Torque allocation strategy for two axles four wheel drive electric vehicle with improvement of economy and stability

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Abstract. Two axles four wheel drive electric vehicle is an important development tendency of electric vehicle. However, how to coordinate the torque distribution between front and rear axles thus ensuring vehicle stability while maximizing motor’s efficiency still confronts great challenges. In this paper, we propose a three-layer hierarchical control method, which not only incorporates prior engineering knowledge into the control policy so as to relieve computational burden for real-time usage, but also properly deals with the priority between safety and system efficiency. Simulations are conducted to verify the effectiveness of the proposed method. Results show that the derived control policy can ensure high system efficiency when safety is guaranteed. Simultaneously, it can actively decrease the motor torque to improve vehicle stability when wheel slip occurs.

1. Introduction

Recently, energy crisis and environmental pollution have become priority concern for countries all over the world. Because transportation section is the major consumer of fossil fuels and is always blamed for waste gas emission, many countries have taken great efforts to investigate high-efficiency and environmentally-friendly vehicular technology so as to create a more clean transportation system.

Electrification of transportation is one of the effective methods to cope with the increasingly serious problems of energy crisis and environmental pollution. Pure electric vehicles (PEVs), which are propelled by power battery only, is a representative product in the process of transportation electrification. Most traditional PEVs are front-drive or rear-drive only, which means the vehicle is propelled by only one motor in series with a single reduction gear. Despite simple structure of this powertrain configuration, it suffers disadvantages such as relatively poor acceleration performance at high speed and relatively low system efficiency at low required power conditions.

In order to overcome above problems, two axles four wheel drive (4WD) PEV has been proposed, which has two motors with one mounting on the front axle and the other on the rear axle. However, adding another motor complicates the system structure and how to coordinate the working states of the two motors so as to exploit the system’s maximum potential in dynamic and economic improvement while ensuring safety still remains a big challenge. Although, some researchers have proposed some methods, for example, Ref.[1] proposed an adaptive equivalent consumption minimization strategy and Ref.[2] designed a model predictive control based torque optimization control policy for 4WD PEV, safety constraints were not considered in their researches. Ref.[3] proposed a safety-targeted power split strategy for 4WD PEV but the system efficiency is not incorporated. To summarize, few
researches have taken both system efficiency and safety constraints into consideration, which is the main contribution of this work.

In this paper, we propose a three-layer hierarchical control method for 4WD PEV, which can not only improve system efficiency when safety is guaranteed but also ensure vehicle stability when wheel slip occurs. The reminder of this paper is organized as follows: in Section 2, configuration and dynamic modeling of the investigated 4WD PEV are introduced in detail. In Section 3, the three-layer hierarchical control method together with detailed explanation of each layer’s function is described. In Section 4, the proposed method is verified under two specific simulation scenarios and Section 5 concludes the whole paper.

2. Configuration and modelling of the investigated 4WD PEV

Configuration of the investigated 4WD PEV is shown in figure.1, from which it can be seen that the system mainly consists of two motors, two transmissions (namely reduction gears), two motor controller units (MCUs) and one vehicle controller unit (VCU). The VCU receives pedal position signal to detect driver’s power demand and wheel speed signal to judge if wheel slip occurs. Other signals like temperature may also be fed into VCU to determine power constraints of motors and power battery. But because the main topic of this paper is torque allocation between two motors, such environmental constraints are not considered here. After receiving necessary information, VCU decides torque split between front and rear motors according to predefined control policy and sends the control signal to MCU. Finally, motors extract energy from power battery according to MCU signal and propel the vehicle. Main parameters of the investigated 4WD PEV are shown in table.1.

![Configuration of the investigated 4WD PEV](image)

**Figure 1. Configuration of the investigated 4WD PEV**

| Item              | Parameter                  | Value       |
|-------------------|-----------------------------|-------------|
| **Vehicle**       | Cubic mass                 | 2241kg      |
| **Power battery** | Nominal voltage            | 350V        |
|                   | Nominal capacity            | 100kWh      |
| **Rear motor**    | Max. speed                 | 16000rpm    |
|                   | Max. torque                | 650Nm       |
|                   | Max. power @ speed         | 375kW@5900rpm |
| **Front motor**   | Max. speed                 | 18000rpm    |
|                   | Max. torque                | 330Nm       |
|                   | Max. power @ speed         | 193kW@6100rpm |
| **Reduction gear**| Reduction ratio of rear gear| 9.734       |
|                   | Reduction ratio of front gear| 9.325       |
To realize optimal torque allocation of the two motors for the investigated 4WD PEV, its mathematical model is prerequisite. In following, we will introduce the models for the tire dynamics and vehicle longitudinal dynamics.

2.1. Tire dynamics

The longitudinal tire force $F_x$ can be described as the product of the load on the tires $F_z$ and the tire-road friction coefficient $\mu$, which is a function of slip ratio $\lambda$, as described in Eq.(1).

$$F_{xi} = \mu_i(\lambda_i)F_{zi}$$

where $i$ denotes the variables associated with the front or rear wheels.

The magic formula [4] is adopted here to describe the non-linear relationship between $\mu$ and $\lambda$, which is described as following Eq.(2).

$$\mu_i(\lambda_i) = D_x \sin \left\{ C_x \arctan \left[ B_x \lambda_i - E_x (B_x \lambda_i - \arctan (B_x \lambda_i)) \right]\right\}$$

where $B_x$, $C_x$, $D_x$, $E_x$ are respectively the stiffness, shape, peak and curvature factors.

The slip ratio is calculated as following Eq.(3).

$$\lambda_i = \frac{u - r_i \omega_i}{u}$$

where $u$ is the vehicle speed, $r$ denotes the dynamic wheel radius and $\omega$ is the wheel rotation speed.

2.2. Longitudinal dynamics

Because the investigated 4WD PEV is propelled by the front and rear motors, two-axle vehicle model is used to describe its longitudinal dynamics. Compared with traditional mass-point vehicle model, it incorporates the longitudinal load transfer during acceleration or deceleration. The detailed description of the model is as follows.

The aerodynamic force $F_A$ can be expressed by:

$$F_A = \frac{C_D A u^2}{21.15}$$

The load on the front axle $F_{zf}$ and rear axle $F_{zr}$ considering weight transfer can be described by:

$$F_{zf} = \frac{m}{a + b} \left( gb - \frac{du}{dt} h_{CG} \right) - \frac{h_A}{a + b} F_A$$

$$F_{zr} = \frac{m}{a + b} \left( gb + \frac{du}{dt} h_{CG} \right) + \frac{h_A}{a + b} F_A$$

where $m$ is cubic mass of the vehicle, $a$ and $b$ are the distance from center of gravity to front and rear axles respectively, $g$ is gravitational constant $9.8 m/s^2$, $h_{CG}$ is the height of center of gravity, $h_A$ is the height of the point where aerodynamic force applies.

The rotational acceleration of the front and rear wheels can be expressed as:

$$\dot{\omega}_i = \frac{1}{J_i} (M_i i_i - F_{zi} \mu_i r_i)$$

where $M$ is the output torque of front or rear motor, $i$ is reduction ratio of front or rear transmission. $J$ is the moment inertia of front or rear axle.

3. Three-layer hierarchical torque allocation algorithm

The requirements of the torque allocation algorithm for 4WD PEV include at least following three aspects. Firstly, the algorithm should limit its computational burden within some certain range so as to facilitate real-time and on-board usage. Secondly, it should ensure driving safety to avoid occurrence of wheel slip. Thirdly, configuration of 4WD enables relatively flexible torque split between two motors and the algorithm should take this advantage to maximize the efficiency of overall system.

In order to satisfy the above mentioned three requirements, we propose a three-layer hierarchical torque allocation algorithm, which is shown in figure.2. In the first layer, the proposed algorithm focuses on real-time application, thus prior engineering knowledge is incorporated into the torque
allocation map, which sets the ratio of rear motor torque to front motor to fixed value. If the wheel slip occurs and the difference of front and rear wheels’ speed exceeds certain value, the algorithm will enter the second layer, where safety is set as the priority and sliding mode control will be used to adjust motor’s torque output so that the slip ratio can be controlled around optimal value so as to maximize longitudinal force. If the vehicle is within safety boundary but in some conditions the motor’s working points slide into low-efficiency area, the algorithm will enter the third layer and economy performance of the system will be set as the priority. Within technical bounds, the algorithm will actively change the ratio of two motors’ torque so as to improve overall efficiency of the system. The detailed description of the three layers is demonstrated below.

3.1. First layer: Application
In this layer, the key is to set the value of fixed ratio of rear motor’s torque to front motor’s torque. Because the two motors have relatively similar efficiency map, their optimal torque ratio is close to their maximum torque ratio or their maximum power ratio. After incorporating prior engineering knowledge and elaborate designing, we set the ratio of rear motor’s torque to front motor’s torque as 7:3.

3.2. Second layer: Safety
In this layer, sliding mode control is used to make slip ratio close to optimal value. The difference of front and rear wheel speed \( e \) can be expressed as the function of slip ratio:

\[
e = \omega_f - \omega_r = \frac{\lambda_f - \lambda_r}{(1 - \lambda_f)(1 - \lambda_r)} \tag{8}
\]

If \( s_0 \) represents the proportion that front axle’s torque takes up in total required torque at current moment and \( s = s_0 + \Delta s \) at next moment, then Eq.(7) can be reformulated as:

\[
\dot{\omega}_f = \frac{1}{J_f} [sT_{req} - r_f\mu_f(\lambda_f)F_{zf}] \tag{9}
\]

\[
\dot{\omega}_r = \frac{1}{J_r} [(1 - s)T_{req} - r_r\mu_r(\lambda_r)F_{zr}] \tag{10}
\]

where \( T_{req} \) represents the required driving torque.

Assume front and rear axles have the same moment inertia and tire radius, which means \( J_f = J_r = J \) and \( r_f = r_r = r \), then the derivative of \( e \) can be expressed as:

\[
\dot{e} = \dot{\omega}_f - \dot{\omega}_r = \frac{1}{J} [(2s - 1)T_{req} - \mu_f(\lambda_f)F_{zf} - \mu_r(\lambda_r)F_{zr} r] \tag{11}
\]

The sliding mode control rule can be designed as:
\[ s = s_0 - k_1 \text{sign}(e) \]  
\[ \text{Eq.(12)} \]

where \( k_1 \) must satisfy the condition \( 0.5 > k_1 > k_{1\text{min}} = \left| \frac{\mu_f (\lambda_f F_{zf} - \mu_r (\lambda_r F_{zr}) r - (2s_0 - 1) T_{req}}{2T_{req}} \right| \)

When the torque ratio \( s \) is managed by Eq.(12), sliding condition \( e \dot{e} < 0 \) can be satisfied and the sliding surface \( e = 0 \) could be a stable invariant set.

3.3. Third layer: Economy

In this layer, particle swarm optimization [5] is adopted to search for the optimal torque split ratio between front and rear axles. The objective function to be maximized is as follows:

\[ J_{\text{cost}} = s T_{req} \left( \frac{u_i}{T_f} \right) + (1 - s) \Gamma \left( \frac{u_i}{T_r} \right) \left( 1 - s \right) T_{req} - \gamma \Delta s^2 \]  
\[ \text{Eq.(13)} \]

where function \( \Gamma \) maps motor’s speed and torque to motor’s efficiency. The above objective function includes three parts. For the first two parts, it tries to maximize the overall efficiency of two motors. Considering the technical bound of motor control property, the motor’s torque should not change sharply, thus the third term is added to restrict the motor’s torque change. \( \gamma \) is a positive scaling factor to make the motor efficiency and torque slip change at the similar quantity. A negative sign is added to the third term because torque slip change is to be minimized but the total cost means to be maximized.

4. Simulation and verification

In order to verify the proposed torque split method, two specific scenarios are designed. In the first scenario, we fixed the acceleration pedal opening to 15%. The simulation result is shown in figure.3. It can be seen that at first stage, namely when the front motor’s speed is below 1163r/min and the rear motor’s speed is below 1210r/min, the output torque of front and rear motors follows the predefined pedal map and the ratio of rear motor’s torque to front motor’s torque is 7:3. When the front motor’s speed reaches 1163r/min and the rear motor’s speed reaches 1210r/min (corresponds to vehicle speed 15km/h), the rear motor begins to quit driving and the demand power is mainly provided by the front motor. The reason is that if the ratio of two motor’s torque still follows the fixed value, both front and rear motors will enter into low-efficiency area, thus the control algorithm enters into the third stage economy-targeted control and increases front motor’s torque to make it work in high-efficiency area.

In the second scenario, we let the vehicle accelerate at full acceleration pedal. The simulation result is shown in figure.4. It can be seen that limited by the road adhesion condition, the wheel slips for four times. However, when the wheel slip happens, the control algorithm will enter into the second layer safety-targeted control and actively decreases motor torque to make slip ratio close to optimal value thus maximizing the longitudinal force so as to avoid deteriorating slipping. From the vehicle speed, it can be seen that owing to the safety-targeted control, the vehicle achieves relatively smooth acceleration.
5. Conclusion
In this paper, we propose a three-layer hierarchical torque allocation algorithm for 4WD PEV, which can not only be used for real-time application but also improve system overall efficiency and safety. Two specific designed scenarios are used to verify effectiveness of the proposed method. Results show that the control algorithm will let the rear motor quit driving when required power is low for improvement of system efficiency and will actively decrease motors’ torque so as to increase vehicle stability when vehicle accelerates at full acceleration pedal.

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