

A lithium battery and ultracapacitor hybrid energy source for an urban electric vehicle

Abstract. In this article simulation results of hybrid energy source performance for a small urban electric car are presented. The main energy storage based on LiFePO_4 cells exploited at low temperatures deteriorates significantly performance reducing range and dynamics of the vehicle. An improvement of properties can be achieved through supporting the main storage by an ultracapacitor energy storage. Based on the developed hybrid energy source model the advantages of usage of an additional source are presented.

Streszczenie. W artykule przedstawiono wyniki badań symulacyjnych ukazujące korzyści hybrydyzacji źródła energii dla miejskiego samochodu elektrycznego. Podstawowy magazyn energii oparty na ogniwach LiFePO_4 eksploatowany w niskich temperaturach znacząco pogarsza swoją wydajność, obniżając zasięg i możliwości dynamiczne pojazdu. Poprawę właściwości można uzyskać wspierając podstawowy magazyn superkondensatorowym magazynem energii. Na podstawie stworzonego modelu hybrydowego źródła energii pokazano zalety stosowania dodatkowego źródła. (**Litowo-superkondensatorowe hybrydowe źródło energii dla miejskiego pojazdu elektrycznego**)

Słowa kluczowe: magazyn energii, superkondensator, hybrydowe źródło energii, pojazd elektryczny

Keywords: energy storage, ultracapacitor, hybrid energy source, electric vehicle

Introduction

A high-performance on-board electric energy storage is the main obstacle to development of electric vehicles available at more affordable prices. In order to ensure high efficiency and good motion properties there are imposed many requirements on electrical energy sources, as high power and energy density, long cycle-life, reliability, wide temperature range and no emission of pollutants. The most common energy storages/sources in electric vehicles are fuel cells, electrochemical batteries and ultracapacitors. However, installing only one type of energy storage/source is often insufficient, so many applications use a hybrid energy storage, consisting of more than one type, to complement the each single type drawbacks.

Hybridization of the source enables us to solve some key problems encountered in electric vehicles as:

- regenerative braking, while the main source of energy is unidirectional (e.g. fuel cell [1,2]) or availability of fast charge is heavily limited (e.g. lead-acid battery [3]),
- providing large power pulse, while the main source is designed to average power (e.g. energy storage based on molten-salt battery [4]),
- significant deterioration of energy storage performance in harsh exploitation conditions (e.g. sub-zero winter temperatures) [5].

Examples of energy storages, which are sensitive to the operating conditions are those made from popular LiFePO_4 cells. This type of lithium battery provides the energy density at the level of 80-110Wh/kg [6,7] and power density at the level of 500W/kg [7] in pulse, which may satisfy the dynamic requirements of an electric vehicle. However, decent performance relates solely to temperatures close to nominal (25°C). Low temperatures and high currents (above 1 C-rate) cause a drastic decrease in capacity and increase internal resistance which in turn causes reduction in range of the vehicle, deterioration of the efficiency and reduces power [6,8-11]. High temperatures and currents also significantly reduce the battery life time [12,13].

Battery performance improvement can be achieved by using additional ultracapacitors, which will reduce the battery current. Since there are no chemical variations on the electrodes in ultracapacitors they are characterized by small changes in capacitance and resistance with temperature, long life and high power density above 6000W/kg [14]. However, relatively low energy density at the level of 5Wh/kg [14] excludes the possibility of use commercially available off the shelf ultracapacitors as the main energy storage in an electric vehicle.

Hybrid energy storage for EV

There are many possible topologies for a battery and ultracapacitor hybrid [15]. Figure 1 shows basic approaches to combining energy sources. In the simplest configuration (Fig 1a), the energy storages are connected in parallel with each other and the load. The same terminal voltage of device causes that difference in power distributions between them is determined only by their internal resistance. Passive hybrid is suitable for use in supply starter motors but is ineffective for source of propulsion power for electric vehicles. In order to optimize merging of ultracapacitors and batteries into one pack power electronic converter is required to manage power flow between them and main DC bus of drive converters. Figure 1b shows one instance of active hybrid. This topology allows direct exchange of energy between the load and capacitors without the use of converter, which is advantageous for frequent vehicle dynamic states. The main flow of energy from the battery is controlled by a DC-DC converter, which enables power division but increases losses. Moreover, such a system imposes constraints on the ultracapacitor voltage acceptable values. The output voltage must be greater than the BEMF of drive motors. This in turn forces us to use high voltage ultracapacitors storage, what is less effective, because of the usage of smaller cells, which have worse properties [14]. In an alternative system topology (Fig. 1c) an additional storage is connected to the battery through bidirectional DC-DC converter. This configuration has been selected for implementation in this research. The DC-DC converter allows proper division of power load between two storages as well as control of energy flow between storages, in order to maintain the proper voltage on ultracapacitors.

The goal of control strategy of active hybrid energy storage is to cover average power demand from main source (battery) and at the same time to cover all power fluctuation related to deceleration and acceleration from ultracapacitors. The ultracapacitor source is recharged during regenerative braking or from batteries at periods of low power demand. Table 1 presents parameters of a battery pack applicable in small electric car dedicated for urban areas. Such an energy storage provides ca. 100km driving range for the car in nominal conditions. A range like this is acceptable for such a vehicle if the design is aimed at commuters. Parameters of proposed ultracapacitors pack are presented in Table 2. The size of pack is determined by expected maximal value of pulse power in dynamic states and maximal energy recovered during deceleration.

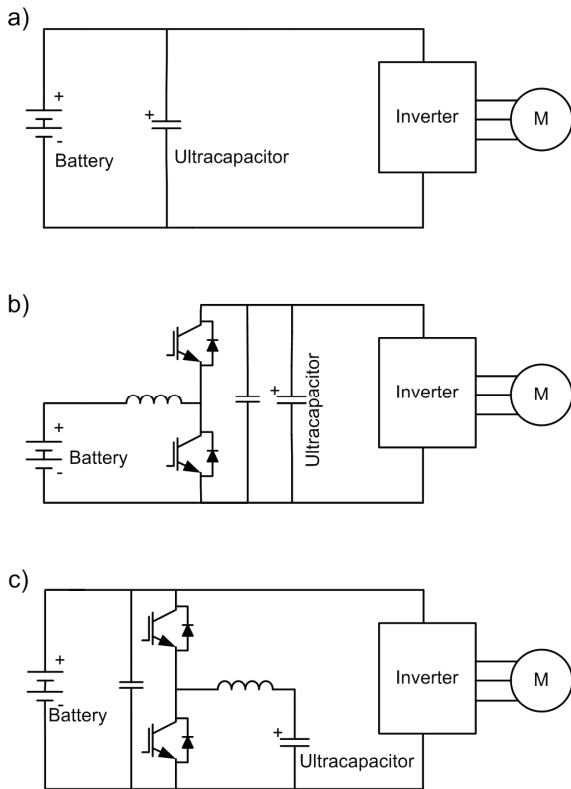


Fig.1. Hybrid energy storage systems: a) passive hybrid, b) active hybrid with low voltage batteries and high voltage ultracapacitors, c) active hybrid with low voltage ultracapacitors and high voltage batteries

Table 1. Battery pack for small electric vehicle

Battery energy storage	
Voltage	165V
Cell	LiFePO4 - EVPST-55AH
Current capacity	55Ah
Energy	9.1 kWh
Mass	110kg

Table 2. Ultracapacitor pack for small electric vehicle

Ultracapacitor energy storage	
Voltage	105V
Cell	Maxwell K2 series
Capacity	50F
Energy	0.081kWh
Mass	14.5kg

Simulation Model

The following section describes models of components of the hybrid energy storage and model of a vehicle with its powertrain. Developed models are employed to simulate power flow, to estimate power losses, and to estimate overall efficiency and range of the car. All models are coded in Matlab / Simulink environment using the PLECS toolbox.

A. Battery model

The dynamic characteristics of the battery pack is modelled by Thevenin-based model [8,16-18], shown in Figure 2, where U_{OCV} corresponds to open circuit voltage of the battery and is a function of the state of discharge (SOD). A resistor R_S connected in series with a parallel RC branch models an ohmic drop and polarization effect [8,19,20].

A discharge capacity change resulting from change in discharge current and temperature is modelled using method described in [8,21]. Model parameters are based on cells manufacturer's data [7]. In addition battery model includes internal resistance variation as a function of SOC [6,20] and temperature [6,10,11]. Figure 3 shows

comparison of simulation result and real characteristic published by the manufacturer [7].

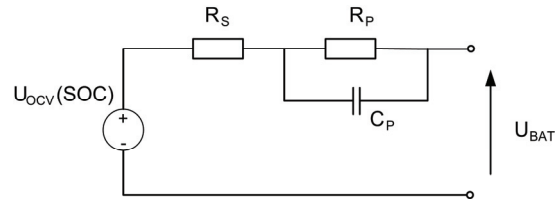


Fig.2. Electrochemical battery model

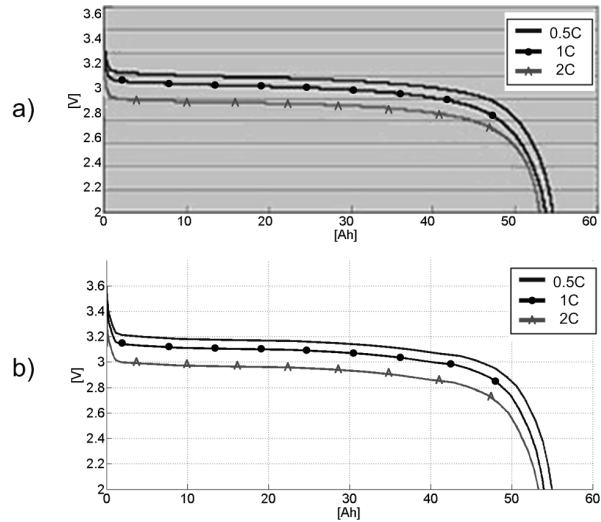


Fig.3. Discharge characteristic. a) real data b) simulation results

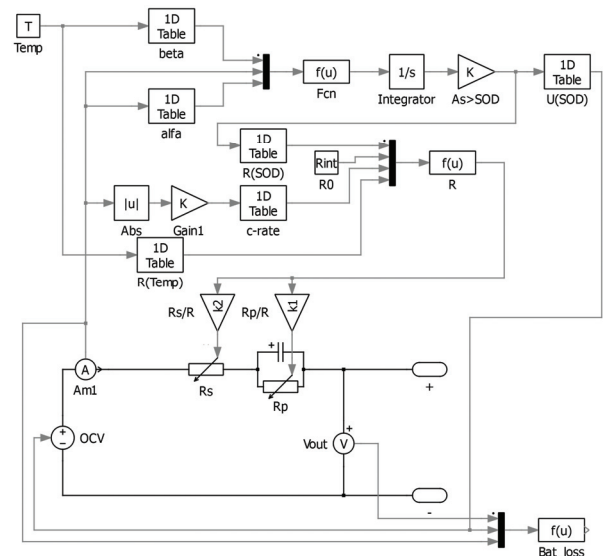


Fig.4. PLECS circuit of battery model.

B. Ultracapacitors model

The simplified ultracapacitor model is shown in Figure 5. This model is composed of a resistor R , which is responsible for the electrical losses due to non-zero internal resistance of an ultracapacitor, and a capacitor C , which corresponds to ultracapacitor's capacitance [22]. Model does not take into account the transient voltage change in dynamic state, but is sufficient to evaluate power losses. Value of R resistance is set to ESR (Equivalent Series Resistance) for worst case scenario, i.e. highest DC current. The change in capacitance and resistance related to the temperature [14] is calculated in initialization commands.

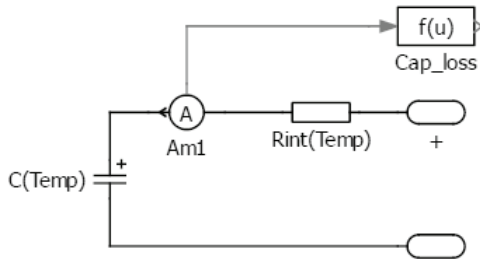


Fig.5. PLECS circuit of ultracapacitor model

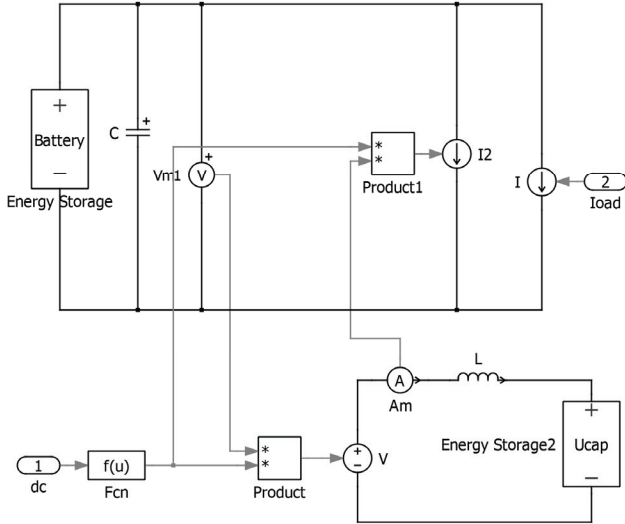


Fig.6. PLECS circuit of the active hybrid energy source.

C. DC converter losses

A continuous model of the converter was implemented at this stage of simulation. An IGBT+D power losses were calculated based on equations (1-8) [23] and Semikron SK100GB066T module parameters given in [24].

Losses per transistor:

- (1) $P_{cond_tr} = D \cdot (I_{tr} \cdot V_T + I_{tr}^2 \cdot r_T)$
- (2) $E_{sw} = E_{on} + E_{off}$
- (3) $P_{sw_tr} = f_{sw} \cdot E_{sw} \cdot (I_{tr} / I_{rated}) \cdot (V_{tr} / V_{rated})$
- (4) $P_{tr} = P_{cond_tr} + P_{sw_tr}$

Losses per diode :

- (5) $P_{cond_d} = (1-D) \cdot (I_d \cdot V_T + I_d^2 \cdot r_T)$
- (6) $P_{sw_d} = f_{sw} \cdot E_{rr} \cdot (I_d / I_{rated}) \cdot (V_d / V_{rated})$
- (7) $P_d = P_{cond_d} + P_{sw_d}$

Total losses :

- (8) $P_{tot} = P_{tr} + P_d$

where: D - duty cycle, I_{tr} - transistor current, I_d - diode current, I_{rated} - rated current, V_{tr} - transistor voltage, V_d - diode voltage, V_{rated} - rated voltage, V_T - threshold voltage, E_{off} - energy dissipation during turn-off time, E_{on} - energy dissipation during turn-on time, E_{rr} - energy dissipation during reverse recovery (diode), r_T - forward slope resistance, f_{sw} - switching frequency.

D. Vehicle dynamics and resistance forces

Figure 7 shows a schematic diagram of a vehicle model that calculates vehicle speed based on power consumed from the source. Wheel power is calculated taking into account the efficiency of the drive and direction of the

power flow. The resultant resistance force is a sum of rolling resistance forces (9) and aerodynamic resistance (10). It is assumed that the car is equipped with speed controller to enable tests under standardized speed cycles.

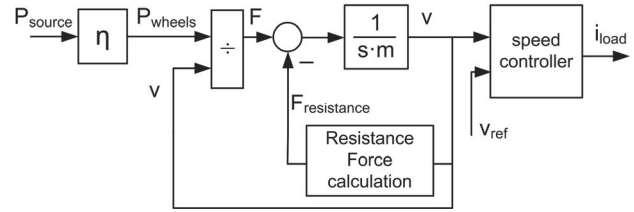


Fig.7. Vehicle dynamics model

$$(9) \quad F_R = m \cdot g \cdot f_0$$

$$(10) \quad F_A = \frac{1}{2} \cdot \rho_A \cdot C_x \cdot S \cdot v^2$$

where: m - mass, g - gravitational acceleration, f_0 - road friction coefficient, C_x - aerodynamic resistance coefficient, S - car frontal surface, v - speed of a vehicle.

Simulation

A comparison tests of the non-hybrid lithium battery source and described hybrid source were carried out. Two reference driving cycles were taken into account. Speed profiles are shown in Figures 8 and 9. The ECE15 is a normalized European driving cycle for urban area. It is characterized by constant acceleration which is rarely seen during real driving. Second cycle represents real variations of speed, recorded during medium traffic conditions in Warsaw using GPS receiver with sample time less than 2 seconds. This cycle is characterized by more frequent changes of speed and larger accelerations at low speeds in comparison to the ECE15.

Table 3 shows parameters used in the implementation of the simulation model. Assumed vehicle attributes correspond to a small urban car [25], and rolling resistance coefficient corresponds to dry asphalt or concrete road [26].

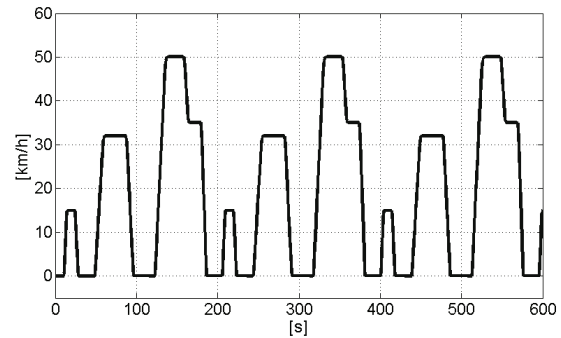


Fig.8. Normalized driving cycle ECE15

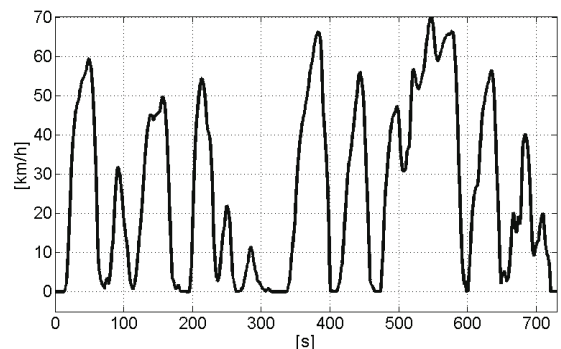


Fig.9. Driving cycle recorded in Warsaw on 01.06.11 between 08:50 and 09:05 a.m. (Bus line No.525)

Table 3. Model parameters

Parameter	Value
total mass - m	1100kg (+20kg for hybrid)
aerodynamic coefficient - C_x	0.34
car frontal surface - S	2 m ²
rolling friction coefficient - f_0	0.012
converter switching freq.- f_{sw}	15kHz
efficiency of powertrain - η	85%

Table 4. Simulation result for fresh cells

		ECE15		Real cycle	
		Battery	Hybrid	Battery	Hybrid
35°C	Range	116.01	122.22	94.44	100.14
	Power losses	3.51%	2.38%	4.51%	3.25%
25°C	Range	114.97	121.19	92.98	99.2
	Power losses	3.77%	2.70%	4.86%	3.66%
10°C	Range	102.48	115.99	80.9	92.99
	Power losses	6.19%	2.97%	7.82%	4.24%
0°C	Range	88.95	112.86	75.7	90.63
	Power losses	7.93%	3.26%	10.40%	4.88%
-5°C	Range	71.25	109.77	65.35	87.81
	Power losses	8.95%	3.61%	11.04%	5.30%

Differences in temperatures of individual cells have not been investigated at this stage. A uniform temperature was assumed. The results presented in Table 4 refer to a fresh cell with nominal properties.

This clearly shows that the hybridization effect on improving the performance of vehicle, especially at low temperatures, is not negligible, and should be taken into account as technically justified. Larger range of the vehicle with hybrid source results not only from increased efficiency but also from a smaller decrease in capacity. This is due to smaller battery currents. For the battery source in ECE15 cycle at 0°C range reduction is 22.6% and 38% at -5°C, whereas for the hybrid it is 6.8% and 9.4% respectively. This means ca. 24km and 39km more for the discussed car if equipped with hybridized energy storage.

A hybrid source limits the maximum current of the battery through supporting power flows during acceleration and deceleration phases by ultracapacitors. When driving at a constant speed power consumption is supported only from batteries. Power distribution between storages is shown in Figures 10 and 11.

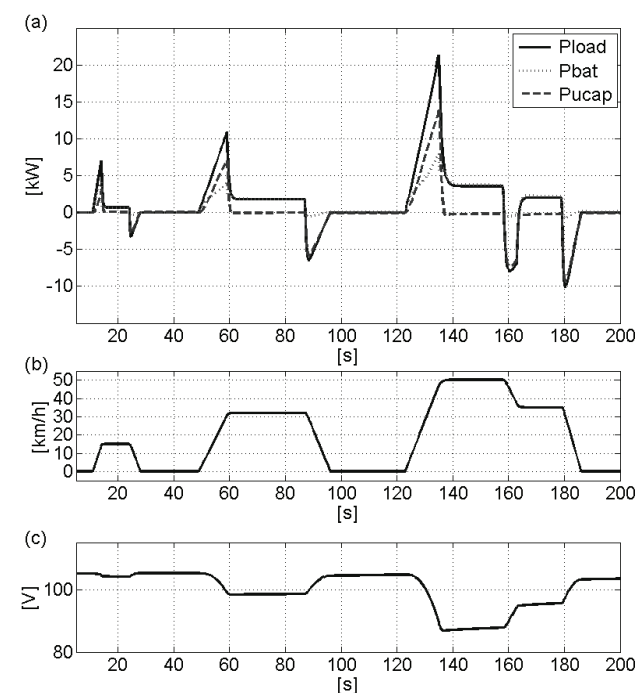


Fig.10. a) Power distribution in ECE15, b) vehicle speed, c) ultracapacitors voltage

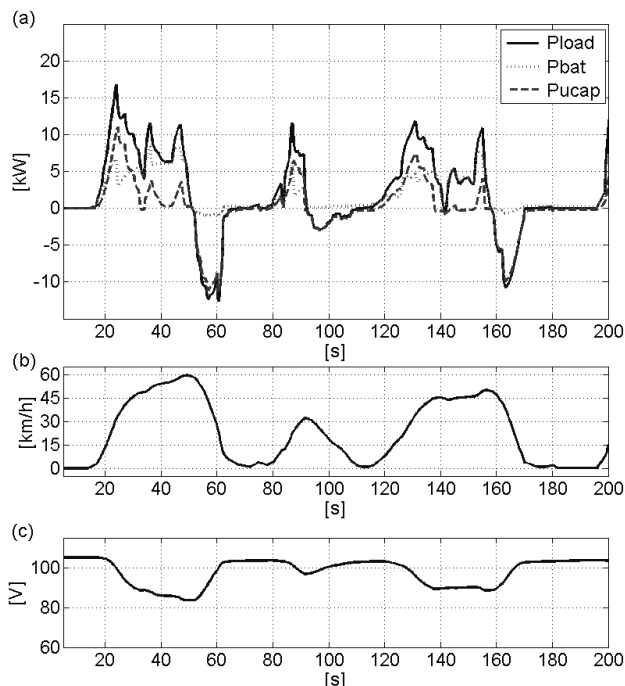


Fig.11. a) Power distribution in real cycle (Fig. 9), b) vehicle speed, c) ultracapacitors voltage

Operating parameters of both batteries and ultracapacitors deteriorate with time and with the increased number of charging-discharging cycles. Their lifetime performance is strongly dependent upon the conditions under cells are being used, so it's difficult to definitely determine how the aging process will proceed. Further simulations (Table 5.) were run for battery that is about half of its life. It was assumed based on studies in [11, 27] that for such battery capacity decreases by 10%, its internal resistance increases by 20%. Assuming that one cycle of the battery corresponds to 200 full cycles of capacitors, it can be estimate that the capacitor lifetime is 2-3 times longer than batteries [7,14]. For the case of a half-life battery the 5% decrease in ultracapacitors' capacity and 20% increase in ultracapacitors' resistance is assumed based on test results published in [28].

Table 5. Simulation results for half-life cells

		ECE15		Real cycle	
		Battery	Hybrid	Battery	Hybrid
35°C	Range	103.5	107.63	80.88	86.05
	Power losses	4.58%	2.74%	5.84%	3.85%
25°C	Range	101.43	106.59	80.28	85.41
	Power losses	4.93%	2.82%	6.04%	3.98%
10°C	Range	84.79	101.41	65.35	79.82
	Power losses	8.52%	3.53%	9.80%	5.17%
0°C	Range	43.15	98.2	---	75.7
	Power losses	10.53%	4.23%	---	5.99%
-5°C	Range	---	95.19	---	70.93
	Power losses	---	4.39%	---	6.54%

When battery is partially used up supporting by ultracapacitors is more significant. In the low temperature deterioration of power performance is so serious that the vehicle is not able to drive in accordance with aforementioned driving cycles. This problem is solved by a

hybrid source, where most of the power pulse is provided by the ultracapacitors. This clearly shows that in this case hybridization is not only technically justified, but is essential to maintain dynamics of the vehicle.

Money, weight and volume issues

Hybridization, besides substantial benefits imposes greater requirements. For studied case, mass of LiFePO₄ cells is 110kg and volume is 60 dm³ [7]. Additional storage mass is a 13% (14.5kg) of batteries mass and its volume is 15dm³ [14]. Hybridization increases significantly the cost of energy source. Retail price of the ultracapacitor pack (Table 2) and converter is 50% of price of the battery cells (Table 1) and battery management system. However ultracapacitors prices are still coming down and this fall is stronger than in battery case [29]. Despite these costs, hybrid energy source may be profitable through extending lifetime and vehicle range as well as through preserving power capability under all conditions.

Conclusion

The paper presents the benefits of hybridization of an energy storage for an urban electric vehicle. Simulation results show how combination of lithium batteries and ultracapacitors improves the efficiency and reliability of the source. The hybridized source can provide desired maximal power independently to battery ageing process, in various temperature conditions. Energy recovered during regenerative braking is stored firstly in ultracapacitors, which makes this process more efficient than in case of storing it in an electrochemical battery. At the same time hybridization reduces the maximum battery current and number of executed cycles, slowing down battery ageing process and extending time periods between maintenance (costly battery replacement operations).



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