Simulation research on regenerative braking control strategy of electric vehicle

S W Zhou¹ and Q Y Wang¹,²
¹College of Mechanical Engineering and Automation, Northeastern University, Shenyang Liaoning 110819, China
E-mail: qywangedu@163.com

Abstract. In view of the shortage of cruising range of current electric vehicles, the research on the regenerative braking system of electric vehicles has been carried out. Aiming at improving energy utilization rate, combined with the working characteristics of electric motor and battery, a regenerative braking control strategy based on braking intensity is proposed. The control strategy model is built in MATLAB/Simulink firstly, and then the control strategy is verified by the integrated simulation of AVL CRUISE and MATLAB. The simulation results show that the energy utilization rate of the proposed control strategy under custom mild and moderate braking conditions can reach 34.8% and 21.5% respectively.

1. Introduction
Under the current social background of depletion of energy and deteriorating ecological degradation, new energy vehicles represented by electric vehicles have gradually become research hotspots in the automotive field due to their low energy consumption, low ecological damage and high electronic integration [1]. However, due to the technical shortcomings of power batteries, the driving range of electric vehicles is greatly limited, which is also an important reason why today's electric vehicles have not been widely promoted.

Vehicles operating under urban conditions need frequent braking and deceleration, and a lot of energy is consumed in the braking process. For electric vehicles, its unique regenerative braking system can recover part of the energy consumed in the braking process, thus significantly improving the endurance mileage and energy utilization rate of the vehicle. However, the magnitude of the regenerative braking force is limited by factors such as the energy storage device, the motor, and the structure of the brake system [2,3]. This paper focuses on the regenerative braking control strategy of electric vehicles, and a common precursor pure electric vehicle is taken as the research object. Through the control algorithm, the front and rear axle braking force and the relationship between mechanical braking force and regenerative braking force are coordinated in order to achieve stable braking and recover considerable braking energy.

2. Braking force distribution of front and rear axles
In the braking state of the vehicle, the distribution of the braking force of the front and rear axles is related to the steering stability of the vehicle and the degree of utilization of the attachment conditions. In addition, the distribution of braking force and the locking of the front and rear wheels also affect the operation of the regenerative braking system [4].
2.1. Brake force distribution safety zone

When the vehicle is in the braking state, if the front and rear axle wheels are locked at the same time, it is beneficial to the utilization of the attachment conditions, and is also beneficial to improving the braking stability of the vehicle. The braking force relationship of the front and rear axles at this time is referred to as ideal braking force distribution curve (I curve).

\[ F_j = \frac{1}{2} \left[ L_b^2 + \frac{4h_g L}{G} F_j - \left( \frac{GL_h}{h_g} + 2F_j \right) \right] \]  \hspace{1cm} (1)

In the expression: \( F_r \) is the rear axle braking force; \( F_f \) is the front axle braking force; \( L_b \) is the distance from the center of mass to the rear axle; \( h_g \) is the centroid height; \( L \) is the wheelbase; \( G \) represents the gravity of the whole vehicle.

Under the road surface with a certain adhesion coefficient, the distribution curve of breaking force between the front and rear axle is called F Line when the front wheels of the car are locked and the rear wheels are not locked.

\[
\begin{align*}
F_f &= \varphi \frac{G}{L} (L_b + zh_g) \\
F_r &= Gz - F_f
\end{align*}
\]  \hspace{1cm} (2)

In the expression: \( \varphi \) is the adhesion coefficient of the road surface (0.8 in this paper); \( z \) stands for braking strength.

The ECE (Economic Commission of Europe) R13 braking regulation formulated by the United Nations Economic Commission for Europe is formulated from the perspective of meeting the braking efficiency of vehicles. The regulation stipulates the minimum rear axle braking force in the braking process of vehicles. The distribution curve that meets the ECE regulatory line is called the M curve:

\[ F_j = \frac{z + 0.07 G}{0.85} \left( L_b + zh_g \right) \]  \hspace{1cm} (3)

As shown in figure 1, the range enclosed by the M line f line and the I line and the horizontal axis coordinates is referred to as a safe area for the distribution of braking force between the front and the rear axle during vehicle braking [5].

2.2. Brake force distribution algorithm

When braking, a electric vehicle can only recover the energy added to the drive shaft. In order to recover more energy, the braking force distribution curve should be as close as possible to the M curve. Figure 1. Braking force distribution between front and rear axle.
curve. On the other hand, in order to pursue better braking performance, it is necessary to increase the braking force of the rear axle so that the distribution curve is close to the I curve [6,7]. Considering the above situation, the following algorithm is obtained:

When the braking strength $z \leq 0.1289$, the braking force of the front and the rear axle are distributed according to the OA line, that is, the braking force of the whole vehicle is provided by the front axle. In the expression: point A is the intersection of the abscissa axis and the M curve. The corresponding braking strength of point A is 0.1289.

When the braking strength $z > 0.1289$, the braking force of the front and the rear axle are distributed according to the AB part of the M curve. The point $B_1$ is the intersection of the $B_1C_1$ line and the M curve, the line $B_1C_1$ is parallel to the BC line, and the braking force of the front axle is 90% of the BC line. Point C is the intersection of the corresponding f curve and I curve under the road surface adhesion coefficient.

When the braking strength $z \geq 0.542$, the braking forces are distributed according to $B_1C$ line.

\[
\begin{align*}
F_f &= 0.3784Gz + 3764.5325 \\
F_r &= Gz - F_f
\end{align*}
\]  

(4)

When the braking strength is greater than the adhesion coefficient of the road surface, the braking force of the front and the rear axle is distributed according to the I curve.

3. Regenerative brake intervention control strategy
The regenerative braking intervention control strategy is responsible for balancing the regenerative braking force with the friction braking force. When the braking strength $z < 0.2$, the braking force of the front axle is preferentially provided by the regenerative braking force; When braking strength $z \geq 0.2$, the share of regenerative braking force in front axle braking force is determined by fuzzy controller.

3.1. Design of fuzzy controller
The control of regenerative braking force has the characteristics of nonlinearity, randomness and time variation, so it is difficult to express the control process with mathematical model. Fuzzy control mimics human reasoning and decision-making process from behaviour : using fuzzy rules to complete fuzzy reasoning. It does not require a mathematical model to achieve precise control. So it is very suitable for controlling the regenerative braking force, and the fuzzy controller shown in figure 2 is proposed.

![Figure 2. Design of fuzzy controller.](image)

![Figure 3. Membership function graph of fuzzy variables.](image)

Firstly, according to the characteristics of the input and output variables, the membership function as shown in the Figure 3. is established, and then combined with practical experience, 27 fuzzy rules shown in table 1 have been developed.
3.2. Regeneration braking force limitation and correction

In the above, the regenerative braking coefficient \( k \) is obtained by using the fuzzy controller. However, the regenerative braking is restricted by the operating characteristics of the motor and the battery, and it is necessary to limit and correct the \( k \) value and the regenerative braking force.

First, it is necessary to specify the conditions for regenerative braking intervention based on the parameters of the battery SOC and the vehicle speed \( v \). When the battery SOC value is high (reaching the threshold value of 95%), in order to prevent the battery from overcharging, the front axle does not use regenerative braking. When the vehicle speed is too low, the recovered regenerative energy is limited too, and the condition for charging the battery is not satisfied, thus the regenerative braking is turned off.

In addition, the maximum braking force of regenerative braking is also limited by the operating characteristics of the motor: when the motor speed is lower than the rated speed, the motor is in the constant torque zone; when the motor speed is greater than the rated speed, the motor is in the constant power zone as shown in figure 4.

What’s more, when the motor speed is too low, the induced electromotive force generated by the motor is low too, however, the regenerative braking at low speed is not good, so the vehicle should turn off regenerative braking when the motor working at speed less than 500 r/min. To sum up, the model of regenerative braking force limit value shown in formula (5) is obtained.

\[
F_{r,\text{max}} = \begin{cases} 
0 & 0 \leq n < n_{\text{min}} \\
\frac{T_{\text{p}}i_{m}}{r\eta_f} & n_{\text{min}} \leq n < n_0 \\
9550\frac{P_{\text{max}}i_{m}}{nr} & n \geq n_0 
\end{cases}
\]  

(5)

---

**Table 1. Fuzzy rule.**

| i  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|----|---|---|---|---|---|---|---|---|---|----|----|----|----|----|
| SOC| S | S | S | S | S | S | S | S | M | M | M | M | M | M |
| \( z \) | S | S | S | M | M | M | L | L | L | S | S | S | S | M |
| \( v \) | S | M | L | S | M | L | S | M | L | S | L | S | M | M |
| \( k \) | M | VL | L | M | VL | L | L | VL | L | M | L | M | M | VL |

---

**Figure 4.** Speed-torque curve of the electric motor.
In the expression: $F_{elmax}$ stands for the largest regenerative braking force; $T_N$ is the maximum braking torque of the motor; $P_{max}$ is the maximum power of the motor; $n$ is the instantaneous speed of the motor; $i_m$ and $\eta_T$ is the transmission ratio and transmission efficiency of the motor to the front wheel; $n_0$ is the rated speed of the motor; $r$ represents the radius of the wheel.

4. Simulation calculation

In order to verify the regenerative braking control strategy proposed in this paper, the control strategy developed in this paper is first modeled by MATLAB/Simulink, and the generated SIMULINK control strategy is compiled to generate dynamic link library files (dll file). Then, the generated dll file is imported into the electric vehicle model built by AVL CRUISE software, and the simulation analysis can be performed after the data bus connection is successfully completed. The vehicle model and the simulation data parameters of each component are shown in table 2. The control strategy model built by SIMULINK is shown in figure 5, and the vehicle model built by AVL CRUISE is shown in figure 6.

**Table 2. Simulation parameters.**

| Parameter                        | Unit   | Parameter value |
|----------------------------------|--------|-----------------|
| Vehicle weight                   | kg     | 1500            |
| Gravity acceleration             | m/s$^2$| 9.8             |
| Centroid height                  | m      | 0.56            |
| Wheelbase                        | m      | 2.4             |
| Distance from centroid to rear axle | m | 1.25          |
| Wheel radius                     | m      | 0.279           |
| Maximum torque of the motor      | (N·m)  | 240             |
| Maximum motor power              | kW     | 75              |
| Battery nominal voltage          | V      | 320             |
| Battery capacity                 | (A·h)  | 110             |

**Figure 5.** Simulink model of control strategy.

**Figure 6.** Vehicle model based on AVL CRUISE.

In order to verify the effectiveness of the proposed control strategy, two brake conditions were defined to simulate the driving state of electric vehicle in mild and moderate braking conditions. The energy recovered during the braking process can be obtained by comparing the rate of change of the SOC value in the simulation result with the parameter data of the battery. The energy recovery efficiency during braking can be expressed as expression (6).
\[ \eta_{\text{reg}} = \frac{\Delta SOC \cdot U_N \cdot Q_N \cdot 3600}{1/2 m \Delta v^2} \]  

In the expression: \( \eta_{\text{reg}} \) represents energy recovery; \( \Delta SOC \) represents the increment of the SOC; \( U_N \) is charging nominal voltage; \( Q_N \) is battery capacity; \( \Delta v \) represents the change value of electric vehicle speed during braking.

The simulation results of mild braking are shown in Figure 7. Under mild braking conditions, the electric vehicle started to decelerate from 40 km/h and the braking strength was set to 0.2. The simulation results show that the vehicle speed reduced to 0 after 5.67s braking time, the recovered energy is 35481J, and the energy recovery rate is 34.8%.

The simulation results of moderate braking are shown in Figure 8. In the case of moderate braking, the vehicle started to brake at 72 km/h, and after 5 seconds, the car stops, recovered 64627J of energy in this process, and the energy recovery rate was 21.5%.

5. Conclusions
In order to improve the cruising range of electric vehicles, a regenerative braking control strategy based on fuzzy control was proposed under the premise of fully considering the working characteristics of the motor and battery. The control strategy and the vehicle model were firstly built using MATLAB/Simulink and AVL CRUISE respectively. After that the simulink model of the control strategy was compiled into a dynamic link library file (dll file) and then embedded in AVL CRUISE. In order to verify the proposed control strategy, simulations were performed in custom moderate and mild braking conditions. The simulation results show that under medium and mild braking conditions, the energy recovery efficiency of the regenerative braking system is 21.5% and 34.8% respectively.
References

[1] Ye M and Guo J W 2013 Regenerative Braking and Its Control Technology on Electric Vehicle (Beijing: China Communications Press) pp 52-57
[2] Poursamad A and Montazeri M 2008 Control Eng. Pract. 16 861-73
[3] Chen Z Y, Yang Y et al 2016 J. Northeast Univ. 37 1750-63
[4] Yan C Y, Jiang B et al 2017 Electric Vehicle Motor Control and Drive Technology Zhao H Q ed. (Beijing: Mechanical Industry Press) pp 163-72
[5] Shi Q S 2009 Key technologies research on energy management problems of pure electric vehicles (Shandong, China: Shandong University)
[6] Guo Z J, Yue D D et al 2018 Mach. Des. Manuf. 1 173-7
[7] Chen Y, Bei S Y et al 2016 Mod. Manuf. Eng. 12 62-7