

Study on Stability Control of Electrical Vehicle Based on Regenerative Braking System

Qingzhang Chen
Changshu Institute of Technology

ABSTRACT

A regenerative braking system coordinated controller was developed for a front wheel drive BEV that also includes an ultra-capacitor storage system. This controller integrates the dual-motor regenerative braking with the hydraulic braking and stability control systems.

The vehicle braking mode and the distribution of braking torque were determined according to the vehicle braking requirements, vehicle status and energy storage system (battery plus ultra-capacitor) state, and the stability control torque was provided according to the real-time vehicle stability condition. Simulation results show that, compared with a motor unilateral independence control strategy, the integrated coordinated controller improves the vehicle's stability when the vehicle corners while braking.

CITATION: Chen, Q., "Study on Stability Control of Electrical Vehicle Based on Regenerative Braking System," *SAE Int. J. Commer. Veh.* 8(1):2015, doi:10.4271/2015-01-1565.

INTRODUCTION

Hybrid vehicle and electric vehicle regenerative braking systems require fast response and effective energy recovery while not adversely affecting stopping distance or stability[1,2]. Despite significant advances in technology and control, there are still some fundamental issues with regenerative braking. For example, at lower speeds, there is often insufficient brake torque available from the regenerative system alone to meet the braking requirements; hence it is typical to include conventional hydraulic brakes along with the regenerative system[3,6].

Additionally, the state of charge and rate of charge capability of the regenerative system may render the regenerative system alone incapable of handling the braking requirements alone. As such, blending and matching the motor regenerative braking torque with the hydraulic braking torque become key design requirements for regenerative braking systems [4,5,9]. This paper takes a two-wheeled motor front-drive electric vehicle regenerative braking system as the research object and develops the regenerative braking system with an integrated control system.

STRUCTURE OF THE SYSTEM

Figure 1 shows a system schematic illustrating the structural principle of the regenerative braking system under study herein.

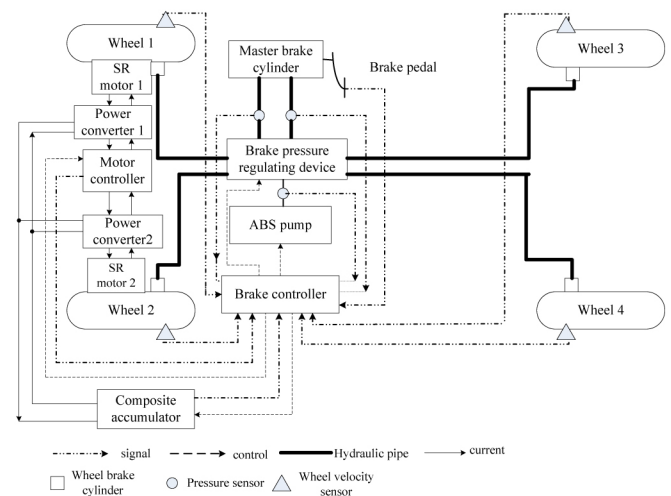


Figure 1. Structural principle of the regenerative braking system

It can be seen that the hydraulic anti-lock braking system (ABS) and regenerative braking system coordinate in the braking process, and thus the braking motors must function in anti-lock braking mode. According to the vehicle's overall braking demand, the required amount of hydraulic braking torque is determined and then controlled by the pressure regulating device.

The motor braking torque and vehicle slip rate are calculated in accordance with braking force distribution requirements of front and rear wheels, and the braking need. The regenerative braking is realized by adjusting the brake power and torque of two switched reluctance motors. The energy storage device is composed of lead-acid batteries and super-capacitors, so as to ensure a high energy density and power density; the super-capacitors play a role of energy buffering, allowing more full recovery and use of electrical braking energy.

INTEGRATED CONTROL STRATEGIES

The targets of the regenerative braking control strategy include: braking stability, driver's brake feel and maximum energy recovery [11,12]. When there is brake demand of the vehicle, the system determines the braking mode and the ratio of braking torque distribution according to the brake demand, and then provides the motor and/or hydraulic brake torque, and recovers energy according to the front wheel brake demand and state of charge of the energy storage.

Figure 2 shows the integrated strategy of regenerative braking stability control. It can be seen that the regenerative braking of the front axle motor is worked in anti-lock brake mode, a voltage of E_a is added to the input bus of the motor to realize anti-lock brake, and the rear axle brake process is still the original hydraulic ABS braking mode. Hydraulic ABS braking mode is applied for the front and rear axle in the emergency braking process where regenerative braking alone cannot meet the braking requirements. The control method to maximize energy recovery is determined according to the input of integrated system.

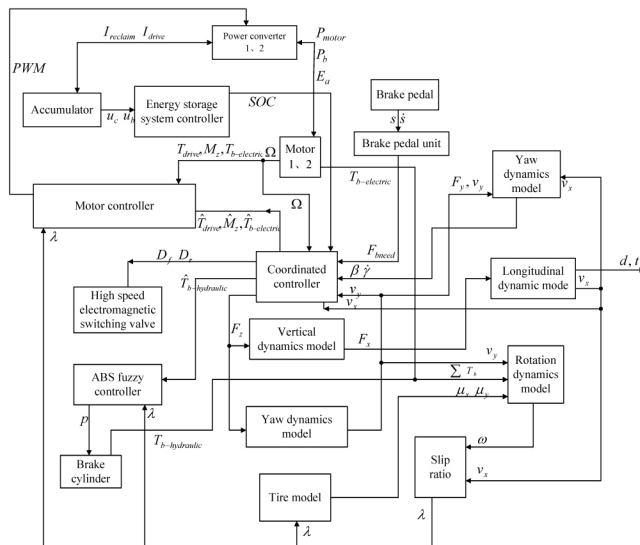


Figure 2. Integrated control strategy of regenerative braking stability

When the coordinated controller gets the information of vehicle operating conditions and motion status, vehicle stability control will be carried out according to the obtained parameters such as $\beta, \dot{\gamma}, v_x, v_y$, and vehicle motion status is adjusted by the yaw torque $\hat{M}_z$, which is produced by the left and right motors on the front wheel. The vehicle braking need F_{bneed} is communicated to the coordinated

controller by brake pedal pressure unit during the braking process, then (1) the maximum torque $T_{b-electric-max}$ is determined according to the braking strength and the energy storage state of charge (SOC), (2) the appropriate braking mode model will be determined, (3) the best braking force distribution coefficient with front and rear axle will be determined according to status of the parameters of vehicle mass-center, (4) determine and send the input parameters D_f, D_r to the high-speed switching valves, (5) the braking torque amount $\hat{T}_{b-hydraulic}$ of hydraulic brake system is determined, according to the speed and wheel slip ratio value λ , and (6) carry out anti-lock braking control process using the motor controller and hydraulic ABS fuzzy controller.

Figure 3 is the master flow chart of the coordinated controller. It can be seen that the coordinated controller is the core of the whole system, factors of control strategy, such as vehicle stability, regenerative braking, energy recovery and hydraulic brake are interrelate and restrict.

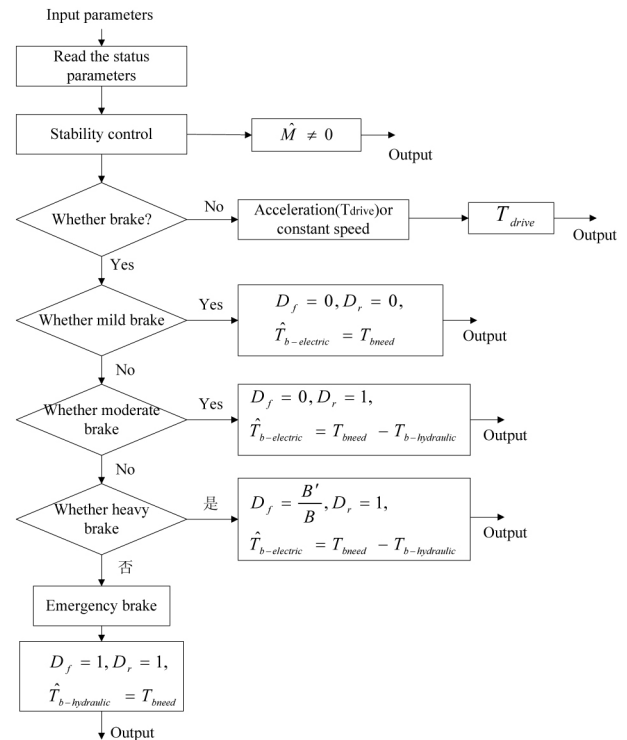


Figure 3. The master flowchart of coordination controller

SYSTEM MODELING

Vehicle Model

In this thesis, we are mainly concerned with the stability control by the two in-wheeled motors. The drag force is neglected. The heave, roll and pitch motions of vehicle are neglected in the dynamic model due to only lateral control being concerned in the system modeling [7]. The simplified free body diagram used to develop the dynamics of the vehicle is shown as Figure 4.

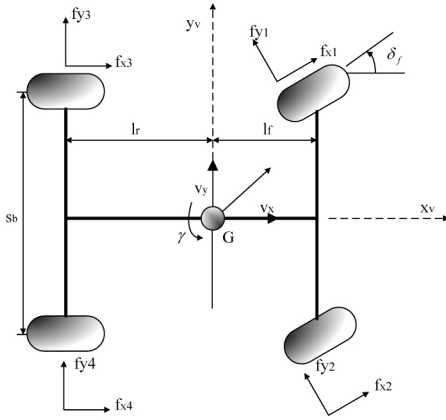


Figure 4. The simplified model for the dynamics of the vehicle

$$\begin{cases} m(\dot{v}_x - v_y \gamma) = f_{xf} \cos \delta_f + f_{xr} - f_{yf} \sin \delta_f \\ m(\dot{v}_y - v_x \gamma) = f_{xf} \sin \delta_f + f_{yr} + f_{yf} \cos \delta_f \\ J\dot{\gamma} = l_f (f_{xf} \sin \delta_f + f_{yf} \cos \delta_f) - l_r f_{yr} + \frac{s_b}{2} (\Delta f_x - \Delta f_{yf} \sin \delta_f) \end{cases} \quad (1)$$

Where

$$\begin{aligned} f_{xf} &= f_{x1} + f_{x2} & f_{yf} &= f_{y1} + f_{y2} \\ f_{xr} &= f_{x3} + f_{x4} & f_{yr} &= f_{y3} + f_{y4} \\ \Delta f_x &= (f_{x4} - f_{x3}) + (f_{x2} - f_{x1}) \cos \delta_f & \Delta f_{yf} &= f_{y2} - f_{y1} \end{aligned}$$

$f_{xi}(\lambda_i)$ and $f_{yi}(\alpha_i)$ are directly depend on the tire slip coefficient λ_i and tire slip angle α_i respectively.

$$\begin{aligned} \alpha_1 &= \delta_f - \tan^{-1} \left(\frac{v_y - (n_t \cos \delta_f) \dot{\delta}_f - (n_t \cos \delta_f - l_f) \gamma}{v_x + (n_t \sin \delta_f) \dot{\delta}_f + (n_t \sin \delta_f - \frac{s_b}{2}) \gamma} \right) \\ \alpha_2 &= \delta_f - \tan^{-1} \left(\frac{v_y - (n_t \cos \delta_f) \dot{\delta}_f - (n_t \cos \delta_f - l_f) \gamma}{v_x + (n_t \sin \delta_f) \dot{\delta}_f + (n_t \sin \delta_f - \frac{s_b}{2}) \gamma} \right) \\ \alpha_3 &= -\tan^{-1} \left(\frac{v_y - l_r \gamma}{v_x - \frac{s_b \gamma}{2}} \right) \\ \alpha_4 &= -\tan^{-1} \left(\frac{v_y - l_r \gamma}{v_x + \frac{s_b \gamma}{2}} \right) \end{aligned} \quad (2)$$

According to the magic formula of Pacejka, the lateral forces are as follow [8],

$$f_{yi}(\alpha_i) = \mu d_i \sin \left[\left(\frac{5}{4} - \frac{\mu}{4} \right) c_i \tan^{-1} \left\{ (2 - \mu) b_i (1 - e_i) \alpha_i + e_i \tan^{-1} \left\{ (2 - \mu) b_i \alpha_i \right\} \right\} \right] \quad (3)$$

The longitudinal forces are as follow,

$$\begin{aligned} f_{xi}(\lambda_i) &= D_i \sin(C_i \arctan(B_i \Phi_i)) \\ \Phi_i &= (1 - E_i) \lambda_i + \left(\frac{E_i}{B_i} \right) \arctan(B_i \lambda_i) \\ D_i &= a_1 f_{zi}^2 + a_2 f_{zi} \\ B_i C_i D_i &= (a_3 f_{zi}^2 + a_4 f_{zi}) / \exp(a_5 f_{zi}) \\ C_i &= b_0 \\ B_i &= B_i C_i D_i / (C_i D_i) \\ E_i &= a_6 f_{zi}^2 + a_7 f_{zi} + a_8 \end{aligned} \quad (4)$$

The f_{zi} is the vertical force on the i th wheel, which is expressed as follow,

$$f_{z1} = \frac{m}{2(l_f + l_r)} (l_r g + \dot{v}_x h_g) - \frac{m h_g}{2 s_b} \dot{v}_y \quad (5)$$

$$f_{z2} = \frac{m}{2(l_f + l_r)} (l_r g + \dot{v}_x h_g) + \frac{m h_g}{2 s_b} \dot{v}_y \quad (6)$$

$$f_{z3} = \frac{m}{2(l_f + l_r)} (l_f g - \dot{v}_x h_g) - \frac{m h_g}{2 s_b} \dot{v}_y \quad (7)$$

$$f_{z4} = \frac{m}{2(l_f + l_r)} (l_f g - \dot{v}_x h_g) + \frac{m h_g}{2 s_b} \dot{v}_y \quad (8)$$

The $f_{xi}(\lambda_i)$ is the longitudinal force provided by the ground. The coefficients $b_i, c_i, d_i, e_i, B_i, C_i, D_i$ and E_i depend on the tire characteristics, on the road conditions, and on the vehicle operational conditions. They represent the lateral and longitudinal stiffness factor, shape factor, peak value, and curvature factor respectively.

The $a_1 \sim a_8$ and b_0 are the fitting coefficients which are used to determine to value of B_i, C_i, D_i and E_i .

During braking, (here only the front in-wheel-motor electrical light braking is considered, due to the stability of the vehicle being the main concern) then the longitudinal forces are as follow,

$$f_{xi} = f_{x-bi} = M_{mbi} r \quad (9)$$

M_{mbi} is the braking torque applied on the wheel by the i th in-wheel-motor, and r is the effective radius of the wheels. The front wheel motor braking torque are expressed as follow,

$$\begin{aligned} f_{x1} &= M_{mb1} / r = \eta_1 i_{g1} T_{b-electric1} / r \\ f_{x2} &= M_{mb2} / r = \eta_2 i_{g2} T_{b-electric2} / r \end{aligned}$$