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New regenerative braking control strategy for rear-driven electrified minivans

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ABSTRACT

As of to 2012, minivan ownership stood at 20 million units in China, accounting for 16% of the passenger car market. In this article, comprehensive research is carried out on the design and control of a regenerative braking system for a rear-driven electrified minivan. For improving the regeneration efficiency by as much as possible, a new regenerative braking control strategy called "modified control strategy" is proposed. Additionally, a control strategy called "baseline control strategy" is introduced as a comparative control strategy. Simulations and hardware-in-loop (HIL) tests are carried out. The results of the simulations and the HIL tests show that the modified control strategy offers considerably higher regeneration efficiency than the baseline control strategy. In normal deceleration braking, the regeneration efficiency of the modified control strategy reaches 47%, 15% higher than that of the baseline control strategy. In addition, improvement in the fuel economy of electric vehicles operating on the ECE driving cycle and enhanced with the modified control strategy is greater than 10%, which is 3% higher than that with the baseline control strategy.

1. Introduction

Regenerative braking is one of the important and most widely used technologies in electrified vehicles. This technology can afford fuel savings by converting the kinetic energy of a moving vehicle into electric energy during deceleration [1,2]. To realize it, the electric motor will be controlled to operate as a generator converting the vehicle's kinetic energy into electricity, and the recovered energy will be stored in the battery which can be a significant assistant of the energy used in the future during driving processes. However, the regeneration efficiency is restricted by factors such as braking safety, braking comfort, and brake pedal feel. Thus, it is difficult to conduct the research for improving the regeneration efficiency while considering the abovementioned factors comprehensively [3].

Nowadays, regenerative braking systems are mainly equipped on the electrified passenger cars and buses. Considering the sizeable market share of electrified passenger cars, a numbers of studies have been conducted on regenerative braking systems and control strategies for passenger cars. Gao [6] proposed two regenerative braking strategies for a passenger car equipped with a front axle motor. However, neither of the strategies can achieve good balance between regeneration efficiency and braking efficiency. For a hybrid electric vehicle (HEV) equipped with a continuously variable automatic transmission (CVT), Kim [7,8] put forth a control strategy that maintains the electric motor in the high efficiency area at all times by adjusting the CVT gear ratio. The regeneration efficiency is improved by 8% compared with the original vehicle without the CVT. Another control strategy is proposed for a HEV with a six-speed automatic transmission; herein, the regenerative and frictional brake are well coordinated, and the adequate braking comfort is ensured. Chu [9] designed a strategy based on the ideal front–rear braking force distribution curve; both braking stability and fuel economy of the vehicle were considered. The present authors developed a regenerative braking system based on the Electronic Stability Program (ESP) platform. Control strategies were proposed, based on road test results, a fuel economy enhancement of more than 25% was achieved under the Economic Commission for Europe (ECE) driving cycle [10]. Additionally, a new type of regenerative braking system [12] and hydraulic control algorithm have been studied [11]. Brake pedal feel and braking comfort are easy to achieve with electrified buses. More importantly, although most buses are rear driven, their masses large, and a huge amount of energy is available for recovery. The present authors have proposed various control systems for different types of electrified buses [15]. Bench tests and road tests have been conducted [16,17], electric buses equipped with the developed

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regenerative braking systems have completed the demonstrative serving. Many other studies have been conducted in this area [3,13,14,18–21].

In contrast to the studies cited above, in this study, a minivan equipped with a rear axle motor is discussed. Minivans are extremely common in the Chinese market. According to China's minivan market analysis report (2012), minivan ownership stood at 20 million units until 2012, accounting for sixteen percent of the passenger car market. Furthermore, two million minivan units are sold annually in the Chinese market. Because of the differences in the typical configurations of electrified passenger cars and buses, the following difficulties exist at the technical level in conducting research for improving the regeneration efficiency of electrified minivans.

1. Because the target minivan is rear driven and has low mass, the amount of total recoverable energy is small. Thus, the regeneration efficiency would be limited.
2. Brake pedal feel would be affected during regenerative braking owing to the modulation of wheel pressure, and it is difficult to ensure good brake pedal feel.
3. The target minivan is sensitive to changes in the braking torque because of low inertia. Thus, it is difficult to guarantee braking comfort.

Regenerative braking control strategy plays a significant role in improving the regeneration efficiency and braking comfort of a vehicle. If the regenerative and frictional brake are well coordinated, high regeneration efficiency and good braking feeling are achieved [4,5]. In order to solve the problems above, the hydraulic braking pressure and the motor torque would be controlled coordinately according to the regenerative braking control strategy. In this study, comprehensive research on the design and control of a regenerative braking system for a rear-driven electrified minivan is conducted. Regeneration efficiency improvement is analyzed in detail. The rest of this paper is organized as follows. Section 2 details the scheme and modeling of the regenerative braking system. Section 3 discusses the regenerative braking control strategy and the hydraulic control algorithm. The control strategy is validated in Section 4, and the results of simulations and HIL tests are presented as well. Section 5 analyzes fuel economy improvement under the ECE driving cycle. Section 6 lists the conclusions of this study.

2. System outline and modeling

2.1. System outline

A new type of regenerative braking system called EABS control unit which is based on the Anti-lock Braking System (ABS) is proposed for the target vehicle [12]. The EABS control unit is composed of two main parts, i.e., are the hydraulic pressure modulator and brake control unit, as shown in Fig. 1. Antilock braking control and regenerative braking control are integrated into the EABS control unit. The hydraulic pressure modulator modulates wheel cylinder pressure during regenerative braking for achieving high regeneration efficiency and good brake pedal feel. The configuration of the hydraulic pressure modulator of the EABS control unit is shown as Fig. 2. Where RR is rear right, FL is front left, FR is front right, RL is rear left. AV is Inlet valve, EV is Outlet valve. The hydraulic pressure modulator is on basis of the conventional hydraulic pressure modulator of the Anti-lock Braking System (ABS). Six high speed solenoid valves and two stroke simulators are added.

The overall structure of the developed regenerative braking system is shown in Fig. 3. The EABS control unit is mounted in the

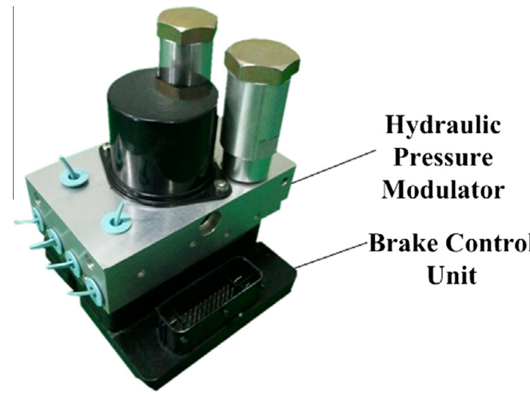

Fig. 1. Picture of the EABS braking system.

braking line between the master cylinder and the wheel cylinders, the position at which the ABS control unit is mounted in conventional hydraulic braking systems.

2.2. System modeling

For the sake of simulation, the regenerative braking system should be modeled. In this study, vehicle dynamics, tires, electric motor, battery, and hydraulic braking system are modeled in MATLAB/Simulink. Detailed modeling methods for vehicle dynamics and tires are given in [15], and the models of the electric motor, battery, and hydraulic braking system models are explained as follows.

2.2.1. Electric motor model

In this study, the electric motor model was built based on the experimental data of the electric motor in an M30, an electric minivan supplied by the Beijing Motor Group. Specifics of the modeling process are as follows.

The electric motor's torque is expressed as follows:

$$T_m = f_m(n_t) \tag{1}$$

The power of the electric motor is expressed as follows:

$$P_m = T_m n_t \tag{2}$$

where T_m denotes electric motor torque (Nm), n_t denotes electric motor speed (rad/s), which can be obtained using a rotational speed sensor, P_m denotes electric motor power. Motor torque is obtained according to motor speed using a lookup table. For improving model accuracy, the driving mode and braking mode efficiencies of the electric motor are considered separately. The driving mode efficiency η_m and braking mode efficiency η_g are expressed as follows.

When the electric motor is in the driving mode,

$$\eta_m = f_{\eta 1}(T_m, n_t). \tag{3}$$

When the electric motor is in the braking mode,

$$\eta_g = f_{\eta 2}(T_m, n_t). \tag{4}$$

Considering the electric motor's response lag, the first-order transfer function of the electric motor can be written as follows:

$$G(s) = \frac{T_{act}}{T_{dmd}} = \frac{1}{0.05s + 1} \tag{5}$$

which represents the relationship between the actual torque of the electric motor T_{act} and the torque demand of the electric motor T_{dmd}.