Review on torque distribution strategies for four in-wheel motor drive electric vehicles

Yong Li 1,*, Huifan Deng 2, Xing Xu 1 and Haobin Jiang 2

1 Automotive Engineering Research Institute, Jiangsu University, Zhenjiang, China.
2 School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang, China.

*Corresponding author e-mail: liyongthinkpad@outlook.com

Abstract. Electric vehicle (EV) with four independent in-wheel motor is over-actuated systems. The wheel torque distribution can be realized through a large number of methods to satisfy the economic and safety demands. This paper aims at providing a review of the economic-based torque distribution strategies, safety-based torque distribution strategies and coordination control of torque distribution strategies based on both safety and economy. This paper not only provides a comprehensive analysis of torque distribution strategies for in-wheel-motor EVs but also puts forward the future and emphasis of future study, which will promote the development of torque distribution strategy with safety and economy for in-wheel-motor drive EVs.

1. Introduction
Recently, as a new energy and environment-friendly vehicle, the in-wheel motor drive electric vehicle (EV) has been rapidly developed thanks to its high efficiency, non-pollution, low noise and so on. Differing from the traditional driving manner, the in-wheel motor drives the wheel directly. Thus, the in-wheel motor drive EV has unique advantages, such as simple and compact structure, high energy-efficiency, and independent control of the torque [1]. Studying the torque distribution of the drive system is of great significance to the research of four in-wheel motor drive (4IWMD) EV.

For the 4IWMD EV, each driving wheel adopts a driving motor as the driving source. And, there is no direct restriction between the mechanical parts between the power sources. The coordinated operation between the driving wheels must be ensured in the control strategy and control method. The torque coordinated control technique is how to control the torque of each driving wheel in order to achieve the goal of stable and safe driving. The wheel torque distribution mainly depends on the working position of each wheel motor under the same torque demand. And, the efficiency of motor and motor controller will be different under different torque demand. The wheel torque distribution also affects the steering characteristics of the vehicle, including the indirect influence of the wheel torque distribution and the direct influence of the left and right wheel torque distribution. The method of moment distribution has an influence on the economy and operation stability of the vehicle, so it is necessary to study both energy saving and safe wheel torque distribution to improve the vehicle's comprehensive performance [2].

A large number of literature studied on torque distribution of in-wheel-motored EVs have appeared, the existing articles emphasize on discussing the torque distribution strategy. However, there is no review about torque distribution used in EVs. This study intends to fill this gap. In addition, torque
distribution coordinated control strategies for 4IWMD EV considering economy and safety are put forward, and future trends of the torque distribution strategy, especially the torque-distribution coordinated control strategy, are discussed [3-5].

This paper first introduces the concept and characteristics of torque distribution strategy. Then it analyzes the present situation of torque distribution strategy researchers as well as the challenges in torque distribution strategy model construction and key technology. The last part is the prospect of torque distribution strategy researches and applications.

2. Review of torque distribution strategies in EVs

There is no transmission inside the in-wheel motor drive, which not only brings the problems of integration control but also leads to electronic differential and driving torque coordination. The torque coordinated control of the electric wheel is used to solve these problems, so its research scope includes the following aspects [6-10].

(1) Each in-wheel motor can be controlled individually, which provides good condition for the optimal torque distribution. The torque coordination control can dynamically allocate driving torque between driving wheels according to the driving conditions. The energy flow is optimized and distributed to each driving wheel to save energy.

(2) The individual controllable wheel motor creates conditions for the vehicle safety integration control, such as traction control system (TCS) and electronic stability program (ESP), which can be combined for the torque coordination control. By reducing the participation of braking force in active safety control, the function of reducing energy loss is reduced.

(3) Under the premise of considering the safety and economy of 4IWMD EV, the coordination torque distribution control is considered both in safety and economy.

Therefore, the torque control coordination technology for 4IWMD EV becomes an essential research field that must be solved in the vehicle controller.

2.1. Economy-based torque distribution of 4IWMD EV

Since the energy density of an EV is lower than that of a fuel vehicle, how to use energy properly is also an important key technical issue in control and drive systems and vehicle design. According to the current literature, the energy-saving driving strategies of distributed drive systems are mainly studied from the aspects of the motor model, traction control system, and energy feedback.

2.1.1. Torque distribution strategy based on the motor model. Literature [11] only considers the copper consumption and the energy formula of the motor is used to derive the extreme value of the driving torque of one in-wheel motor. The torque distribution of the left and right wheel is proportional to the driving distance of each wheel. However, this method is only used for the two-wheel drive system, and the steering system should meet the requirements of Ackermann steering.

The operating range can be used to improve its overall utilization efficiency due to the different efficiency in different working ranges. As described in [12, 13], the maximum efficiency is employed to determine the torque distribution coefficient matrix, which is also used as the key control strategy for torque distribution optimization. The overall energy efficiency of the motor coefficient increases by 3%. However, this control strategy only addresses the requirements of the city operating conditions and does not analyze the energy of the vehicle when it is turning.

Wang proposed allocation scheme for controlling the energy efficiency to improve the redundant execution system. The wheel torque is used as the control variable, and the motor efficiency map is simplified into a function related with the motor torque. Motor drive and regenerative braking are considered to achieve the lowest energy consumption. However, the simplified motor efficiency map is different from the actual characteristics and the different types of motor efficiency characteristics are not exactly the same. Therefore, this method is not versatile and has certain limitations [14-16].

Literature [17] studies the energy consumption model of permanent magnet synchronous motor (PMSM) and designs the optimal distribution strategy. But the motor is just tested on the test bench.
The motor efficiency map and the motor efficiency optimization are studied for the efficiency optimization in [18] where two different motors under two different conditions are compared. The results show that the drive system efficiency can be significantly improved by the efficiency map method with different working conditions. But, the efficiency optimization cannot be achieved due to motor efficiency simplification.

In [19, 20], the dual-motor drive system is proposed to analyze the torque distribution problem based on the loss model. The correctness of the conclusions is verified by the simulation of the circulating conditions.

The literature [21, 22] proposed the optimal torque optimization distribution method based on the motor loss model of the 4IWMD EV drive system. The motor loss model of the permanent magnet synchronous in-wheel motor was established. The results show that the optimal system efficiency can be achieved by the average distribution. But the conclusion has its limitation due to the boundary conditions such as motor parameters and control algorithms.

Li used the motor loss model to derive the relationship between torque distribution coefficient and system efficiency from the perspective of motor control. Through the optimization algorithm, the optimal distribution coefficient can be obtained, and simulation shows that this method can increase the efficiency by up to 3% [23].

2.1.2. Torque distribution strategy based on the traction force control. In [11], the relationship between the slip ratio and the friction coefficient in the region with a low slip rate is analysed. The derivative rate is derived to obtain the optimal slip rate that minimizes the power consumed by the vehicle. The optimal result is that the slip ratio of the drive wheels is equal. However, it is only suitable for two in-wheel motor drive EVs. Yu combined the motor braking and drive efficiency characteristics to distribute the torque between the front and rear axles. The maximum the recovery energy efficiency and drive energy efficiency is achieved [12]. Yamakawa studied the total wheel drive force distribution method to minimize the friction power of all wheels [24].

Literature [25] proposed the optimal tire force distribution method for four-wheel drive vehicles. The control objective is to maximize the vehicle's acceleration capability without affecting the vehicle's steering performance. Assuming that the driver controls the steering wheel and restricts longitudinal forces from yawing, the optimal allocation method can increase the vehicle's maximum acceleration capability by 16%.

The minimum sum of the tire force utilization of each drive wheel proposed in [26] is the control target. The method of optimal distribution of drive force is obtained to meet the lateral force and yaw moment required to track the ideal model.

The literature [27] analyzes the influence of the driving force distribution coefficient of the front and rear axles on the vehicle operation at different times. But, the impact of performance does not analyze the influence of driving force distribution on the energy consumed by the vehicle.

2.1.3. The torque distribution strategy based on energy feedback. Energy feedback is one of the ways to save energy in EVs. Literature [28] gave a very detailed discussion of the current status and development of regenerative braking systems.

The researcher proposed a global energy-saving control allocation algorithm for multi-wheel independent drive EVs. The results show that the front and rear in-wheel motors are only energy-saving control distribution algorithms in which both the drive and in-wheel motors have both drive and regenerative braking, which is superior to the traditional control allocation algorithm in energy saving [29,30].

Wang proposed a 4IWMD EV economical driving force distribution model under safety constraints. The mathematical model based on nonlinear control allocation is established. The objective function and constraint conditions are defined to achieve the highest efficiency. The quadratic programming method is used for the solution of the proposed objective function [31].
The research studied energy management strategy to optimize the distribution of drive torque, and verified on a 4IWMD EV in [32]. The literature [33] studied the regenerative braking force distribution of two in-wheel motor drive EV. However, the motor recovery efficiency used is the average efficiency.

2.2. Safety-based torque distribution of 4IWMD EV
At present, the literature of the electric wheel drive system mainly focus on the active safety control, according to the active safety integration as the control target. That can be classified into two categories: one is to improve the stability of the vehicle's handling and the other is the target of vehicle road tracking control.

2.2.1. The torque coordination control based on maneuverability and stability.

Eiichi proposed the concept of pavement adhesion consumption, which is the ratio of the actual tire force generated by the ground to the maximum tire force available [34, 35].

Osama proposed that the minimum surface adhesion consumption rate is the objective function to optimize the distribution of wheel torque expressed in Eq. (1). And, the influence of combustion engine on vehicle stability is studied, and the results show that in order to improve the stability of the vehicle, the weight system of the rear axle should be larger [36,37].

\[ J = \sum_{i=1}^{4} C_i \frac{F_{yi}^2 + F_{yi}^2}{\mu_i^2 F_{yi}^2} \] (1)

Direct yaw moment control is a driving force control method that changes the vehicle driving force to achieve a stable driving of the vehicle. In view of the characteristic of electric wheel power independent controllable, this method can be fully applied in the torque coordinated control with active safety as the goal. Literature [38-40] investigates the optimal control yaw moment independent method to improve the maneuverability of the vehicle. The semi-optimal control method is more applicable due to its simple structure and good control effect. With this control method, the maneuverability and stability of the vehicle are improved. Literature [41] analyzes the weight coefficients of tire longitudinal force and lateral force distribution to improve the controllability and safety of the vehicle. The influence of different weight distribution coefficients on vehicle responsiveness and stability is pointed out.

The literature [42, 43] studies the fuzzy control scheme for torque distribution and verifies on a 6 × 6 wheel motor drive EV. In [44], two parallel PI controllers are used for torque distribution. One PI controller is employed to define the front and rear wheel torque distribution coefficient. The other PI controller is used to define the left and right wheel torque distribution coefficient. The distribution rules reduce the calculation load. However, the advantages of the independent in-wheel drive system are not taken.

The literature [45-47] studies a logic to deal with motor failure. In the event of a motor drive failure, this method will close both the failed drive wheel and guarantee a part of the drive capacity. But, the longitudinal driving performance of the vehicle is weakened and the problem of reasonable driving under the failure condition cannot be completely solved. Liu proposed an electric wheel torque optimal control allocation method based on the weight of the center of mass slip angle and the failure condition of the motor to ensure the stable operation of the vehicle [48]. Chu proposed a multi-constrained distributed method for the vehicle driving force control. The method solves the problem of driving force control distribution of 4IWMD EV under the condition of driving slipping and driving failure. However, the failure control of 4IWMD EV is not related to the failure diagnosis of the electric drive wheel [49].

Luo proposed a control method for the lateral stability of EV based on model predictive control (MPC). The range of the vehicle stability and the yaw response is enlarged by means of the MPC coordinated control [50].
2.2.2. The torque coordination control based on the path tracking ability. Researchers studied the vehicle motion control of IWMD EV. The robust model tracking control method solved the problem of the driving of the electric wheel on the low attached road [51, 52]. Borelli used MPC to control vehicle steering and braking to achieve autonomous driving. The control performance was established through the system reference output and the real output. The constraint index was established by inputting the variation, and the cost function is designed [53, 54].

Zhou used the MPC to perform yaw control of the vehicle and solve the optimal braking force [55]. Experimental results show the braking torque value was not reasonable as a result of excessive excitation or controller parameter conditioning.

Zhang investigated the coordinated control of single-wheel and multi-wheel torques, and optimized the trajectory of the vehicle. The scope of participation of braking force in the stability control of the entire vehicle is reduced [56].

In [57], the yaw moment control method with variable torque distribution is used to improve the linear response of the vehicle. The adjustment of the torque distribution and the driving torque is validated by experiments. However, it is very difficult to realize the adhesion property of road surface directly.

The literature [58] studies the path trajectory with the driver's corner input as the desired path. This method makes full use of the friction circle with a large vertical load. However, the overall tire utilization rate is not high.

2.3. Torque distribution strategy based on economy and safety.

According to the current research, economy and safety methods are used as the driving force distribution of 4IWMD EV. However, the optimal driving force distribution cannot be achieved by the current distribution method with the vehicle movement state under certain conditions. That will affect the economic efficiency and safety of the vehicle. Moreover, the operating conditions of the vehicle are complex and changeable. It is necessary to adopt a reasonable driving force distribution method according to the motion state of the vehicle [59].

Wang proposed a multi-objective optimization driving force distribution algorithm based on control allocation, which satisfies the driving force allocation requirement of the economy as the main target. The driving force distribution demand with safety as the vehicle under unsteady condition is also considered. The system failure of the independent drive system was solved. However, the efficiency of the battery of the drive system is not considered [31].

Wu proposed a wheel torque distribution method considering both of energy-saving distribution and safety. In the normal stable condition, the wheel torque distribution is carried out with energy saving as the goal. And, the control of the right and left wheel torque is carried out with the demand of the yaw moment. But the function of braking energy recovery is not considered for energy saving [60].

3. Conclusion

Safety or economy method is used for driving force distribution of the 4IWMD EVs, which is limited. However, both of safety and economy method should be considered based on the motion state of the vehicle. The purpose of this paper is to comprehensively investigate the torque distribution strategies for 4IWMD EVs. The current torque distribution strategies designed for in-wheel-motored EVs are presented and analyzed in this paper.

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