A Novel Wheel Skid Control Based On Motor Energy Distribution Model

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Abstract. How to realize wheel slip control with parameters that can be measured and not relying on hardware precision is a difficult problem in vehicle traction control. From the point of view of energy transfer, this paper uses the feature that the rotational kinetic energy of the wheel increases abnormally when slipping, and proposes a wheel slip control method based on the motor energy distribution model. This method only requires the motor phase voltage, phase current and wheel speed that are easy to measure. In this paper, a complete vector control model of permanent magnet synchronous motor is established, and a PI control algorithm framework is built based on one-wheel vehicle model. The simulation results verify the effectiveness of the proposed algorithm.

1. Introduction
Distributed drive electric vehicles have become a hot topic in recent years due to their simple structure and potential for complex vehicle dynamics control [1]. As a difficult problem in the active safety control of automobiles, the four-wheel distributed drive electric vehicle bottom-level torque control method has become the focus of research in recent years [2-3]. The existing anti-skid control method is mainly based on slip ratio anti-skid control method [4-6] and MFC control method [7-8]. These two methods require accurate vehicle speed information or torque information, which is difficult to achieve in practice.

Based on the above methods, this paper proposes a new wheel anti-skid control method based on motor energy distribution model. From the energy point of view, this method uses the feature that the vehicle's rotational kinetic energy increases abnormally during slipping to design an anti-skid control algorithm. This method requires neither precise vehicle speed nor torque sensors. The torque command value issued by the upper controller is adjusted by comparing the power that the motor should assign to the wheel when the current vehicle speed is not slipping and the mechanical power actually consumed by the wheel. In turn, the output torque of the motor is reduced to achieve the purpose of anti-slip.

2. Energy Distribution Model
Figure 1 is a simplified model of one-wheel vehicle. When the vehicle is in the ideal driving condition, the kinetic energy of the vehicle is increased under the condition of complete adhesion:
It can be seen that for the distributed drive electric vehicle, there is no inertia of the engine and the transmission part, and the kinetic energy increment is the sum of the kinetic energy increment of the whole vehicle and the incremental kinetic energy of the wheel. The rotational kinetic energy of the wheel under fully attached conditions is:

\[ T_2 = \frac{1}{2} J_\omega \omega^2 \quad (2) \]

According to the above two formulas (1) and (2), under the condition of complete adhesion, the ratio of wheel kinetic energy to vehicle kinetic energy is:

\[ K = \frac{T_2}{T_1} = \frac{J_\omega}{J_\omega + Mr^2} \quad (3) \]

It can be seen that K is a constant value, that is to say, under the condition of complete adhesion, the ratio of the increase of the rotational energy of the wheel to the increase of the kinetic energy of the whole vehicle is fixed.

From the perspective of power transmission, when the vehicle is in the ideal driving condition, the longitudinal motion equation of the vehicle can be described as:

\[ T = (J_\omega + Mr^2) \frac{d\omega}{dt} \quad (4) \]

The mechanical power consumed by the vehicle is:

\[ P = T\omega = (J_\omega + Mr^2) \frac{d\omega}{dt} \omega \quad (5) \]

It can be seen that under fully attached conditions, the mechanical power P of the motor consists of two parts. Among them, \( J_\omega \omega \) can be regarded as the mechanical power consumed by the rotation of the wheel, and \( Mr^2 \omega \) can be regarded as the mechanical power consumed by the translation of the whole vehicle. Under the condition of complete adhesion, the mechanical power consumed by the rotation of the wheel accounts for a certain proportion of the total power consumption of the entire vehicle. In other words, the power that the motor distributes to the wheels when the slip does not occur at the actual wheel speed is constant.

According to the above power transfer characteristics, a new anti-skid control method is proposed in this paper. The basic principle is: the mechanical power \( P_\omega \) consumed by the wheel at the actual speed is obtained according to the angular velocity and the moment of inertia of each wheel. \( P_\omega \) is the power that the motor should be assigned to the wheel when the wheel does not slip at the current speed. The constrained power is obtained by comparing the sizes of \( P_\omega \) and \( P_\omega \). Then the constrained power generate the constraint torque by the PI controller to adjust the torque output request value issued by the upper controller, and then generate the motor torque command value. The torque output of the driving wheel is controlled according to the motor torque command value, thereby achieving the purpose of anti-slip.
3. Design of Anti-skid Algorithmic Controller

3.1. One-wheel Vehicle Model

This paper only studies the longitudinal motion slip of the vehicle, so the vehicle model is simplified into a one-wheel vehicle model to facilitate research. The longitudinal motion of the car shown in Figure 1 can be described as:

\[ J_\omega \ddot{\omega} = T - r F_d, \quad M \dot{V} = F_d - F_{dr}, \quad F_d(\lambda) = \mu N, \quad V_\omega = \omega r, \quad \lambda = \frac{V_\omega - V}{V_\omega} \]  \hspace{1cm} (6)

The model of the relationship between the adhesion coefficient and the slip ratio between the wheel and the road surface uses the widely used magic formula [9]. The simulation reference of the vehicle running resistance is obtained by using the look-up table method according to GB18352.3-2005, and is obtained according to the empirical formula (7):

\[ \frac{F_y}{F_{dr}} = a \times M + b \]  \hspace{1cm} (7)

Among them, \( F_y \) is the rolling resistance of the car, \( F_{dr} \) is the total resistance value, and \( a \) \& \( b \) is the coefficient of the car at various speeds.

The vehicle parameters in this paper refer to the vehicle parameters of paper [10], and the main parameters are: \( M=360kg, \quad r=0.22m, \quad J_\omega = 0.5 \). Figure 2 shows the One-wheel vehicle model block diagram.

| Symbol | Definition |
|--------|------------|
| M      | Total Weight |
| r      | Wheel radius |
| \( J_\omega \) | Wheel inertia |
| \( \omega \) | Wheel speed |
| V      | Vehicle Speed |
| T      | Driving torque |
| \( F_d \) | Longitudinal Friction of Wheels (Traction Force) |
| \( F_{dr} \) | Vehicle running resistance |
| \( \mu \) | Adhesion coefficient |
| N      | Vertical load of wheel |
| \( \lambda \) | Slip rate |

3.2. Permanent Magnet Synchronous Motor vector control model

Permanent magnet synchronous motor (PMSM) has become the main choice of electric vehicle drive motor because of its good performance [11]. This paper establishes a complete PMSM vector control model to obtain the three-phase current dynamic value of permanent magnet synchronous motor, and calculate the output power value \( P_\omega \).

The basic principle of vector control is to transform the PMSM mathematical model in the stationary coordinate system into a synchronous rotating coordinate system through coordinate transformation to achieve complete decoupling. Under the synchronous rotating coordinate system axis, the stator voltage of the PMSM can be expressed as follows [12]:

\[ u_d = R i_d + \frac{d \psi_d}{dt} - \omega \psi_q, \quad u_q = R i_q + \frac{d \psi_q}{dt} + \omega \psi_d \]  \hspace{1cm} (8)

The stator flux linkage equation is:
Combined with the above four equations, the stator voltage equation can be obtained as:

$$\psi_d = L_d i_d + \psi_f, \quad \psi_q = L_q i_q$$

(9)

At this point, the electromagnetic torque equation can be written as:

$$T_e = \frac{3}{2} p \psi_d [i_d (L_d - L_q) + \psi_f]$$

(10)

In the above formula, the meanings of the respective symbols are shown in table 2:

The motor output power is calculated as follows [13]:

$$P_e = \eta m U I \cos \phi$$

(12)

Among them, $\eta$ is the efficiency including motor electrical loss and mechanical loss. The well-designed permanent magnet motor efficiency value is generally above 0.9; m is the motor phase number, this paper uses three-phase permanent magnet synchronous motor; U is phase voltage, I is the phase current; $\cos \phi$ is the power factor of the motor, generally close to 1.

It can be seen that the mathematical model of the three-phase PMSM realizes complete decoupling, and only needs to separately control the d and q axis voltages of the motor. This paper is a three-phase permanent magnet synchronous motor control for electric vehicles. The basic control structure is shown in Figure 3. The three-phase stator current $i_d, i_q, i_c$ is equivalently converted to the DC component $i_d, i_q$ under the $d - q$ axis by Clark variation and Park transformation. In this paper, the current loop closed-loop control of $i_d = 0$ is used, and the reference torque $T_{ref}$ is multiplied by the torque current ratio $K_t = 1.5 p \psi_f$ as the q-axis reference current input. d, q-axis current is controlled by current loop PI to obtain d, q-axis reference voltage, d, q-axis voltage is obtained by anti-Park transformation to obtain the static coordinate system $\alpha, \beta$ axis voltage. The $\alpha, \beta$ axis voltage is vector-modulated (SVPWM) to obtain six PWM signals to control the inverter's six switches on and off, thereby outputting a three-phase voltage control motor rotation.

Matlab/Simulink encapsulates the permanent magnet motor module. The user only needs to specify the electrical parameters of the motor. The electrical parameters of the motor are set to: DC bus voltage is 560V, stator winding resistance is 0.958, d-axis inductance is 0.00525H, q inductance is 0.00525H, the permanent magnet flux linkage , and the motor pole number is 8.

![Fig. 2: One-wheel vehicle model block diagram](image)

![Fig. 3: PMSM vector control block diagram](image)
3.3. Controller Design

This section is the core chapter of the article, mainly about the design of algorithm controller based on PI control. Vehicle slippage generally occurs at start-up or low-speed conditions. When constructing the control algorithm of this paper, the following assumptions are made:

i. Wheel and motor coaxial.

ii. The loss due to rolling resistance and air resistance during driving is a certain value and is reflected in the efficiency of the motor.

Mechanical motion equation of the motor:
\[ J_m \ddot{\omega} = T_s - T - B\omega \]  
(13)

Where \( J_m \) is the motor moment of inertia and the value is 0.03; \( \dot{\omega} \) is the motor shaft rotational acceleration (wheel rotation acceleration); \( T \) is the load torque (drive torque); \( B \) is the damping coefficient, \( \omega \) is the mechanical angular velocity of the motor (wheel speed), \( B\omega \) is a small value that is ignored here.

Combining formula (6) with this formula, we can get the coupled motion formula of vehicle and motor:
\[ (J_\omega + J_m) \ddot{\omega} = T_s - rF_d \]  
(14)

The built controller is shown in Fig. 4. According to the foregoing theory, the motor output power is multiplied by the proportional coefficient \( K \) to obtain the rotational power \( P_\omega \) that the motor should be assigned to the wheel when the wheel is not slipped at current speed. The power \( P_\omega \) consumed by the wheel at the actual speed is obtained from the wheel speed and the acceleration. When the wheel slips, the rotational power consumption increases abnormally, and the values of \( P_\omega \) and \( P_a \) differ greatly. The difference \( E \) between \( P_\omega \) and \( P_a \) is adjusted by PI to generate a constraint torque to adjust the torque command value \( T^* \) issued by the upper controller. Low-pass filter \( \tau_1, \tau_2 \) is added to the control algorithm to filter out noise interference in the signal. The slip determination module is used to limit the algorithm to output only when there is a slip trend or slip. When the wheel has a slip trend, the wheel acceleration increases abnormally. When the difference between \( P_\omega \) and \( P_a \) exceeds a certain value, the slip occurs. Therefore, the slip determination condition is set to: When \( \dot{\omega} > 0 \) and \( E = (P_\omega - P_a) > E_{lim} \), the controller outputs the output value of the PI controller, otherwise the output is zero, where \( E_{lim} \) is the set limit value.

4. Simulation and Analysis

The simulation is based on the control framework established in Figure 5.

Figure 5 shows the anti-slip effect of the control algorithm presented in this paper. The upper controller commands the torque \( T^* = 120 \text{Nm} \), PI parameter is: \( k_p = 0.5, k_i = 0.6 \), and the vehicle enters the low adhesion coefficient road surface at 2s. It can be seen that the vehicle quickly slips when the...
control is not added, and the wheel speed increases sharply. After the control algorithm is added, when the wheel starts to have a slip trend, the controller outputs the adjustment torque to reduce the command torque of the upper controller, thereby controlling the torque output of the motor to suppress the wheel slip.

Figure 6 shows the anti-slip effect of the control algorithm under different command torques. It can be seen that the control algorithm can control the slip rate below 0.2 under different degrees of slip torque, so that the vehicle can run normally.

Fig. 7 is a simulation result of changing the integral coefficient $ki$ of the PI controller. It can be seen that the slip ratio is about 0.3 at $ki=0.3$, and the car has a slight slip. As the $ki$ coefficient increases, the slip ratio becomes smaller, but when $ki=0.9$, the reference torque ripple becomes larger, which is not conducive to system stability. Considering that $ki$ is around 0.6, the controller has better comprehensive performance.

Fig. 8 is a simulation result of changing the proportion coefficient $kp$ of the PI controller. It can be seen that as the $kp$ increases, the slip ratio becomes smaller and smaller, and the anti-slip effect is better. However, it can also be seen that when the $kp$ is too large, the command torque is excessively cut, which is not conducive to the acceleration performance of the automobile. Considering comprehensively, $kp$ has a better overall effect from 0.5 to 1.
5. Conclusion
This paper presents a wheel slip control method based on motor energy distribution model. This method does not require precise chassis speed or motor torque, and only uses the phase voltage, phase current of the motor and wheel speed for anti-skid control.

When the wheel slips, the mechanical power consumed by the wheel increases abnormally, forming a difference from the power that the motor should assign to the wheel when it is not slipping. PI control is used to adjust the error between these two powers. When it is detected that the wheel starts to have a slip tendency, the controller outputs the constraint torque to adjust the torque command issued by the upper controller, thereby reducing the motor torque output to prevent slippage.

Simulation results verify the effectiveness of the anti-skid control method.

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