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Review

Review of Energy-Saving Technologies for Electric Vehicles, from the Perspective of Driving Energy Management

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Abstract: The driving range of electric vehicles (EVs) is still an important factor restricting their development. Although the rising battery energy density has reached a bottleneck, which is a key constraint, the drive energy management strategy also has a significant effect and can improve the driving range of EVs, since wheel traction torque control can directly optimize the driving energy consumption of EVs. In order to comprehensively analyze the current research status of driving energy management and clarify its development direction, this review focuses on the driving energy management strategy of EVs and systematically summarizes the configurations and power distribution strategies of the dual-motor coupling drive system (DCDS), as well as torque vectoring control strategies of the decentralized drive system. Firstly, driving energy losses are analyzed in detail, which mainly include electric loss, tire slip energy dissipation, and the power of cornering resistance. Secondly, typical configurations of the DCDS are introduced, and the power distribution strategies of the DCDS are comprehensively reviewed. Finally, as an interesting energy-saving technology, energy-saving torque vectoring, generally applied to decentralized drive systems, is reviewed in detail in terms of its energy-saving pathways and control strategies, which are classified as front-and-rear torque vectoring and left-and-right torque vectoring. Research findings indicate that the driving range of EVs can be effectively increased by applying a driving energy management strategy based on several novel multi-power source drive systems. The development of a driving energy management strategy and the required novel drive systems will be a valuable and crucial direction for further energy conservation in EVs.

Keywords: electric vehicle; energy efficiency; power management; independent drive; torque distribution control

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1. Introduction

Electric vehicles (EVs) are considered to be a significant solution to reduce air pollution caused by the transportation industry due to their zero-emission characteristics [1–3]. Meanwhile, EVs are also considered to be the best platform for autonomous vehicles because of their excellent control performance. However, the inadequate driving range of EVs is still a crucial constraint to their development [4]. The means to improve the driving range of EVs can be roughly summarized as design means and control means (Figure 1). The design means mainly refer to the design of the batteries, motors, and body structure of EVs, which are considered to be the fundamental means to increase the driving range of EVs. The control means mainly refer to the control of the vehicle subsystems, such as the braking system, steering system, and active suspension system, which could directly or indirectly reduce the driving energy, and they are generally quick-acting and effective means for improving the driving range of EVs.

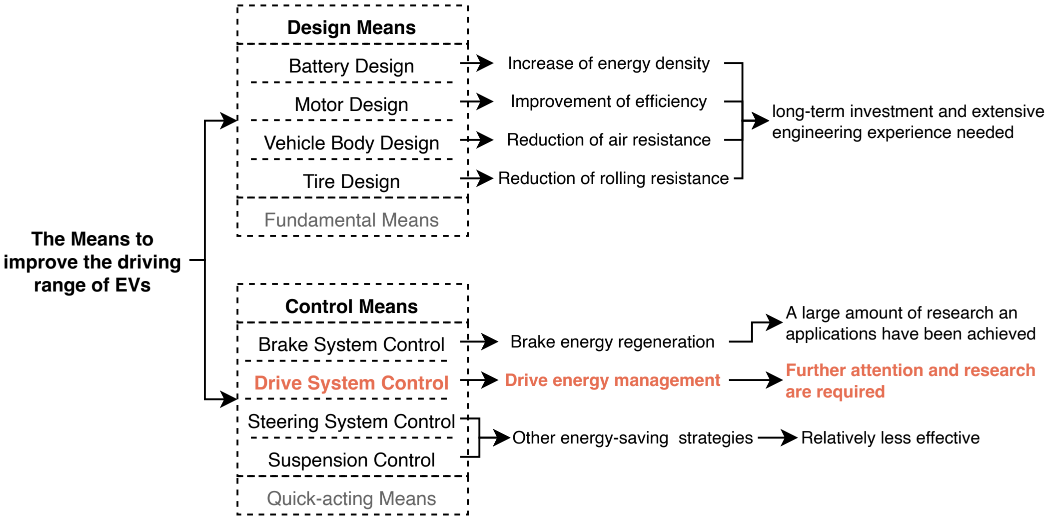

Figure 1. The means to improve the driving range of EVs.

In terms of design means, battery design is still the most important means of increasing the powertrain efficiency and driving range of EVs, but the development of traditional battery technology seems to have hit a plateau. Whether it is the energy density or power density of the battery, it is difficult to achieve a massive increase in the short term [5]. Even now, the maximum energy density of the widely used Lithium-ion battery is generally less than 300 Wh/kg [6]. The design of the physical structure and electromagnetic parameters of the motor is considered to be the key means to increase the driving range of EVs because the efficiency of the motor has a direct impact on the driving efficiency of EVs. However, the current structural design bottlenecks, such as space limitations and the thermal load of the motor, make it hard to significantly improve the efficiency of the motor. The body or tire design of the vehicle is the traditional means to reduce the driving resistance of the vehicle, but whether reducing the air resistance through the aerodynamic design of the vehicle body or reducing the driving energy consumption through lightweight design or low-resistance tire design, other vehicle performance requirements, such as space capacity, passive safety, maneuverability, and stability, restrict the continued improvement of these design-based energy-saving approaches; hence, this kind of solution is full of contradictions, and it is also hard to continuously increase the driving range of EVs in the short term. Therefore, improving the driving range of EVs through design means is a process that requires long-term investment and extensive engineering experience, which makes it difficult to achieve immediate results in a short period of time.

Compared to design means, control means are currently the more effective means to increase the driving range of EVs, which is expected to achieve results in a short time. For EVs, the application of the motor provides them with better control performance, more responsive and flexible torque response, and better dynamic performance, for example, than traditional vehicles with internal combustion engines. Additionally, the power generation characteristics of the motor also provide a hardware foundation for braking energy recovery. Therefore, among the various control means, the control means for the drive system that maximize the motor performance have a more direct and efficient effect on the driving range of EVs.

Braking energy recovery through the controlling drive system and braking system is the most important means to increase the driving range of EVs among various control means, and there has been extensive research on braking energy management in recent years [7]. Moreover, braking energy management strategies have already been applied to mass-produced vehicles over the past few decades [8–10].

Owing to the excellent performance of the motor mentioned above, the direct control of the drive system also has a crucial role in increasing the driving range of EVs because the driving efficiency of the drive system would directly impact the energy consumption of EVs. Depending on its arrangement, the drive system of EVs can be classified as a centralized drive system or a decentralized or distributed drive system. The centralized drive system can change the working points of the motors through a power distribution strategy among multiple motors based on the multi-motor coupling drive system (MCDS), so the motors can have a greater chance to work in their high-efficiency area to achieve energy conservation [11]. The decentralized drive system can directly change the driving torque of each drive wheel through front-and-rear torque vectoring and left-and-right torque vectoring, which can effectively optimize the energy losses of EVs, such as the electric loss, the tire slip energy, and the energy consumption caused by cornering resistance, to achieve energy conservation [12].

There has been extensive research on driving energy management, but the effectiveness of driving energy management in improving the driving range of EVs has not received sufficient attention, and there are not many applications in mass-produced vehicles. To gain a more systematic understanding of driving energy management and to facilitate the further application of the driving energy management strategy in mass-produced EVs, this review systematically summarizes the various technologies that can be used to improve the driving range of EVs from the perspective of driving energy management; this review focuses on providing a comprehensive summary of the configurations and power distribution strategies for the dual-motor coupling drive system (DCDS) and a systematical summary of energy-saving torque-vectoring control strategies for the decentralized drive system.

The rest of this paper is organized as follows. Section 2 provides a detailed analysis of the power losses that occur during vehicle driving and summarizes the feasible energy-saving pathways for different energy-saving means based on the analysis results. Section 3 summarizes the energy-saving means for the DCDS, which is divided into two parts: a summary of the DCDS configurations and a summary of power distribution strategies for the DCDS. Section 4 summarizes the energy-saving means with torque vectoring. Both front-and-rear torque vectoring and left-and-right torque vectoring for energy saving are systematically analyzed. The overall conclusions are given in Section 5.

2. Driving Energy Loss Analysis

During the driving process of EVs, the energy input from the battery will be consumed in many processes before it can be utilized to increase the kinetic energy and overcome the driving resistance of the vehicle. These energy losses, termed driving energy losses, do not contribute directly to the vehicle's propulsion, but most of them are affected by the drive system. Reducing these energy losses by controlling the drive system is a critical aspect of driving energy management, which deserves significant attention.

Driving energy losses are primarily composed of electric loss, the mechanical loss of the drivetrain, tire slip energy dissipation, and the power of cornering resistance (Figure 2). Subsequently, a detailed analysis of each of these energy losses will be analyzed in detail.

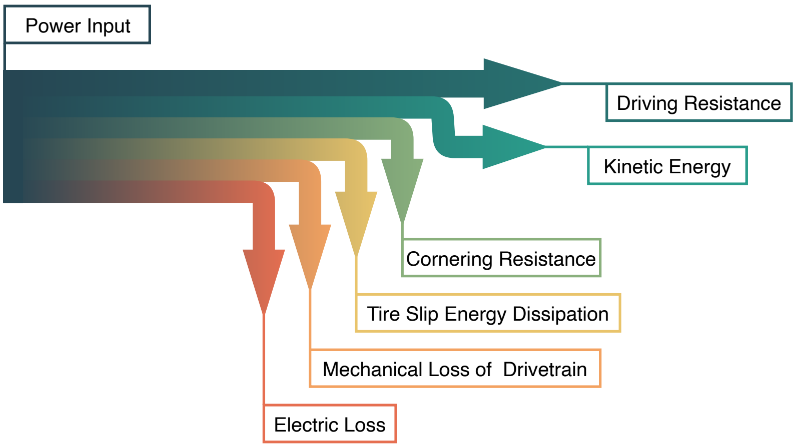

Figure 2. Power losses during vehicle driving.

Electric loss accounts for the largest proportion of driving energy losses in general and mainly includes the discharge loss of the battery and the power loss of the electrical system.

The discharge loss of the battery is mainly generated by the internal resistance of the battery, and its main influencing factors are the circuit current and the state of charge of the battery [13]. Under normal circumstances, the discharge loss of the battery is not significantly affected by the control strategy of the drive system.

The power loss of the electrical system is generally caused by motors and inverters, which are mainly determined by the output torque and the output speed of the motors. Electrical system efficiency can well reflect the numerical scale of the power loss of the electrical system, which can be expressed as follows:

$$\eta_e(T_{M1}, T_{M2}, \ldots, T_{Mn}, n_{M1}, n_{M2}, \ldots, n_{Mn}) = \frac{P_{\text{in}} - P_{\text{loss}}}{P_{\text{in}}} \tag{1}$$

where η_e is the electrical system efficiency; T_{Mi} and n_{Mi} are the output torque and the output speed of the motor i, respectively; and P_{in} and P_{loss} are the input power and the power loss of the electrical system, respectively.

P_{loss} comprises copper loss P_{Cu}, iron loss P_{Fe}, inverter loss P_{inv}, mechanical friction loss P_m, and stray loss P_s from the perspective of the internal structure of the electrical system [14], which can be expressed as follows:

$$P_{\text{loss}} = \sum P_{\text{Cu}} + \sum P_{\text{Fe}} + \sum P_{\text{inv}} + \sum P_m + \sum P_s \tag{2}$$

For an electrical subsystem that contains only one motor, the electrical system efficiency can be mapped to the output torque and the output speed of the motor through experiments on the electrical system. This is because the electrical system efficiency is generally less affected by factors other than the output torque and the output speed of the motor. Through an efficiency map, the electrical system efficiency can be directly obtained using the output torque and the output speed of the motor. However, to accurately calculate electrical system efficiency, an accurate efficiency model of the electrical system is still necessary.

The mechanical loss of the drivetrain mainly refers to the additional energy consumption caused by the rotation of mechanical components, such as mechanical friction loss, oil stirring loss, and other energy losses. Similar to electrical system efficiency, drivetrain efficiency can well reflect the numerical scale of the mechanical loss of the drivetrain as well, which is commonly assumed to be constant when calculating driving energy in EVs.

Due to the physical properties of pneumatic tires, a tire will inevitably slip during its force-generating process, which results in additional energy consumption. This energy consumption, termed tire slip energy dissipation, can be classified as longitudinal tire slip energy dissipation and lateral tire slip energy dissipation according to the slip direction of the tire. In [15], an estimation formula for tire slip energy dissipation based on the brush tire model was proposed as follows:

$$P_s = F_{xsi} v_{xi} + F_{ysi} v_{yi} \tag{3}$$

where F_{xsi} and F_{ysi} are the longitudinal and lateral slip forces of the tire, respectively; v_{xi} and v_{yi} are the longitudinal and lateral slip speeds of the tire, respectively.

Furthermore, longitudinal tire slip energy dissipation can subsequently be precisely calculated and expressed as the slip ratio.

Under driving conditions, the dynamic equation of tire rotation (Figure 3) can be expressed as follows:

$$T_t - F_x R_w = J_w \dot{\omega}_w \tag{4}$$

where T_t is the traction torque of the wheel; F_x is the longitudinal tire force; ω_w is the angular velocity of the wheel; R_w is the rolling radius of the wheel; and J_w is the wheel rotational inertia.

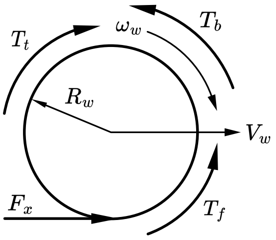

Figure 3. Schematic of tire rotation.

Longitudinal tire slip energy dissipation is the difference between the input power and output power of the wheel in the longitudinal direction, which can be expressed as follows:

$$P_{sl} = T_t \omega_w - F_x V_w \tag{5}$$

where V_w is the longitudinal velocity of the wheel center.

The slip ratio s is an important parameter for characterizing tire slip, which can generally be calculated by the following expression under driving conditions:

$$s = \frac{\omega_w R_w - V_w}{\omega_w R_w} \tag{6}$$

Substituting Equations (4) and (6) into Equation (5), the expression of longitudinal tire slip energy dissipation can be derived as follows:

$$P_{sl} = T_t \omega_w s + J_w \omega_w \dot{\omega}_w (1 - s) \tag{7}$$

In the steady state, Equation (7) can be simplified to the following expression:

$$P_{sl} = T_t \omega_w s \tag{8}$$

During the cornering process of the vehicle, even if the total traction force of the vehicle remains unchanged before and after entering the corner, the speed of the vehicle will decrease slightly during the process of cornering, which is called the phenomenon of cornering speed reduction. The main reason for this phenomenon is that during the process of cornering, the lateral tire force generated by the steering wheel has a component that is opposite the vehicle's direction of motion, which results in additional energy consumption. This component is called cornering resistance [16]. It is influenced by various factors, including the steering wheel angle, the additional yaw moment generated by traction torque distribution, and the vehicle's motion states. Due to the complexity of these factors, it is challenging to calculate cornering resistance with a high degree of precision. However, the expression of cornering resistance in steady-state cornering can be roughly derived based on the linear 2-degree-of-freedom (2-DOF) single-track vehicle model (Figure 4) [17,18].

In Figure 4, assuming that the front wheel angle and the sideslip angle at the center of gravity (COG) are small, the dynamic equation of the vehicle during steady-state cornering can be expressed as follows:

$$\begin{cases} -m\omega_r V\beta = F_{xf} - F_{yf}\delta + F_{xr} - F_{dr} \\ m\omega_r V = F_{xf}\delta + F_{yf} + F_{yr} \\ 0 = \left(F_{xf}\delta + F_{yf}\right)L_f - F_{yr}L_r + M_z \end{cases} \tag{9}$$

where m is the mass of the vehicle; L_f and L_r are the length from the COG to the front and rear wheel axles, respectively; V is the resultant velocity of longitudinal and lateral velocities; δ is the steering angle of the front wheels; β is the sideslip angle at the COG; ω_r is the yaw rate of the vehicle; F_{xf} and F_{xr} are the total longitudinal tire forces of the front and rear axles; F_{yf} and F_{yr} are the total lateral tire forces of the front and rear axles; F_{dr} is the driving resistance; and M_z is the additional yaw moment generated by the distribution of traction torque.

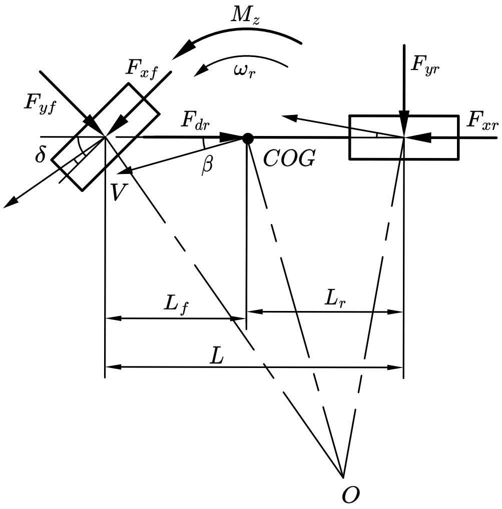

Figure 4. Linear 2-DOF single-track model.

In the first term of Equation (9), the total longitudinal tire forces have an extra component in addition to overcoming driving resistance, which is the cornering resistance F_{cr}:

$$F_{cr} = \left(F_{xf} + F_{xr}\right) - F_{dr} = -m\omega_r V\beta + F_{yf}\delta \tag{10}$$

Substituting the other terms of Equation (9) into Equation (10) and ignoring the small terms, the expression of cornering resistance can be derived as follows [18]:

$$F_{cr} = m\omega_r V\left(\frac{L_r}{L}\delta - \beta\right) - \frac{\delta}{L}M_z \tag{11}$$

where $L = L_f + L_r$ is the wheelbase of the vehicle.

Thus, the power of cornering resistance P_{cr} can be derived as follows:

$$P_{cr} = F_{cr}V = m\omega_r V^2\left(\frac{L_r}{L}\delta - \beta\right) - \frac{\delta}{L}VM_z \tag{12}$$

From Equation (12), the power of cornering resistance is directly related to the vehicle state parameters δ, V, and β. Moreover, a conclusion can be derived that the additional yaw moment M_z has a direct effect on reducing the power of cornering resistance during steady-state cornering. Through simulation investigations, Refs. [19,20] pointed out that during the cornering process, whether the vehicle is front-wheel drive, rear-wheel drive, or four-wheel drive, distributing all traction torque to the outer wheels could minimize the power of cornering resistance, which is consistent with the conclusion above. Furthermore, this conclusion was further verified by conducting experiments on actual vehicles in [17]. Therefore, an effective energy-saving means for decentralized drive EVs is to use the additional yaw moment generated through traction torque distribution to reduce the power of cornering resistance, which can be achieved by torque vectoring.

Among the driving energy losses analyzed above, electric loss, tire slip energy dissipation, and the power of cornering resistance can be directly affected by driving energy management. Correspondingly, the energy-saving pathways of driving energy management mainly include improving the electrical system efficiency, reducing tire slip, and reducing cornering resistance. As shown in Figure 5, for the MCDS, the main energy-saving pathway is to improve the electrical system efficiency through a power distribution strategy; for a decentralized drive system, the main energy-saving pathways are improving the electrical system efficiency, reducing tire slip, and reducing cornering resistance through front-and-rear torque vectoring and left-and-right torque vectoring. It should be noted that the power distribution strategy in the MCDS and torque vectoring in the distributed drive system are both methods of driving energy management. They both aim to reduce energy consumption by controlling the drive system. Despite having different implementation methods, they share high similarity in principle. A detailed review of them will be covered in the following chapters.

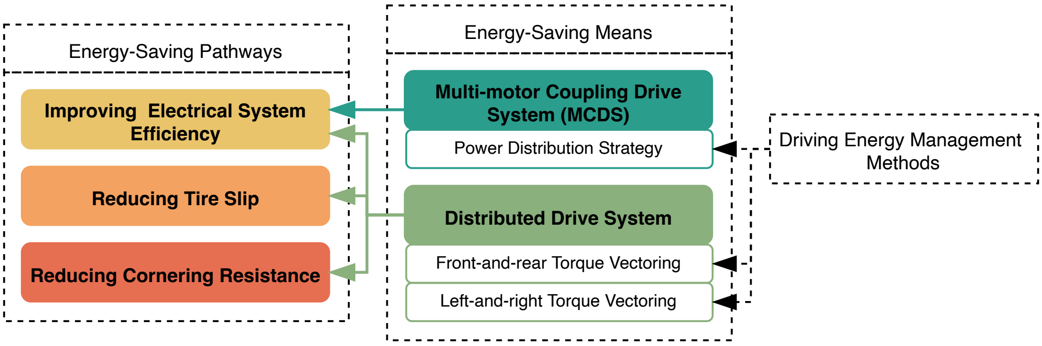

Figure 5. Energy-saving pathways and means of driving energy management.

3. Dual-Motor Coupling Drive System

The MCDS is an electrical drive system that incorporates multiple motors coupled through a mechanical structure. This kind of drive system can optimize the working points of each motor by distributing power, torque, and speed among multiple motors to achieve energy conservation. Over the years, the MCDS has received widespread attention due to its energy conservation potential. Since two motors can almost fully release the energy conservation potential of the MCDS and more motors would not significantly improve the energy-saving effect due to possible increases in mass and cost, most of the research on MCDSs in recent years has focused on the DCDS. Therefore, this chapter mainly focuses on the DCDS.

3.1. Configuration of DCDS

There are three types of DCDSs based on their power coupling patterns: the dual-motor torque-coupling drive system (DTCDS), the dual-motor speed-coupling drive system (DSCDS), and the variable dual-motor coupling drive system (VDCDS). Each type has distinct configurations.

A characteristic of the DTCDS is that its output torque is the linear summation of the output torque of the two motors, and its output speed is proportional to the output speed of the two motors. Based on this characteristic, the efficiency of the DTCDS can be improved by distributing the output torque of the two motors to optimize the working points of each motor [21,22]. For a typical DTCDS, the output ends of the two motors are connected through a specially designed coupler or directly connected to the same element (Figure 6) so that the output torque of the drive system can be transferred freely between the two motors. Moreover, the DTCDS can switch between single-motor driving mode and dual-motor torque-coupling driving mode to reduce the transmission loss caused by the idle rotation of the non-driving motor, which can further improve the energy conservation potential of the DTCDS. This can be achieved through the utilization of clutches and the matching design of mechanical structures such as the reducer and coupler [23]. In addition, since torque coupling is the simplest power coupling pattern, the configuration of the DTCDS can be diverse. Broadly speaking, in addition to the typical DTCDS introduced above, the front-and-rear-independent-drive axle is also a kind of DTCDS.

A characteristic of the DSCDS is that its output speed is the linear summation of the output speed of the two motors, and its output torque is proportional to the output torque of the two motors. Based on this characteristic, the DSCDS can flexibly optimize the working points of each motor by distributing the output speed of the two motors so that the efficiency of the DSCDS can be effectively improved. Since a planetary gear system is characterized by multiple degrees of freedom and a linear relationship between the speeds of each component, which fits the coupling requirements of the DSCDS quite well, it becomes the preferred coupler for the DSCDS. In a typical DSCDS, each of the two motors is connected to one of the input ends of a planetary gear system so that the output end of the planetary gear system can deliver the coupled power (Figure 7) [24–27]. Furthermore, the DSCDS can also switch between single-motor driving mode and dual-motor speed-coupling driving mode to provide more options for transmission ratio selection. This can be achieved through the utilization of brakes and the matching design of mechanical structures [28].

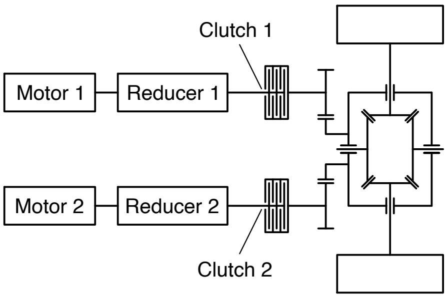

Figure 6. Schematic of typical DTCDS.

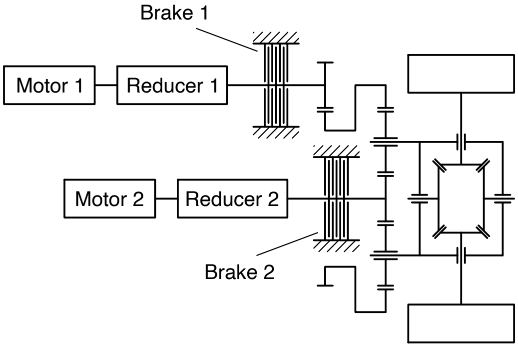

Figure 7. Schematic of typical DSCDS.

Table 1 shows the comparison of the DTCDS and DSCDS. Due to the different transmission system characteristics of the DTCDS and DSCDS, their coupling output torque and coupling output speed are different. Therefore, there are different optimization methods for the working point of the motors. Generally, the DTCDS can effectively improve the driving efficiency of EVs in the medium-speed low-torque and medium-speed medium-torque working states by optimizing the working points of the motors, while the DSCDS can effectively improve the driving efficiency of EVs in the low-speed medium-torque and high-speed medium-torque working states by optimizing the working points of the motors.

Table 1. Comparison of DTCDS and DSCDS.

DCDS Configuration	Coupling Output Torque	Coupling Output Speed	Feasible Driving Modes
DTCDS	Linear summation of the output torque of the two motors	Proportional to the output speed of the two motors	Single-motor drive mode and dual-motor torque-coupling driving mode
DSCDS	Proportional to the output torque of the two motors	Linear summation of the output speed of the two motors	Single-motor drive mode and dual-motor speed-coupling driving mode

In order to simultaneously achieve the beneficial effects of both the DTCDS and DSCDS, the VDCDS was designed. The VDCDS is capable of switching among various driving modes: single-motor drive, dual-motor torque-coupling drive, and dual-motor speed-coupling drive; this can be achieved through the implementation of complex mechanical structure with clutches, brakes, or some other actuators [29]. In some kinds of VDCDSs, hollow shaft motors are needed to achieve a more compact structure of the drive system and a better arrangement of mechanical components [30]. Figure 8 shows a novel VDCDS configuration proposed in [31], where the output shaft of motor 1 passes through the inner hole of the output shaft of motor 2 to achieve a coaxial arrangement. This VDCDS configuration can achieve four driving modes: motor 1 driving mode, motor 2 driving mode, dual-motor torque-coupling driving mode, and dual-motor speed-coupling driving mode; these can be switched by controlling three clutches and one brake. Through the study of parameter matching and the power distribution strategy, the energy conservation potential of this VDCDS configuration could reach about 10% compared to traditional single-motor drive systems.

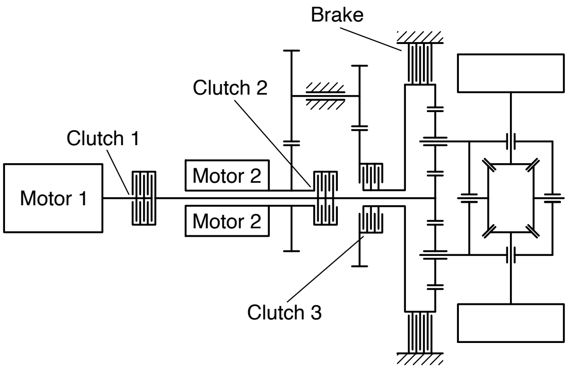

Figure 8. Schematic of a novel VDCDS.

3.2. Power Distribution Strategy of DCDS

To tap into the energy-saving potential of the MCDS, a power distribution strategy is essential. The primary objective of a power distribution strategy is to optimize the distribution of output power from each motor, which aims to enhance the efficiency of the drive system without compromising its performance. As shown in Figure 9, for the DCDS, the main effect of a power distribution strategy is the optimization of the working points of two motors, resulting in an effective improvement in the load of the motors. This ensures that the working points of the motors can operate more within the high-efficiency area of the motors, thereby improving the driving efficiency of the DCDS.

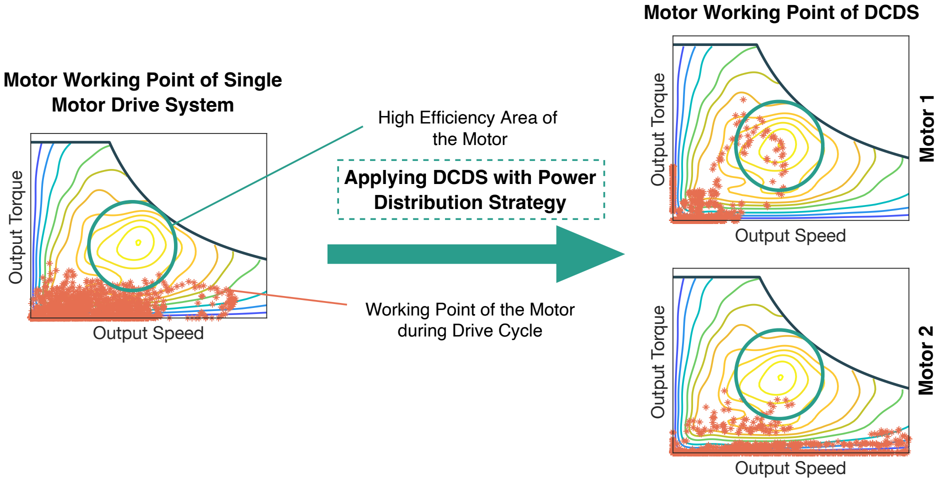

Figure 9. Working point optimization schematic of motors with power distribution strategy in DCDS.

As shown in Figure 10, the main function of the power distribution strategy in the DCDS is to determine the optimal driving mode and the optimal power distribution ratio of the two motors under different working conditions based on the required traction torque T_{td} and the vehicle speed u_a; a driving mode switching signal can then be to the clutches or brakes, and an output torque or output speed control signal can be sent to the two motors.

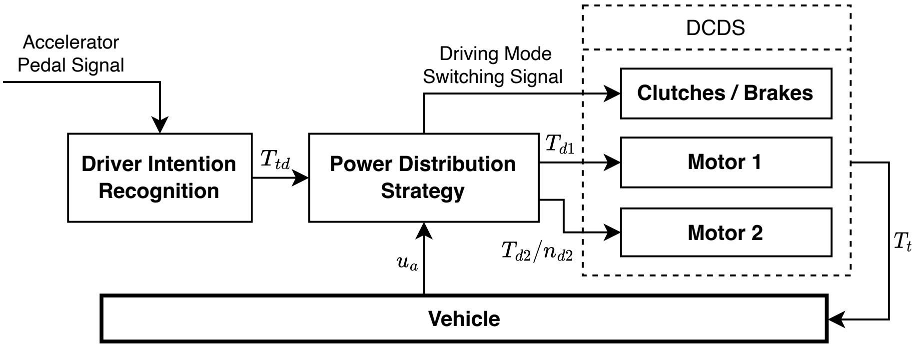

Figure 10. Typical power distribution control system of DCDS

The simplest power distribution strategy for the DCDS is the rule-based strategy. This identifies the driving modes of the DCDS and the power distribution between motors using rules based on offline optimization, which takes the optimal electrical system efficiency as the optimization objective. This strategy does not rely on complex algorithms, so its computation cost is low, and it is suitable for implementation. However, the energy-saving effect of this strategy is not as good as expected when there are many control objectives in complex conditions. Some researchers improved this strategy and achieved better energy-saving effects. Ref. [32] improved the rule-based strategy by combining the two-parameter-based mode-switching control strategy and the power-split control strategy, which resulted in some energy-saving rate improvements. Ref. [33] designed a dual fuzzy controller to achieve optimal power distribution, in which the control rules of the system were optimized using a genetic algorithm to improve the control accuracy and optimization effect with multiple objectives.

Although the rule-based power distribution strategy already has a decent effect on energy conservation, there is still a certain gap between its control effect and the global optimal result. In order to further tap into the energy-saving potential of the DCDS, researchers have also conducted extensive research on power distribution strategies based on global optimization algorithms.

Among the global optimization algorithms, the dynamic programming (DP) algorithm has been extensively studied due to its simplicity and effectiveness [34,35]. However, DP has the disadvantage of excessive computation, and the real-time executability of the power distribution strategy based on DP tends to be poor when the control object model is complex. Moreover, the calculation process of DP requires the accurate vehicle motion states of the entire future driving process, which are difficult to accurately predict. This further affects the vehicle application of DP. Therefore, some researchers have focused on the optimization of the parameter update process, the improvement of the calculation efficiency, and the enhancement of the prediction accuracy of future vehicle motion states and combined DP with other optimization algorithms to improve its performance in the power distribution strategy. It should be noted that while some studies focused on optimizing DP for hybrid drive systems, these optimization approaches are also applicable to the DCDS.

Ref. [36] proposed an iterative DP approach that converges to the optimal control strategy within an adaptive multidimensional search space to reduce the computing time. Ref. [37] derived an analytic solution for the optimal torque-split decision at each point in time and the state grid by utilizing a local approximation of the gridded cost-to-go, which significantly reduced the computation time by orders of magnitude. Ref. [38] proposed a piecewise Markov-based velocity prediction method, which utilizes the acceleration sign to enhance the performance of the vehicle motion state prediction. Ref. [39] trained a radial basis function neural network based on the optimization results of DP, leading to a significant improvement in the real-time executability of the power distribution strategy.

4. Energy Conservation Control Strategy of Torque Vectoring

Torque vectoring is a chassis technology in the vehicle that directly controls the traction torque of each drive wheel, and it can be classified as front-and-rear torque vectoring and left-and-right torque vectoring according to the direction of the torque flow distribution. Torque vectoring can directly affect the powertrain efficiency since it can directly control the output torque of the corresponding motor of each drive wheel; hence, there has been extensive research on the energy conservation potential of torque vectoring (Figure 11).

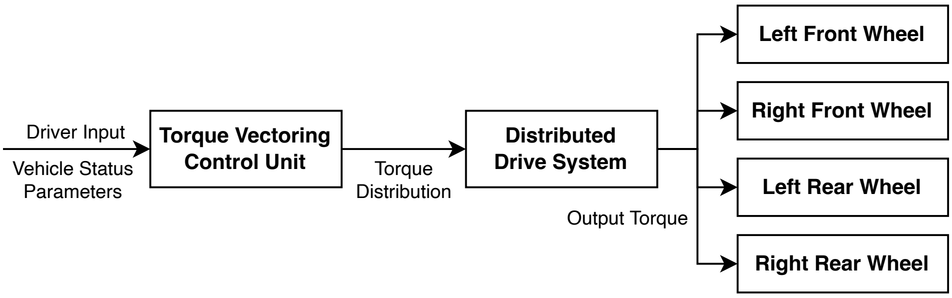

Figure 11. Control concept of torque vectoring

4.1. Front-and-Rear Torque Vectoring

Front-and-rear torque vectoring can directly control the traction torque distribution ratio of the front and rear drive axles, which is one of the most effective means of driving energy management. The main energy-saving pathways of front-and-rear torque vectoring are improving the electrical system efficiency and reducing tire slip. Front-and-rear torque vectoring has the most potential as driving energy management technology for vehicle application, because it can be realized in vehicles where the traction torque of the front and rear drive axles can be controlled independently, and thus, there is no need to rely on the drive system containing a complex mechanical structure or the four-wheel-independent-drive system. Moreover, various automobile enterprises have developed many EVs with dual-motor front-and-rear-independent-drive axles, and these vehicles can all apply front-and-rear torque vectoring, which further promotes the development of front-and-rear torque-vectoring technology.

In the driving energy management strategy by means of front-and-rear torque vectoring, the analysis of electrical system efficiency is an important part, and there are generally two methods, as mentioned in Chapter 2. The first method is to create an efficiency map through experiments on the electrical system so that the electrical system efficiency can be directly derived by referring to the map based on the output torque and the output speed of the motor. The second method is to build an accurate efficiency model of the electrical system, which enables the electrical system efficiency to be derived through the output of the model.

A simple and effective driving energy management strategy is to derive the electrical system efficiency by efficiency mapping and develop the front-and-rear torque-vectoring control strategy based on this [40–44]. Ref. [45] took the minimum total input power of all the motors as the optimization objective based on the efficiency map of the motors and then developed an online front-and-rear torque-vectoring control algorithm based on the optimized results, which effectively improved the electrical system efficiency, especially in low-torque region. Ref. [46] processed the offline optimization results into a map related to the total output torque of the drive system and the vehicle's velocity, which further improved the real-time performance of the driving energy management strategy. Based on the offline optimization results, Ref. [47] reached the conclusion that adopting single-axle drive in the low-torque region while adopting evenly distributed drive in the high-torque region could maximize the driving efficiency, and a similar conclusion was derived by analyzing the loss characteristics of motors in [48,49].

For EVs directly driven by permanent-magnet in-wheel motors, during the driving process, because of the existence of permanent magnets inside the motors, when the non-working motors are towing, towing losses, including iron loss and mechanical friction loss, are inevitable [50]. These energy losses are normally ignored in the analysis of electrical system efficiency based on efficiency mapping. In this circumstance, an accurate efficiency model of the electrical system could reflect the energy losses more accurately [51]. Ref. [52,53] developed an efficiency model for a four-wheel-independent-drive EV that considered the copper loss, iron loss, and mechanical friction loss of the permanent-magnet synchronous motor. Then, the efficiency model was used to minimize the summation of the output power and energy loss of the motors. Ref. [54] tested the influences of the motor temperature and proposed a correction model based on the temperature difference. Through vehicle tests, Ref. [14] concluded that in order to maximize the energy efficiency of the drive system and avoid towing losses, the total traction torque requirement should be evenly distributed among all motors.

The analysis of tire slip energy dissipation is also an important part of driving energy management by means of front-and-rear torque vectoring. When the slip ratio exceeds the critical value and the tire experiences excessive slip, the slip of the tire can lead to a significant increase in energy dissipation [55]. This situation should be avoided by the control of the drive system. Therefore, some researchers took tire slip energy dissipation into account in driving energy management to achieve a better drive energy conservation effect. Ref. [56] proposed a hierarchical front-and-rear torque-vectoring algorithm (Figure 12), which is composed of three layers. The first layer applies a fixed torque distribution ratio. When the tire slips excessively, the second layer is activated and employs sliding mode control to adjust the slip ratio to the optimal value. If the motor efficiency drops sharply and the vehicle remains within the safety boundary, the third layer is triggered, and the particle swarm optimization algorithm is utilized to search for the optimal torque distribution ratio and maximize the drive system efficiency. Ref. [57] took the variations in road adhesion into account and developed a multi-objective optimal front-and-rear torque-vectoring energy-saving strategy, which combines with anti-slip regulation (ASR) to achieve a better energy conservation effect and eliminate excessive tire slip.

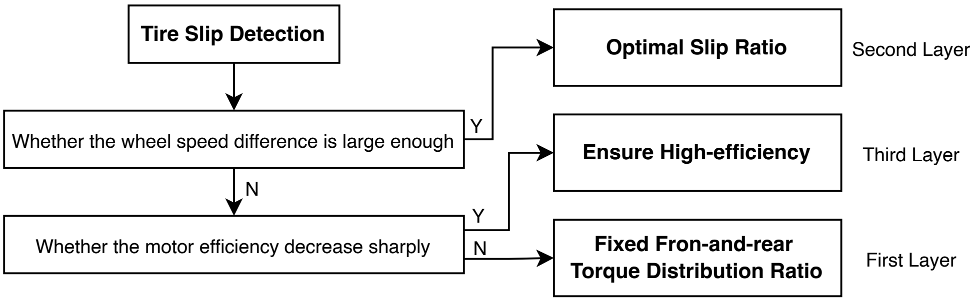

Figure 12. Schematic of a hierarchical front-and-rear torque-vectoring algorithm.

4.2. Left-and-Right Torque Vectoring

Left-and-right torque vectoring can directly control the traction torque distribution ratio of the left and right drive wheels. In the last few decades, researchers have extensively studied the impact of this technology on enhancing the active safety and stability of vehicles [58–61]. With in-depth research on left-and-right torque vectoring, its energy-saving effect on vehicles has been gradually noticed [62–64]. The main energy-saving pathways of left-and-right torque vectoring include improving the electrical system efficiency [18,65], reducing tire slip energy dissipation [66], and reducing the power of cornering resistance [18,67], which can comprehensively improve the powertrain efficiency. It is worth noting that left-and-right torque vectoring will generate an additional yaw moment, which might make the vehicle unstable if it is not properly controlled. Therefore, in the driving energy management strategy by means of left-and-right torque vectoring, taking the stability of the vehicle into account is necessary, and hence, complex control strategies are normally needed. In addition, left-and-right torque vectoring is generally applied to four-wheel-independent-drive EVs, in which front-and-rear torque vectoring is also needed.

A typical torque-vectoring control strategy is shown in Figure 13 [65,68,69]. Firstly, the total demanded traction torque T_d is determined based on driver intention recognition. Secondly, the demanded yaw rate ω_{rd} and demanded sideslip angle of the COG β_d of the vehicle are determined based on a coordinated control algorithm of economy and stability, which is normally based on a reference vehicle model and an optimization algorithm for energy conservation. Then, the demanded additional yaw moment ΔM_{zd} is determined based on a controller. Lastly, the traction torque of each drive motor T_{ti} can be derived based on the torque distribution module. This strategy can effectively enhance the efficiency of the drive system while maintaining the vehicle stability within a reasonable range. Many researchers have proposed better strategies for energy conservation based on this strategy by utilizing advanced control algorithms. Ref. [70] proposed an energy-saving torque-vectoring strategy based on a nonlinear model predictive controller, which concurrently optimizes the reference yaw rate and the torque allocation of each wheel to achieve stable cornering performance with low energy consumption. Ref. [71] developed an energy-efficient torque-vectoring algorithm by combining the experimentally measured efficiency map of the electrical system, the optimization results from a nonlinear quasi-static vehicle model, and drivability requirements for a comfortable and safe cornering response. Simulation results showed that the algorithm achieved over 5% average input power saving in steady-state cornering with lateral acceleration over 3.5 $\mathrm{m/s^2}$. Ref. [72] proposed a phase-plane-based controller for driving energy management by means of torque vectoring, which adapts to driving situations by optimizing the weights for vehicle maneuverability and stability performance. The controller could effectively balance the handling and stability performance of the vehicle and the energy conservation effect of the drive system. Ref. [73] proposed a deep-reinforcement-learning-based torque distribution strategy in which the torque distribution task is explicitly formulated as a Markov decision process so that the vehicle dynamic characteristics can be approximated, which significantly enhances the real-time executability of the driving energy management strategy.

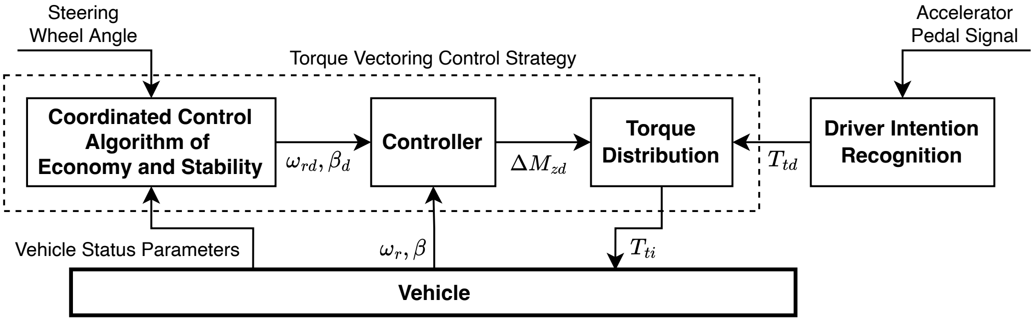

Figure 13. Typical torque-vectoring control strategy.

Developing a coordinated control strategy by combining torque vectoring with other vehicle dynamic control methods could further improve the effect of the driving energy management strategy. Ref. [74] combined driving energy management with braking energy management and optimized the drive energy and the braking energy, respectively, which improved the overall efficiency of the vehicle. The combination of torque vectoring with active steering could also improve the performance of EVs [75,76]. Ref. [77] studied how active steering and torque vectoring affect the cornering efficiency of four-wheel-independent-drive EVs. In this study, for the specific studied vehicle, the addition of rear active steering could reduce 10% of energy consumption of the vehicle.

5. Conclusions

Driving energy management is a crucial means of increasing the driving range of EVs because the energy efficiency of EVs can be directly optimized by the control of the drive system. For a centralized drive system, the main energy-saving means is to optimize the output power of each motor in the drive system so as to improve the electrical system efficiency based on the DCDS. For a decentralized drive system, the main energy-saving means is to directly optimize the output power of each drive wheel so as to reduce the electric loss, tire slip energy dissipation, and the power of cornering resistance through torque vectoring.

The DCDS is a typical configuration of an MCDS, which has been the subject of widespread studies in recent years. A DCDS can be classified as a DTCDS, DSCDS, or VDCDS according to the power coupling pattern of the drive system. The simplest power distribution strategy for the DCDS is the rule-based strategy, which is effective in improving the powertrain efficiency and has a low computation cost, and thus, it is suitable for implementation. The optimization results of a power distribution strategy based on DP could nearly approach the global optimal results, which shows its high energy conservation potential.

Torque vectoring is another interesting and effective way to reduce the driving energy losses of EVs. The energy-saving pathways of front-and-rear torque vectoring are improving the electrical system efficiency and reducing tire slip energy dissipation. Hence, the analysis of electrical system efficiency and tire slip energy dissipation is an important part of the driving energy management strategy. The comprehensive energy conservation effect of left-and-right torque vectoring has been studied and verified in recent years, and many advanced control algorithms are utilized to improve the effect of the driving energy management strategy by means of torque vectoring.

It can be determined that whether through power distribution strategies based on the DCDS or through torque vectoring based on a decentralized drive system, driving energy management can significantly improve the efficiency of the drive system and thus increase the driving range of EVs. In the current situation, where the increase in the battery energy density has reached a bottleneck, driving energy management will be an effective means to further improve the driving range of EVs, and it will also be a valuable and crucial direction for further energy conservation in EVs.

However, most of the driving energy management strategies are still in the simulation verification stage, which means that their robustness and real-time executability lack verification. This is mainly because EVs with novel multi-power drive systems such as the MCDS and decentralized drive system are still in the early stage of development. If advanced drive technologies for EVs are further developed, high-efficiency driving energy management strategies could also be further implemented so that the driving range of EVs could be further improved.

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