a potential issue such as a malfunctioning sensor or a condition that could lead to instability it should provide clear warnings to the driver. This could be through visual or auditory alerts, or even haptic feedback, to ensure the driver is aware of the situation and can take appropriate action.

4.4. Validation Methods

The validation methods is crucial for establishing the credibility and reliability of the proposed models and methods, especially when introducing innovative approaches like using a single inverter for two motors in an electric vehicle (EV) drivetrain. Here are some key strategies and methods that can be employed to validate the proposed models and systems:

4.4.1. Simulation-Based Validation

MATLAB/Simulink Simulations: One of the primary methods for validating the proposed models is through detailed simulations. MATLAB/Simulink can be used to simulate the entire EV drivetrain, including the single inverter controlling two motors. The simulation should replicate various driving conditions, such as acceleration, deceleration, cornering, and different load scenarios, to evaluate how the system performs under each condition. Performance metrics like motor efficiency, torque distribution can be analyzed to determine the effectiveness of the system.

4.4.2. Comparison with Dual Inverter Systems:

The simulation results should be compared against a traditional dual inverter system to highlight the benefits and any potential trade-offs of the single inverter approach. This comparative analysis will provide insight into whether the proposed system meets or exceeds the performance of existing systems.

4.4.3. Hardware-in-the-Loop (HIL) Testing

Real-Time Testing with HIL: Hardware-in-the-Loop testing allows for real-time validation of the control algorithms and inverter operation using physical components. By integrating the control system with simulated vehicle dynamics, HIL testing can provide a more accurate assessment of how the proposed single inverter system will perform in real-world conditions. This method helps identify any potential issues related to timing, control response, or interaction between the inverter and the motors.

4.4.4. Prototype Development and Testing

Building a Physical Prototype: Constructing a physical prototype of the EV drivetrain with the single inverter setup is essential for practical validation. This prototype should be tested under controlled conditions to measure key performance metrics such as torque output, power efficiency, thermal management, and system response time. Testing can be conducted on a dynamometer to simulate real driving conditions while controlling variables such as speed, load, and environmental factors.

4.4.5. On-Road Testing:

After initial lab-based testing, the prototype should be subjected to on-road testing to evaluate its performance in real-world conditions. This phase involves testing the vehicle under various scenarios, including different weather conditions, road surfaces, and driving styles, to ensure the system's robustness and reliability.

5. Simulation Results

The main objective of this simulation is to validate the theoretical soundness of a novel connection method for electric differentials in electric vehicles (EVs), which utilizes a single inverter to control multiple motors. This approach aims to reduce system cost and complexity while maintaining high performance and efficiency.

The simulation tests were conducted using MATLAB/Simulink for permanent magnet synchronous motors (PMSMs) with the following parameters: PN=37 kW, fsN= 50 Hz, UN = 380 V, p = 4, Rs = 0.6 Ω, Ld= 0.0014H, Lq= 0.028H, F = 0.0014 Nms/rad, J = 0.02 kgm2, and TLN = 10 Nm.

The simulation was conducted using MATLAB/Simulink with a variable-step solver to accommodate the varying dynamics of the system. The solver selection was set to "auto," allowing MATLAB to automatically choose the most appropriate solver for the simulation. The maximum step size was configured to 0.0001, ensuring fine granularity in the time steps for accurate capture of the system dynamics. The minimum step size was set to a very small value, allowing the solver to adjust as needed during the simulation. The simulation's time span was defined from 0 to 13.69 seconds, corresponding to the duration of the vehicle dynamics analysis. The zero-crossing detection was controlled using local settings with a nonadaptive algorithm, ensuring stability in the simulation by managing the detection of events where signals change signs. These settings were selected to balance computational efficiency with the need for precision in modeling the electric differential system.

We conducted the simulation for a duration of 13.69 seconds, as illustrated in Fig. 7. The schematic of the electric vehicle during this simulation is presented, with system inputs comprising the reference speed (Fig. 8) and the reference rotation angle (Fig. 9). The electrical differential is computed according to the equations described in Section 3.1. Using these equations, the reference speed of the right wheel is determined. since our primary focus is not on control methods, given their minimal impact on overall speed. the converter first supplies power to the primary motor, after which the supply to the secondary motor is calculated based on the equations detailed in Section 4.2. The current speed of the wheels is monitored using sensors, which measure the error rate in speed, facilitating accurate feedback and adjustments.

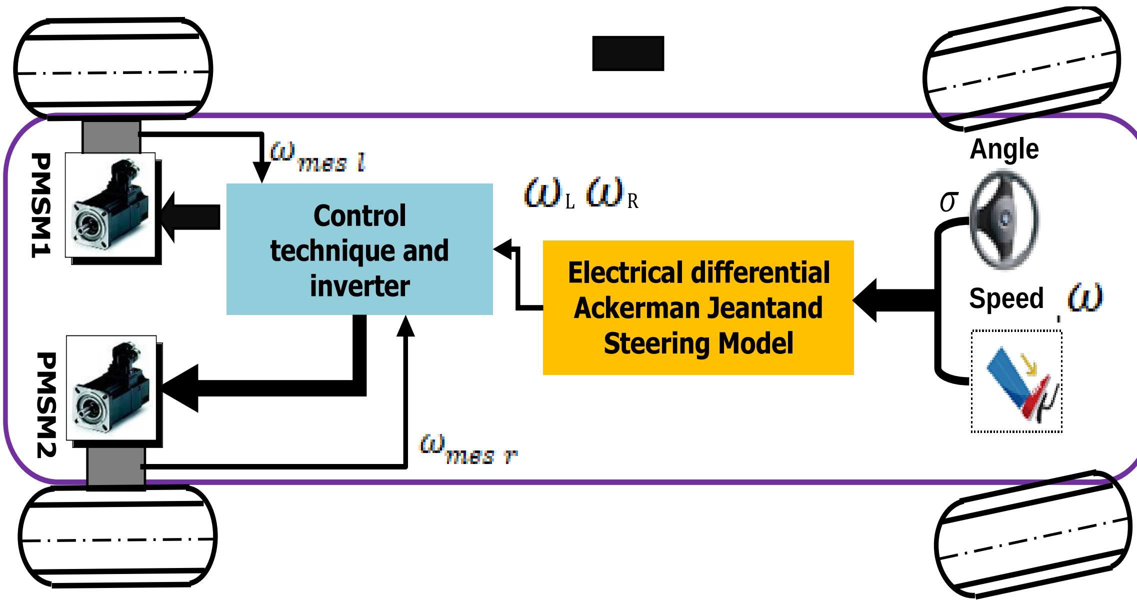

Fig. 7. Block diagram of the EV system

The parameters chosen for the simulation, including the motor specifications and driving conditions, were selected based on common industry standards and the typical operational requirements of electric vehicles. For instance, the motor's power rating and speed were aligned with those of mid-range electric vehicles, which ensures the relevance of the simulation results to real world applications. the driving conditions, such as the FTP-75 driving cycle, were selected to replicate standard urban driving scenarios, which are representative of the environments where electric vehicles are most commonly used. These choices help to ensure that the simulation outcomes are not only theoretically sound but also practically applicable.

In this simulation, our focus lies solely on the connection method's theoretical validity rather than the intricacies of the motor or the control method employed. Our aim is to ensure the theoretical soundness of the connection method, paving the way for subsequent experimental verification of its validity.

Fig. 8 illustrates the FTP 75 driving cycle, which serves as the reference speed for the vehicle in the simulation, Fig. 9 representing typical urban driving conditions. Additionally, it shows the changes in the angle of the wheels during the simulation. The combined depiction of the driving cycle and wheel angles provides a comprehensive view of the vehicle's dynamic behavior and turning maneuvers under simulated conditions [40], [41].

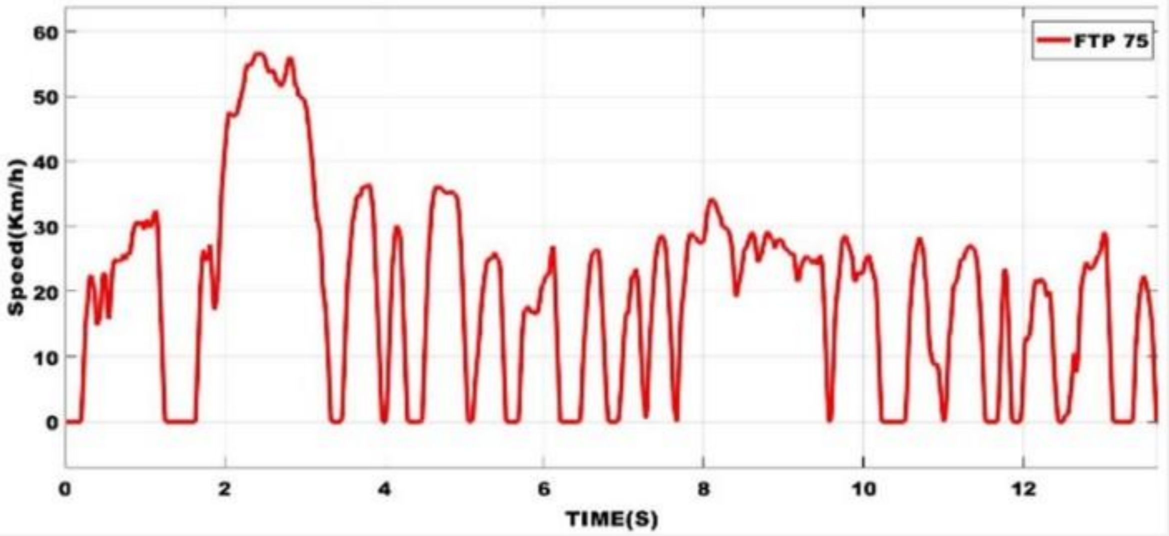

Fig. 8. FTP 75 driving cycle

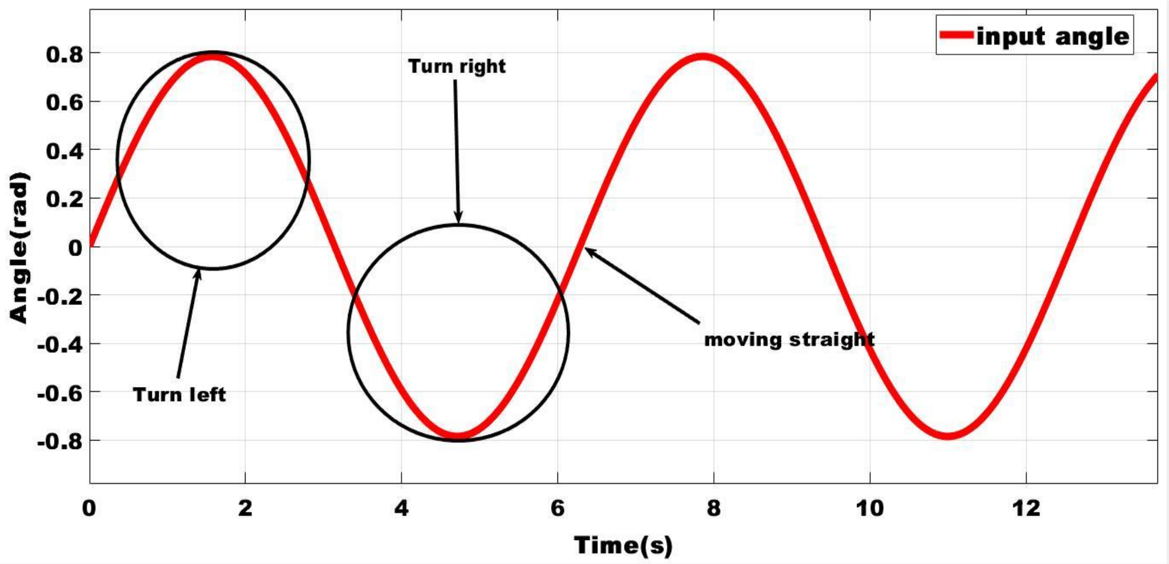

Fig. 9. Angle of wheels changes

The simulation was executed for a duration of 13.69 seconds, achieving a peak speed of 56.7 km/h and maintaining an average speed of 21.2 km/h. The obtained results are as follows [42]:

During right turns, the speed of the left wheel surpasses that of the right wheel, while during left turns, the speed of the right wheel exceeds that of the left wheel. However, during straight driving, both wheels maintain an equal speed Fig. 10, Fig. 11 the speeds of the two wheels during the simulation, highlighting how the electric differential adjusts wheel speeds during right and left turns. During right turns, the speed of the left wheel surpasses that of the right wheel, while during left turns, the speed of the right wheel exceeds that of the left wheel. During straight driving, both wheels maintain equal speeds. The figure also shows the speed difference between the two wheels, confirming the presence and effectiveness of the differential mechanism in managing speed variations [43]-[46].

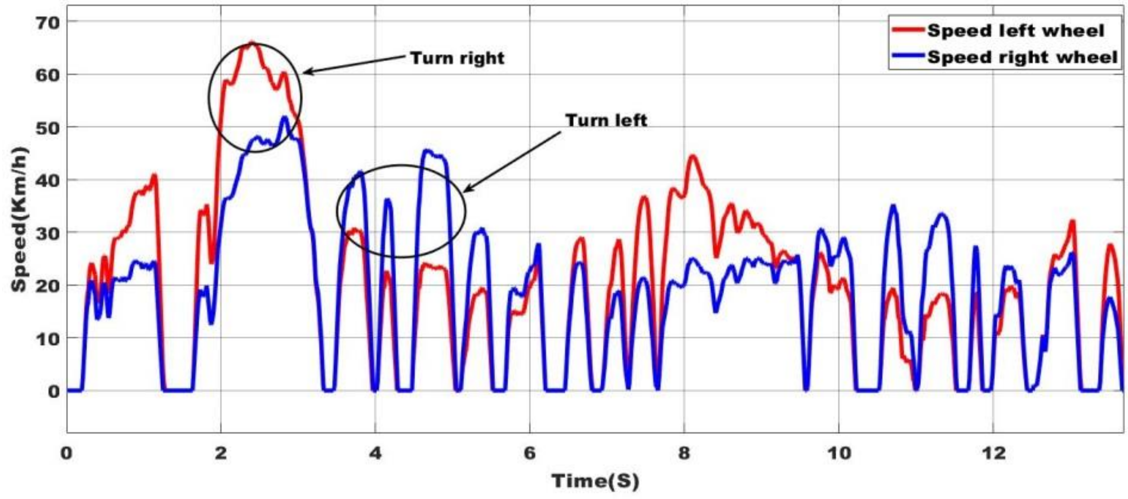

Fig. 10. The speeds of two wheels

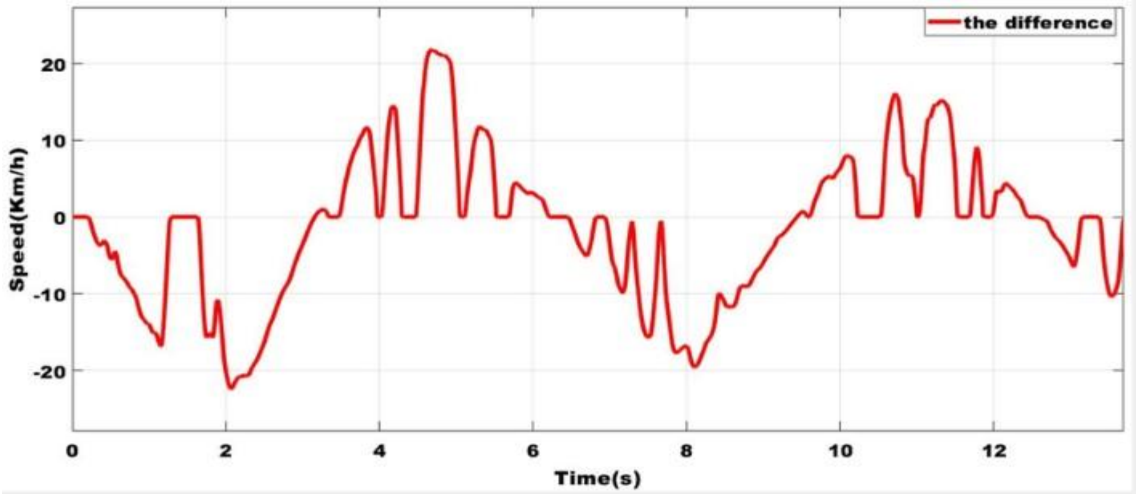

Fig. 11. the difference between the speeds

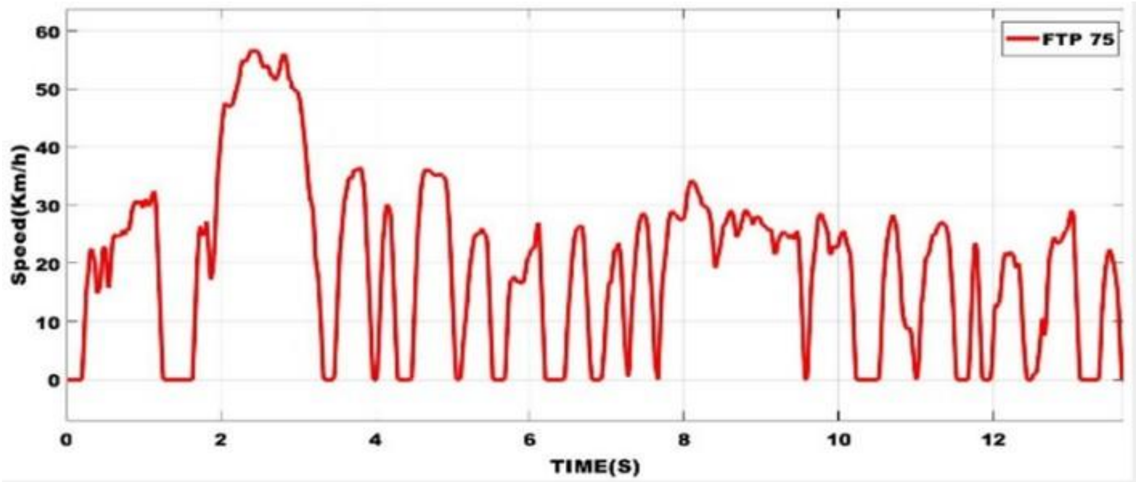

Fig. 12. The real speed and the reference speed of EV

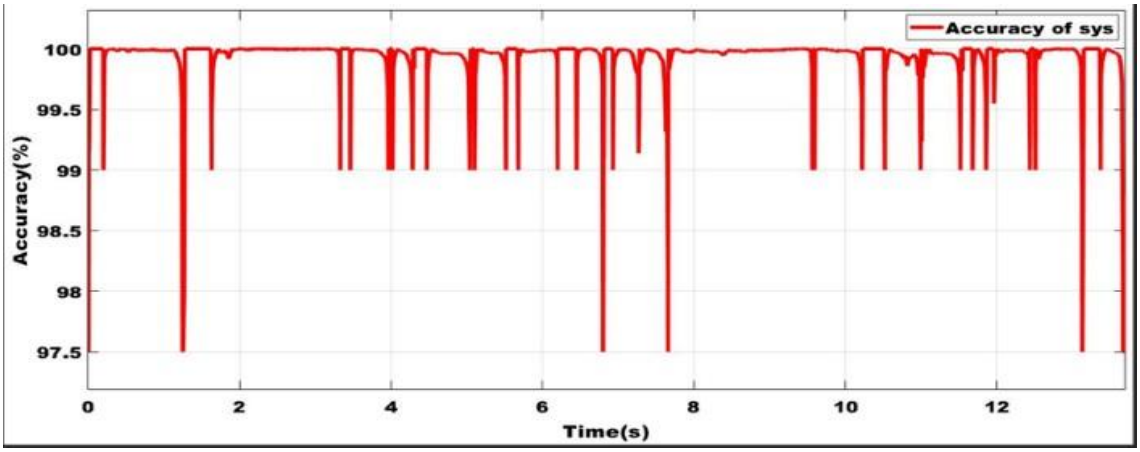

Fig. 13. System accuracy

A comparison between the reference speed and the actual speed of the vehicle, as depicted in Fig. 12, Fig. 13, compares the vehicle's actual speed with the reference speed, illustrating the high accuracy of the electric differential system. The system's accuracy ranges from 97.5% to 100%, as depicted in the accuracy graph. This high level of accuracy signifies the satisfactory performance of the proposed single-inverter electric differential system, demonstrating its potential for improving the efficiency and reliability of EV drivetrains [47]-[49].

One of the potential sources of error in the reported accuracy range of 97.5% to 100% is sensor inaccuracies. The electric differential system relies heavily on sensor data to monitor and adjust the wheel speeds and steering angles. Any inaccuracies in sensor readings, such as those caused by noise, latency, or calibration errors, could lead to deviations in the system's performance. For instance, a small error in the speed sensor could result in incorrect adjustments to the motor control, potentially leading to less efficient torque distribution or even instability during sharp turns. To mitigate this, it is crucial to use high-precision sensors and implement filtering techniques to reduce the impact of noise. Further studies could also explore the effects of sensor inaccuracies under varying environmental conditions to better understand their influence on the system's overall robustness [50].

Table 2 presents a comparison between the current study and several related publications. It is important to note that the type of motor or control method is specifically highlighted only when the research objective focuses on motor control or torque enhancement. In cases where these aspects are not central to the study, they are not emphasized. The comparison also illustrates the diversity in the use of inverters, ranging from 4-inverter and 2-inverter systems to single-inverter configurations. The adoption of a single-inverter system, as demonstrated in this study, represents a cutting-edge approach that offers significant potential for improvements in system efficiency and cost-effectiveness.

Table 2. Comparison of the proposed approach with similar method

Reference	Type of motor	Control method	Number of inverters
This paper	PMSM	no mention	1
[11]	no mention	no mention	4
[12]	no mention	no mention	1
[13]	BLDC	fuzzy control	2
[16]	BLDC	fuzzy control	4
[19]	IPMSM	DTC control	4
[21]	Induction motor	FOC	2

Table 3 provides a comparison of different approaches based on the number of inverters used in the systems, specifically, configurations with one, two, and four inverters. The 4-inverter system is noted for its superior stability and precise control during turning maneuvers. However, this advantage comes at the cost of increased system complexity and higher expenses, which in turn complicates maintenance. the 2-inverter approach offers a balance between robust control and reduced cost, but it requires additional systems to enhance turning performance and stability. on the other hand, the single-inverter approach, although still in the experimental and developmental stages, shows great promise in the field of electric vehicles, offering potential benefits in terms of cost reduction and system simplicity.

Table 3. Comparison of Strengths and weaknesses

Reference	Number of Inverters	Strengths	Weaknesses
This paper, [12]	1	Lower cost Simple system Less complexity	Still under testing and development
[13], [21]	2	Combines powerful control with improved cost	requires some additional systems in order to improve cornering and stability
[16], [19]	4	Strong control and stability	High cost of the system old system complex system

Compared to existing solutions that utilize multiple inverters, the proposed single-inverter system offers a more cost-effective and less complex alternative. Traditional systems require individual inverters for each motor, increasing both the cost and complexity of the system. The proposed system not only simplifies the drivetrain architecture but also maintains high performance, making it a competitive solution in the field of EV technology.

The findings from this simulation have broad implications for the EV industry:

- Cost Reduction: By using a single inverter to control multiple motors, the proposed system can significantly reduce manufacturing costs, making EVs more affordable for consumers.
- Increased Efficiency: The improved efficiency of the drivetrain can extend the range of EVs, providing a practical benefit for consumers who require longer travel distances between charges.
- Simplified Design: The reduction in system complexity can simplify the design and maintenance of EVs, benefiting manufacturers with easier assembly processes and potentially lower maintenance costs.

The findings from this simulation suggest that the proposed single-inverter electric differential system significantly improves drivetrain efficiency while reducing system cost and complexity. This improvement in EV performance has potential real-world applications, such as enhancing the range and reducing the manufacturing costs of EVs. The results support the theoretical validity of the connection method, paving the way for further experimental validation and real-world implementation.

While the simulation results are promising, this study was conducted in a simulated environment, which may not fully capture the complexities and challenges of real-world implementation. Future research should focus on experimental validation of the proposed system in practical settings, including integration into a full-scale vehicle prototype. Additionally, exploring the scalability of the single-inverter system in various EV models and configurations, as well as investigating long-term reliability and performance under different operational conditions, would be valuable. Further advancements in control strategies and real-time optimization techniques could lead to even greater enhancements in EV drivetrain technology.

6. Conclusion

This study has demonstrated the successful enhancement of the electrical differential system in electric vehicles by transitioning from a dual-inverter setup to a more efficient single-inverter system. The simulation results confirmed that the proposed system achieves a high level of accuracy, exceeding 97%, which underscores its potential for improving the efficiency and performance of EV drivetrains.

Theoretical contributions of this research include the development of a novel approach to optimizing electronic differential systems, which simplifies the overall drivetrain architecture while maintaining high performance. This contribution is particularly significant as it offers a new perspective on how to effectively reduce system complexity and cost in electric vehicles.

The move from two inverters to one has significant practical implications for the design, cost, and efficiency of electric vehicles. By simplifying the drivetrain architecture, the proposed system can lead to more compact vehicle designs, which are easier to manufacture and maintain. This reduction in components not only lowers manufacturing costs but also enhances energy efficiency by reducing the system's weight and complexity. Furthermore, the cost savings associated with using a single inverter can make EVs more affordable, potentially accelerating their adoption in the market.

However, this study is not without its limitations. The primary limitation is that the research was conducted in a simulated environment, which may not fully capture the complexities and challenges of real-world implementation. Future research should focus on experimental validation of the proposed system in practical settings, including the integration of the system into a full-scale vehicle prototype. Additionally, further exploration into expanding the system to more complex configurations, such as four-wheel drive setups, would be valuable.

In terms of future work, researchers are encouraged to build on the findings of this study by exploring the scalability of the single-inverter system in various EV models and configurations. Investigating the long-term reliability and performance of the system under different operational conditions would also be beneficial. Moreover, extending the research to include advanced control strategies and real-time optimization techniques could lead to even greater enhancements in EV drivetrain technology.

In summary, this article contributes to the growing body of knowledge in the domain of electric vehicle technology by providing a new approach to drivetrain optimization that promises to reduce costs and improve efficiency. The findings not only advance our understanding of electronic differentials but also open new avenues for future research and development in this rapidly evolving field.

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