CHEMICAL ENGINEERING TRANSACTIONS

VOL. 66, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Songying Zhao, Yougang Sun, Ye Zhou

ISBN 978-88-95608-63-1; **ISSN** 2283-9216

DOI: 10.3303/CET1866220

Research on Regenerative Braking Combined Control Method for ESP of Pure Electric Vehicles

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Through the analysis of the regenerative braking system of pure electric vehicles, a series type of regenerative braking control strategy based on a full decoupling braking system is proposed from the perspective of vehicle braking dynamics. The main factors influencing the regenerative braking control of pure electric vehicles are analyzed. Based on this, several common braking control strategies of regenerative systems are elaborated and analyzed according to the main influencing factors. Through the comparative analysis of the braking control strategies of the regenerative system, it is found that the parallel linkage brake control strategy can better meet the safe operation of pure electric vehicles. Compared with the original control strategy, the regenerative braking combined control strategy can improve the energy recovery rate when the vehicle is braking at high braking intensity and it can also improve the failure safety of the electronic control system when the vehicle is braking at high speed or at medium and high intensity.

1. Introduction

In today's society, low-carbon environmental protection and low-carbon economy have gradually become the theme of the era. With the development of science and technology, the automotive sector has been developing rapidly and hybrid vehicles and pure electric vehicles have become the main development trend in the automotive industry in the face of low-carbon economic era. The use of brake energy recovery technology can efficiently improve energy efficiency and it is currently one of the main methods to achieve energy conservation and emission reduction in the field of new energy vehicles. However, the development and use of any technology requires an improvement process. At this stage, when the vehicle is braking at high speed or at high intensity, the electronic control system will fail and the motor brake will quickly exit. If it is because of the motor brake force occupies excessive proportion so that the hydraulic braking force cannot compensate in time, the driver and the passengers will be in danger.

Based on these problems, this paper proposes a serial regenerative braking control strategy that considers the failure safety of the electronic control system in both dimensions of vehicle speed and braking intensity to improve the regenerative braking energy recovery rate and vehicle economy on the premise of ensuring vehicle braking safety and motor braking failure safety.

2. Literature review

With the rapid development of transportation and the rapid growth of absolute numbers, China has become the world's largest automotive market. By the end of 2013, the number of cars in China had reached 137 million. The number of casualties in traffic accidents in China has been ranked first in the world for ten consecutive years, the number of cars accounts for only 1.9% of the world and the death toll accounts for 15% of the world. On average, one person died in a car accident every five minutes, and one person was injured in a car accident every minute. It is obvious that traffic accidents have become "the first harm in China." Therefore, regarding the safety technology of automobiles, Shan et al. showed in the research that the early active safety technologies for automobiles mainly included the Anti-locking Brake System (ABS), and then developed the Acceleration Slip Regulation (ASR) based on ABS, that is, Traction Control System (TCS). According to a study by Audi in Germany, 40% of accidents are related to the lateral instability and sliding of

Please cite this article as: Zhang H., 2018, Research on regenerative braking combined control method for esp of pure electric vehicles, Chemical Engineering Transactions, 66, 1315-1320 DOI:10.3303/CET1866220

the car when the car is driven between 80 and 100km/h. When the speed exceeds 160km/h, almost every car accident is related to lateral instability. In order to ensure the stability of the vehicle under extremely complex conditions, ESP is developed on the basis of ABS and ASR. It is a new generation of automotive active safety control system. From the beginning, the main research purpose of the ESP system is to improve the lateral stability of the vehicle to prevent skidding, thus reducing the occurrence of car accidents (Shan et al., 2016). In their research, Wu et al. proposed that the 21st century is an era of low-carbon economy. Hybrid electric vehicles and pure electric vehicles have become the trend of the automotive industry. Brake energy recovery technology improves energy efficiency and is one of the effective means for energy-saving and emission reduction of new energy vehicles.

Kong et al. divide the regenerative braking control method on the current vehicle into two types: one is the parallel regenerative braking. This method simply superposes the motor brake and the traditional hydraulic brake, and the energy recovery rate is relatively low. It is common in the semi-decoupled brake system. The other is series regenerative braking. This method uses electromechanical power preferentially. Insufficient braking force uses hydraulic braking force to compensate. The recovery rate of regenerative braking energy is relatively high (Kong et al., 2017). In the study, Zhang et al. showed that the vehicle braking system must ensure the safety of the vehicle during braking while satisfying the driver's braking needs. In order to ensure the safety of the vehicle during braking, the United Nations Economic Commission for Europe (UNECE) has established the ECER13 braking regulations. The ECER13 brake regulations set out clear requirements for the front and rear axle braking force distribution of two-axle vehicles and stipulated the range of front and rear axle braking force distribution coefficients (Zhang et al., 2016). In the study, Emirler et al. proposed that the research on the control strategy for the braking energy recovery of new energy vehicles should consider the safety, economy and comfort of the vehicle, among which vehicle safety is particularly important. According to the braking energy recovery hardware system scheme, the braking energy recovery control strategy can be divided into a parallel control strategy and a series control strategy (Emirler et al., 2015). In addition, Pan et al. detailed description of the regenerative braking system for automobiles. The brake regeneration system refers to the recovery and reuse of braking energy of the vehicle. There are many types of energy recovery, such as electric energy recovery and hydraulic energy recovery. Zhang and so on stated that, in pure electric vehicles, the use of motor regenerative braking system for energy recovery has a very significant effect (Zhang et al., 2015). Among them, the hydraulic brake energy recovery is used for pure electric vehicles, because the hydraulic energy recovery power density is higher than the electric energy recovery, under the same conditions, it can recover and release more energy at the same time, that is, it can better improve the driving range of electric vehicles. In addition, the use of hydraulic energy recovery makes minor changes to the vehicle's powertrain, making it simpler and more reliable than electrical energy recovery control (Pan et al., 2015). Ahn et al. conducted an experimental study on the hydraulic regeneration system of electric vehicles. The research results show that the displacement of the hydraulic pump/motor is different, the energy recovered by the accumulator and the flywheel and the recovery efficiency are different. The larger the displacement, the more energy is recovered. However, when the pump/motor displacement is higher than a certain value, the energy recovery efficiency of the hydraulic brake energy recovery system will decrease due to the increase of the resistance on the pump/motor; in addition, the data shows that the energy recovery efficiency of the accumulator is lower than the recovery efficiency of the flywheel. Good matching between components of the hydraulic system is required to achieve optimal energy recovery (Ahn et al., 2017). At the same time, Kong also conducted a research experiment on the recovery efficiency of braking energy for electric vehicles. The results show that using ECPS electro-hydraulic hybrid vehicles can increase the driving range by about 25% compared to electric vehicles without ECPS; as the motor load is reduced, the depth of discharge of the battery is reduced and the battery life is extended; the main factor affecting the efficiency of ECPS braking energy recovery is pump/motor displacement (Kong, 2017).

In summary, the safety and stability of pure electric vehicles, energy recovery, regenerative braking, and hydraulic regenerative braking systems in regenerative braking have been described in detail. Based on the analysis of the regenerative braking system of pure electric vehicles, a series regenerative braking control strategy based on the fully decoupled braking system is proposed from the perspective of vehicle braking dynamics. The main factors affecting the regenerative braking control of pure electric vehicles are analyzed. On this basis, according to the main influencing factors, several common thermal storage system brake control strategies are elaborated and analyzed. And through the comparative analysis of the thermal storage system's brake control strategy, it is found that the parallel linked brake control strategy can better meet the safe operation of pure electric vehicles. Compared with the original control strategy, the combined strategy of regenerative braking can improve the energy recovery rate of the vehicle when braking at high intensity, and it can also improve the safety of the electronic control system.

3. Vehicle braking dynamics and ECE regulations

3.1 Analysis of vehicle braking dynamics

First of all, the braking dynamics of vehicles is analyzed. Under the condition of ignoring the air resistance, the force of vehicles when braking on the horizontal road is shown in Figure 1.

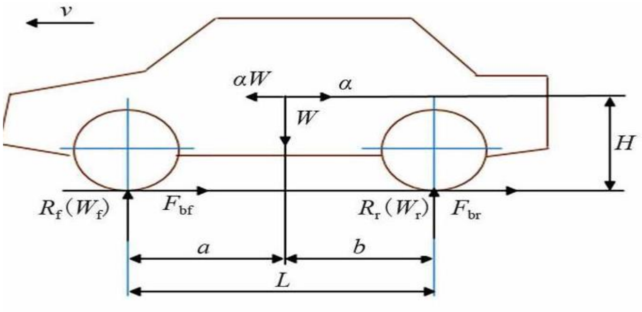

Figure 1: The force of the car when braking on the horizontal road

In the figure above, Wf and WR are the front and rear axle loads when the car is stationary; wind and Rr are the front and rear axle loads when the car is braking; a and b are the distances from the mass center of vehicles to the front and rear axles; H i the mass center of vehicles to the road; L is the wheelbase; W is the mass of the car; Fhf and Fhr are the braking forces on the front and rear axles; a is the vehicle deceleration. According to the force relationship, there will be front wheel locking, rear wheel locking and front and rear wheel locking together during the braking process according to conditions such as front-rear axle load distribution, front-rear axle braking force distribution and coefficient of road adhesion. In these three cases, the front wheel locking is a steady working condition, but it will lead to the loss of the steering capability of vehicles; the rear wheel locking is a dangerous working condition, which may lead to the sideslip of the rear wheel or even spin; at the time of the simultaneous locking of the front and rear wheels, if the adherence conditions are used better, the side slip can be avoided and the front wheel will lose its steering capability only at the maximum braking intensity. The simultaneous locking of the front and rear wheels is an ideal situation. Therefore, the front-rear braking force distribution coefficient that satisfies the simultaneous locking of the front and rear wheels is the ideal braking force distribution coefficient and the front-rear braking force distribution curve is the ideal braking force distribution curve.

3.2 Analysis of ECE regulations

The vehicle braking system must satisfy the driver's braking needs while ensuring the safety of the vehicle during braking. In order to ensure the safety of the vehicle in the braking process, the United Nations Economic Commission for Europe has established the ECERl3 braking regulations. The ECERl3 braking regulations set forth clear requirements for the front and rear axle braking force distribution of two-axle vehicles and stipulated the range of the distribution range of front-rear axle braking force.

4. Control strategy of braking energy recovery for pure electric vehicles

The research on the control strategy of braking energy recovery for new energy vehicles should consider the safety, economy and comfort of vehicles, among which the vehicle safety is particularly important. According to the braking energy recovery hardware system scheme, he control strategy of braking energy recovery can be divided into parallel control strategy and series control strategy. For the full decoupling braking energy recovery system, in order to improve the braking energy recovery rate and ensure vehicle braking safety and simple algorithm development, this paper adopts a serial regenerative braking control strategy.

First of all, there are many factors that influence the recovery of regenerative braking energy and the influencing factors for different regenerative braking systems are also different. Figure 1, 2 and 3 are the regenerative braking system structures of central motor type, wheel-side motor type and wheel hub motor type:

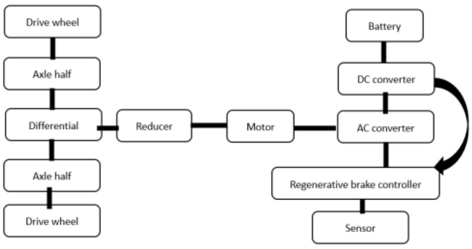

Figure 2: Central motor type regenerative braking system

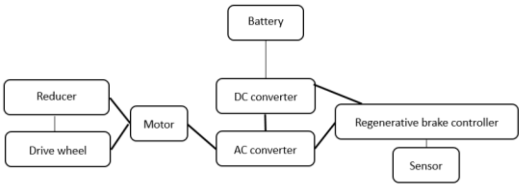

Figure 3: Wheel rim motor regenerative braking system

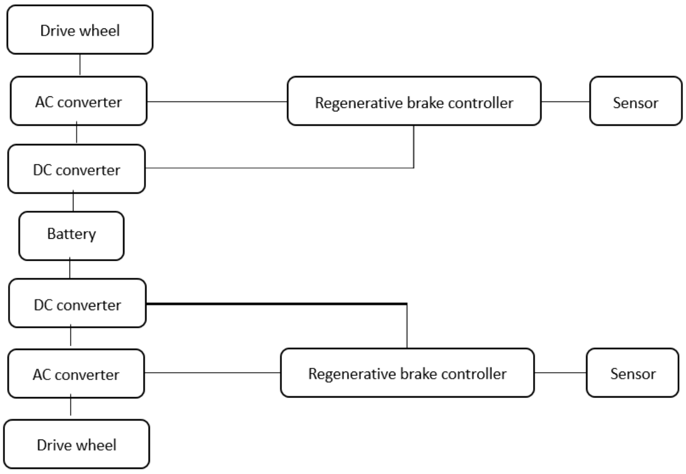

Figure 4: Wheel hub motor regenerative braking system

The specific control strategies include the distribution strategy of electro-hydraulic braking force and the control strategy of hydraulic braking force distribution of front and rear axles, described as follows:
The vehicle control unit monitors the current state of the vehicle and the driver’s input. The vehicle state information includes the vehicle speed and the wheel speed. The driver’s input includes the accelerator pedal, the brake pedal, the master cylinder pressure and the gear position information.
Based on the current state information of the vehicle and the driver’s input, the driver's driving intention is identified. Under the premise that the vehicle speed is not 0, if the brake pedal opening is not 0, the vehicle enters the braking mode; if the brake pedal opening is 0, the vehicle speed is greater than Vmin (Vmin is the lowest stabilized vehicle speed that the vehicle can constantly maintain, which is the electric climbing stabilized vehicle speed in this strategy. Take Vmin=10 knl/h) and the accelerator opening is 0, then the vehicle enters the sliding mode; if the accelerator opening is greater than 0, the vehicle enters the driving mode; if the opening of the accelerator pedal and the brake pedal is 0 and the vehicle speed is not greater than Vmin, the vehicle enters the electric climbing mode.
In the braking mode, based on the vehicle state of vehicle speed, brake pedal opening and the master cylinder pressure and the driver's input, the braking intention is identified and the braking force demanded by vehicles and the distribution of motor braking force and the hydraulic braking force are determined. This step needs to be performed on the basis that the battery is not fully charged and the battery and the motor are in a normal state. Otherwise, the hydraulic brake is used alone, while the motor brake is not used. In the sliding mode, the

hydraulic braking force does not work and the motor outputs l/2Fhf braking force (Fhf is the maximum adhesion of vehicles on roads with low adherence coefficient such as ice and snow).
In the sliding mode, the hydraulic braking system does not work, the motor output 1/2Fhf braking force considering the vehicle's sliding stability on roads with different adhesion coefficient and the vehicle's sliding kinetic energy (FHF is the maximum adhesion of vehicles on roads with low adherence coefficient such as ice and snow).
The regenerative braking control model of vehicles is built using the Matlab/Simulink software. In the process of vehicle braking, the Cruise is used to establish the full vehicle model. The target model adopted in this paper is a front engined front wheel pure electric vehicle and the motor output shaft is directly connected with front wheels through the main reducer. The technical parameters of the vehicle are shown in Table 1.

Table 1: Main assembly structure and technical parameters

Vehicle quality m/kg	1600
Wheelbase l/mm	2600
High heart h/mm	550
Scroll radius r/mm	307
Motor rated power P_e/KW	50
Motor Power P_{max}/KW	80
Motor rated torque T_e/(N.m)	150
Motor peak torque T_m/(N.m)	240
Battery voltage U/V	288
Battery capacity C/Ah	90
Main reduction ratio	4.211

The Cruise-Interface module is used as an interface to transfer the variables such as vehicle speed, brake pressure and motor external characteristics in the full vehicle model to the Matlab/Simulink and the control signals calculated by the latter are obtained. The control of the vehicle model is equivalent to the vehicle control unit HCU in the real vehicle.

5. Analysis of simulation results

In the following, with the initial vehicle speeds of 80 km/h and 100 km/h, the braking tests under different braking intensities are taken as examples to verify the control strategies proposed in this paper. Figure 5 shows the vehicle speed and deceleration when the vehicle is braking at low braking intensity.

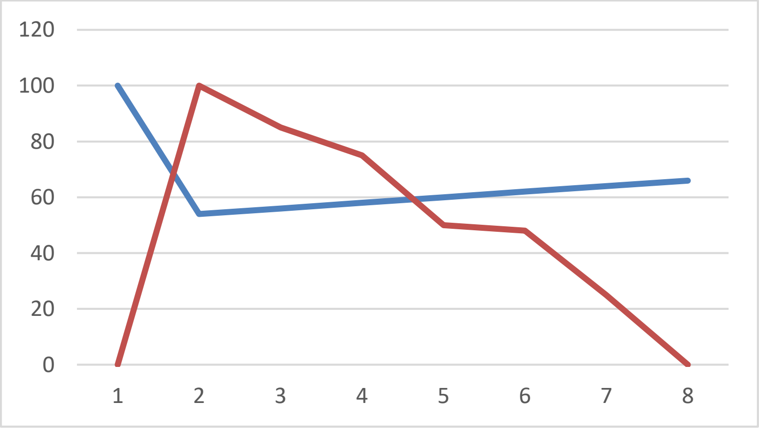

Figure 5: Small intensity braking speed changes

As it can be seen from the figure that the braking process starts from t=54 s and ends at t=66 s. After the start of braking, the output torque of the motor changes along the external characteristic curve of the motor, but the braking torque of the motor cannot meet the required braking torque. Therefore, the front and rear wheel cylinders actively pressurize to compensate the motor braking force. When the motor outputs the maximum motor torque (about 140N·m) and remains stable, the pressures of the front and rear wheel cylinders remain basically unchanged. When the vehicle speed reduces to about 10km/h, the braking torque of the motor decreases rapidly and the regenerative braking starts withdrawing. However, the brake pedal remains relatively stable and the hydraulic pressure of the front and rear axles begins to increase to compensate the motor braking force. When the motor braking force completely withdraws, the vehicle is braked by hydraulic pressure alone to stop the vehicle. According to the analysis results of the motor torque and the wheel cylinder pressure during the medium-intensity braking of the vehicle, it can be seen that the motor output 1/2Fcmx braking power and remains unchanged; the wheel cylinder hydraulic pressure increases; and the output hydraulic braking power compensates the motor braking force. When the vehicle speed reduces to about 10km/h, the braking torque of the motor decreases rapidly and the vehicle is stopped by the hydraulic braking force. At the braking of medium-high speed and medium-high intensity, the output torque of the motor is limited to improve the failure safety of the motor.

6. Conclusion

This paper studies the control strategy of regenerative braking for pure electric vehicles and proposes a series type of regenerative braking control strategy based on a full decoupling braking system. A control strategy model and a full vehicle model are established for the simulation verification of this control strategy and the following conclusions are obtained.

When the vehicle is under low-intensity braking, the motor braking force is fully utilized and the recovery rate of regenerative braking energy is relatively high, so the energy conservation is significant. When the vehicle is under medium-high speed and medium-high braking intensity, the braking torque of the motor is limited, which improves the failure safety of the electronic control system and ensures the braking stability of vehicles. The motor brake in other control strategies completely withdraws when the vehicle is under high-intensity braking while this strategy reserves part of the motor braking force and recovers the kinetic energy of vehicles, which improves the vehicle economy.

This paper only verifies the braking control strategy and braking energy recovery under normal braking conditions. The cycle working condition test should be followed in order to verify the energy recovery of the developed control strategy under the cycle working conditions.

Acknowledgement

The ninth batch project of university education and teaching reform in Guangzhou: Research on the integration of automotive vocational curriculum practice and innovation in higher vocational education under the background of innovation and entrepreneurship (2017F42).

Reference

Ahn J.K., Jung K.H., Kim D.H., Jin H.B., Kim H.S., Hwang S.H., 2017, Analysis of a regenerative braking system for hybrid electric vehicles using an electro-mechanical brake, International Journal of Automotive Technology, 10(2), 229-234, DOI: 10.5772/10183

Emırler K., Kahraman M., Şentürk O.U., Acar B., Aksun Güvenç, Güvenç L., 2015, Lateral stability control of fully electric vehicles, International Journal of Automotive Technology, 16(2), 317-328, DOI: 10.1007/s12239-015-0034-1

Kong C.L., 2017, Regenerative braking control for in-wheel driven pure electric vehicles, Power Electronics, 5, 20-8, DOI: 10.1504/ijehv.2011.044370

Pan C.F., Zhang X.L., Chen L., Chen L., 2015, Energy consumption characteristics of regenerative braking system of pure electric vehicle, Journal of Henan University of Science and Technology, 6 ,1672-6871, DOI: 10.15926/j.cnki.issn1672-6871.2015.06.011

Shan L.U., Liu Z.Q., Jin G.E., Qing Y.E., 2016, Simulation study on regenerative braking strategy of pure electric vehicle based on fuzzy control, Journal of Changsha University of Science & Technology, 71, 15-47, DOI: 10.4271/2018-01-0411

Wu J., Guo Z., Shen Y., 2015, Analysis and research on the regenerative braking control strategy of pure electric vehicles electric liquid brake system, Science & Technology & Innovation, 35, 11-4, DOI: 10.4271/2005-01-1581

Zhang Q., Fu X.L., Li K., Xin G.J., 2015, Matching optimization of power system and regenerative braking strategy for pure electric vehicle. School of control science and engineering, 3, 1004-731X, DOI: 10.16182/j.cnki.joss.2016.03.013

Zhang Z., Wang G., Zhang L., Zhao J., He C., Zhang Z., 2017, Braking force distribution strategy based on electromagnetic-mechanical coupled regenerative braking system, Zhongnan Daxue Xuebao, 48(6), 1530-1537, DOI: 10.4271/2018-01-0827