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New evaluation methodology of regenerative braking contribution to energy efficiency improvement of electric vehicles

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ABSTRACT

Comprehensive research is conducted on the design and control of a regenerative braking system for electric vehicles. The mechanism and evaluation methods of contribution brought by regenerative braking to improve electric vehicle's energy efficiency are discussed and analyzed by the energy flow. Methodologies for calculating the contribution made by regenerative brake are proposed. Additionally a new regenerative braking control strategy called "serial 2 control strategy" is introduced. Moreover, two control strategies called "parallel control strategy" and "serial 1 control strategy" are proposed as the comparative control strategy. Furthermore, two different contribution ratio evaluation parameters according to the deceleration braking process are proposed. Finally, road tests are carried out under China typical city regenerative driving cycle standard with three different control strategies. The serial 2 control strategy offers considerably higher regeneration efficiency than the parallel strategy and serial 1 strategy.

1. Introduction

Due to the shortage of non-renewable resources, along with concerns about environmental issues, hybrid technologies and alternative fuels are being increasingly investigated and utilized. Automobiles are required to be greener and more efficient. Control optimization algorithms have been used for energy management in automotive power systems [1]. The applicability of alternative fuel in a compression ignition engine is discussed [2]. Methods to improve efficiency of spark ignition engines are researched [3]. Design methods for vehicle light-weighting are studied [4]. Among these proposed solutions, electrified vehicles, such as hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and plug-in hybrid electric vehicles (PHEVs), are promising in improving the efficiency of powertrain energy conversion and reduction of hazardous carbon-dioxide and nitride emission. Regenerative braking system (RBS) is widely used in these electrified vehicles. Brake pedal feel will be affected during regenerative braking owing to the modulation of wheel pressure. The electric motor in RBS also works as a generator to convert the vehicle's kinetic energy into electricity, thus the salvaged energy is stored in the battery for later use. In a conventional braking system, about one third of the energy of the power, originally in the form of kinetic energy, is wasted in the form of heat during deceleration [5]. Therefore, recapture of this wasted kinetic energy is mandatory. The kinetic energy recovery system (KERS) rotating flywheel, has been applied. The hydraulic regenerative braking, which features in high power density and energy conversion efficiency, has been applied in heavy vehicles [6]. Control strategies of hydraulic regenerative brake are also studied [7].

Regenerative braking control strategy is needed to improve both regeneration efficiency and braking comfort. If the regeneration and frictional braking are well-coordinated, high regeneration efficiency and good braking feeling are achieved [6]. Making a trade-off between performance and cost, the electro-mechanical RBS becomes popular in all kinds of electric vehicles [7]. Especially for all types of electrified vehicles, the electro-mechanical RBS has become standard equipment [8]. For regenerative braking system, there are three important topics, named system design, blended brake control, and energy efficiency evaluation, which are worthwhile researched [9].

The RBS applied in hybrid electric passenger cars is widely investigated [10]. The RBS has been already commercialized by automotive makers and component suppliers, such as Nissan, Toyota and BMW [11]. Cooperative control of regenerative braking and hydraulic braking of an electrified passenger car has been studied [12]. The ultra-capacitor of the regenerative energy is

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Nomenclature

a	acceleration of vehicle
A	frontal area of the vehicle
C_D	coefficient of air resistance
E_{drive}	energy consumption of a vehicle with regenerative braking
E^{*}_{drive}	energy consumption of a vehicle without regenerative braking
E_{drive_f}	energy consumption of a vehicle to overcome rolling resistance during driving situations
E_{drive_i}	energy consumption of a vehicle to overcome gradient resistance during driving situations
E_{drive_w}	energy consumption of a vehicle to overcome aerodynamic drag during driving situations
E_{drive_a}	energy consumption of a vehicle to overcome acceleration during driving situations
$E_{kinetic}$	kinetic energy of a vehicle during driving situations
E_{brake_f}	energy consumption of a vehicle to overcome rolling resistance during braking situations
E_{brake_i}	energy consumption of a vehicle to overcome gradient resistance during braking situations
E_{brake_w}	energy consumption of a vehicle to overcome aerodynamic drag during braking situations
E_o	energy consumption of hydraulic brake during braking situations
E_f	energy consumption of a vehicle to overcome rolling resistance
E_i	energy consumption of a vehicle to overcome gradient resistance
E_w	energy consumption of a vehicle to overcome aerodynamic drag
E_{fw_brk}	energy consumption of front wheel during braking situations
E_{rw_brk}	energy consumption of front wheel during braking situations
E_{brake}	regenerative braking energy
E_{mot_brk}	energy consumption of motor during braking situations
E_r	regenerative braking energy of drive wheel
E_{bat}	regenerative braking energy of battery
E_{regen}	energy consumption of vehicle with regenerative braking
ΔE	reduced energy by regenerative brake
f	rolling resistance coefficient
F_{fw_brk}	braking force of front wheel
F_{rw_brk}	braking force of rear wheel
F_{mot_brk}	braking force of motor
i	gradient resistance coefficient
I_{bat}	current at the battery I/O port
P_{drive}	required power at driven wheels
P_{regen}	required power at driven wheels
T_{mot_brk}	motor torque during braking situations
u	real-time vehicle velocity
U_{bat}	voltage at the battery I/O port
η_d	efficiency of drive unit
η_{charge}	charging efficiency of the battery
$\eta_{discharge}$	discharging efficiency of the battery
η_a	efficiency of axle
η_{bat}	regenerative efficiency of the battery
η_{gen}	generation efficiency of the motor
η_m	motor efficiency
η_{mb}	average efficiency of the motor during generating situations
η_{mt}	average efficiency of the motor during transmission situations
η_r	energy efficiency of vehicle with regenerative braking
η_s	average efficiency of the battery during charging and discharging situations
η_{fd}	efficiency of final drive unit
η_b	efficiency of axle with regenerative braking
δ	conversion coefficient of rotational mass of powertrain
σ	regenerative braking contribution to energy utilization reduction of vehicle
σ_r	contribution ratio to regenerative braking energy transfer process efficiency
σ_c	contribution ratio to regenerative driving range
ω_{mot_brk}	angular speed of the electric motor during braking situations

Abbreviations

BEV	battery electric vehicle
CTCRDC	China typical city regenerative driving cycle
DC	direct current
ECE	European Union Urban Driving Cycle
EUDC	Extra Urban Driving Cycle
FCEV	fuel cell hybrid electric vehicle
HEV	hybrid electric vehicle
KERS	kinetic energy recovery system
NEDC	New European Drive Cycle
RBS	regenerative braking system
regen	regenerative braking
non-regen	no regenerative braking
SOC	state of charge

studied [13]. In regenerative braking control, present research mainly concentrates on the cooperation between regenerative braking and friction braking [6]. A control strategy coordinating the regenerative brake and the pneumatic brake is proposed [14], in order to recapture the braking energy and improve the fuel economy. There are three different braking control strategies for regenerative braking: non-regen, parallel regenerative brake control strategy, and serial 1 strategy. The non-regen one, is set as a baseline, and only friction brakes are utilized during deceleration; the parallel regenerative brake control strategy features an easy implementation without any other hardware needs to be added; for the serial 1 strategy, it coordinates the regenerative and friction brakes in real time, being advantageous over the parallel one with respect to the brake comfort and regeneration efficiency [15]. A new regenerative braking control strategy for rear-driven electrified minivans is designed [16]. Only the potential reduction in fuel consumption enabled by regenerative braking is introduced [17]. Mechanism analysis and evaluation methodology of regenerative braking contribution to energy efficiency improvement of electrified vehicles is proposed [18]. Extended-Kalman-filter-based regenerative and friction blended braking control for electric vehicle equipped with axle motor considering damping and elastic properties of electric powertrain is studied [19]. A contribution rate is proposed to evaluate the fuel economy of the vehicle improved by regenerative brake [20]. However, a few regenerative braking systems with detailed control strategies have been released, especially for contribution ratio to regenerative braking energy transfer efficiency during braking situations. Studies on evaluation of contribution to the energy efficiency improvement on vehicle level have seldom been reported.

In this paper, the authors study the evaluation of contribution brought by regenerative braking to the energy efficiency