Braking Stability-Oriented Regenerative Braking Control Strategy of Twin Motor 4WD Electric Vehicle

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Keywords: Electric Vehicle, Regenerative braking, I-Curve, Stability

Abstract. Regenerating braking technology benefits energy economy of vehicle, being and the important way to improve the energy saving and emission reduction of electric vehicles. To guarantee braking safety and maximize regenerative braking energy, considering the constraints of motor and battery on energy recovery, a strategy of regenerative braking of twin motor 4WD electric vehicle is provided by braking force distribution via I-curve and ECE regulatory curve. A vehicle system simulation model combining the vehicle model and the braking force distribution control model is built. Through the analyses for the strategy braking performance under braking conditions, the results verify the feasibility of control strategy, enabling improving the range of electric vehicles and recovering regenerative braking energy effectively in the case of stability and safety.

Introduction

Facing the issues of shortage of resources and environmental protection, electric vehicles have driven an increasing trend in the development. One of the most critical problems in restricting electric vehicles production to market is short mileage, so it has been an important means to improve the energy utilization by regenerative braking energy recovery in electric vehicles until the battery technology make a major breakthrough.

It is expressed that about 50% or more of the driving energy is lost during the braking process in urban conditions, about 20% in the suburbs [1], if this part of the energy is effectively recovered, the driving range of electric vehicles can be extended by 10% to 30%.

There have been researches [2-5] on the electric vehicle brake energy recovery about the braking force distribution, energy storage and control, the impact of braking performance. Those works have studied the regenerative braking of uniaxial pure electric vehicles based on the principle of maximum energy recovery. The braking force is preferentially distributed to the drive shaft and the regenerative braking is used to recover the braking energy, but in this way, the front and rear braking force distribution deviates from the I-curve, affecting the stability of braking. Wang [6] found through comparative study that braking force of biaxial electric vehicle can be distributed according to the I-curve, both braking energy recovery potential or braking energy recovery efficiency and braking efficiency are capable to achieve the best. But few studies have taken safety and stability into consideration. For solving the problem, this paper proposes a new regenerative braking control strategy based on the distribution theory of the ideal braking force curve and ECE regulatory curve. And Taking into account the constraints of the motor and the battery on the energy recovery, a kind of electro - hydraulic compound braking force distribution strategy is
developed to meet the braking stability requirements and the maximum for recycling braking energy. It’s able not only to ensure the safety and stability of electric vehicles, but also improve efficiency of the recovery of braking energy.

**Brake Stability Requirement**

To ensure the stability of the vehicle in the braking process[6], two requirements needs to be met.(1) The braking force distribution curve closes to I curve from below, to prevent the rear wheels locked before front wheels .(2) Meet ECE braking regulatory requirements.

**Ideal Braking Force Distribution Theory**

The braking force distribution of I- curve can ensure the rear and front wheels lock at the same time on any road whatever adhesion coefficient, to make good use of ground adhesion conditions and ensure the safety and stability of vehicle braking. As shown in Figure.1 and Figure. 2, relationship [7] between braking force of front axle and rear axle as the following:

\[
F_{u2} = \frac{1}{2} \left[ \frac{G}{h_g} \sqrt{b^2 + \frac{4h_g L}{G}} F_{u1} - \left( \frac{Gb}{h_g} + 2F_{u1} \right) \right]
\]  

(1)

Where \( F_{u1} \) and \( F_{u2} \) are respectively the braking force of the front and rear wheels of the vehicle, \( G \) is the vehicle gravity, \( b \) is the distance from the center of the vehicle to the center line of the rear axle, \( L \) is the distance between the front and rear axles, \( h_g \) is the height of the center of the vehicle.

**ECE Regulatory Curve**

As shown in Figure.3, the braking regulation of ECE puts forward clear requirements on front and rear axle braking force of the biaxial vehicles. When the brake strength \( z = 0.2 \sim 0.8 \), the front axle utilization adhesion coefficient curve should be on the rear axle utilization adhesion coefficient curve to make the front wheels lock before the wheels to ensure the vehicle braking direction stability. And the utilization adhesion coefficient \( \Phi \leq ( z + 0.07 ) / 0.85 \) and close to \( \Phi = Z \) curve to ensure high using efficiency of the adhesion.
Constraints of Regenerative Braking Force

Motor Constraint

When the electric vehicle regenerative braking, the motor is converted to the work of the generator, the braking energy can be converted into electrical energy stored in batteries and other energy storage devices. The mathematical model [8] of the motor is as follows.

\[
F_d = \begin{cases} 
\frac{T_n i_g i_o}{r \eta_f}, & n_{\text{min}} < n < n_N \\
3600P_N / u_a \eta_f, & n \geq n_N \\
0, & n \leq n_{\text{min}} 
\end{cases} 
\]  

(2)

Where \( F_d \) is the electric braking force, \( T_n \) is nominal torque, \( i_g \) and \( i_o \) respectively, are the transmission ratio of gearbox and transmission ratio of final reduction drive, \( \eta_f \) is transmission efficiency, \( r \) is wheel rolling radius, \( P_N \) is motor rated power, \( u_a \) is speed; \( n \) is motor speed, \( n_N \) rated speed of motor, \( n_{\text{min}} \) is failure speed of the motor regenerative braking.

In a braking process, in order to ensure the stability and safety of braking, the proportion of braking force distribution needs to be adjusted. If the maximum regenerative braking force of the motor can’t meet the braking force required by the driving wheel, the hydraulic power compensation is needed. If the speed is too low, the regenerative braking function should be turned off.

Battery Constraint

The relationship among charging power, electromotive force, internal resistance and current of the battery is as follow.

\[
P_b = (U_b - IR_b)I
\]  

(3)

Where \( P_b \) is charging power, \( U_b \) is electromotive force, \( R_b \) is internal resistance, \( I \) is current.

As the battery electromotive force and internal resistance changes with the battery
SOC, so the battery charging power is also a function of SOC. When the regenerative braking of electric vehicles works, in order to protect the battery, the battery charging power needs to be used as a constraint to determine the regenerative braking force. The braking power should not exceed the battery charging power, otherwise it will damage the battery. When emergency braking, the rapid increase in braking strength, will have a huge charge current, which will damage the battery and affect the safety of the braking, regenerative braking function should be closed.

**Regenerative Braking Control Strategy**

The main idea of this strategy is studied that braking force distribution between front axle and rear axle in the double motor mode is in accordance with I-curve distribution as far as possible. If the distribution of front and rear braking force can’t meet the I-curve, making sure the braking force distribution curve below the I-curve and meet the requirements of the total force and ECE regulations.

![Regenerative Braking Control Strategy](image)

The distribution strategy is shown in Figure 4. Z-line is the distribution line of the total demand force. The front and rear axle braking force is on the Z-line to meet the total force demand. Point A, which is the intersection of I-curve and Z-line, can both meets the total braking force requirements and meet the braking force distribution of I-curve. β-line is the hydraulic braking force distribution the front and rear axle, Point C is the intersection of β-line and Z-line. The pure hydraulic braking force of the front and rear axle is distributed in accordance with Point C. Point B located at Z-line is between Point A and C, when the force distribution according to the point, braking stability is better than that of the pure hydraulic braking of the vehicle but inferior to I-curve. The distribution strategy is in accordance with Point A to distribute the front and rear the electro-hydraulic braking force as far as possible. When the Point A distribution can’t be met, braking force distribution is according to Point B. When the motor braking force completely exits, braking force distribution is according to Point C. The specific calculation process is as follows.

1. When the speed \( v_0 \) is below 5 km/h, hydraulic braking is used only and the regenerative braking function is closed.
2. When the braking strength is \( 0 < z < 0.7 \), ECU according to the brake master cylinder pressure calculates the total demand braking force \( F_z \), and distributes the
front and rear braking force $F_{RI}$ and $F_{FI}$ accordance with the I-curve, namely

$$F_{FI} = Gz(b + zh_g) / L \quad (4)$$

$$F_{RI} = Gz(a - zh_g) / L \quad (5)$$

$$F_z = F_{FI} + F_{RI} \quad (6)$$

The actual braking forces, the front $F_{xb1}$ and the rear $F_{xb2}$, are composed of hydraulic braking forces, the front axle $F_{hy-f}$ and the rear $F_{hy-r}$, and the regenerative forces, the front motor $F_{reg1}$ and the rear motor $F_{reg2}$, as below

$$F_{xb1} = F_{hy-f} + F_{reg1} \quad (7)$$

$$F_{xb2} = F_{hy-r} + F_{reg2} \quad (8)$$

In order to ensure the stability of braking when wheels lock, giving priority to make the front axle force distribution meet the demand of the I-curve distribution, and when braking force distribution curve deviate from the I-curve, making the braking force distribution at the bottom of the I-curve ensure that the front wheel is locked first, Braking force distribution can be calculated.

$$F_{reg1} = \min(\max(F_{reg-f}(n)), F_{FI}) \quad (9)$$

$$F_{hy-f} = F_{FI} - F_{reg1} \quad (10)$$

$$F_{reg2} = \min(\max(F_{reg-r}(n)), F_{RI} - \frac{1 - \beta}{\beta} F_{hy-f}) \quad (11)$$

$$F_{hy-r} = \frac{1 - \beta}{\beta} F_{hy-f} \quad (12)$$

(3) When the emergency braking ($z \geq 0.7$), the driver's desired braking strength increases rapidly and the safety of braking has become a prime target. Because the dynamic properties of regenerative braking system is a kind of soft braking in emergency situations, in order to ensure the safety requirements of braking, emergency braking regenerative braking is no longer involved in.

**Experimental Simulation**

** Modeling**

On Matlab/ Simulink (2014) and AVL Cruise(v2014) platform, vehicle model and the braking control model are built, and simulating under a variety of braking conditions to verify the feasibility of the regenerative braking energy recovery strategy.

**Simulation**

Choose a dual motor four drive pure electric vehicle as the object, its main parameters can be seen in Table.1.
In order to evaluate the effect of braking energy recovery, this paper defines the energy recovery rate $\eta$ as the evaluation index [9]

$$\eta = \frac{E_b}{E_K} \times 100\%$$

(12)

Where the $E_b$ and $E_K$ are braking energy recovery and vehicle kinetic energy.

$$E_b = \int UI dt$$

(13)

$$E_K = \frac{1}{2}mv_0^2$$

(14)

Where the $U$ and $I$ are respectively the voltage and current of the power supply in the braking process, the $m$ is the vehicle quality.

The strategy is simulate on road surface with good adhesion coefficient with three different braking strength, namely low, medium and high. The initial SOC of the battery is 40% and the initial speed is 100km/h. The results appear as shown below.

As shown in Figure. 5 and Figure. 6, when the low-intensity braking is performed, the required braking torque is smaller than the maximum regenerative braking torque that can be increased by the motor. The braking torque is all provided by the regenerative braking torque of the front and rear motors, Hydraulic braking torque is zero.

As shown in Figure. 7 and Figure. 8, when moderate braking is performed, maximum regenerative braking torque of the motor is not sufficient to provide required braking torque, part of braking torque is provided by hydraulic braking torque. As the speed decreases, the regenerative braking torque increases and the

| project                              | specification | unit |
|--------------------------------------|---------------|------|
| The vehicle kerb mass                | 1250          | kg   |
| Wheelbase                            | 2400          | mm   |
| Distance from center of mass to front axle | 1200          | mm   |
| Distance from center of mass to rear axle | 1200          | mm   |
| Height of the center of mass         | 540           | mm   |
| Nominal voltage                      | 144           | V    |
| Front and rear motor rated power     | 10            | kw   |
| Front and rear motor peak power      | 20            | kw   |

Figure 5. z=0.07 battery SOC changes.
Figure 6. z=0.07 braking torque.
Figure 7. z=0.07 battery SOC changes.
Figure 8. z=0.07 braking torque.
hydraulic braking torque decreases. When the velocity reduces to 5 km/h, the regenerative braking is invalid.

As shown in Figure 9 and Figure 10, when the emergency braking is performed, the regenerative recovery braking is turned off and the energy recovery can’t be performed. The battery SOC is not changed, and the braking torque is all provided by the hydraulic braking torque.

As shown in Table 2, compared with the energy recovery of different braking strength, the energy recovery rate of low braking strength is high. With the increase of braking strength, the hydraulic torque will gradually participate in the braking, and the energy recovery will gradually decrease.

Table 2. Energy recovery of different braking strength.

| Braking strength (z) | Recoverable energy (KJ) | Braking energy recovery (KJ) | Efficiency (%) |
|---------------------|-------------------------|----------------------------|----------------|
| 0.07                | 551.70                  | 443.40                     | 80.37          |
| 0.26                | 551.70                  | 380.84                     | 69.03          |
| 0.79                | 551.70                  | 0                          | 0              |

Conclusion

(1) A regenerative braking control strategy based on I curve and ECE regulation curve and considering the constraint of the battery and the motor is put forward. The strategy not only can be used for braking energy recovery, but also improve braking stability.
(2) A joint simulation model on Matlab/Simulink (2014) and AVL Cruise (2014) platform are built. The simulation is carried out under the three braking conditions of low, moderate and emergency. The simulation results show that the proposed strategy has high energy recovery efficiency under the condition of low braking strength and is suitable for urban conditions with frequent braking. Compared to single-axis vehicle under the same conditions, the efficiency improves significantly. Low-speed and emergency braking, the regenerative brake is closed to meet the braking stability and safety requirements.

(3) The strategy has reference and practical significance for the improvement of electric vehicle mileage, solving the battery quality bulky, reasonable coordination of the distribution of electric vehicles combined braking.

Acknowledgment
This research was financially supported by Guangdong province science and technology plan projects (2015B010119001, 2016B090918089, 2015A08083002)

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