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REGENERATIVE BRAKING CONTROL STRATEGY OF ELECTRIC VEHICLES BASED ON BRAKING STABILITY REQUIREMENTS

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ABSTRACT–Electric vehicles are effective way to solve energy and environmental problems, but the promotion and application of electric vehicles are suppressed by their limited endurance range seriously. The regenerative braking technology is an important method to increase the endurance range of the electric vehicle. During the braking process, the kinetic energy of the electric vehicle can be converted into electric energy and stored in the energy source device with the regenerative braking system, so the endurance range of the electric vehicle can be increased accordingly. In order to increase the efficiency of energy recovery, a regenerative braking strategy with the optimization distribution algorithm is proposed in this paper, and the braking forces of the front and rear axles are distributed optimally with variable ratios based on the braking strength. With the optimal braking force distribution ratio and related constraint conditions, the regenerative braking control strategy was designed to meet the braking stability and the maximum braking energy recovery. And then a simulation model of the braking control strategy was built with MATLAB/Simulink software, and the simulation tests on UDDS and NEDC cycle conditions were done to verify the effectiveness of the designed regenerative braking control strategy. Compared with the control strategy of ADVISOR software, the braking energy recovery efficiency was improved more than 51.9 % while maintaining the braking stability.

Key words : Braking strength, Braking force distribution, Regenerative braking, Energy recovery

1. INTRODUCTION

Facing the energy crisis and environmental pollution problems, electric vehicles have become the development trend of modern vehicle technology gradually (Zhou *et al*., 2013; Holmberg *et al*., 2014). However, the short endurance mileage affects the large-scale popularization and application seriously. Therefore, it is the urgent problem to increase the endurance mileage in the future development of electric vehicles. The regenerative braking technology is a useful method to prolong the driving range of the electric vehicles. With the regenerative braking system, the kinetic energy of the vehicle can be converted into electric energy and stored in the energy source device during the braking process, so the endurance mileage of the electric vehicle can be increased accordingly (Oleksowicz *et al*.,2013; Chu *et al*., 2014). Zhang and Yang (2010) gives the statistics data from the American Electric Power Research Institute on the actual operation of electric vehicles in some cities in the United States. The data shows that the regenerative braking technology can increase the driving range by 10 % to 20 % when the electric vehicle stops and starts in urban road traffic conditions frequently. Therefore, the regenerative braking technology has great significance for improving energy efficiency and increasing mileage.

In present, the research is focused mainly on the control strategy and recovery efficiency with simulation and test (Guo *et al*., 2011). Li *et al*. (2005) proposed a strategy for the distribution of braking forces according to the ECE regulation line and the fold lines, which are composed of the front and rear ground braking force relationship lines and the abscissa when the front wheel is locked. It can meet the requirements of the brake regulations and maximization of the recovery energy, but it will reduce the braking stability and braking efficiency inevitably due to the fold lines deviate from the ideal curve. Guo *et al*. (2008) proposed a method to maximize the regenerative braking force. When the maximum regenerative braking force of the motor is sufficient to meet the braking force demand of the driving wheel, the driving wheel only uses regenerative braking. When the braking force demand of the driving wheel exceeds the maximum braking force of the motor, the friction braking force is also required to supplement the rest part of the braking force besides the regenerative braking force. For the braking forces on the front and rear axles are distributed according to the ideal curve, the braking force of the motor cannot be used fully, so the energy recovery

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may be not maximized. Li *et al*. (2007) proposed a distribution and control law of the regenerative braking force and hydraulic braking force, but the constraints of various factors on energy recovery are not considered. Gao *et al*. (2001) gave an ideal distribution strategy and an optimal energy recovery strategy, but the adhesion of the front wheels cannot be utilized fully. Kim *et al*. (2011) and Ko *et al*. (2014) proposed a fuzzy control strategy to distribute the regenerative braking force and the hydraulic braking force. Mutoh *et al*. (2007) proposed an ABS-based braking force distribution strategy to prevent rear wheel locking. Tjonnas and Johansen (2010) considered the change of the front and rear wheel load condition and realized an optimal braking force distribution by controlling the longitudinal slip ratio of each tires. In addition, the method improved the braking stability of the vehicle effectively. Based on the continuity of the regenerative braking strength of electric vehicles, Lian *et al*. (2013) proposed a new braking force distribution strategy. With the characteristics of the hydraulic proportional control valve, the proportional function of the braking force distribution curve was optimized by the objective function. Based on the fuzzy control algorithm, Seki *et al*. (2009) proposed a regenerative control strategy to realize the coordinated control of regenerative braking and hydraulic braking of hybrid vehicles. Ye *et al*. (2008) proposed a strategy based on maximum brake recovery control. Lee and Nelson (2005) studied the influence of vehicle inertia on regenerative braking and verified that the braking energy recovery rate can increase 8 ~ 13 % by reducing the inertia of the rotating parts.

The aim of the regeneration control strategy of the electric vehicle is to ensure the recovery of braking energy as much as possible on the basis of ensuring the braking stability (He *et al*., 2012). However, in these studies, the influence of the braking strength and load variation on the front and rear axles is not considered, and therefore, under these conditions, it is difficult to achieve the braking stability of the electric vehicle with the traditional methods.

In order to solve this problem, the braking force variable ratio optimization distribution algorithm is proposed in this paper. At the same time, considering the constraints of motor characteristics and power battery characteristics on braking energy recovery, a regenerative braking control strategy for re-distribution of front axle braking force was designed. With the combination of experimental data and mathematical model, the simulation model of control strategy was built in the Matlab/Simulink environment. At the same time, the simulation tests were carried out under the two typical urban cycle conditions of UDDS and NEDC. The simulation results show that the regenerative braking control strategy proposed in this paper is effective and it can realize the energy recycling better.

In the following, the braking force optimization distribution algorithm with variable ratios is proposed firstly, and the influence of battery and motor characteristics on the regenerative braking process is analyzed secondly, and the relevant constraints of regenerative braking on electric vehicles are determined thirdly, then the re-distribution of the braking force of the front wheel and the regenerative braking energy recovery control strategy is designed fourthly, and the simulation models and test results are analyzed and discussed finally.

2. OPTIMAL BRAKING FORCE DISTRIBUTION ALGORITHM

During the vehicle braking process, the braking stability is demand. In order to ensure the braking stability, ECE braking regulation is used widely. In the following, the ECE braking regulation is introduced firstly, and then the optimal braking distribution algorithm is designed and analyzed.

2.1. ECE Braking Regulation

ECE braking regulation is the international standard for automotive brake systems, and it gives unified regulations on the braking systems of M, N and O vehicles. In order to ensure the stability of the driving direction and the good braking performance, the regulation has made relevant requirements on the braking force distribution range of the front and rear axles. For the passenger car, the braking force distribution requirements are as follows (Fu *et al*., 2014):

(a) For the biaxial vehicle with φ 0.2 ~ 0.8, in which φ is the adhesion coefficient between the tire and road surface, the braking strength meets the condition $z \geq 0.1 + 0.85(\varphi - 0.2)$;

(b) When the braking strength z is between 0.15 and 0.8, with various load conditions, the utilization adhesion coefficient curve of the front axle should be located above that of the rear axle;

(c) When the braking strength z is between 0.3 and 0.45, and the utilization adhesion coefficient curve of the rear axle does not exceed the straight line determined by the formula $\varphi = z + 0.05$, the utilization adhesion coefficient curve of the rear axle is allowed to be located above that of the front axle.

In the above distribution requirements for passenger car, (a) is the mandatory regulatory standard for the vehicle braking distance, and (b) and (c) are both braking stability standards. According to the above mandatory brake standard requirements, the following mathematical inequalities can be obtained.

When $0.1 \leq z \leq 0.61$, the inequality that meets the braking distance requirement is obtained as:

$$\begin{cases} \varphi_f \leq \dfrac{z + 0.07}{0.85} \\ \varphi_r \leq \dfrac{z + 0.07}{0.85} \end{cases} \tag{1}$$

When $0.15 \leq z \leq 0.8$, the inequality that meets the requirements of braking stability is obtained as:

$$\varphi_f \geq \varphi_r \tag{2}$$

With inequalities (1) and (2), the range of the braking force distribution coefficient β that satisfies the braking regulation can be obtained as:

$$\begin{cases} \beta \leq \dfrac{z^2 h_g + z(l_r + 0.07h_g) + 0.07l_r}{0.85zl} & 0.1 \leq z \leq 0.61 \\ \beta \geq \dfrac{-z^2 h_g + z(l_r - 0.07h_g) + 0.07l_r}{0.85zl} & 0.1 \leq z \leq 0.61 \\ \beta \geq \dfrac{zh_g + l_r}{l} & 0.15 \leq z \leq 0.8 \end{cases} \tag{3}$$

Where z is the brake strength; l_r is the distance between the center of gravity and the rear axle (m); l is the distance between the front and rear axles (m); h_g is the height of the vehicle center of gravity (m).

When the actual vehicle braking force distribution coefficient β satisfies the inequalities (3), the vehicle may meet the requirements of the braking direction stability.

2.2. Optimization Distribution Algorithm with Braking Force Variable Ratio

With different braking strengths, under no-load and full-load conditions, the braking force distribution should be optimized to ensure the braking stability and improve the safety of the brake system. An optimization distribution algorithm is designed by considering the minimum value of the sum of the squares of the differences between the utilization adhesion coefficient and the braking strength of the front and rear axles. Then the objective function of optimization distribution algorithm with braking force variable ratios can be obtained as follows:

$$F = \min[(\varphi_{fn} - z)^2 + (\varphi_{rn} - z)^2 + (\varphi_{ff} - z)^2 + (\varphi_{rf} - z)^2] \tag{4}$$

Where z is selected with 0.2, 0.3, 0.4, 0.5, 0.6, 0.7,0.8 respectively; φ_{fn} is the utilization adhesion coefficient of front axle under no-load condition; φ_{rn} is the utilization adhesion coefficient of rear axle under no-load condition;

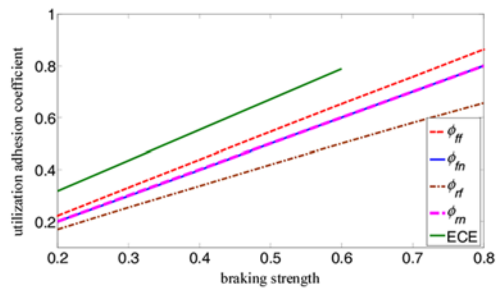

Figure 1. The relationship between the utilization adhesion coefficients and the braking strengths of the front and rear axles.

φ_{ff} is the utilization adhesion coefficient of front axle under full-load condition; φ_{rf} is the utilization adhesion coefficient of rear axle under full-load condition.

In this paper, the M1 electric vehicle is selected and the relevant parameters can be obtained from the dSPACE ASM model. The main vehicle parameters are shown in Table 1.

In the following, the optimization distribution algorithm with variable ratio at different braking strength is expounded.

(a) With the vehicle parameters under full-load and no-load conditions and the corresponding braking strength z values, the corresponding constraints are obtained from inequality (3) respectively for the braking force variable ratio optimization distribution algorithm.

(b) According to the objective function of the optimization distribution algorithm in equation (4) and the corresponding constraints obtained in (a), the mathematical model of the braking force optimization distribution coefficient β can be established.

(c) Using the nonlinear constraint optimization fmincon() function in the optimization toolbox, the optimal distribution coefficient β can be solved with the model in (b).

The optimization results are shown in Table 2.

According to the optimized braking force distribution coefficient in Table 2, the relationship between the utilization adhesion coefficient curve and the braking strength of the front and rear axles of the vehicle under no-load and full-load conditions can be established, as shown in Figure 1.

It can be seen from Figure 1 that the utilization adhesion coefficient curves of the vehicle under no-load and full-load

Table 1. Main parameters of the M1 electric vehicle model.

Load condition	Mass m (kg)	h_g (m)	l_f (m)	l_r (m)	l (m)
No-load	1418	0.510	1.064	1.596	2.66
Full-load	1739	0.553	1.239	1.421	2.66

Table 2. The optimized β value corresponding to different braking strengths z.

braking strengths z	0.2	0.3	0.4	0.5	0.6	0.7	0.8
The optimized β value	0.6383	0.6575	0.6767	0.6959	0.7150	0.7342	0.7534

conditions both meet the mandatory braking standards of the ECE regulation, which guarantees the braking direction stability requirements of the vehicle during the braking process.

3. REGENERATIVE BRAKING CONSTRAINT CONDITIONS

During the braking process, the regenerative braking force is restricted by the braking force distribution requirements of the front and rear axles brakes, motor characteristics and battery characteristics. The detailed constraint conditions are analyzed in the following.

3.1. Front and Rear Axles' Braking Force Distribution Requirements

The braking force distribution ratio of the front and rear axles is a very important design parameter to improve the braking performance of the vehicle, and it affects the braking stability, the braking efficiency, and the use of the road adhesion conditions significantly. In this paper, the above-mentioned optimization distribution algorithm with braking force variable ratio is used to perform the front and rear axles' braking force distribution.

During the deceleration braking process, according to the brake awareness, the driver depresses the brake pedal to obtain the desired braking strength (Wang *et al*., 2009). In order to simplify the analysis, this paper only considers the horizontal road condition and assumes that the vehicle mass is known. Based on the definition of the braking strength, the desired braking force can be obtained as follows:

$$F_b = mgz \tag{5}$$

Where m is vehicle mass (kg); z is braking strength; g is gravity acceleration (N/kg).

According to the above-mentioned optimization distribution algorithm with braking force variable ratio, the front and rear axles' braking forces can be distributed as follows:

$$\begin{cases} F_{xb1} = \beta F_b = \beta mgz \\ F_{xb2} = (1-\beta)F_b = (1-\beta)mgz \end{cases} \tag{6}$$

3.2. Motor Characteristics

As an energy conversion device in a regenerative braking system, the motor is one of the main factors that affect energy recovery. The regenerative braking torque that the motor can provide is influenced by factors such as motor torque-speed characteristics and the vehicle speed. When the electric vehicle brakes, according to the relationship between the instantaneous speed of the vehicle and the speed u_a of the motor, the instantaneous speed n of the motor during the braking process can be obtained as follows:

$$n = \frac{u_a i_g i_o}{0.377 \cdot r \cdot \eta_T} \tag{7}$$

Where i_o is the main reducer transmission ratio; i_g is the transmission ratio; r is the wheel radius; η_T is the mechanical transmission efficiency, and 0.9 is used in this paper.

The motor operates in the generator state during the regenerative braking process, and its torque output characteristics are almost same as that in the motor state, so the maximum braking torque $T_{ere_{\max}}$ of the motor can be obtained as:

$$T_{ere_{\max}} = \begin{cases} \dfrac{9549P_e}{n_n} & n \le n_n \\ T_e & n \ge n_n \end{cases} \tag{8}$$

Where P_e is motor rated power (kW); T_e is motor rated torque (N·m); n_n is motor rated speed (r/min).

According to the relationship among power, torque and speed, the maximum power $P_{ere_{\max}}$ of the regenerative brake of the motor is obtained as:

$$P_{ere_{\max}} = \frac{T_{ere_{\max}} \cdot n}{9549} \tag{9}$$

In addition, it is considered that the motor cannot convert all regenerative braking energy into electrical energy. And during the charging process of the battery, all the regenerative energy cannot be charged into the battery due to the loss, so the maximum generation power $P_{ere_{chg_{\max}}}$ can be considered as:

$$P_{ere_{\mathrm{chg}}} = P_{ere_{\max}} \cdot \eta_{ere} \tag{10}$$

Where η_{ere} is the regenerative braking power generation efficiency, which is obtained by considering the motor power generation efficiency and the battery charging efficiency comprehensively. However, in practical applications, in order to protect the battery, the battery charging power should be limited when the battery State of Charge (SOC) is high. If the motor charges too much power to the battery during the regenerative braking process, it will not only damage the battery, but also may even bring accidental danger to the passengers on the electric vehicle. Therefore, under the condition that the maximum charging power $P_{ere_{\max}}$ of the battery is known, the maximum generating power should be corrected. The corrected maximum regenerative braking power $P_{ere_{\max}}$ is as follows:

$$P_{ere_{\max}} = \min\left\{P_{ere_{chg_{\max}}}, P_{\mathrm{chg}}\right\} \tag{11}$$

With equations (8) ~ (11), the actual maximum torque $T_{ere_{\max}}$ of the motor at a certain rotation speed can be obtained as:

$$T_{ere_{\max}} = \frac{9549P_{ere_{\max}}}{n \cdot \eta_{ere}} \tag{12}$$

Considering the motor power and torque variation characteristics during the regenerative braking process, as well as the motor power generation efficiency and battery charging performance in practical applications, the maximum braking torque of the motor at any speed can be obtained as:

$$T_{emax} = \begin{cases} \min\left\{\dfrac{9549P_{ere_{max}}}{n \cdot \eta_{ere}}, \dfrac{9549P_e}{n}\right\} & n \le n_n \\ \min\left\{\dfrac{9549P_{ere_{max}}}{n \cdot \eta_{ere}}, T_e\right\} & n \ge n_n \end{cases} \tag{13}$$

In addition, when the vehicle brakes at a low speed, the kinetic energy of the electric vehicle is insufficient, and the motor speed is lower, and the motor drive reverse electromotive force is lower, so the regenerative braking capability is reduced. In order to ensure the safety during the braking process, when the motor speed drops to 500 r/min, the regenerative braking force that the motor can provide is set to 0, so the regenerative braking torque calculation model can be designed as:

$$T_{reg} = \lambda(n) T_{emax} \tag{14}$$

Where $\lambda(n)$ is the correction factor related to the motor speed, which is described as:

$$\lambda(n) = \begin{cases} 0 & n \le 500r/min \\ 1 & n \ge 500r/min \end{cases} \tag{15}$$

From the above analysis, the maximum regenerative braking force provided by the motor is:

$$F_{reg} = \frac{T_{reg} \cdot i_o \cdot i_g \cdot \eta_T}{r} \tag{16}$$

3.3. Battery Characteristics

The battery is not only the energy source of the electric vehicle but also the energy storage element in the regenerative braking system. According to relevant research, it is found that the electromotive force and the internal resistance of the battery will both change with the SOC variation. Therefore, the battery charge-discharge efficiency also changes. In order to reflect the changes of the recovered energy more accurately during the regenerative braking process, an experimental study of the charge and discharge characteristics of the power battery is required. A series of charge and discharge experiments were performed on the 38.4 V/40 Ah lithium battery through the ARBIN power battery test system. With the measured charging and discharging data, the fitting tool in Matlab software was used to establish the correspondence fitting function between the open circuit voltage and the SOC curve as follows:

$$\begin{aligned} OVC_{SOC} = & -471.85SOC^8 + 3206.9SOC^7 - 8285.0SOC^6 \\ & + 10982SOC^5 - 263.8SOC^4 + 3633.5SOC^3 \\ & - 920.13SOC^2 + 127.6SOC + 31.022 \end{aligned} \tag{17}$$

The battery charge efficiency can be obtained by fitting method as:

$$\begin{aligned} \eta_c = & \ 0.1663SOC^2 - 0.0015I^2 - 0.4507SOC \\ & - 0.0516I + 0.0231I \cdot SOC + 99.6597 \end{aligned} \tag{18}$$

The battery discharge efficiency can be obtained by fitting method as:

$$\begin{aligned} \eta_d = & -0.3223SOC^2 - 0.0014I^2 + 0.1797SOC \\ & - 0.0574I + 0.0228I \cdot SOC + 99.4267 \end{aligned} \tag{19}$$

4. REGENERATIVE BRAKING CONTROL STRATEGY

With the optimal braking force distribution ratio and related constraint conditions, the regenerative braking control strategy can be designed to meet the braking stability and the maximum braking energy recovery. Due to the complex relationship between the braking stability and the braking energy recovery of electric vehicles, two issues should be considered when designing the control strategy. First, how to determine the braking force distribution ratio on the front and rear axles to achieve the vehicle braking stability and safety. Second, how to distribute the ratio of the regenerative braking force and the mechanical braking force on the drive shaft to achieve maximum recovery braking energy. Therefore, it is an effective way to improve energy recovery by increasing the proportion of the motor's regenerative braking force distribution on the drive shaft. In order to maximize the recovered energy, the front axle braking force is re-distributed based on the above-mentioned optimization algorithm. If the motor braking force can meet the demand braking force of the front axle, only the motor braking force is used, and the mechanical braking force is not used. If the motor braking force cannot satisfy the front axle's demand braking force, the mechanical braking force is added to make up for the shortage part of the braking force besides the regenerative braking force. In addition, the SOC of the power battery should be considered. If the battery SOC is too high, it is not suitable for charging the battery. Therefore, SOC = 0.95 is taken as the maximum value for starting regenerative braking energy recovery. Based on the analysis above, the braking force distribution control strategy can be designed as shown in Figure 2.

The specific steps are as follows:

(1) According to the current vehicle speed and the brake pedal position, the current total demand braking force F_b is determined;

(2) The braking force distribution coefficient is determined under vehicle braking stability conditions. The current corresponding braking force distribution coefficient β can be obtained by the optimization distribution algorithm with braking force variable ratio, and then the braking forces of the front and rear axles F_{xb1}, F_{xb2} are distributed firstly.

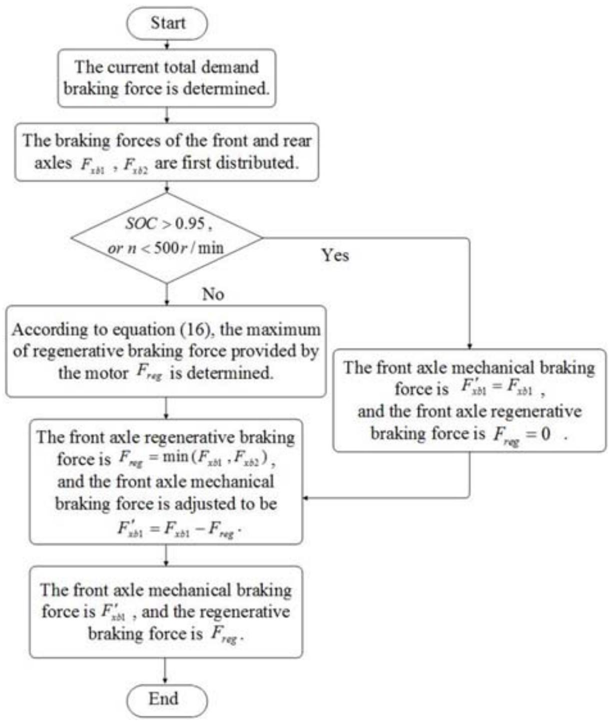

Figure 2. Regenerative braking control strategy flow chart.

(3) If the current battery SOC exceeds the charging threshold 0.95 or the current wheel speed n is below the set speed 500r/min, the regenerative braking is not activated. The total demand braking force is provided by the front and rear axles' mechanical braking force. The front axle mechanical braking force is $F'_{xb1} = F_{xb1}$, and the rear axle mechanical braking force is F_{xb2}.

(4) If the conditions in step (3) are not met, the regenerative braking is allowed, and the front axle's braking force must be re-distributed. The maximum regenerative braking force F_{reg} provided by the motor is calculated with equation (16). Then, considering the constraints of the motor characteristics, the regenerative braking force provided by the front axle is determined as $F_{reg} = \min(F_{xb1}, F_{reg})$, and the front axle mechanical braking force is adjusted to be $F'_{xb1} = F_{xb1} - F_{reg}$.

5. SIMULATION

In order to verify the validity of the designed regenerative braking control strategy, a regenerative braking model was built based on the optimization distribution algorithm with braking force variable ratio, and then the model is used to modify the <VC> control strategy in the ADVISOR 2002 pure electric vehicle model, and the simulation was done under the CYC_UDDS and CYC_NEDC urban road cycle conditions. CYC_UDDS and CYC_NEDC urban road cycle conditions are accepted internationally to simulate the changes of the vehicle speed and the braking process in urban and suburban traffic conditions.

The modified simulation model is shown in Figure 3, and it can calculate the mechanical braking force of the front and rear wheels according to the demand of the braking strength of the driving condition.

By embedded in the ADVISOR 2002 simulation environment, the simulation tests under the CYC_UDDS

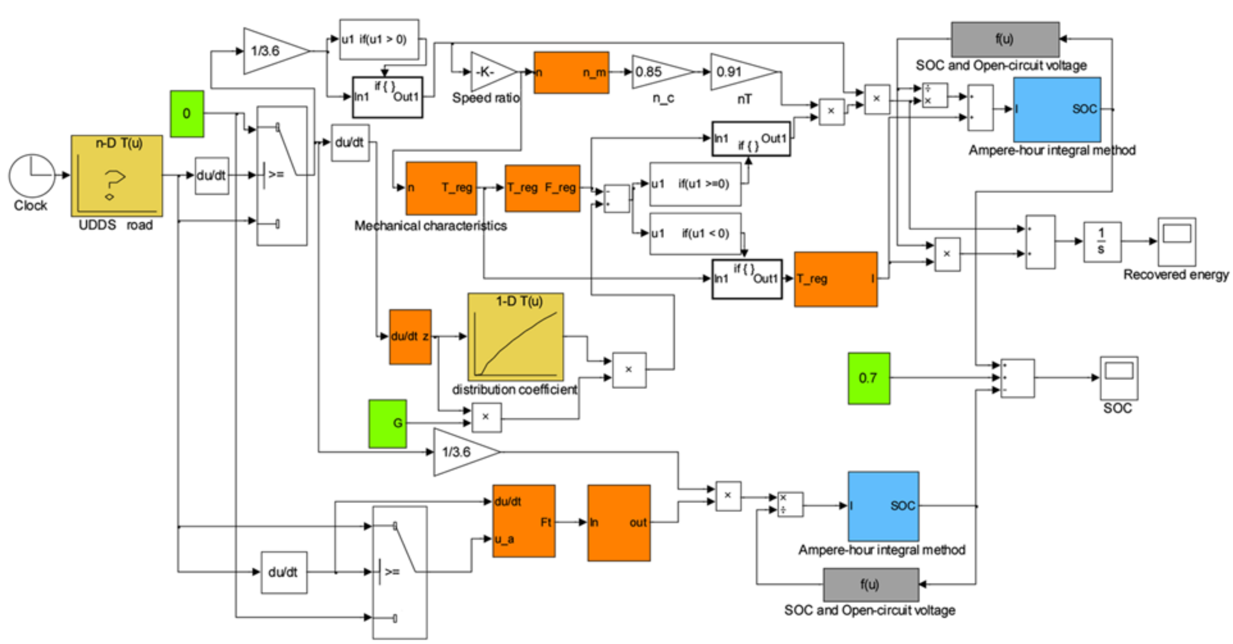

Figure 3. Simulation model of the braking force distribution system.

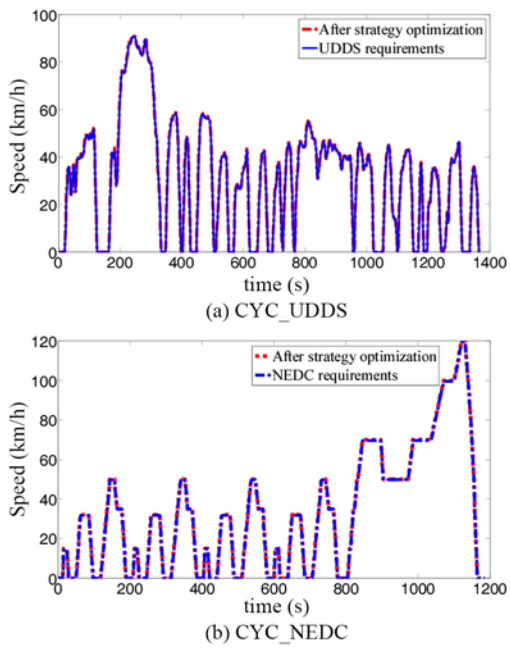

Figure 4. Speed change curve.

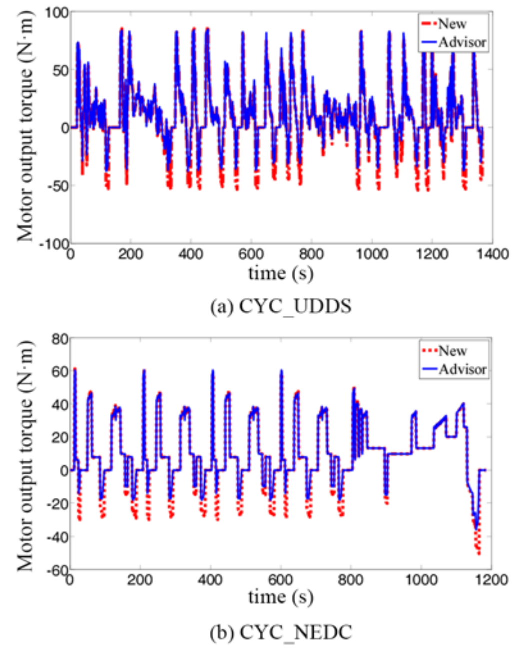

Figure 5. Motor torque simulation curve.

and CYC_NEDC urban road cycle conditions were done to verify the validity of the regenerative braking control strategy. The simulation results are as follows:

Figure 4 gives the comparison results of the simulated vehicle speed and the required speed under CYC_UDDS and CYC_NEDC urban road cycle conditions. It can be seen that the two curves are consistent, so the vehicle with the designed control strategy can complete the whole simulation process according to the real-time vehicle speed requirements of the simulation working conditions.

Figure 5 gives the motor torque variations with the designed regenerative braking control strategy and ADVISOR control strategy under the CYC_UDDS and CYC_NEDC conditions respectively. It can be seen that the positive motor torque output is coincident for the same driving force is determined with the same driving strategy during the driving process. During the vehicle braking process, two different strategies are used. The first is the designed regenerative braking strategy in this paper, which is called new strategy, and the second is the strategy in the ADVISOR software, which is called as advisor strategy. In the two conditions, the negative motor torque output generated with the new strategy is larger than that generated with the advisor strategy, which may be caused by the maximum motor's regenerative braking force with the new strategy. Therefore, with the new strategy, the proportion of the motor braking torque increases and the braking energy recovery increases accordingly.

Figure 6 gives the simulation curves of the battery SOC with the two strategies. From the simulation results, it can

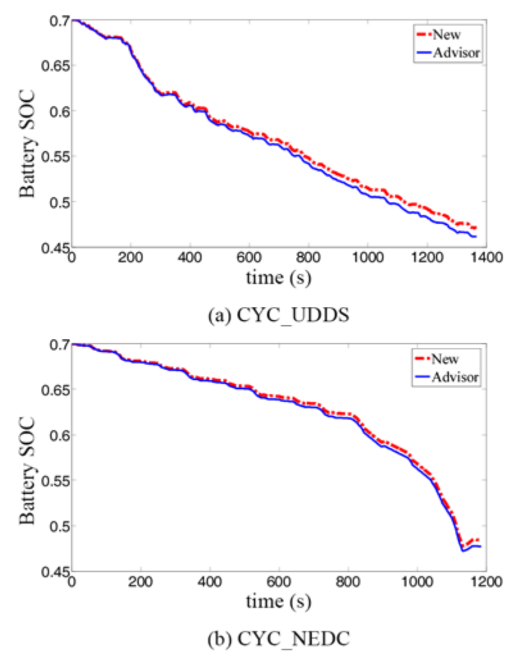

Figure 6. Battery SOC simulation curve.

be seen that the battery SOC is in a state of continuous decline from the initial value 0.7, but there are many small fluctuations due to the impact of regenerative braking energy recovery. The small fluctuations also show that the battery is indeed in the charging and discharging process frequently under cyclic dynamic conditions indirectly. In addition, the braking strategy designed in this paper makes

Table 3. Energy recovery comparison.

	UDDS			NEDC		
	ADVISOR strategy	NEW strategy	Optimization effect/%	ADVISOR strategy	NEW strategy	Optimization effect/%
Total braking energy/kJ	1697	1655	2.47	1027	1011	1.56
Recovered energy/kJ	565	878	55.4	374	559	49.47
Brake energy recovery efficiency/%	33.3	53.1	59.46	36.4	55.3	51.9
Remaining SOC	0.4615	0.4714	2.15	0.4771	0.4843	1.51

the battery SOC decline slower for it can recover more braking energy.

The effect of the regenerative braking energy recovery is shown in Table 3. The results show that the new strategy designed in this paper improves the energy recovery efficiency of ADVISOR, and demonstrates the advantages of the regenerative braking control strategy in braking energy recovery.

Under CYC_UDDS cycle conditions, the braking energy recovery efficient of the advisor strategy is 33.3 %, however, the efficient of the new strategy increases to 53.1 %, and the optimization effect is 59.46 %. In addition, the remaining SOC is increased from 0.4615 to 0.4714. Under CYC_NEDC cycle conditions, the energy recovery efficient of the advisor strategy is 36.4 %, however, the efficient of the new strategy increases to 55.3 %, and the optimization effect is 51.9 %. In addition, the remaining SOC is increased from 0.4771 to 0.4843. With the simulation analysis, it can be seen that the new strategy designed in this paper can optimize the braking force distribution, and reduce the braking energy consumption, and increase the energy recovery and reduce the battery energy consumption, and the braking energy recovery efficiency is improved more than 51.9 %, so it has great value for extending the endurance mileage of electric vehicles.

6. CONCLUSIONS

Regenerative braking technology is regarded as a key energy-saving technology for electric vehicles. Aiming at the problem of low energy recovery rate and poor braking performance of ADVISOR original strategy, the optimization braking force distribution algorithm with braking force variable ratios is proposed in this paper. For the braking force distribution ratio is optimized at the various braking strength, the directional stability of the vehicle is improved effectively. At the same time, considering the influencing factors of the regenerative braking, the energy recovery control strategy is studied. Under the premise of satisfying the braking directional stability, a regenerative braking control strategy is proposed for re-distribution of the front axle braking force of electric vehicles based on the motor and battery characteristics.

The simulation model of the control strategy is designed and embedded in the ADVISOR simulation environment, and the simulation tests were done under the typical international CYC_UDDS and CYC_NEDC cycle conditions. The results show that the regenerative braking control strategy proposed in this paper can recover more braking energy under the premise of ensuring the safety and stability of the vehicle, and the braking energy recovery efficiency increases from 33.3 % to 53.1 % under CYC_UDDS conditions, and it increases from 36.4 % to 55.3 % under CYC_NEDC conditions. So the designed regenerative braking control strategy has practical significance for electric vehicles to increase driving range and economic efficiency.

However, the road slope is not considered in this paper, and the braking process is assumed on the horizontal road. In addition, the proposed regenerative braking control strategy is only tested under the ADVISOR software simulation environment. Therefore, the real electric vehicle test on the road will be the future work direction to verify the actual performance of the control strategy. Furthermore, considering the influence of the road slope, to extend the application range of the braking force distribution strategy and the regenerative braking control strategy to the slope road will also the working direction in the future.

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