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Comparison between two braking control methods integrating energy recovery for a two-wheel front driven electric vehicle

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ABSTRACT

This paper presents the comparison between two braking methods for a two-wheel front driven Electric Vehicle maximizing the energy recovery on the Hybrid Energy Storage System. The first method consists in controlling the wheels slip ratio while braking using a robust sliding mode controller. The second method will be based on ECE R13H constraints for an M1 passenger vehicle. The vehicle model used for simulation is a simplified five degrees of freedom model. It is driven by two 30 kW permanent magnet synchronous motor (PMSM) recovering energy during braking phases. Several simulation results for extreme braking conditions will be performed and compared on various road type surfaces using Matlab/Simulink®. For an initial speed of 80 km/h, simulation results demonstrate that the difference of energy recovery efficiency between the two control braking methods is beneficial to the ECE constraints control method and it can vary from 3.7% for high friction road type to 11.2% for medium friction road type. At low friction road type, the difference attains 6.6% due to different reasons treated in the paper. The stability deceleration is also discussed and detailed.

1. Introduction

The recent come-back and attractiveness of the Electric Vehicle (EV) is due to the improvement done on many components and subsystems constituting the vehicle, mainly: the battery in terms of energy and power density and the motor in terms of efficiency, high torque-to-weight ratio, high power-to-weight and more improved control systems. Joint-ventures of cars manufacturers and research cooperation also play an important role in the emergence of the EV.

The main focus and originality of the paper concern the comparison between two control methods of regenerative braking in terms of stability and potential energy recovery on several road types and conditions during braking operation while respecting the directives, regulations and constraints, preserving security and maneuverability of the vehicle. This proposed comparative study has not yet been encountered in literature. The EV considered for simulation is a two-wheel front driven vehicle. The electrical drive motors are 30 kW permanent magnet synchronous motors (PMSM).

The vehicle will be equipped with a pure mechanical braking system for the rear wheels and a hybrid electrical/mechanical braking systems in the front wheels, in order to take advantages of the charge transfer during braking. Fig. 1 illustrates the vehicle actuators and the components of the hybrid energy storage system.

Research works proposing regenerative braking control and vehicle stability are treated in [1–4]. It can be based either on several design control strategies like phase-plane control method for electric bus in [5], or vehicle model like rear-driven electrified minivans in [6]. The considered control variable is the wheel slip trying to avoid wheels skidding while braking and spinning while accelerating. Several control methods based on Lyapunov theory combined with optimal predictive control can be found in [7,8].

In this paper, it has been taken into consideration two types of braking control. The first one is a braking control system based on a sliding mode controller for longitudinal slip of the wheels, as used in literature by [9–11]. The second one is based on the inequality rules cited in the international Braking Regulation of the Economic Commission for Europe of the United Nations Organization No.13 Harmonized (UN/ECE R13H) for Road Vehicles of category M1 (vehicles used for the carriage of passengers and comprising not more than eight seats in addition to the driver's seat). An

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Nomenclature

Vehicle design parameters
m mass of the vehicle
r wheel radius
L wheelbase of the vehicle
l_r (respectively l_f) distance of the rear (respectively front) wheel axle to the center of mass of the vehicle
h distance from the ground to the center of mass of the vehicle
J_{wi} wheel inertia (i could be f for front, r for rear)

Constant coefficients
b viscous friction coefficient at each wheel axle
c_1, c_2 and c_3 Burckhardt tire model coefficients
g gravitational constant
c_D aerodynamic drag wind resistance coefficient
c_{roll} rolling resistance coefficient

Cinematic variables
$\ddot{x}$ acceleration/deceleration of the vehicle
j deceleration of the vehicle (positive value)
z deceleration rate
ω_{ij} the angular speed rotation of the wheel ij (i could be f for front, r for rear - j could be r for right, l for left)
μ_{ij} friction coefficient
λ_{ij} resultant slip coefficient
λ_{Lij} longitudinal slip coefficient
λ_{Sij} lateral slip coefficient
$\lambda_{Lij,ref}$ reference longitudinal slip coefficient
v_{wij} speed of the wheel ij
λ_{max} slip coefficient leading to a maximal friction coefficient for a certain road type and condition
v prescribed test speed
d stopping distance

μ_f (respectively μ_r) friction coefficient for the front (respectively rear) wheels

Dynamic Forces/Torques
F_{xij} friction force in the road-wheel contact patch acting on wheel ij in the direction of the vehicle longitudinal direction
$F_{roll,ij}$ rolling resistance force acting on wheel ij
F_{drag} aerodynamic drag force due to wind resistance
T_{mj} traction torque transmitted through the gear by the IPMSM at the front left or right wheel
T_{bij} braking torque acting on wheel ij
F_{zij} vertical normal force acting on the wheel ij
u_{ij} torque input of the slip controller
F_{bf} front braking force
F_{br} rear braking force
β ratio between friction front force and total friction force

Estimated dynamics and error bounds
s sliding surface
$\tilde{\lambda}_{Lij}$ slip error
η convergence rate of the $\tilde{\lambda}_{Lij}$
θ_c the boundary layer width
F boundary function for f
β' bounds on the estimation error on g
$\hat{c}_D, c_{Dmax}, c_{Dmin}$ estimated, minimal and maximal value of aerodynamic drag wind resistance coefficient
$\hat{m}, m_{min}, m_{max}$ estimated, minimal and maximal value of vehicle mass
$\hat{r}, r_{min}, r_{max}$ estimated, minimal and maximal value of wheel radius
$\hat{c}_{roll}, c_{rollmin}, c_{rollmax}$ estimated, minimal and maximal value of rolling resistance coefficient

anti-lock braking system (ABS) is being integrated. Other proposed braking mechanical/electrical cooperative strategies based on ECE working conditions, seen from different perspectives, can be found, for example, in [12] and [13] for rear wheel regenerative brake system for a three-wheel vehicle, [14] for a hybrid bus, [15] for introducing a new kind of brake-by-wire system called the direct drive electro-hydraulic brake and [16] for designing a longitudinal collision avoidance control. All these mentioned strategies are based on ECE regulations and constraints, each one fulfilling distinct special requirements in terms of vehicle type and working conditions, The proposed constraints control method is dedicated to a two-wheel front driven electric vehicle having in concern a maximal energy recovering capability, thus a maximal admissible front wheels braking forces application, while ensuring stability and security.

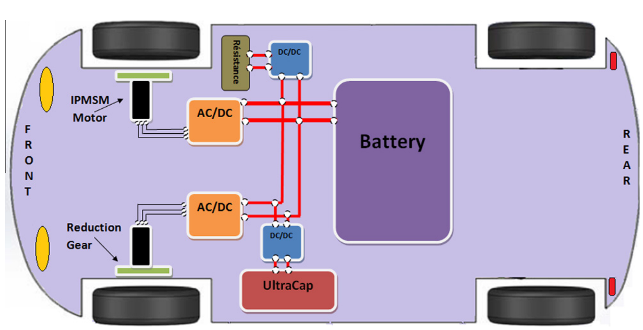

Fig. 1. Vehicle Actuators and HESS Components.

The PMSM type of motor is being chosen for its high power density, high efficiency, wide speed range and fast torque-response. Its control will be integrated in the model and used for simulation purposes in order to output the electrical torque, electrical power and recovered energy quantity. Inputs and outputs of each model and control block used for the system are presented in Fig. 2. The output energy will be recovered by a hybrid energy storage system (HESS). These blocks are modeled in Simulink® software.

Mathematical model of the vehicle is described in Section 2. Section 3 presents the sliding mode (SM) slip controller. In Section 4, the proposed braking control based on ECE R13H constraints regulation controller has been designed and explained. The HESS is briefly described in Section 5. Finally, a discussion on the results and control strategies is taken up in Section 6 where some of Matlab/Simulink® blocks and details will be shown. System simulation results will be analyzed and compared according to various road types.

2. Vehicle modeling

2.1. Longitudinal force equilibrium

The vehicle model is presented extensively in [17–20]. The model will be based on a 5 degrees of freedom model taking into consideration the longitudinal movement and the rotation of the