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Comparative analysis of two hybrid energy storage systems used in a two front wheel driven electric vehicle during extreme start-up and regenerative braking operations

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ABSTRACT

This paper presents the comparative study of two hybrid energy storage systems (HESS) of a two front wheel driven electric vehicle. The primary energy source of the HESS is a Li-Ion battery, whereas the secondary energy source is either an ultracapacitor (UC) or a flywheel energy system (FES). The main role of the secondary source is to deliver/recover energy during high peak power demand, but also to increase battery lifetime, considered among the most expensive items in the electric vehicle. As a first step, a techno-economic comparative study, supported by strong literature research, is performed between the UC and the FES. The design and sizing of each element will be presented. The comparison criteria and specifications are also described. The adopted approach in this paper is based on an academic non-oriented point of view. In a second step, each of the HESS will be integrated in a more global Simulink model which includes the vehicle model, the traction control system (TCS), the regenerative braking system and the vehicle actuators. Simulation tests are performed for an extreme braking and vehicle starting-up operations. Tests are realized on two different surface road types and conditions (high and low friction roads) and for different initial system states. In order to show the most appropriate storage system regarding compactness, weight and battery constraints minimization, deep comparative analysis is provided.

1. Introduction

Since 2004, the number of electric vehicle (EV) manufacturers has substantially increased, motivated by three majors factors which are the industry, the technology and the market [1]. From a technological point of view, the constraints related to the acceptance of electric vehicles by the public consist of a restricted autonomy of the vehicle and a lack of developed infrastructure (charging terminals, standardization of accessories, sales channels and distribution, technical support, after-sales service, spare parts...). The research and development efforts carried out on batteries, fuel cells and other alternative energy source have direct effects on the autonomy issue [2]. On the other hand, the climate changing (estimated average temperature raising of 6 °C by 2050 [3] and atmospheric concentration of greenhouse gases [4]) is another incentive for researchers and users to elaborate and encourage the clean energy approach.

Thanks to what has been cited above, adding also the technological advances, the scarcity of oil as well as economic and strategic reasons (energy consumption, energy independence strategy), the electric vehicle industry resumes its emergence. This recovery stands on seven main pillars: (1) improvement in battery technologies [2], (2) rise of infrastructure [5,6], (3) commercial offer in evolution, (4) a further partnership between manufacturers, (5) an almost final conclusion for manufacturers stating that the electric vehicle could represent a larger market share in the future, which encouraged competition and therefore investment at all levels, (6) technology sponsored by the governments [7], and laws [8,9], (7) a more mastered technology which led the most reluctant manufacturers [10] to announce their presence in the market for e-mobility.

Energy storage elements for electric vehicles have their share portion in the technological advances. As primary energy storage, the battery has a high energy density but a low power density. The use of other energy storage elements with a high power den-

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Nomenclature

Vehicle design variables and 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_g	distance from the ground to the center of mass of the vehicle
E_{ke}	kinetic energy of the vehicle
V	vehicle velocity

Cinematic variables

μ_{max}	maximal friction coefficient for a certain road
λ_i	slip coefficient of the wheel i
λ_{max}	slip coefficient corresponding to a maximal friction coefficient
β_{hb-max}	ratio between friction front force and total friction force assuring maximal front/rear braking ratio

Ultracapacitor electrical variables and parameters

U_{c0}	voltage across capacitor
U_{c0min}	ultracapacitor minimal voltage
U_{c0max}	ultracapacitor maximal voltage
I_{c0}	ultracapacitor current
C_0	ultracapacitor capacitance
P_0	ultracapacitor maximal power
ΔE_{UC}	total energy to be recovered from an UC
E_{UC}	energy capacity of the UC

Flywheel energy system variables and parameters

T_{FW}	flywheel torque
J_{FW}	moment of inertia of the flywheel
ω	angular rotation speed
r_o	outer radius
r_i	inner radius
h	length of the flywheel cylinder
ρ	rotor material density
σ_r	radial stress
σ_t	tangential stress
ν	poisson ratio
K	shape factor of the flywheel
N_{max}	maximal permissible speed
σ_{tmin}	minimal tensile strength
E	energy stored in the fywheel
E_{FW}	energy capacity of the FES
E_{lim}	energy limit achieved
e_v	kinetic energy per volume
e_m	kinetic energy per unit mass

Flywheel electrical motor variables and parameters

K_w	winding factor
A	specific electric loading
B_{gav}	specific magnetic loading
L_m	length of the machine
D	diameter
D_{in}	inner diameter
D_{out}	outer diameter
N	machine rotational speed
N_c	number of conductors in series per phase
E_v	electromotive force
η	power efficiency
$\cos\varphi$	power factor
P_{kW}	output power
Φ_p	flux per pole
f	frequency
p	number of poles

Abbreviations

ABS	Anti-Lock Braking System
CFT	Clutched Flywheel Transmission
CVT	Continuous Variable Transmission
EDLC	Electric Double Layer Capacitors
ECE	Economic Commission for Europe
ESS	Energy Storage System
EV	Electric Vehicle
FES	Flywheel Energy Storage
FIA	Fédération Internationale de l'Automobile
FW	Flywheel
HESS	Hybrid Energy Storage System
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ISG	Integrated Starter Generator
KERS	Kinetic Energy Recovery System
SEI	Solid Electrolyte Interface
SOC	State of Charge
SOE	State of Energy
TCS	Traction Control System
UC	Ultracapacitor
UN	United Nations
WHP	William Hybrid Power

sity, known as secondary energy storage, aims to complement the battery especially in regenerative braking and start up of the vehicle. This substitution will enhance the battery life as well as the dynamic performance of the vehicle. The combination of the two energy storage elements requires power electronics based converters associated with control and measurement instrumentation, known as hybrid energy storage system (HESS). The secondary energy storage could be either a flywheel or an ultracapacitor (UC).

1.1. State of the art

The flywheel and the UC have both draw researchers' attention as a secondary energy storage element. High-speed flywheels are a potential emerging technology with competitive characteristics if compared to established battery and ultracapacitor in certain vehicular applications.

A general presentation of energy storage technologies can be found in [11–14]. Authors in [12] address various aspects such as historical evolution of energy storage systems, technical characteristics and interaction between smart grid and micro-grids applications. For automotive application, authors in [15] make a review on the flywheels used on vehicles. General comparisons with supercapacitors are also treated, in terms of rated power, energy capacity, specific energy, specific power, system weight and cost. The comparison data specifications had been taken from the energy storage elements manufacturers. The comparison is carried out as an apple to apple comparison, without any particular applications. Tables of flywheels research groups and manufacturers are also listed with their fields of interest.

Optimal energy management for a battery assisted by flywheel for EV is being proposed in [16,17]. The flywheel is coupled to the drive line of a continuous variable transmission (CVT). The results