Research on Brake Force Distribution Control Strategy of Electric Vehicle

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Abstract. An effective regenerative braking control strategy can increase the energy recovery efficiency of electric vehicles. Through the analysis of the braking force distribution constraint conditions of electric vehicles, under the stable working conditions to ensure that the wheels are not locked, the braking force is distributed to the driving wheels as much as possible, and the front and rear wheel braking force distribution control lines are proposed and distributed according to the braking force. The control line has a control strategy in place. The ADVISOR software was used to build the electric vehicle model, and the control strategy was embedded in it. The results show that compared with the ADVISOR braking force distribution strategy, the braking energy recovery rate and battery life are improved. Verify the effectiveness of the control strategy.

1. Introduction
Electric vehicle regenerative braking, that is, the motor can generate braking force when the vehicle is braking, and the braking energy is recovered in the mode of power generation, which can extend the driving range of the electric vehicle, and has become a research hotspot at home and abroad. Literature [1-3] analyzes the distribution of braking force from the braking strength, and improves the ideal braking force distribution to achieve the purpose of improving energy recovery efficiency. The literature [4-10] on the anti-lock braking system, the hydraulic brake system was analyzed and improved. Different control strategies are proposed separately.

2. Brake force distribution constraints
For a typical car, the distribution of the braking force of the front and rear axles will affect the directional stability and the degree of attachment conditions during braking. When the brake system braking force is sufficient, the following three situations may occur in the car brake:

1) The front wheel is first locked and then dragged and then the rear wheel is locked and dragged. This is a stable condition, but the car loses steering ability during braking and the adhesion conditions are not fully utilized.

2) The rear wheel first locks and drags, then the front wheel locks and drags. This is an unstable condition, and the rear axle may have side slip and the adhesion utilization rate is also low.

3) The front and rear wheels are both locked and dragged. This is an ideal condition and the adhesion conditions are better utilized.
From the perspective of ensuring the stability of the car, there must be no case where only the rear wheel is locked or the rear wheel is locked earlier than the front wheel. As far as possible, the front wheel is locked first or the front and rear wheels are locked at the same time. The purpose of the car brake is not to lock the wheel, but if the car obtains sufficient deceleration, the ideal state is that the front and rear wheels are in a rolling state, and the car can obtain a sufficiently high brake deceleration. When the front and rear wheels are locked at the same time, the front and rear wheel braking force distribution should satisfy the ideal braking force distribution curve (I line), which is expressed as Equation (1):

$$
\begin{align*}
F_{bf} + F_{br} &= Gz \\
F_{bf} &= L_b + z h_g \\
F_{br} &= L_a - z h_g
\end{align*}
$$ (1)

Where: $F_{bf}$ — Front wheel braking force; $F_{br}$ — Rear wheel braking force; $G$ — Car gravity; $z$ — Braking strength; $L_b$ — Car mass center to front axle distance; $L_a$ — Car center of mass to rear axle distance; $h_g$ — Centroid height.

The current wheel lock and the rear wheel are not locked are the brake force distribution called the $f$ line, expressed as Equation (2):

$$
F_{br} = \frac{L - \varphi h_g}{\varphi h_g} F_{bf} - \frac{G L_b}{h_g} \quad (\varphi = 0.7)
$$ (2)

Where: $\varphi$ — Adhesion coefficient; $L$ — Front and rear axle spacing.

In order to meet the requirements for braking performance, the braking force must be distributed to meet the corresponding foul. According to the ECE regulations, for the various cars between $\varphi = 0.2 \sim 0.8$, Braking strength must be met $z \geq 0.1 + 0.85(\varphi - 0.2)$. Therefore, the ECE regulatory line is obtained, which is expressed as Equation (3):

$$
\begin{align*}
F_{bf} &= z + 0.07 \frac{G}{0.85} \left( \frac{L_b + z h_g}{L} \right) \\
F_{br} &= Gz - F_{bf}
\end{align*}
$$ (3)

In summary, in order to ensure the braking stability and braking efficiency of the vehicle, the front and rear wheel braking force distribution should be in the area enclosed by the $I$ line, the horizontal axis, the ECE regulation line and the $f$ line. As shown in Figure1.
3. Research on energy recovery control strategy

3.1. Brake force distribution control line
When the electric vehicle is braked, only the energy on the drive wheels can be recovered. Therefore, in order to increase the energy recovery efficiency, it is necessary to distribute as much brake force as possible to the drive shaft. Therefore, when formulating the braking force distribution strategy, it is necessary to ensure the stability and braking efficiency of the vehicle brake. The specific control strategy is as follows:

4. Low-intensity braking
When the braking strength demand is small, the braking force is fully borne by the drive shaft. That is, when \( z < 0.15 \), the regenerative braking force generated by the motor can meet the braking demand. The front axle braking force is the regenerative braking force of the motor. The rear axle braking force is zero. When the regenerative braking force is less than the braking demand, the front axle is the maximum regenerative braking force, the hydraulic system intervenes to compensate for the remaining braking force demand, and the rear axle braking force is zero. Expressed as Equation (4):

\[
\begin{align*}
F_{bf} &= F_b \\
F_{br} &= 0 \\
F_{m} &= \begin{cases} 
F_b & F_b \leq F_{m-car} \\
F_{m-car} & F_b > F_{m-car}
\end{cases} \\
F_{HF} &= \begin{cases} 
0 & F_b \leq F_{m-car} \\
F_b - F_{m-car} & F_b > F_{m-car}
\end{cases}
\end{align*}
\]  

(4)

Where: \( F_{bf} \) — Front axle braking force; \( F_b \) — braking force demand; \( F_{br} \) — rear axle braking force; \( F_{HR} \) — rear axle hydraulic braking force; \( F_m \) — braking force generated when the motor participates in braking; \( F_{m-car} \) — maximum braking force currently available by the motor; \( F_{HF} \) — Shaft hydraulic braking force;
5. Medium strength braking
As the braking strength demand increases, the regenerative braking force cannot meet the braking demand, and the braking force cannot be supplemented only by the front axle hydraulic pressure, so the rear axle hydraulic brake is intervened. The maximum regenerative braking force is assigned to the front axle. The regenerative braking force output when the motor participates in braking changes with the front axle braking force, and the front axle hydraulic braking force complements the residual braking force requirement. The rear axle hydraulic braking force complements the total braking force demand. Expressed as Equation (5):

\[
F_{bf} = F_{m-max}
\]

\[
F_{br} = F_{Hr} = F_h - F_{bf}
\]

\[
F_m = \begin{cases} 
F_{bf} & F_{bf} \leq F_{m-cur} \\
F_{m-max} & F_{bf} > F_{m-cur}
\end{cases}
\]

\[
F_{Hf} = \begin{cases} 
0 & F_{bf} \leq F_{m-cur} \\
F_{m-max} - F_{m-cur} & F_{bf} > F_{m-cur}
\end{cases}
\]

Where: \( F_{m-max} \) —Maximum braking force of the motor.

6. High-intensity braking
The braking force generated by the braking system exceeds the adhesion limit of the road surface, and the corresponding wheel should be locked at this time. When locked, the tire will drag on the ground, which not only aggravates the tire wear, but also reduces the stability of the car due to the decrease of the adhesion coefficient. Therefore, the wheel should be prevented from locking. At this time, the braking force distribution curve should not exceed the f line. The distribution curve at this stage is designed to be parallel to the f-line and to the left of the f-line, in order to ensure that the distribution of the braking force does not allow the front wheel to lock first. Expressed as Equation (6):

\[
F_{bf} = F_{m-max}
\]

\[
F_{br} = F_{Hr} = F_h - F_{bf}
\]

\[
F_m = \begin{cases} 
F_{bf} & F_{bf} \leq F_{m-cur} \\
F_{m-cur} & F_{bf} > F_{m-cur}
\end{cases}
\]

\[
F_{Hf} = \begin{cases} 
0 & F_{bf} \leq F_{m-cur} \\
F_{m-max} - F_{m-cur} & F_{bf} > F_{m-cur}
\end{cases}
\]

7. Emergency braking
In order to ensure safety, the braking force is distributed according to the I line. Expressed as Equation (7):

\[
\begin{cases} 
F_{bf} + F_{hr} = Gz \\
F_{bf} = \frac{L_h + zh_g}{L_a - zh_g}
\end{cases}
\]
7.1. Brake force distribution strategy

The braking force distribution control line of the above braking, by the cooperation of the hydraulic braking system and the braking force of the motor, can always make the distribution of the braking forces of the front and rear wheels in accordance with the control line, thereby obtaining the maximum energy recovery. However, in the distribution of the front and rear wheel braking forces, the closer the distribution point is to the ideal braking force distribution line, the higher the reasonable degree of braking force distribution, the greater the braking efficiency that the vehicle can obtain, and the adhesion conditions to the road surface. The more fully utilized. The brake power distribution control line is only the front and rear wheel brake force distribution lines proposed to prevent wheel lock and regulatory requirements. Therefore, in actual use, if the motor can provide a braking force smaller than the brake strength realization value line, the corresponding braking force should be such that the braking force distribution point is closer to the I line as possible without affecting the energy recovery.

According to the working principle of the motor, when the speed of the motor output shaft is low due to the low speed of the vehicle or the lock of the wheel may occur, the back electromotive force generated by the motor is small, so that it is difficult for the motor to charge the energy storage device. And when the vehicle speed is very low, in order to reliably stop, it is necessary to completely adopt the hydraulic brake system, and the transition from regenerative braking to hydraulic braking should achieve a gradual transition to avoid sudden changes in the speed of the vehicle. To achieve this, introducing the motor torque speed influence factor $k_{m_{\omega_{m}}}$, Expressed as Equation (8):

\[
k_{m_{\omega_{m}}} = \begin{cases} 
0 & \omega_m \leq 50\text{rad/s} \\
\frac{\omega_m - 50}{50} & 50 < \omega_m \leq 100\text{rad/s} \\
1 & \omega_m > 100\text{rad/s}
\end{cases}
\]  

(8)

Where: $\omega_m$ —Motor speed.

For the regenerative braking of electric motors, the safety and use of the energy storage system must also be considered. When the state of charge SOC of the battery is small, the battery is allowed to be charged; and when the SOC is high, the battery is prohibited from being charged, so as to avoid shortening the battery life caused by overcharging. Introducing the influence factor of the energy storage system $k_{SOC}$, to explain the influence of the energy storage system on the braking torque of the motor, Expressed as Equation (9):

\[
k_{SOC} = \begin{cases} 
1 & SOC \leq 0.8 \\
10(0.9 - SOC) & 0.8 < SOC \leq 0.9 \\
0 & 0.9 < SOC \leq 1
\end{cases}
\]  

(9)

Therefore, at a certain speed, the available braking force of the motor is expressed as Equation (10):

\[
F_{m_{avail}} = \frac{T_{\text{max}}}{i_0 i_g k_{m_{\omega_{m}}} k_{SOC}} \frac{\eta}{r}
\]  

(10)

Where: $T_{\text{max}}$ —Motor maximum torque; $i_0$ —Final drive ratio; $i_g$ —Transmission ratio; $\eta$ —Driveline efficiency; $r$ —Wheel roll radius.

In summary, the control logic for the energy recovery braking force distribution is shown in the Figure 2:
Calculate battery open circuit voltage and charge internal resistance $V_{oc}$, $R_{ch}$

Calculate friction brake

$\alpha > \alpha_{\text{min}}$

$Y$

$\alpha > \alpha_{\text{min}}$

N

$Y$

$T > T_{\text{max}}$

N

$Y$

SOC < 0.5

N

Calculate motor speed and available torque $T_{\text{av}}$

Calculate the required braking force $F_{\text{br}}$

Calculate the maximum braking force of the front wheel $F_{\text{br},\text{f}}$

Calculate the minimum braking force of the front wheel $F_{\text{br},\text{f}}$

Calculate available braking force of the motor

Calculate motor braking force, braking torque and braking power $F_{\text{br}}, T_{\text{br}}$ and $P_{\text{br}}$

Calculate the maximum charging power determined by the maximum charging current and the maximum terminal voltage $E_{\text{max}}, I_{\text{max}}$

Calculate the maximum charging power of the battery

Calculate the demand motor braking force, braking torque and braking power

$P_{\text{max}} > P_{\text{req}}$

$Y$

$E = f(P_{\text{req}})$

$E = f(P_{\text{max}})$

Calculate the actual torque and braking force of the motor $T_{\text{br}}, F_{\text{br}}$

$T_{\text{br}} > T_{\text{max}}$

N

$Y$

Front wheel friction braking force $F_{\text{f}}$

Rear wheel friction braking force $F_{\text{r}}$

$F_{\text{f}} = F_{\text{max}} - F_{\text{r}}$

Figure 2. Energy recovery braking force distribution control logic diagram
8. MATLAB simulation and results analysis

The ADVISOR 2002 software is used to build the electric vehicle model structure, including the cycle working module, the final drive module, the gearbox module, the motor and controller module, the control strategy module and the energy storage module. As shown in Figure 3.

![Figure 3. Pure electric vehicle model structure](image)

Embed the developed control strategy module into the control strategy module in Figure 4-1 and press EDE+EUDC respectively. Five test cases of UDDS, FTP, 1015 and HFET were simulated. And compared with the ADVISOR brake force distribution strategy, the results are shown in TABLE I and Figure 4.

| Working condition           | ECE+EUDC | UDDS  | FTP   | 1015  | HFET  |
|-----------------------------|----------|-------|-------|-------|-------|
| No brake feedback           | 75.255   | 73.417| 60.427| 90.274| 66.026|
| ADVISOR control strategy    | 76.907   | 75.884| 64.131| 91.109| 66.657|
| Brake power distribution control strategy | 78.064 | 78.703| 66.876| 91.923| 67.145|

As can be seen from TABLE I, the braking energy recovery technology can improve the battery life, and thus extend the mileage of the electric vehicle. By comparing with the ADVISOR brake force distribution control strategy, the brake force distribution control strategy developed in this paper can increase the remaining battery capacity by an average of 1.4%.
It can be seen from Fig. 4-3 that after the electric vehicle is subjected to feedback braking, the energy efficiency of the whole vehicle is obviously improved. After adopting the braking force distribution control strategy formulated in this paper, the vehicle efficiency is further improved. Under the condition of HFET, the electric vehicle runs at a relatively stable state with high vehicle speed, and the energy efficiency of the whole vehicle is high. However, due to the infrequent braking, the energy efficiency improvement of the whole vehicle is not obvious after using the control strategy.

9. Conclusion
Based on the analysis of the braking force constraints of electric vehicles, the front and rear wheel braking force distribution control lines are proposed, and the braking force distribution control strategy is formulated accordingly. The MATLAB/ ADVISOR was used to build the vehicle model of the electric vehicle, and the different control conditions were selected to simulate the control strategy. The simulation results show that the developed control strategy can guarantee the braking stability of electric vehicles and recover more braking energy under different working conditions.

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