TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
ELECTRICAL ENGINEERING | ELEKTROTECHNIKA

1-E/2016

DOI: 10.4467/2353737XCT.16.037.5299

MACIEJ WIECZOREK, MIROSŁAW LEWANDOWSKI*

HYBRID ENERGY STORAGE SYSTEM FOR ELECTRIC VEHICLES

HYBRYDOWY ZASOBNIK DO ZASTOSOWANIA W POJAZDACH ELEKTRYCZNYCH

A b s t r a c t

The paper presents a model of hybrid energy storage, which allows to connect any number of modules to the system. Due to significant differences in the performance of various types of modules, such as power, and energy density, price, operating temperature, etc., combining them into a single system allows to extend their lifetime or reduce weight. The main objective of the authors was to provide a method for power distribution among devices making up the system, which ultimately will enable an optimisation of the power management strategy. An important parameter of the system is the possibility of its adjustment and upgrades. The summary identifies further directions of research.

Keywords: hybrid energy storage system, power control algorithm, electric vehicle, hybrid power supply, power control simulation

S t r e s z c z e n i e

W artykule przedstawiono model hybrydowego zasobnika energii, który umożliwia dołączenie do systemu dowolnej liczby zasobników. Ze względu na znaczne różnice w parametrach różnych typów zasobników, takich jak gęstość mocy i energii, cena, temperatura pracy itp., połączenie ich w jeden system umożliwia wydłużenie ich życia czy zmniejszenie masy. Głównym celem autorów było przedstawienie metody rozdziału energii pomiędzy urządzenia wchodzące w skład systemu, która docelowo umożliwi optymalizację strategii zarządzania energią. Ważnym parametrem systemu ma być możliwość jego konfiguracji i modernizacji. W podsumowaniu określono dalsze kierunki badań.

Słowa kluczowe: hybrydowy zasobnik energii, algorytm sterowania mocą, pojazd elektryczny, hybrydowe źródło mocy, symulacja regulacji mocy

* M.Sc. Eng. Maciej Wieczorek, Ph.D. D.Sc. Eng. Mirosław Lewandowski, Faculty of Electrical Engineering, Warsaw University of Technology.

1. Introduction

Dynamic development of autonomous [1–6] and network-powered [8, 11] electrified transportation at the turn of the last century enforces further research of more efficient energy storage systems (ESS). Inefficiency and low energy density, as compared to liquid fuels, is a major obstacle for the development and dissemination of autonomous electric vehicles. ESS used in traction power systems allow the management of energy received during regenerative braking [7] and power supply in the states of low voltage in the catenary [8]. ESS with an output power range from 1 to 100 MW are used in the power system, in which their task is to equalise the loads and improve energy quality [9]. Despite the intensive work performed on the construction of electrochemical batteries, especially lithium-ion (li-ion) technology in terms of energy density, which in the case of li-ion battery is approx. 200 Wh/kg, they are not able to match values obtained for fossil fuels (diesel – 26000 Wh/kg). The current ESS solutions, however, are able to cover a significant part of the mentioned applications. Other issues for the different types of ESS are low power density, which is directly connected with charging time, and conditions, such as operating temperature, lifetime and price. In this case, the solution turned out to be a hybrid energy storage system (HESS). The combination of two or more types of energy storage devices in the system allows to obtain their best performance, prolongation of life and reduce their weight in comparison with the ESS using only one type of batteries [10]. The most-common types of devices used in HESS systems are li-ion batteries and supercapacitors. Li-ion batteries have the highest energy density of electrochemical energy storages, but they also have significant limitations of the load and charging current. Supercapacitors can take and give much more power; however, the energy stored in the unit of mass is about ten times smaller than in li-ion batteries [12]. Therefore, the battery is used as proper energy storage and the supercapacitor supports the battery in dynamic load conditions and collects the energy gained during regenerative braking. HESS systems also consider the use of other types of energy storages. For electrochemical batteries, lead-acid batteries have the lowest price per unit of stored energy, but due to their high weight, installing them in a vehicle involves additional energy losses. The fuel cells are taken into account because of the high energy density, however, limited access to the infrastructure supplying liquid oxygen and low efficiency decrease their potential possibility to be used in electric vehicles. High-speed flywheels and superconducting coils are also worth to be taken into consideration as a part of HESS. Different configurations of HESS systems and energy management strategies are presented in [2–6, 9, 10, 12].

Depending on the demand for power and energy as well as the working conditions of the system, it may be advantageous to build HESS with more than two types of energy storages. There is also the possibility of connecting the generating devices to the network on the same principle as the storages, provided that the energy transfer is possible only in one direction. Figure 1 presents a diagram illustrating the parameters of various types of energy storage devices, which is helpful in selecting the optimal configuration and power management strategies for HESS.

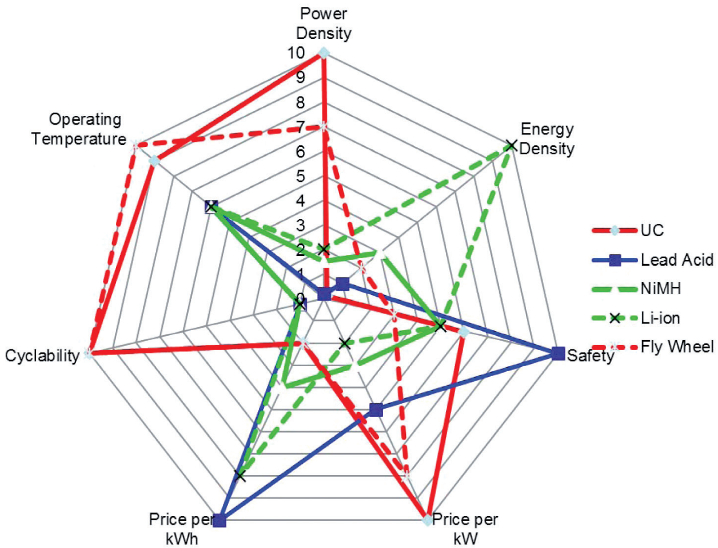

Fig. 1. Diagram showing the parameters of the different types of energy storage on a scale of 0 (worst) to 10 (best)

2. Converter model

There are many topologies of buck-boost *DC*/*DC* converters. The study used a half-bridge configuration, due to the highest efficiency [14, 15]. A half-bridge converter is a power electronic device whose static and dynamic properties depend mainly on the type of driver and the semiconductor connectors. A common feature of the connectors is the ability to work in two states: conducting state in which even at very large values of current flowing through the switch, the voltage drop on it is limited to a few volts, and barrage state, in which even at very high voltages at the terminals of the connector the current flowing through it does not exceed the value, expressed in milliamps. We adopted a mathematical description of the connector as an ideal switch between two states: the conducting state ($g_{ij} = 1$) and the barrage state ($g_{ij} = 0$).

In the boost mode, the T_{i1} transistor is off ($g_{i1} = 0$), and the T_{i2} transistor is in a conductive or a barrage state. The dynamics of the system shown in Fig. 2 are described by the following equations:

$$g_{i1} = 0,\ g_{i2} = 0$$

$$L_i \frac{di_{Li}(t)}{dt} = u_{Zi}\left(i_{Li}(t)\right) - u_{DC} - R_i i_{Li}(t) \quad i = 1, 2, \ldots, n \tag{1}$$

$$g_{i1} = 0,\ g_{i2} = 1$$

$$L_i \frac{di_{Li}(t)}{dt} = u_{Zi}\left(i_{Li}(t)\right) - R_i i_{Li}(t) \quad i = 1, 2, \ldots, n \tag{2}$$

where:

L_i – inductance in the branch of the *i*-th energy storage device,
R_i – resistance in the branch of the *i*-th energy storage device,

$i_{Li}(t)$ – current w in the branch of the i-th energy storage device,
$u_{Zi}(i_{Li}(t))$ – voltage of the i-th energy storage device,
u_i – Ti_2 transistor voltage,
n – number of energy storage devices connected to the system.

In the buck mode, the T_{i2} transistor is off (g_{i2} = 0), and the T_{i1} transistor is in conductive or barrage state.

$$g_{i1} = 1,\ g_{i2} = 0$$

$$L_i \frac{di_{Li}(t)}{dt} = u_{Zi}\left(i_{Li}(t)\right) - u_{DC} - R_i i_{Li}(t) \tag{3}$$

The commutation phase is described by following equation:

$$g_{i1} = 0,\ g_{i2} = 0,\ \mathrm{sgn}[i_{Li}(t)] = -1$$

$$L_i \frac{di_{Li}(t)}{dt} = u_{Zi}\left(i_{Li}(t)\right) - R_i i_{Li}(t) \tag{4}$$

When the i_{Li} reaches 0:

$$g_{i1} = 0,\ g_{i2} = 0,\ \mathrm{sgn}[i_{Li}(t)] = -0 \tag{5}$$

Taking into account the relations (1.1–1.5), we can obtain the equation for all states of the converter.

$$L_i \frac{di_{Li}(t)}{dt} = u_{Zi}\left(i_{Li}(t)\right) - R_i i_{Li}(t) - u_i\left(u_{DC}, u_{Zi}, g_{i1}, g_{i2}, \mathrm{sgn}[i_{Li}(t)]\right) \tag{6}$$

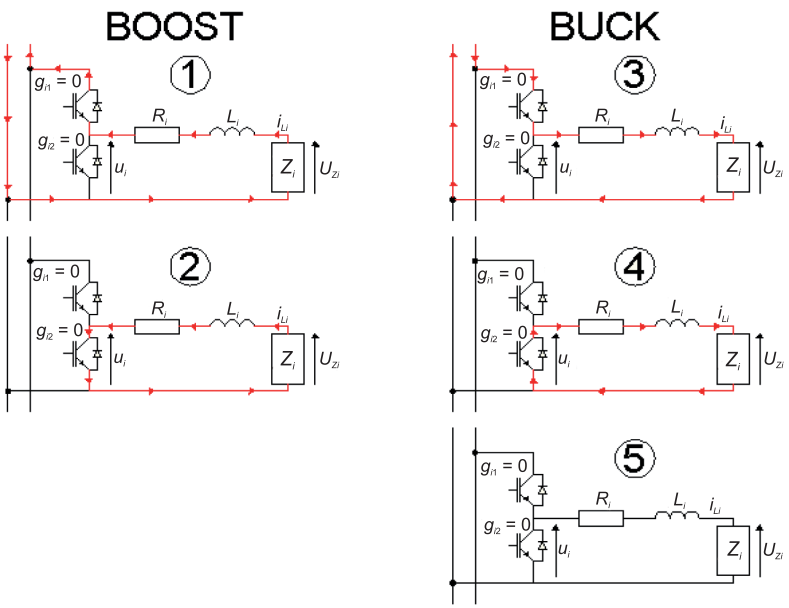

Fig. 2. Equivalent circuit of the converter including energy storage device (Zi) and current flow for different switching states

Where u_i is described by the following function:

$$u_i = u_{DC}\left|\left(\frac{\operatorname{sgn}[i_{Li}(t)]+1}{2}\operatorname{sgn}[i_{Li}(t)]\right)-g_{i1}-g_{i2}\right|+ \\ +u_{Zi}(1-\left|\operatorname{sgn}[i_{Li}(t)]\right|)(1-g_{i1}-g_{i2}) \quad (7)$$

The function of the voltage $u_{Zi}(i_{Li}(t))$ depends on the assumed mathematical model of the energy storage device. Some issues concerning the models have been described in [16].

3. HESS model with n energy storage devices

The diagram of the system with n storage devices connected using half-bridge converters is shown in Fig. 3. The model of the system is described by the equations:

For meshes with storage devices:

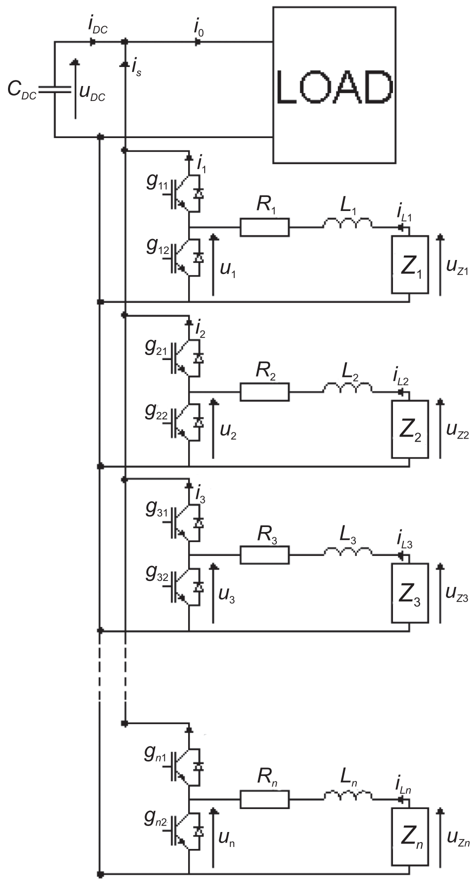

Fig. 3. Diagram of the HESS with n connected types of storage devices

For nodes:

$$i_0 = i_{DC} + i_s \tag{8}$$

$$i_s = \sum_{i=1}^{n} i_i \tag{9}$$

where:

i_0 – load current,
i_{DC} – C_{DC} capacitor current,
i_s – total HESS current,
i_i – current of i-th storage device on DC line.

DC line equation:

$$C_{CD} \frac{du_{DC}}{dt} = -i_{DC} \tag{10}$$

The relation between currents i_i, i_{Li} and voltages u_i, u_{DC} can be described by:

$$i_i = m_i l_{Li} \tag{11}$$

$$u_i = m_i u_{DC} \tag{12}$$

where:

m_i – a modulation ratio of i-th converter and $m_i \in (0, 1)$.

4. Control of the studied HESS

We can now design a control algorithm for the HESS using reference and measured voltages $u_{DC_{ref}}$ and u_{DC}, reference power coefficients γ_{i_ref}, measured currents i_0 and i_{Li} as an input values. The *DC* line requires a closed-loop control of capacitor voltage u_{DC} in order to define the reference current i_{DCref}:

$$i_{DC_{ref}} = K_{uDC}(t)\left(\left(u_{DC_{ref}} - u_{DC}\right)\right) \tag{13}$$

where:

$K_{uDC}(t)$ – function of the voltage regulator.

The reference current i_{s_ref} was obtained from (5).

$$i_{s\_ref} = i_0 - i_{DC_{ref}} \tag{14}$$

Reference current of each converter i_{i_ref}:

$$i_{i\_ref} = \gamma_i i_{s\_ref} \tag{15}$$

$$\gamma_i \in (-11, 11) \tag{16}$$

$$\sum_{i=1}^{n} \gamma_i = 1 \tag{17}$$

$i = 11, 22, 33, ..., n$

where:

γ_i – sets the part of the load power that *i*-th energy storage device has to supply.

For $i_0 > 0$, $\gamma_i < 0$ means that the storage receives energy and $\gamma_i > 0$ that it gives energy. For $i_0 < 0$, $\gamma_i > 0$ means that the storage receives energy and $\gamma_i < 0$ that it gives energy.

Based on the modulation ratio obtained in the previous calculation cycle or, in case of the first cycle, the assumed initial value of m_i and (8) current i_{Li_ref} is determined.

$$i_{Li\_ref} = \frac{i_{i\_ref}}{m_i} \tag{18}$$

Reference voltage u_{i_ref} is obtained using current regulator $K_i(t)$.

$$u_{i\_ref} = K_i(t)\left(i_{Li\_ref} - i_{Li}\right) + u_{Zi} \tag{19}$$

Reference modulation ratio m_{i_ref} is calculated from (9).

$$m_{i\_ref} = \frac{u_{i\_ref}}{u_{DC}} \tag{20}$$

In the next cycle $m_i = m_{i\_ref}$

5. Simulation results

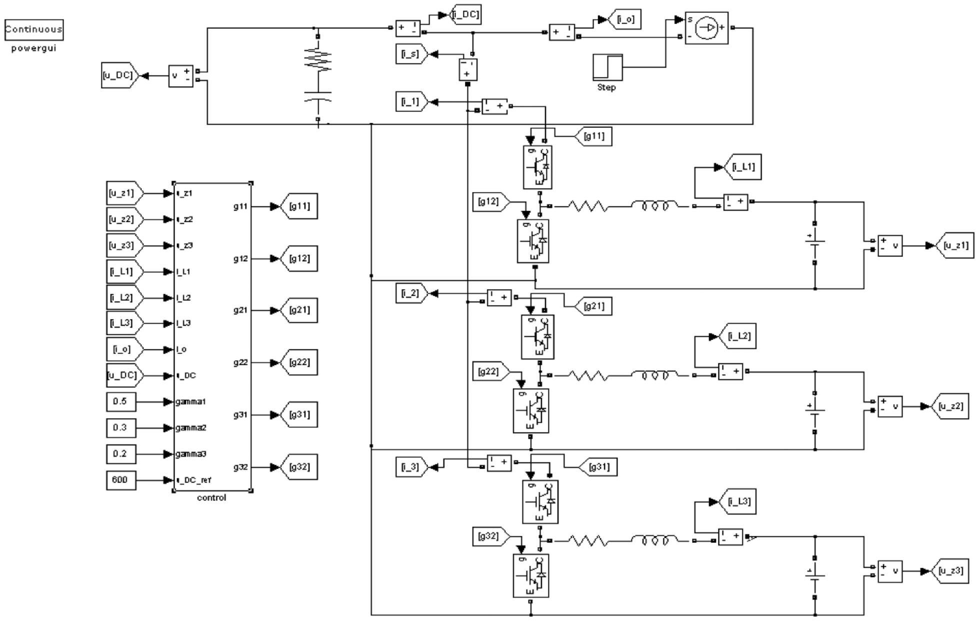

Fig. 4. Diagram of the HESS in Matlab-Simulink

The study of the control system was made for three energy storage devices for the following assumptions:

- Energy storages are modelled as a voltage sources,
- Load is modelled as a controlled current source.

Simulations were performed in Matlab-Simulink.

a) b)

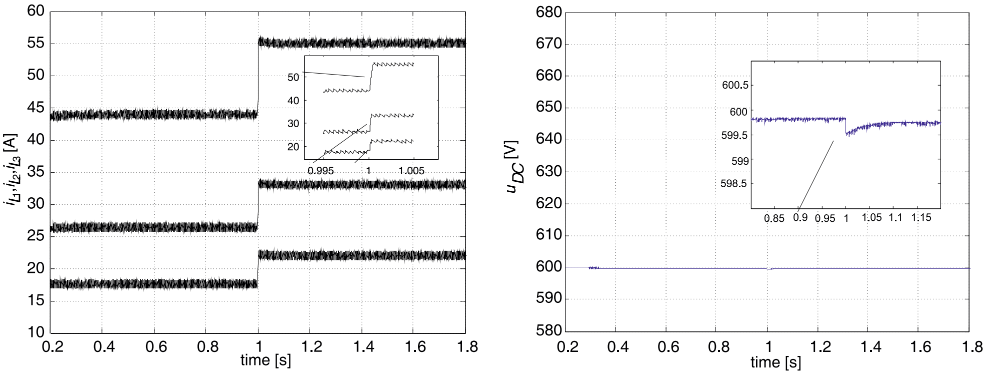

Fig. 5. System response to a step load current change: a) storage devices currents, b) *DC* line voltage

Figure 5 shows the currents of the storage devices and the *DC* line voltage response to a step change in load current. Assumed constant parameters: $\gamma_1 = 0.5$, $\gamma_2 = 0.3$, $\gamma_3 = 0.2$, $u_{DC_{ref}} = 600$ V, $u_{Z1} = u_{Z2} = u_{Z3} = 550$ V. Load current: for $t = (0, 1)$ $i_0 = 80$ A, for $t = (1, 0)$ $i_0 = 100A$. The increase in load current causes a decrease in the *DC* capacitor voltage (Fig. 5b). The control system enforces an increase of the storage device currents (Fig. 5a) and restores the reference DC line voltage. Despite the changes in the load current, the storage device currents are consistent with the planned power distribution.

a) b)

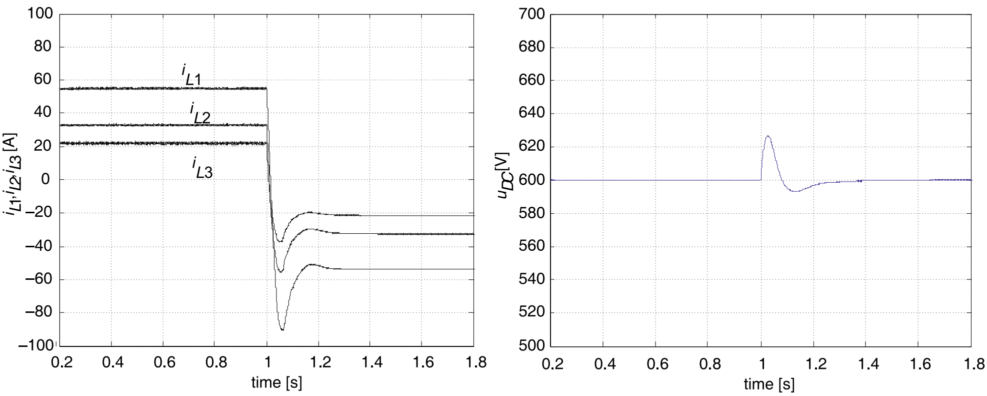

Fig. 6. System response to a step load current direction change: a) storage devices currents, b) *DC* line voltage

Figure 6 shows the currents of the storage devices and the *DC* line voltage response to a step change in direction of the load current. Assumed constant parameters: $\gamma_1 = 0.5$, $\gamma_2 = 0.3$, $\gamma_3 = 0.2$, $u_{DC_{ref}} = 600$ V, $u_{Z1} = u_{Z2} = u_{Z3} = 550$ V. Load current: for $t = (0, 1)$ $i_0 = 100$ A, for $t = (1, 0)$ $i_0 = -100$ A. When the load current value is negative, the HESS is receiving energy. As a result of the current change, the DC capacitor voltage (Fig. 6b) is increasing. The control system enforces a temporary increase in the current drawn by the storage devices to restore the reference voltage on the DC line. Currents $i_{L1} = i_{L2} = i_{L3}$ (Fig. 6a) have the values for which the powers are consistent with the given coefficients γ.

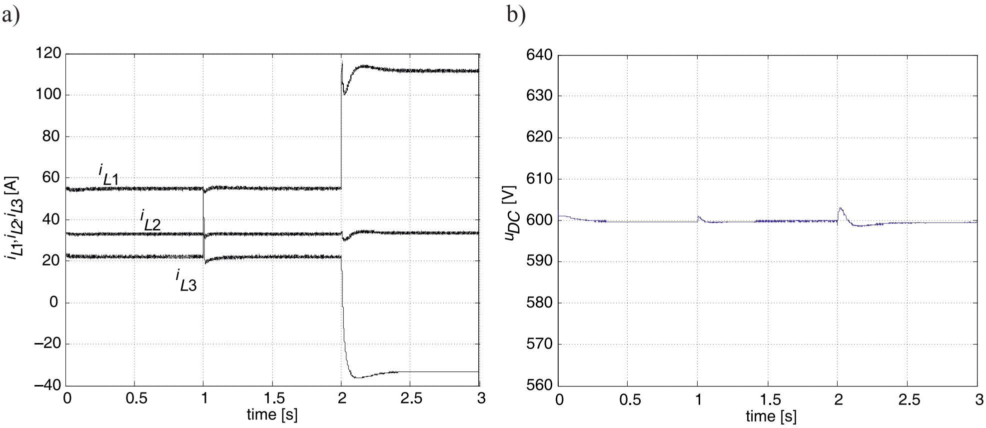

Fig. 7. System response to changes in the coefficients of power distribution: a) storage devices currents, b) *DC* line voltage

Figure 7 shows the currents of the storage devices and the *DC* line voltage response to changes in the coefficients of power distribution. Assumed constant parameters: $u_{DC_{ref}} = 600$ V, $u_{Z1} = u_{Z2} = u_{Z3} = 550$ V, $i_0 = 100$ A. Power distribution coefficients: for $t = (0, 1)$ $\gamma_1 = 0.5$, $\gamma_2 = 0.3$, $\gamma_3 = 0.2$, for $t = (1, 0)$ $\gamma_1 = 0.2$, $\gamma_2 = 0.3$, $\gamma_3 = 0.5$ and for $t = (2, 3)$ $\gamma_1 = -0.3$, $\gamma_2 = 0.3$, $\gamma_3 = 1$. The proposed system allows a planned distribution of energy received and delivered by the HESS system. It also enables flow of energy between the devices connected to the system.

6. Conclusions

The proposed model HESS allows attachment of any number and configuration of the energy storage and/or generative devices. This enables optimisation of the system depending on the needs and constraints of the application. The presented system also provides the ability to modify or upgrade the system without changing the converter. We defined the most important issues concerning HESS systems that require further analysis as:

- Optimal selection of types and sizes of devices in the system, depending on the load and the criteria, such as price, weight, operating costs, etc., combined with an appropriate weight to the optimising function,

- Determining the range of storages voltage and *DC* line voltage,
- Choosing converters most appropriate for a given system,
- Establishing an energy management strategy for the already selected set of devices. The strategy should be chosen as to minimise losses in the device, and to maximise the life of the most expensive components of the system.

References

[1] Bazzi A.M., *Electric Machines and Energy Storage Technologies in EVs and HEVs for Over a Century*, Electric Machines & Drives Conference (IEMDC), 2013 IEEE International, 12–15 May 2013, pp. 212, 219.

[2] Santucci A., Sorniotti A., Lekakou C., *Power split strategies for hybrid energy storage systems for vehicular applications.* Journal of Power Sources 258, 2014, pp. 395–407.

[3] Allègre A.L., Trigui R., Bouscayrol A., *Different energy management strategies of Hybrid Energy Storage System* (*HESS*) *using batteries and supercapacitors for vehicular applications*, Vehicle Power and Propulsion Conference (VPPC), 2010 IEEE, 1–3 Sept. 2010, pp. 1, 6.

[4] Mapelli F.L., Tarsitano D., Annese D., Sala M., Bosia G., *A study of urban electric bus with a fast charging energy storage system based on lithium battery and supercapacitors*, Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER), 2013.

[5] Allègre A.L., Trigui R., Bouscayrol A., *Flexible real-time control of a hybrid energy storage system for electric vehicles*, Electrical Systems in Transportation, 2013.

[6] El Fadil H., Giri F., Guerrero J.M., Tahri A., *Modeling and Nonlinear Control of Fuel Cell / Supercapacitor Hybrid Energy Storage System for Electric Vehicles*, IEEE Transactions on Vehicular Technology, ID: VTSI-2013-01387.R1.

[7] Szeląg A., *Efektywność hamowania odzyskowego w zelektryfikowanym transporcie szynowym*, „Pojazdy Szynowe", 4/2009, pp. 9–16.

[8] Daoud M.I., Abdel-Khalik A.S., Elserougi A., Ahmed S., Massoud A.M., *DC Bus Control of an Advanced Flywheel Energy Storage Kinetic Traction System for Electrified Railway Industry*, Industrial Electronics Society, IECON 2013, 39th Annual Conference of the IEEE, 10-–13 Nov. 2013, .pp.6596–6601.

[9] Kim Y., Koh J., Xie Q., Wang Y., Chang N., Pedram M., *A scalable and flexible hybrid energy storage system design and implementation*, "Journal of Power Sources", No. 255, 2014, pp. 410–422.

[10] Gao L., Dougal R.A., Liu S., *Power Enhancement of an Actively Controlled Battery/ Ultracapacitor Hybrid*, IEEE Transactions on Power Electronics, Vol. 20, No. 1, January 2005.

[11] Barrero R., Van Mierlo J., Tackoen X., *Energy Savings in Puplic Transport*, IEEE Vehicular Technology Magazine, September 2008.

[12] Cao J., Emadi A., *A New Battery/UltraCapacitor Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles*, IEEE Transactions on Power Electronics, Vol. 27, No. 1, January 2012.

[13] Khaligh A., Li Z., *Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art*, IEEE Transactions on Vehicular Technology, Vol. 59, No. 6, July 2010.
[14] Schupbach R.M., Balda J.C., *Comparing DC-DC Converters for Power Management in Hybrid Electric Vehicles*, IEEE, 2003.
[15] Siang Fui Tie, Chee Wei Tan, *A review of energy sources and energy management system in electric vehicles*, "Renewable and Sustainable Energy Reviews", 20, 2013.
[16] Orzyłowski M., Lewandowski M., *Zastosowanie rachunku różniczkowego ułamkowego rzędu do modelowania dynamiki superkondensatorów*, „Przegląd Elektrotechniczny", Vol. 90, No. 8/2014, pp. 13–17.