Simulation Study on Regenerative Braking System of Pure Electric Vehicle with Compound Power Supply

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Abstract. In order to enhance the recovery rate of regenerative braking energy on the premise of ensuring braking safety and stability, an improved braking force distribution scheme for front and rear wheels is proposed in combination with ECE regulations, ideal braking force distribution curve (I) and f lines. Meanwhile, a kind of fuzzy controller is designed, which takes the braking strength, vehicle speed and super-capacitor SOC as input and the ratio of regenerative braking force to total braking force of front wheels as output. The forward and backward simulation module is established in MATLAB and embedded into ADVISOR. In addition, combined with the secondary development of the top layer model of the compound power supply for pure electric vehicle to complete simulation and analysis under the CYC_UDDS driving cycle condition. The results show that the regenerative braking control strategy can improve the recovery rate of braking energy and increase the driving mileage of pure electric vehicle.

1. Introduction

With the increasingly serious problems of ecological environment and energy, pure electric vehicle with the advantages of energy conservation and environmental protection have attracted more and more attention from scholars in related fields at home and abroad. At present, the technology of on-board power supply for pure electric vehicle is not yet matured, trace to its source, these difficulties of insufficient power and short driving distance limit its popularity\cite{1}. Super-capacitor is a kind of physical secondary power supply with super discharge ability and strong pulse power developed with the emergence of new electrode materials in recent years\cite{2}, which has the characteristics of high specific power, fast charging and discharging, long cycling life and so on. Combining it with battery to form a compound vehicle power supply can enhance the power performance and endurance of pure electric vehicle. Similarly, the regenerative braking technology is the main way to save energy and reduce consumption and it is a unique technology for pure electric vehicle. Its function is to convert part of mechanical energy of pure electric vehicle braking into electric energy stored in battery or super-capacitor through regenerative braking system on the premise of ensuring the driving stability\cite{3}. Therefore, regenerative braking plays a significant role in reducing energy consumption, extending driving distance and improving economic performance of pure electric vehicle. In conclusion, combining compound power supply technology with regenerative braking technology can further enhance the driving mileage of pure electric vehicle. On the basis of the simulation model of power distribution control strategy of compound power supply, for the sake of ensuring the braking stability and safety of automobiles and maximize the recovery of braking energy, it is necessary to formulate a reasonable regenerative braking control strategy to solve the problem of braking force distribution.
between front and rear wheels, and to coordinate the relationship between regenerative braking and mechanical braking on driving wheels[4-5]. In reference[6], a hybrid braking force distribution strategy for pure electric vehicle based on fuzzy control is proposed, which combined the ideal braking force distribution curve with fuzzy control. However, this strategy ignored the influence of vehicle speed and didn’t consider the different distribution of braking force between front and rear wheels under the different braking strength. Therefore, it couldn’t improve the recovery of braking energy. In reference[7], considered the influence of vehicle speed on regenerative braking system, and established the braking force distribution curve determined by ECE regulations, ideal braking force distribution curve (I) and f lines. But the minimum braking force distribution of rear wheels when front wheels are locked is not considered. Although this strategy can improve the braking energy recovery, it cannot guarantee the stability and safety when PEV braking. In reference[8], the ideal braking force distribution curve (I) is combined with ECE regulations, and verified its effectiveness by designing different braking control strategies. Due to it hasn’t analyzed the impact of braking strength, vehicle speed and battery SOC on the whole braking system, so it is different to maximum the recovery of braking energy when PEV braking.

Based on this, selecting a precursor pure electric vehicle and studied the distribution problem of front wheels braking force in braking process. An improved distribution scheme of front and rear wheels braking force it put forward in combination with ECE regulations, ideal braking force distribution curve (I) and f lines. Meanwhile, devised a fuzzy controller with braking strength, vehicle speed and super-capacitor SOC as input and the ratio of regenerative braking force to total front wheels braking force as output. The forward and backward simulation module is built in MATLAB/SIMULINK software and embedded it in ADVISOR2002. Ultimately, combined with the secondary development of the top layer model of the compound power supply for pure electric vehicle to complete simulation and analysis under the CYC_UDDS driving cycle condition.

2. Regenerative braking force distribution system

Taking a precursor pure electric vehicle as the research object, an improved braking force distribution scheme for front and rear wheels is proposed by combining with ECE regulations, ideal braking force distribution curve (I) and f lines.

Figure 1 shows the braking force distribution curve, the braking force of front and rear wheels is distributed in accordance with the line segment OA-BC-CD-DE-EF. Among them, OP is the front and rear wheels braking force curve when the dynamic distribution coefficient \( \beta \) is at the minimum value of 0.75. OQ is the front and rear wheels braking force curve when the dynamic distribution coefficient \( \beta \) is at the maximum value of 0.93. Point A represents the braking strength \( z \) is 0.1, and the total braking force provided by the front wheels when the rear wheels braking force is zero. Points B is the intersection of line segment OQ and the braking strength \( z \) is 1. Point C is the intersection of line segment OQ and the f line is 0.7. Point D is the intersection of line segment OP and the f line is 0.7. Point E is the intersection of line segment OP and ideal braking force distribution curve (I).
In conclusion, the braking strength $z$ at the point C is 0.528; the braking strength $z$ at the point D is 0.68; the braking strength $z$ at the point E is 0.79. The improved braking force distribution scheme for front and rear wheels is formulated as follows.

1. $z<0.1$, it belongs to mild braking, the braking force of front and rear wheels are distributed in accordance with the line segment OA, and the braking force needed is small relatively. Under the premise of moderate vehicle speed and SOC permission of super-capacitor, the regenerative braking can be provided by motor completely.

2. $0.1<z \leq 0.528$, it belongs to moderate braking, the braking force of front and rear wheels are distributed in accordance with the line segment BC, and which is provide by mechanical friction braking and motor regenerative braking. Namely, on the basis of ensuring safety and stability when pure electric vehicle braking, the motor braking is adopted as far as possible in front wheels to achieve greater braking energy recovery.

3. $0.528<z \leq 0.68$, it belongs to severe braking, it is required to strengthen the proportion of rear wheels braking force. Meanwhile, the braking force of front and rear wheels are distributed in accordance with the line segment CD, and the proportion of regenerative braking of front wheels decrease with the increase of braking strength $z$.

4. $z \geq 0.68$, it belongs to emergency braking in order to ensure braking safety and reducing distance, only consider mechanical braking; $0.68<z \leq 0.79$, for meeting minimum braking force distribution coefficient requirement of ECE regulations, the braking force of front and rear wheels are allocated according to line segment DE; $z \geq 0.79$, in order to ensure that both front and rear wheels are locked up simultaneously, the braking force distribution of front and rear wheels should follow the ideal distribution curve (I).

3. Regenerative braking control strategy
The braking force provided by the precursor pure electric vehicle must satisfy the braking requirement during compound braking, and the braking force should be as smooth as possible. So the front wheels friction braking force and motor regenerative braking force should be reasonably allocated to ensure the braking requirement and enhance the energy recovery efficiency. In order to coordinate the working mode of front wheels dual braking, factors such as braking strength, charging capacity of storage devices, vehicle speed, motor power generation efficiency and mechanical transmission efficiency should be taken into account to obtain the maximum regeneration braking force furnished by motor and the mechanical friction braking force required by brake[9]. In this paper, for adjusting the proportion of the two braking forces on the front wheels and coordinate the non-linear relationship among the influencing factors, design a fuzzy controller, and combine with the improved braking force distribution scheme of front and rear wheels. Then, a regenerative braking distribution control strategy based on fuzzy control is proposed.
As shown in Figure 2, which mainly consists of braking force distribution module, fuzzy controller module and braking force calculation module. Among, the braking force distribution module can calculate the total braking force of front wheels and the friction braking force of rear wheels in accordance with the braking force distribution scheme of front and rear wheels. The fuzzy controller module can calculate the ratio $K_z$ of regenerative braking force to total braking force of front wheels by fuzzy inference in accordance with the input signals of braking strength $z$, vehicle speed $V$ and super-capacitor SOC value $SOC_{uc}$. The braking force calculation module can combine the input data to calculate the braking force of motor and the mechanical friction braking force of front and rear wheels.

Through the fuzzy control toolbox provided by the software of MATLAB, designed a three input and signal output fuzzy controller for allocating the total braking force of front wheels. The input parameters are: braking strength $z$, whose universe is $[0,1]$, and its fuzzy subset is $\{L,M,H\}$, which symbolize $\{low,medium,high\}$ respectively; vehicle speed $V$, whose universe is $[0,60]$, and its fuzzy subset is $\{L,M,H\}$, which symbolize $\{low,medium,high\}$ respectively; super-capacitor SOC value $SOC_{uc}$, whose universe is $[0,1]$, and its fuzzy subset is $\{L,M,H\}$, which symbolize $\{low,medium,high\}$ respectively. The output parameter is the ratio $K_z$ of regenerative braking force to the total braking force of front wheels, whose universe is $[0,1]$, and its fuzzy subset is $\{VL,L,M,H,VH\}$, which symbolize $\{very low,low,medium,high,very high\}$ respectively.

When formulating the fuzzy rules of regenerative braking force, it is necessary to maximum the recovery of braking energy under the premise of ensuring the safety and stability of the pure electric vehicle. On the basis of the simulation test and theoretical analysis, formulating the fuzzy rules as shown in Table 1.

| $K_z$ | $V$ |
|------|------|
|      | $L$  | $M$ | $H$ |
| $(SOC_{uc}=H)$ | L    | VL  | L   | VL |
| $(SOC_{uc}=M)$ | M    | VL  | L   | VL |
| $(SOC_{uc}=L)$ | H    | VL  | VL  | VL |

4. Simulation test

4.1. Simulation parameters
The simulation parameters as shown in Table 2.

| Parameter name                        | Parameter value | Parameter name                        | Parameter value |
|---------------------------------------|-----------------|---------------------------------------|-----------------|
| Total mass of vehicle (m/kg)          | 1150            | Maximum torque (N·m)                  | 200             |
| Wheelbase (L/m)                       | 2.6             | Monomer capacity (Ah)                 | 90              |
| Height of mass center (hg/m)          | 0.5             | Monomer rated voltage (V)             | 12              |
| Distance from front axle to mass center (a/m) | 1.04          | Serial number                         | 26              |
| Distance from rear axle to mass center (b/m) | 1.56         | Monomer capacity (F)                  | 2500            |
| Wheel radius (r/m)                    | 0.27            | Monomer rated voltage (V)             | 2.5             |
| Peak power (kw)                       | 62              | Number of monomers in series          | 114             |

4.2. Establish model

According to the improved distribution scheme of the front and rear wheels braking force and the distribution strategy of front wheels braking force based on the fuzzy control. Under MATLAB software to establish the backward brake simulation model and forward brake simulation model. The backward brake simulation model is held essential with forward brake simulation model as a supplement, which respectively are as shown in Figure 3 and Figure 4.

4.3. Simulation analysis

The models mentioned above are embedded into the software of ADVOSOR2002, and establish the whole pure electric vehicle model. Meanwhile, the CYC_UDDS driving cycle condition is selected for simulation analysis to verify the effectiveness of the proposed strategy, and compared with the ADVISOR self-contained strategy. The CYC_UDDS driving cycle condition curve as shown in Figure 5.
Figure 5. The driving cycle condition of CYC_UDDS.

Figure 6. Motor torque variation curve under two strategy.

Figure 7. Super-capacitor SOC variation curve under two strategies.

Figure 8. Battery SOC variation curve under two strategies.

From showing in Figure 6, when the motor output torque is greater than zero, the motor torque under the two strategies is basically the same, which is determined by the motor positive torque cycle condition and the vehicle itself, and has nothing to do with regenerative braking control strategy. When the motor output torque is negative, the motor torque curve of the proposed control strategy is mostly under the ADVISOR self-contained control strategy. The results shows that the proposed control strategy enlarges the braking force ratio of the motor and can obtain more braking energy.

Figure 7 shows that the SOC curve of the super-capacitor under the proposed control strategy is above the ADVISOR self-contained control strategy. The results demonstrated that the proposed regenerative braking control strategy enhances the efficiency of braking recovery and recovers more energy during frequent braking conditions.

Figure 8 shows that the SOC value of the battery under the proposed control strategy is significantly larger than that the ADVISOR self-contained control strategy. The results indicated that the proposed control strategy can further slow down the energy consumption speed and prolong the working life of the battery.

Table 3. Simulation results are compared under the two strategies.

|                           | ADVISOR self-contained | Proposed in this paper | Improvement percentage (%) |
|---------------------------|------------------------|-------------------------|----------------------------|
| Motor energy loss (KJ)    | 1774.1                 | 1685.6                  | 4.99%                      |
| Super-capacitor SOC       | 0.7313                 | 0.9857                  | 34.78%                     |
| Battery SOC               | 0.843                  | 0.847                   | 0.47%                      |
Table 3 shows the comparison of driving mileage, super-capacitor SOC, battery SOC and motor energy loss for pure electric vehicle controlled by different strategies under CYC_UDDS driving cycle condition.

5. Conclusion

(1) For the sake of enhancing the recovery rate of regenerative braking energy on the premise of ensuring braking safety and stability, an improved braking force distribution scheme for front and rear wheels is proposed in combination with ECE regulations, ideal braking force distribution curve (I) and f lines. Meanwhile, a kind of fuzzy controller is designed, which takes braking strength, vehicle speed and super-capacitor SOC as input and the ratio of regenerative braking force to total braking force of front wheels as output.

(2) Under the condition of CYC_UDDS driving cycle, utilizing the regenerative braking control strategy brought forward above to simulate and analyze. The results shows that compared with ADVISOR self-contained control strategy, the motor energy loss has improved by 4.99%, super-capacitor SOC value has enhanced by 34.78%, the battery SOC value has improved by 0.47% and the driving mileage has enhanced by 8.66%, which verifies the effectiveness of this control strategy.

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