Torque Distribution Optimization Strategy for Independently Driven Trams with Front and Rear Axles

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Abstract. Electric vehicles have become an emerging research field due to their energy-saving and low-pollution advantages, among which, front- and rear-axle independently-driven vehicles have become the mainstream direction in the future due to their outstanding advantages. The study introduces a comprehensive optimization approach for torque distribution aimed at reducing the total energy usage of electric vehicles driven independently by both front and rear axles, addressing issues like wheezing. At first, the behavior model during the electric vehicle's steering state is established based on the PID algorithm and particle swarm optimization algorithm. Subsequently, the study examines the vehicle's energy usage and steadiness, developing a comprehensive strategy for torque distribution aimed at reducing the motor's energy consumption and improving the vehicle's stability. Finally, the optimization results are compared and analyzed by combining the references and the examples of the ideal state, and the study reveals that the optimization technique suggested in this document yields superior control outcomes. Findings indicate that the torque distribution optimization approach introduced in this study enhances hysteresis., operational stability, torque distribution control performance, and driving safety under the steering condition of electric vehicles.

Keywords: Electric vehicles; front- and rear-axle independently-driven; Torque distribution; surge; Optimization of energy consumption.

1. Introduction

Electric vehicles (EV) are an emerging field. As multiple motors control the tram separately, front and rear axle independent drive EV have the advantages of power, good economy and easy maintenance as well as low manufacturing cost [1-3], so this vehicle has become a major emerging research direction in the field of electric vehicles and will also become the main development trend in the future.

It has become a key research direction to enhance the smoothness and safety of the vehicle by taking the car's motion characteristics into consideration. Benefits of using independent drive vehicles with front and rear axles don’t only lie in the overall vehicle torque distribution method, but also the overall vehicle composition. Torque distribution is used in four-wheel drive systems to regulate the power distribution between the axles to enhance vehicle capability under various operating conditions [4]. However, unbalanced or inaccurate adjustment of torque distribution may lead to the problem of vehicle wheezing. Vehicle wheezing is a phenomenon of instability that occurs in the transmission or drive system when the vehicle is in motion [5]. In the case of improper torque distribution, this could result in an uneven distribution of power among the vehicle's wheels, making the grip between the wheels unbalanced and thus causing vehicle wheezing [6]. Surge may lead to the recurrent application of voltage to the motor terminals over an extended duration., leading to degradation of the motor insulation. Due to the highly hermetic package structure of the vehicle, the axle current and noise induced by the voltage generated by the surge can easily diffuse into other electrical devices, and the diffused noise may lead to malfunctioning of the vehicle controller [7]. Vehicle wheezing not only reduces driving comfort, but also threatens the safety of drivers and passengers and increases vehicle wear. Therefore, for the study of torque distribution, it is of considerable urgency. According to different realisation objectives, torque distribution can be classified into three kinds [8]: improvement of driving stability, reduction of overall vehicle energy consumption, and energy recovery.

The research on optimal torque allocation for energy consumption mainly focuses on the establishment of motor efficiency characteristics and motor energy consumption models. Currently, numerous specialists have conducted studies focusing on the torque distribution in electric vehicles. Yin Andong et al [9] achieved torque allocation grounded on the car's predicted speed and acceleration, according to Markov model and dynamic prediction model, so as to reduce the fuel consumption rate. Qixing et al [10] used particle swarm optimisation algorithm so as to optimise the efficiency of the battery and the motor, and used the result of torque allocation of the dual motor to increase the varieties of EV. Although the above methods can achieve the corresponding torque allocation, all of these methods lead to vibration of the controller.Hu J et al[11] proposed an optimisation scheme of torque allocation coefficient to reduce the lost power of the two motors according to the motor efficiency Map, which in turn conserve a large number of energy, but the acquisition of the motor efficiency Map usually depends on the bench testing of the motors, which makes it difficult to obtain and is of low realizability. To address the above challenges, this paper gives full consideration to a large number of steering conditions, according to the Proportion Integral Derivative (PID) control algorithm [12], in order to achieve the torque distribution control. By this method, Tian Yankang [13] adjusts the output torque and thus the driving wheel speed through the adaptive PID controller, and effectively improves the vehicle's cornering ability and driving safety by applying the swinging torque to the high-speed running vehicle. Li Junwei et al [14] proposed a dual-motor electric vehicle drive torque allocation strategy based on the inertia weight linearly decreasing finite particle swarm algorithm, which on the one hand enhances the efficiency of the drive motors, and on the other hand avoids the phenomenon of skidding of the front and rear wheels caused by the excessively large torque of the front and rear motors. Yang Yajuan et al [15] used the equivalent Brake Specific Fuel Consumption(BSFC) method to allocate the torque between the engine and the motors as well as the torque between the two motors, and then established a hybrid system control strategy under the MATLAB/Simulink environment to accomplish the goal of fuel conservation.

In summary, The ideal distribution of torque in four-wheel vehicles primarily depends on the challenging-to-obtain motor efficiency Map diagrams, with scant attention paid to how other energy uses affect torque distribution. Addressing these shortcomings, this study focuses on the front and rear axles of electric vehicles that operate independently, carries out the research on the whole vehicle drive allocation and power recovery, fully considers a large number of steering conditions, and realises the torque allocation control by using the PID control algorithm.

2. Research methodology

2.1. PID control algorithm

PID control algorithm is a classical closed-loop control method applied to regulate and control the output value of the system within the expected range so as to satisfy different control requirements [16]. The PID controller consists of proportional, integral, and differential components, which represent the three control parameters of the system. Proportional control adjusts the control output according to the proportional relationship between the deviation and the target value in the current state of the system; integral control eliminates the steady state error and improves the static accuracy of the system; and differential control eliminates the overshooting and oscillations in the transient process and improves the dynamic response of the system.

Due to the simplicity and ease of implementation of the method [17], in this paper, the PID controller is chosen to manage the vehicle's torque distribution, while the particle swarm algorithm is employed to fine-tune the PID control settings. The structure of the electric vehicle torque distribution controller is shown in Figure1.

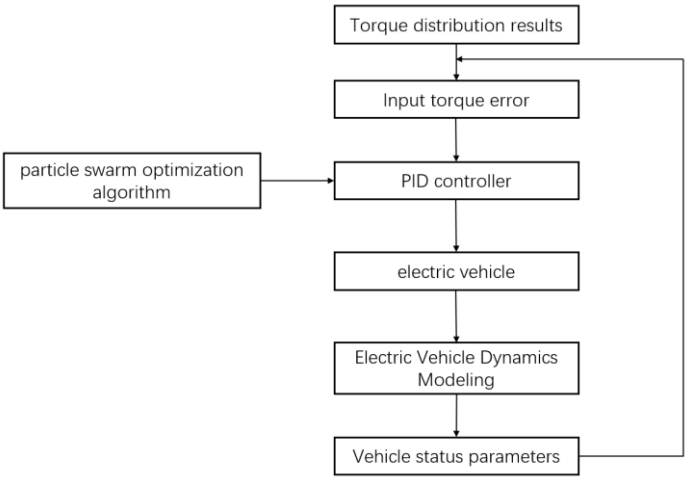


Fig 1. Torque distribution controller for electric vehicles

In this paper, the relevant online parametric self-learning PID controller for electric vehicle torque distribution control is constructed to search for the proportional coefficients, integral coefficients, and differential coefficients of the torque distribution control, so that the obtained torque distribution results and differential coefficients are the most similar to the actual results. The process of controlling electric vehicle torque distribution using PID controller is as follows.

(1) To initialise the parameters and determine the initial values of parameters such as population size, maximum number of iterations, etc. for the particle swarm optimisation algorithm.

(2) Differentiating the outcome of torque distribution from the real performance of electric vehicles is adopted as the primary objective in controlling torque distribution in electric vehicles, which can help the controller to get the desired torque better and reduce the error between the result and the desired value as much as possible, so as to reduce the occurrence of the phenomenon of torque fluctuation and vibration shaking, and to enhance the torque control stability of the electric vehicle, and the torque distribution Adaptation value is calculated by the formula:

$$f_i = \frac{1}{2}\sum_{\mathrm{j}=1}^{i} e_j^2(n) \tag{1}$$

Where, f_i, e_j are the fitness value, input error, respectively, and j is the number of iterations.

(3) Update the parameters of the particle optimisation method to search for the optimal particles within the swarm using the position and velocity update method of the particle swarm optimisation algorithm.

(4) Judge whether the termination condition is satisfied, judge whether the corresponding result of the particle swarm optimization method searching particle is the global particle, and when the torque distribution control result corresponding to the particle satisfies the set error range, it means that the termination criteria are met, resulting in the generation of the most suitable control parameters. of the PID controller K_P, K_i, K_d and controlling the torque under the special working condition of the electric vehicle by using the determined optimal PID control parameters, so as to ensure the EV in a stable operation state under the steering condition.

2.2. Vehicle Dynamics Modeling of Electric Vehicles under Steering Conditions

The forward transverse force balance equation along the X-axis the coordinate framework within an electric vehicle's seven-degree-of-freedom model is:

$$\mathrm{m}(u - vw_r) = (F_{xfl} + F_{xfr})\cos\delta + F_{xfr} - (F_{yfl} + F_{yfr})\sin\delta \tag{2}$$

The rearward transverse force balance equation along the X-axis coordinate system is:

$$m(v+uw_r)=(F_{xfl}+F_{xfr})\sin\delta+F_{yrl}\cos\delta+F_{yrr}-(F_{yfl}+F_{yfr})\cos\delta \tag{3}$$

For the electric vehicle's transverse pendulum, the motion equation is[18]:

$$J_z w_r = l_f[(F_{xfl}+F_{xfr})\sin\delta+(F_{yfl}+F_{yfr})\cos\delta]+\frac{l_w}{2}[(F_{yfl}-F_{yfr})\sin\delta$$
$$+(F_{xfr}-F_{xfl})\cos\delta]+\frac{l_w}{2}(F_{xrr}+F_{xrl})\cos\delta-l_r(F_{yrl}-F_{yrr})+M \tag{4}$$

In equations (1)-(3): F represents the force exerted in various directions on the electric vehicle; m and M denote the vehicle's mass and the extra transverse moment; u, v are the longitudinal and transverse velocities; w_r, J_z represent the lateral speed of the pendulum and the inertia moment; l_f, l_r represent the distances measured from the mass center to both the front and rear axles; l_w, a are the wheelbase and the front wheel angle respectively; l_w, a are the wheelbase and the front wheel angle. l_w, a are wheelbase and front wheel angle, respectively.

The formula is used to determine the EV tire's longitudinal force:

$$F_x = D_x \sin[C_x \arctan[E_x(B_x X-\arctan(B_x X))]] \tag{5}$$

Where: X, B are longitudinal force combination independent variables, coefficient of rigidity; C, D are curve shape factor, peak factor.

The tire lateral force of the vehicle is calculated as:

$$F_y = D_y \sin[C_y \arctan[E_y(B_y X-\arctan(B_y X))]] \tag{6}$$

Where Y is the lateral force combination independent variable.

Under the steering condition, the dynamic vertical load of the tire is calculated as:

$$F_z = mg\frac{l_f}{2l}-h(\frac{v_x}{2l}\pm\frac{v_y l_y}{l l_w}) \tag{7}$$

Where: h and l represent the total of the center of mass height and the gap between the front and back axes, in that order; v_x and v_y symbolize the forward and sideways acceleration, in that order; and g is the gravity of the electric vehicle.

Considering the transverse swing condition under EV steering condition, the lateral deflection angle of EV tires is calculated as [19].

$$\begin{cases}\alpha_{fi}=\delta-\arctan\dfrac{v+w_r l_f}{u\pm w_r l_w/2}\\ \alpha_{ri}=-\arctan\dfrac{v+w_r l_r}{u\pm w_r l_w/2}\end{cases} \tag{8}$$

To develop a linear electric vehicle model with two degrees of freedom, the following are the differential motion equations:

$$J_z w_r = k_r\beta+\frac{(ak_f-bk_r)w_r}{u}-k_f\delta \tag{9}$$

Where: a, b, a symbolize the modification coefficients and the side-to-side bending angle of the mass center, in that order; k_f, k_r are the front wheel and rear wheel lateral deflection stiffnesses, respectively.

2.3. Test parameter setting

Without verifying the efficiency in managing the torque distribution mechanism proposed in this paper for electric vehicles, an electric vehicle is selected for the torque distribution control test, and the structure of the EV is shown in Fig. 2.



Fig 2. Electric vehicle structure [10]

In this paper, the speed of the vehicle is determined to be 45 km/h, the sinusoidal input of the front wheels is $8°$, the signal input period is 15 s, the road surface adhesion factor is 0.5, and the driving torque of the vehicle is 280. Table 1 displays all the parameters of the entire vehicle.

Table 1. Electric vehicle parameters

parameters	numerical value
vehicle mass/kg	1400
center of gravity /m	0.56
Distance from center of mass to front axle/m	1.17
Distance from center of mass to rear axle/m	1.43
tread (on tire) /m	1.52
wheelbases /m	2.70
Wheel Rolling Radius /m	0.34
spring loaded mass /kg	1.020

The torque sensor, gyroscope and steering sensor were installed in the corresponding positions of the electric vehicle, and the testing process was controlled by the electric vehicle microcontroller microcontroller and the vehicle control unit, as shown in Figure 3. STM32F103 series microcontroller MCU is selected to be installed in the controller of the electric vehicle, and LG Chem VCU is installed in the body of the electric vehicle; the sensor is installed at the motor shaft of the electric vehicle, with a measurement range of 0.01~2000 kN/m; the gyroscope is installed in the body of the electric vehicle, with a measurement range of $\pm 30° / s$; the steering sensor is installed on the steering mechanism of the electric vehicle, with a measurement range of . is $\pm 45°$. The site is shown in Fig4.



Fig 3. Electric vehicle torque distribution control test [10]



Fig 4. Electric vehicle site structure [2]

3. Results and discussion

The transverse swing angular velocity, torque distribution results, centre of mass side deflection angle and offset ratio of the EV are tested using the torque distribution control method proposed in this paper.

The test results of the transverse swing angular velocity of the electric vehicle are shown in Fig5. As can be seen in Fig5, the real and ideal values of the lateral swing angle velocity can hardly be observed under the steering condition of electric EV. It shows that the control method designed in this paper can improve the hysteresis under the steering condition of electric vehicle torque distribution, effectively track the ideal value of the lateral swing angle velocity, and be satisfied with the control effect of torque distribution.

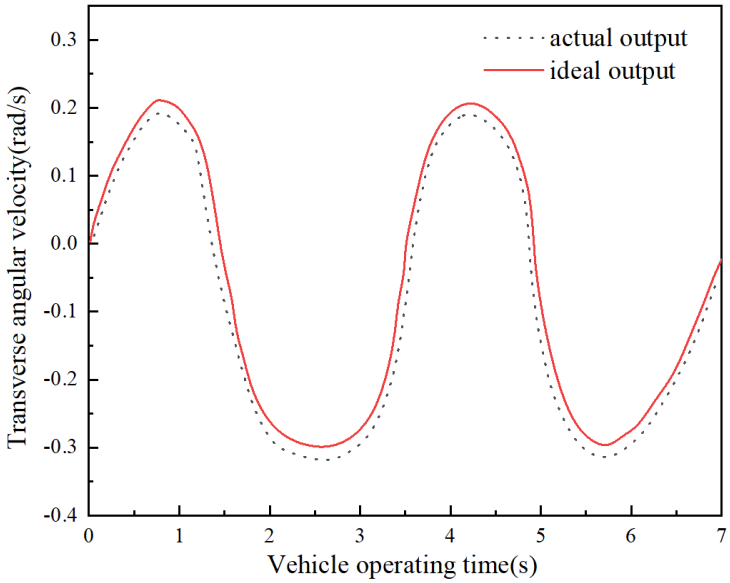


Fig 5. Test results of transverse swing angular velocity of electric vehicle

The torque allocation results of the electric vehicle are shown in Fig6. As shown in Fig6, the method of this paper can be used to effectively allocate the electric vehicle torque to allocate the electric vehicle torque under the steering condition, and there is a certain degree of improvement in the braking torque and driving torque of the two sides of the EV; the electric vehicle trajectory tracking effect is good, which enhances the operation stability of the electric motors under the steering condition.

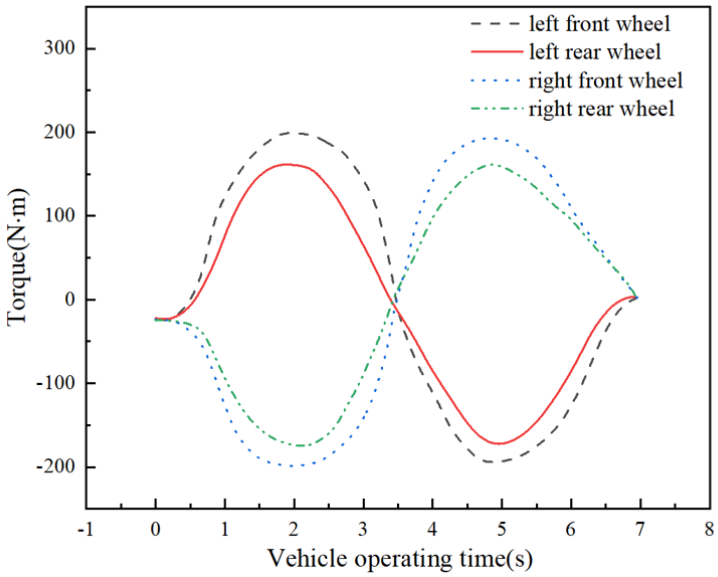


Fig 6. EV torque distribution test results

The test results of the lateral eccentricity of mass of electric vehicles are shown in Figure7. As shown in Fig7, the maximum side deflection angles under steering conditions are all within the range, which indicates that the controllability of electric vehicles has been improved, and the torque distribution of electric vehicles can be controlled so that the centre-of-mass side deflection angle is stabilized in a small range, which has good torque distribution control performance.

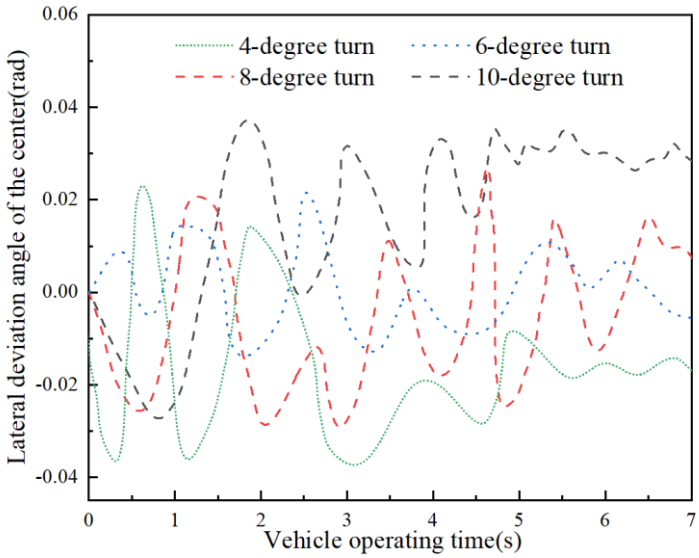


Fig7. Test results of centre-of-mass side deflection of electric vehicle

The slip rate test results of the electric vehicle are shown in Fig8. As can be seen from the figure, the slip rates of the wheels of electric vehicles with the PID control method are lower than that of the wheels, which can meet the stability control requirements of EV under steering conditions. The lower wheel slip rate can improve the driving safety of EV under steering conditions.

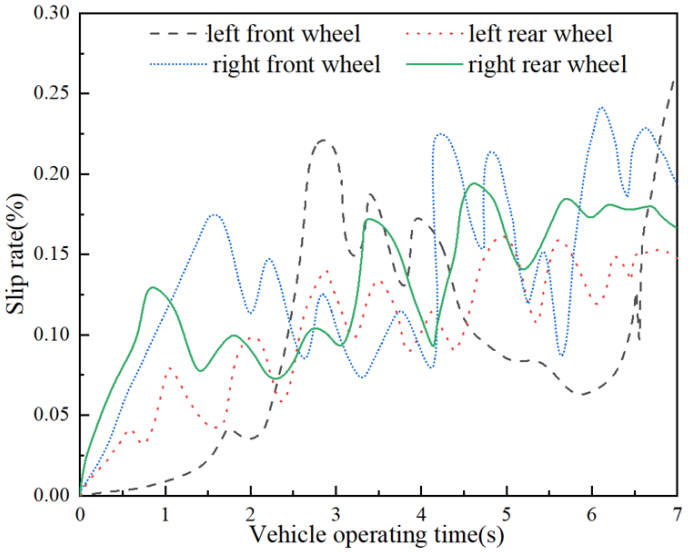


Fig 8. Test results of the slip rate of electric vehicles

Taking whether the electric vehicle can drive in a straight line while driving as a criterion, the method of this paper is used to compare with the front and rear axle dual-motor allocation method proposed in the literature [9] to judge the stability of the three electric vehicle torque control ways, and the test results are shown in Fig. 9. As can be seen in Fig. 9, under the PID torque control proposed in this paper, the deflection angle under the steering condition of the electric vehicle is smaller than that under the control of literature [9], which proves that the torque control methods of this paper is better under the steering condition.

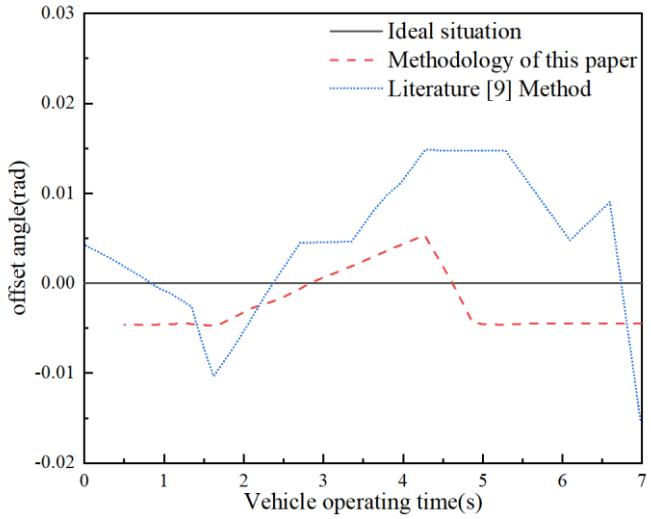


Fig 9. Comparison of stability situation during torque control

4. Conclusion

Taking EV torque as a research object, this paper designs the objective function of torque distribution control, determines the desired torque during the operation of the electric vehicle, and utilizes the designed PID controller to make the electric vehicle operate with the desired swing torque, and improves the operation state of the electric vehicle under steering conditions. In addition, this paper experiments the results of pendulum angular velocity, torque distribution, center-of-mass side deflection test, slip rate test, etc., and finds that these data deviate less from the ideal state, which confirms that the method of this paper can achieve the goal of the accurate torque distribution under the steering condition of electric vehicles. At the same time, by comparing the experimental deflection angle with the deflection angle derived from the two-motor front and rear axle allocation method in

the literature, this paper verifies the accuracy of the control strategy used, thus improving handling stability and the operational safety of the EV, and thus meeting the slip rate optimization objective of the electric vehicle.

This paper focuses on exploring the torque allocation law under the steering condition of EV, and improving the efficiency of the torque distribution control method, obtains the corresponding optimization method of vehicle energy consumption, and finally completes the improvement of the operating state of electric vehicles. However, there are still contents to be improved in this paper:

1. With the rapid development of new energy vehicles and the continuous updating of hybrid models, the PID control method proposed in this paper still has some limitations, and the torque control method for different models should be studied in the future.

2. This paper adopts the particle learning algorithm to carry out experimental simulation, the experimental process does not consider some realistic factors, such as heat conduction, material consumption, etc. Therefore, the subsequent research should include the realistic factors into the scope of research.

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