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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*

| | |
|---|---|
| $\mu_{max}$ | maximal friction coefficient for a certain road |
| $\lambda_i$ | slip coefficient of the wheel $i$ |
| $\lambda_{max}$ | slip coefficient corresponding to a maximal friction coefficient |
| $\beta_{hb-max}$ | 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 |
| $\Delta E_{UC}$ | 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 |
| $\omega$ | angular rotation speed |
| $r_o$ | outer radius |
| $r_i$ | inner radius |
| $h$ | length of the flywheel cylinder |
| $\rho$ | rotor material density |
| $\sigma_r$ | radial stress |
| $\sigma_t$ | tangential stress |
| $\nu$ | poisson ratio |
| $K$ | shape factor of the flywheel |
| $N_{max}$ | maximal permissible speed |
| $\sigma_{tmin}$ | 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 |
| $\eta$ | power efficiency |
| $\cos\varphi$ | power factor |
| $P_{kW}$ | output power |
| $\Phi_p$ | 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