

Design and Performance Analysis of a Novel Regenerative Braking System for Electrified Passenger Vehicles

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ABSTRACT

A novel type of regenerative braking system for electric vehicles is proposed in this paper. Four pressure-difference-limit valves, two relief valves and two brake pedal simulators, are added to the layout of a conventional four-channel hydraulic modulator. The cooperation of relief valves and hydraulic pumps provides a stabilized high-pressure source. Pressure-difference-limit valves ensure that the pressure in each wheel cylinder can be modulated separately at a high precision. Besides, the functions of anti-lock braking system and electronic stability program are integrated in this regenerative braking system. The models of regenerative braking controller and vehicle dynamics are built in MATLAB/Simulink. Hydraulic brake model is built in AMESim through a parameterized and modularized method. Meanwhile, the control strategy of hydraulic brake modulation and brake force distribution are designed. Simulations are conducted via co-simulation interface between MATLAB and AMESim under scenarios of typical braking and ECE driving cycle. Simulation results show that regenerative and hydraulic braking forces are coordinated well during typical braking process, verifying the feasibility and effectiveness of the models built and strategies proposed. Under an ECE driving cycle, the proposed RBS can recover more than 75% of the total recoverable braking energy, which lengthen the vehicle's driving range by more than 24%.

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INTRODUCTION

Electrified vehicles such as hybrid vehicles, fuel-cell vehicles and electric vehicles have gained great research focus due to their environment friendly property. Regenerative braking system has become one of the key components of electrified vehicles since this technology improves driving range by recovering electric energy during deceleration [1, 2].

During regenerative braking, driving motor is operated as a generator which converts kinetic energy to electricity and exerts a brake torque on the vehicle simultaneously. However, the capability of regenerative braking is restricted by factors such as the states of the motor and the battery, therefore a spare friction braking mechanism is equipped as a supplement. Hence regenerative brake cooperates with friction brake to satisfy the total braking demand.

Nowadays, research and development of regenerative braking systems are mainly conducted on system configuration and control strategies.

Toyota, TRW and Honda have developed RBS based on EHB (Electro Hydraulic Brake) systems. EHB is a by-wire brake system, which imports stroke simulators and an additional set of pressure supply unit, can decouple the main cylinders with wheel cylinders via valves control. The EHB based RBS has been implemented successfully in commercialized HEVs, such as Toyota Prius, Ford Escape, and Honda Insight [3, 4, 5].

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. Chu [7] designed a strategy based on the ideal front-rear braking force distribution curve; both braking stability and fuel economy of the vehicle were considered. Zhang [8] 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.

The present authors have been dedicated to the research and development of regenerative braking for a long period and made some progress [9, 10, 11, 12]. In order to further improve the regeneration performance while reducing the system cost and development risk, a new type of electrically controlled regenerative braking system named EESP, which is based on the proven ESP technique, has been developed.

To realize the cooperative control of regenerative braking and hydraulic braking, 4 pressure-difference-limit valves, 2 relief valves, and 2 brake pedal simulators, are added to the layout of a conventional 4-channel hydraulic modulator.

The system composition, control method, braking performance and regeneration effect from co-simulation results of an electric vehicle equipped with the RBS developed are discussed.

EESP SYSTEM CONFIGURATION

System Outline

As illustrated in Figure 1, a complete RBS is generally composed of motor brake subsystem, hydraulic brake subsystem, brake control unit (BCU), vehicle control unit (VCU) and CAN network, but individual diversities merely exist in hydraulic brake configuration.

The overall structure of the EESP hydraulic brake subsystem is shown in Figure 2.

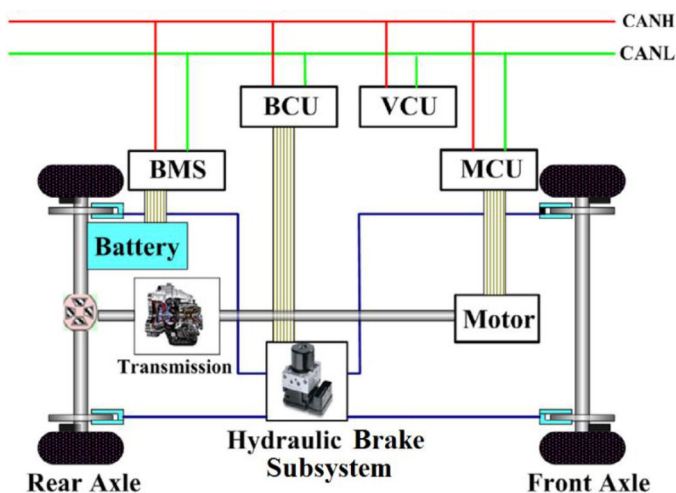


Figure 1. The composition of a general regenerative braking system

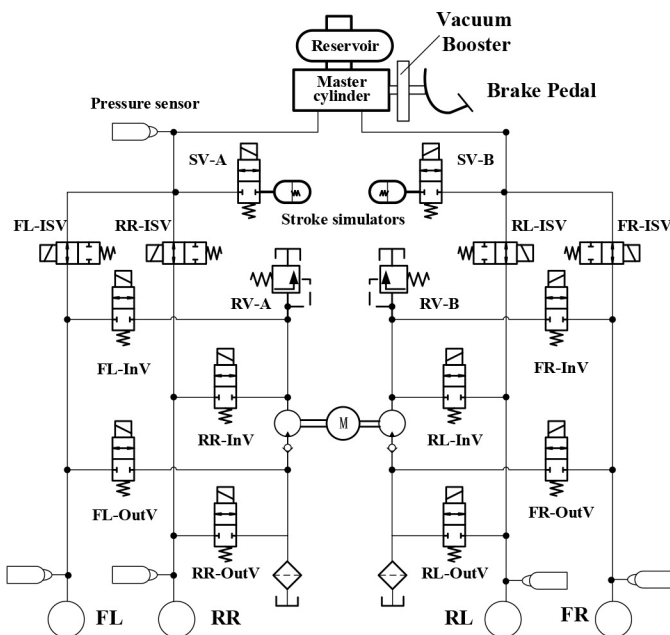


Figure 2. Layout of EESP hydraulic brake subsystem

To realize the cooperative control of regenerative braking and hydraulic braking, four pressure-difference-limit valves, two relief valves, and two brake pedal simulators, are added to the layout of a conventional four-channel hydraulic modulator.

Among the eighteen valves in total, eight normally closed valves (e.g. FL-InV) in the downstream of the brake line are used for ABS/ESP control, which is the similar layout with that of conventional ABS/ESP, nonetheless four inlet valves are replaced by four pressure-difference-limit valves which are more precise in pressure modulation.

Above the eight valves in downstream, four normally open valves named isolation valve (e.g. FL-ISV) are mounted to isolate master cylinder with wheel cylinders. Thus pedal feel is decoupled with brake force. Two relief valves (RV-A, RV-B) with the crack pressure of 15 MPa are equipped in the bypass of the layout. The pumps cooperate with two relief valves serving as a stabilized high pressure source.

Two switch valves (SV-A, SV-B) and two stroke simulators are mounted at the outlet of the master cylinder providing conventional brake pedal feel. The four isolation valves (e.g. FL-ISV) and the two switch valves (SV-A, SV-B) are on-off controlled, while the eight ABS/ESP valves are pulse width modulated (PWM).

The research object in this paper is a front driven electric vehicle, but as described in figure 2, the four wheel cylinders and their inlet as well as outlet valves have the equivalent configuration, therefore this RBS can be equipped on electrified vehicles of all driven types.

Operation Modes of EESP

Benefiting from the relatively individual structure of four wheel cylinders, EESP can realize various brake functions of hydraulic brake, cooperative regenerative brake and ABS/ESP function.

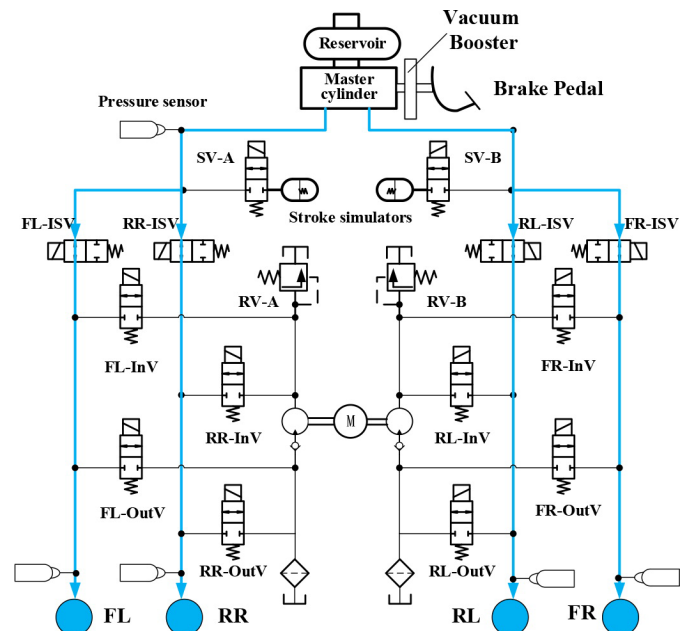


Figure 3. Hydraulic brake mode of EESP

Hydraulic Brake Mode

Under some conditions regenerative brake cannot be implemented such as the battery is full charged, hence normal hydraulic brake is needed. Under these conditions, all of the components of EESP hydraulic pressure modulator are not energized. The brake lines connections are the same with the conventional hydraulic brake system. As shown in Figure 3, the hydraulic fluid from master cylinder directly enters the wheel cylinders without modulation, building up the wheel pressures as demand.

Cooperative Regenerative Brake Mode

Under cooperative regenerative brake mode, the total braking demand is met by the addition of regenerative braking force and friction braking force. The four isolation valves and two switch valves are energized, the hydraulic brake fluid flows into corresponding stroke simulators respectively as illustrated in Figure 4. The connections between master cylinder and the downstream part are cut off, which enables the mechanism decoupling of brake pedal and front wheel cylinders, provides the driver a good pedal feel. Meanwhile, the pump motor, working at a proper rotation speed, coordinates with the two relief valves providing a stabilized high pressure, which is similar as the function of high pressure accumulator in EHB system. The pressure in the pipeline between the pump and inlet valves is just identical with the crack pressure of the two relief valves i.e. 15 MPa.

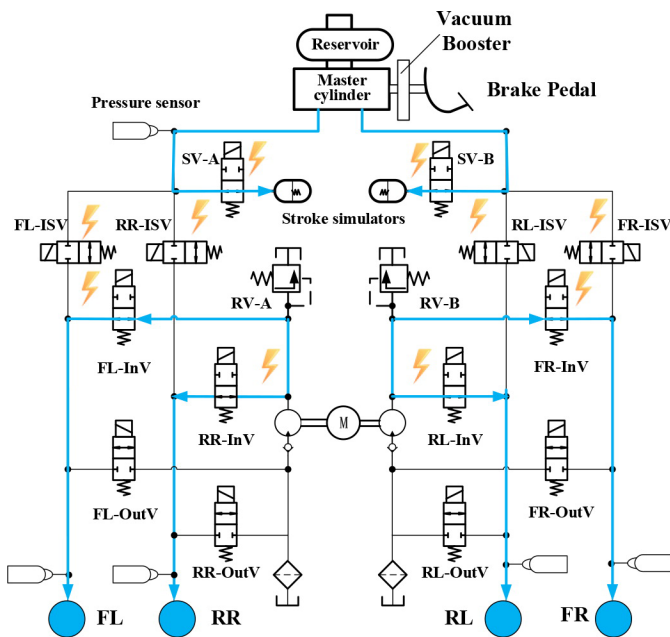


Figure 4. Cooperative regenerative brake mode of EESP

At the start stage of brake, the regenerative braking torque generated by driving motor is applied on the front axle, recovering the kinetic energy of the vehicle. However the generation capability of driving motor is limited by factors such as the change rate of demand torque and vehicle speed, when the regenerative brake torque cannot meet the brake request of front wheels, the hydraulic brake force needs to be exerted.

ABS / ESP Control

When the wheel speed is detected as having a tendency of locking during deceleration procedure, the ABS control function is activated. At this scenario, the upstream six valves i.e. switch valves and isolation valves are not working. The ABS controller integrated in BCU undertakes the responsibility of modulation of the eight valves in downstream to realize the pressure increase, decrease and hold control of each wheel cylinder individually.

When an emergent steering happens to avoid collision or at other critical moments, the vehicle may lose stability suddenly following with a large value yaw velocity, which would activate the ESP control mode. The BCU controls the six valves in the upstream of the hydraulic pressure modulator to be energized, cutting off master cylinder and downstream part. The pump motor works to build up a rapid high pressure. With the same logic of the conventional ESP control, the pressure-difference-limit inlet valve is energized to lead accurate brake fluid into corresponding wheel cylinder fulfilling single-wheel brake to correct the trajectory of the vehicle.

SYSTEM MODELING AND CONTROL ALGORITHM DESIGN

A control system of regenerative braking needs to be established for the simulation and analysis of the regenerative braking procedure. In this study, the model of vehicle dynamics, the tires, the electric motor, the battery and the braking control unit are set up in MATLAB/ Simulink. The model of the whole hydraulic brake system is set up in AMESim simultaneously. The detailed methods for modeling the vehicle dynamics and the tire have been described in [9]. The modeling of the motor and the battery is based on the foundation of [10]. The hydraulic brake system is modeled in AMESim and the procedure is expounded as follows.

The modeling procedure of the hydraulic braking system in AMESim is composed of two parts, i.e. pressure-difference-limit valve modeling and pipeline construction.

Pressure-Difference-Limit Valve

Pressure-difference-limit means that when a high speed on-off valve is controlled under current PWM mode, the pressure difference across the valve is linearly related to the control current. This control method can simplify the valve control procedure and reduce noise significantly.

The configuration of a normally closed inlet valve mentioned is shown in Figure 5. Regarding the initial position of valve core as the origin, the OX coordinate system was established, as Figure 6 shows.

After being energized, the normally closed valve opens, and before the core leaves the valve seat, the electromagnetic force F_e , the restoring spring force F_s , the hydraulic force F_h and the supportive force F_N of the valve seat are exerted on the valve core. The axial balance equation of the valve core in the valve-closed state can be expressed as