BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 64 (68), Numărul 3, 2018
Secţia
ELECTROTEHNICĂ. ENERGETICĂ. ELECTRONICĂ

BATTERY/SUPERCAPACITOR HYBRIDIZATION – SOLUTION TO IMPROVE EFFICIENCY OF A VEHICULAR SYSTEM

BY

ALINA-GEORGIANA BACIU*, **GHEORGHE LIVINŢ, DĂNUŢ IRIMIA**
and MARIAN SILVIU POBORONIUC

”Gheorghe Asachi” Technical University of Iaşi
Faculty of Electrical Engineering

Received: September 5, 2018
Accepted for publication: October 10, 2018

Abstract. In hybrid electric vehicles (HEV), the energy storage device is one of the key components, acting like a buffer to absorb the energy surplus during braking and to provide an energy supplement during acceleration. At the moment, the most used energy storage device is battery, present in various types, from lead-acid or metal-hybrid batteries to lithium-ion batteries. Although, battery technology has a significant increase, they cannot fully satisfy the power demand of a vehicular system in some circumstances. A viable solution would be coupling the battery with another energy storage device with specific power. In this way it is obtained a hybrid energy system (HES) which combines two basic sources, one with high specific energy and the other with high specific power. In this paper is investigated a HES based on battery and supercapacitor. The model was built in Matlab/Simulink environment. The simulation results under urban driving cycle show the validity of the model.

Key words: hybrid system; supercapacitor; battery; modelling; HEV.

1. Introduction

In recent years, researches are orientated towards development of hybrid electric vehicle (HEV) and electric vehicle (EV) powered and displaced

---

*Corresponding author: *e-mail*: alina.baciu@tuiasi.ro

by hybrid energy sources. However, installing only one type of energy storage/source is often insufficient, because none of any energy device can solely fulfill all the demands of HEV in some circumstances.

Hybridization of energy sources involves the combination of two or more energy storage devices, so the advantages of each one can be exploited and the disadvantages of each can be compensated by other (Zhang *et al.*, 2011). The energy system must combine the energy and power requirements of the vehicle together with a large lifetime, safety requirements and a low cost (Feurbaey, 2013).

A hybrid energy system (HES) solves some key problems encountered in hybrid electric vehicles as (Michalczuk *et al.*, 2012):

- regenerative braking, when the main source of energy is unidirectional (*e.g.* fuel cell) or availability of fast charge is heavily limited (*e.g.* lead-acid battery);
- providing large power pulse, while the main source is designed to average power;
- significant deterioration of energy storage performance in harsh exploitation conditions.

In fact, a hybrid energy system consists of two energy storage devices, one with high specific energy and the other with high specific power. So in our case, hybridization of a battery with a supercapacitor can solve the problem of the specific low battery power and the specific low energy of supercapacitors. In this way, the whole system will be much smaller in weight and size than if a single energy storage device would be used; in the same time the performances of the system are improved.

In this paper, the high specific energy source is represented by battery and the high specific power source is represented by supercapacitor. Since the two energy storage devices are complementary in terms of characteristics, putting them together in a hybrid energy system it can be greatly improved the performances of energy storage system (Xiu *et al.*, 2014). Also, using a HES has proven to extend the lifetime of the battery, its efficiency and limits the temperature rising in the battery due to the averaging of the power drawn from the battery system.

2. Proposed Configuration for Hybrid Energy System

The configuration of battery/supercapacitor hybrid energy system developed in the paper is shown in Fig. 1. The model was realised in Simulink environment and for implementation and simulation it was chosen the passive configuration in which the battery is connected in parallel with the supercapacitor and the load (Zhang *et al.*, 2011). The supercapacitor can provide instantaneous power during acceleration or climbing as well as can accept instantaneous regenerative energy during braking (Yu *et al.*, 2010).

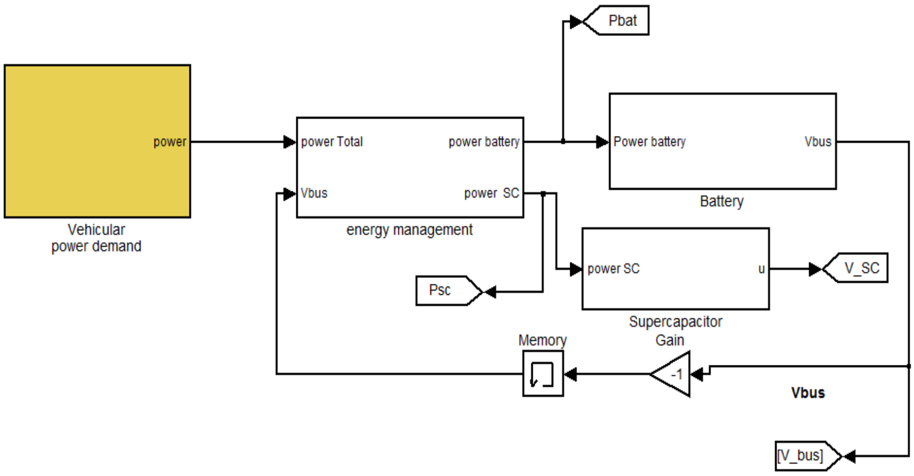


Fig. 1 – Simulink diagram for HES.

3. Components Models

In this section are described the models for the main power system components: the battery, the supercapacitor bank, vehicle dynamics and resistance forces. Developed models are simulated in Matlab/Simulink environment.

A. Battery model

Battery is one of the most recognized and, perhaps, the oldest method for storing energy. Due to their energy density, the secondary batteries or rechargeable cells are still one of the best options available. There are a variety of battery technologies, but the most common are lead-acid (Pb), nickel-cadmium (NiCd) or nickel metal hybrid (NiMH) and lithium ion (Li+) (Buchmann, 2003).

Modelling batteries accurately is challenging because their electrical behaviour is complex and is a nonlinear function of a number of constantly changing parameters, such as internal temperature, state of charge, rate of charge/discharge, etc. For battery modeling was adopted the equivalent circuit based on Thevenin model, shown in Fig. 2, which consists of an open circuit voltage in series with an internal resistance.

The open circuit voltage of battery (U_{OCV}) is a function of state of charge (SOC) and the resistance R_s is connected in series with a parallel RC branch, modelling in this way the ohmic drops and polarization effect (Gao *et al.*, 2002; Zheng *et al.*, 2009).

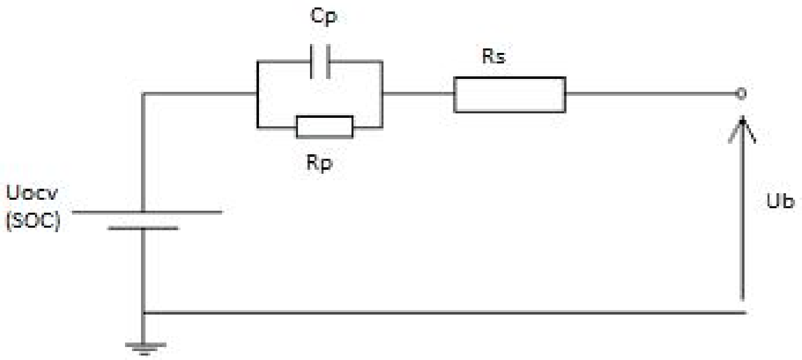


Fig. 2 – Lead-acid battery model.

The equations for the model are expressed as:

$$U_{\mathrm{OCV}} = E_{m0} - K_e(273+\theta)(1-\mathrm{SOC}), \tag{1}$$

$$R_0 = R_{00}\left[1 + A_0(1-\mathrm{SOC})\right], \tag{2}$$

$$R_p = -R_{10}\ln(\mathrm{DOC}), \tag{3}$$

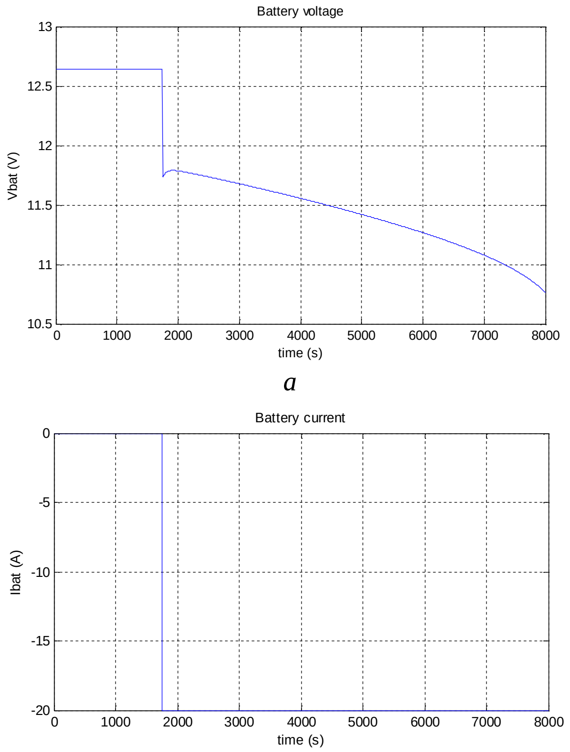
where: E_{m0}, K_e, R_{00}, A_0, R_{10} are constants owning to each battery and DOC and SOC represents depth of discharge, respectively state of charge of battery. The capacity of battery depends on both, temperature and discharge current (Jackey, 2007). For the model it was considered a lead-acid battery pack with six cells connected in series. The main parameters for each cell are listed in the table below.

Table 1

Battery parameters

Type – Lead acid battery	Capacity C [Ah]	Voltage V [V]	ESR [mΩ]
1X	20	1.6	9.3

In Fig. 3 are illustrated the results for battery simulation at discharging to a constant current of 20 A. In Fig. 3 *a* is the battery voltage and in Fig. 3 *b* is the evolution of the battery current.



a

b

Fig. 3 – Simulation results for battery discharging.

B. Supercapacitor model

Supercapacitors present some advantages that recommend them to be used in a hybrid energy system. Among these it can be mentioned: high power density, high storage efficiency, long cycle life and fast charge and discharge (Hongyi & Benteng, 2009).

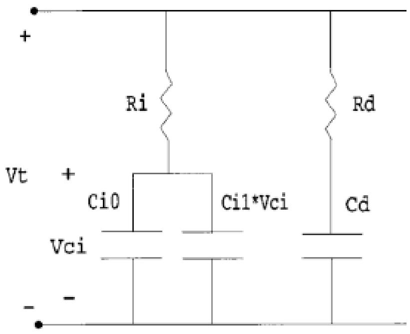


Fig. 4 – Simplified model for supercapacitor.

The simplified model is illustrated in Fig. 4 and it is based on Zubieta model. It presents two branches: $R_i - C_i$ which is the main branch, for energy evolution during charge and discharge cycles and $R_d - C_d$, the second branch, for redistribution of internal loads at the end of charging and discharging (Zubieta & Bonert, 2000).

The global model implemented in Simulink is shown in Fig. 5 and the parameters for supercapacitor are listed in Table 2.

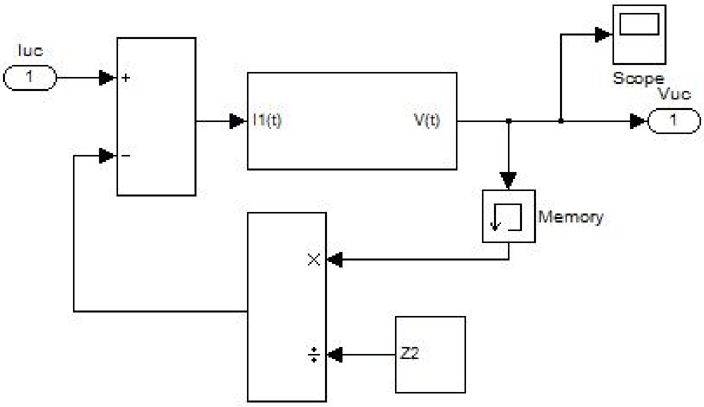


Fig. 5 – Global model in Simulink.

Table 2
Ultracapacitor parameters

Type – Maxwell	Capacity C [F]	Voltage V [V]	ESR [mΩ]	Weight [Kg]
1X	58	15	19	0.68

The model contains 14 modules 58 F/15 V with a specific power of 8.2 kW/kg and energy density of 2.67 Wh/kg. The package consists of 6 elements of 2.5 V and 350 F, Fig. 6.

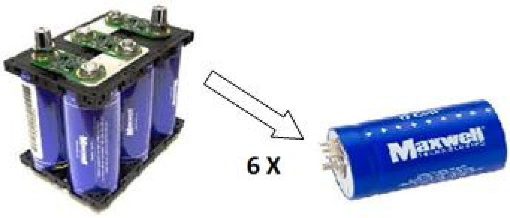


Fig. 6 – Supercapacitor package.

C. Vehicle dynamics and resistance forces

For distribution of power demand between the two energy sources it is necessary to calculate the total power over a driving cycle. For simulation it was used the New European Driving Cycle or NEDC. In Fig. 7 is illustrated the vehicle speed over NEDC.

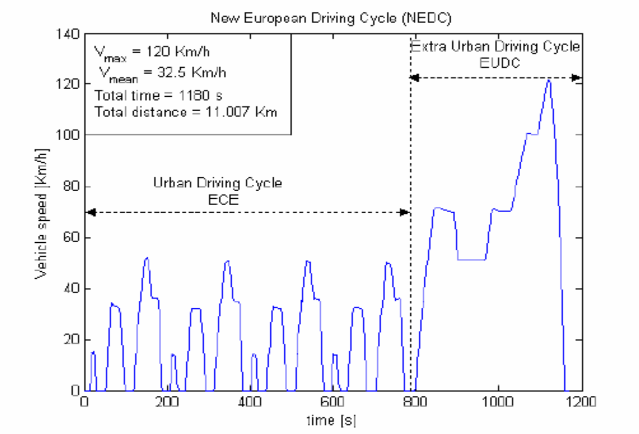


Fig. 7 – NEDC profile.

To obtain the total power demand it was used the basic equation according to which the propulsion power P is calculated as product between traction force F_t and vehicle speed v.

$$P = F_t \times v. \tag{4}$$

Traction force can be expressed as a sum of forces due to rolling resistance F_f, aerodynamic drag, F_{aero}, inertial and gravitational. The expression of traction force is illustrated in equation bellow:

$$F_t = F_g + F_f + F_{\text{aero}} + F_{\text{ac}}. \tag{5}$$

Aerodynamic force (F_{aero}) is calculated according to the expression:

$$F_{\text{aero}} = \frac{1}{2} \times \rho \times S \times v\,, \tag{6}$$

where: ρ is the air density, 1.225 kg/m^3; S – the frontal surface, 0.608 and v – the velocity corresponding to NEDC profile.

Friction force (F_f) is a consequence of deformation in the wheels and/or road surface and it is given by (Mikkelsen, 2010).

$$F_f = m \times g \times C_f\,, \tag{7}$$

where: m is the mass of vehicle; g is the gravitational acceleration 9.8 m/s^2 and C_f is the coefficient of rolling resistance of the vehicle tires, 0.00904.

F_g is proportional to the mass of the vehicle, m, velocity and angle of the slope inclination, α:

$$F_g = m \times g \times \sin(\alpha). \tag{8}$$

The force of acceleration (F_{ac}) results from the second law of Newton according to which:

$$F_{ac} = m \times a \tag{9}$$

where a (m/s^2) is the instantaneous acceleration of the vehicle.

Finally, the Simulink block diagram for power calculation is shown in Fig. 8.

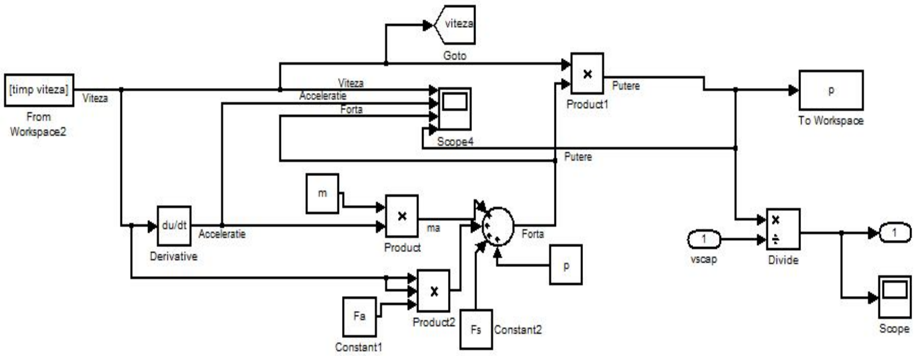


Fig. 8 – Simulink block for power calculation.

4. Simulation Results for Power Flow Distribution Between Sources

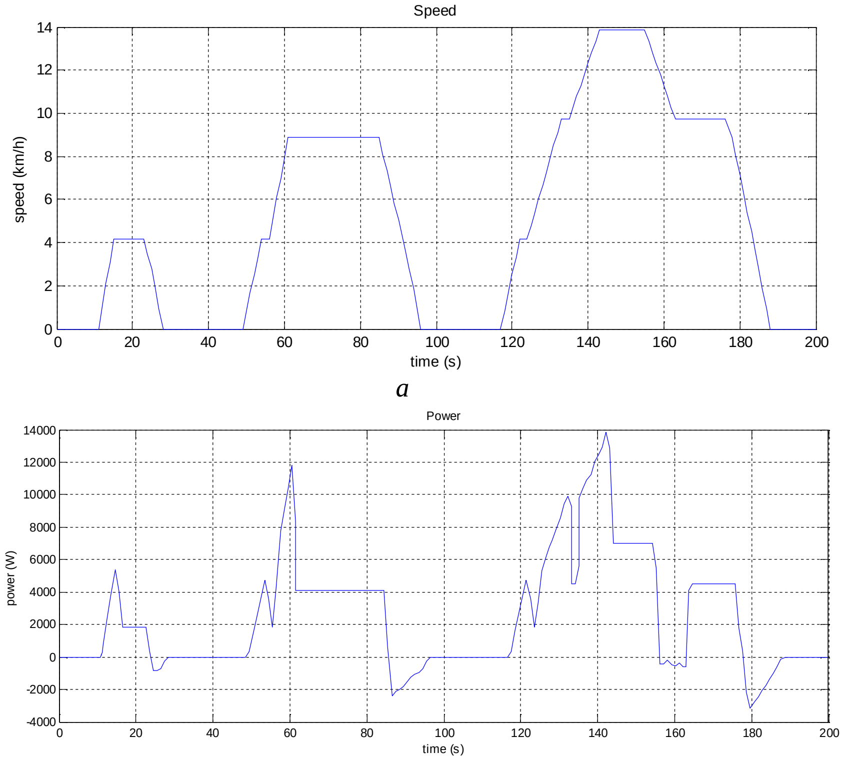
The objective of the simulation model is to examine power flows in the hybrid energy system. The efficiency of the model depends on the efficiencies of its components and on the control of power flow from and to the two energy sources: battery and supercapacitor. This means that both of energy storage devices must be used in its most efficient way in order to maximally benefit from the hybrid concept. For simulation there were used first 200 s of NEDC drive cycle. The speed and power demand profile are illustrated in Fig. 9.

The requirements for power distribution between battery and supercapacitor are:

– to avoid damage battery it is necessary to limit battery discharge and its charge variation; in this case, discharge current is 40A and the charge current is 4 A;

– the supercapacitor allows the supply of power in acceleration phases;

– supercapacitor delivers the remaining power demand during acceleration and recovers energy during braking.



a

b

Fig. 9 – NEDC speed profile and power demand.

In Fig. 10, respectively Fig. 11 are shown the state of charge and the current of battery.

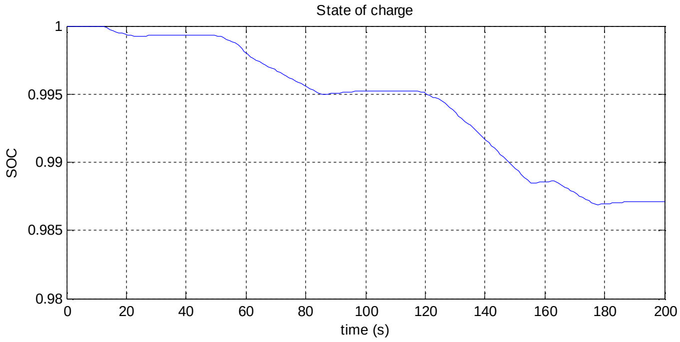


Fig. 10 – State of charge of battery.

It can be seen that the state of charge of battery is maintained in reasonable limits between 0.987 – 1. As it is mentioned in specific requirements the battery current is well limited at 40A and the charge current at 4A.

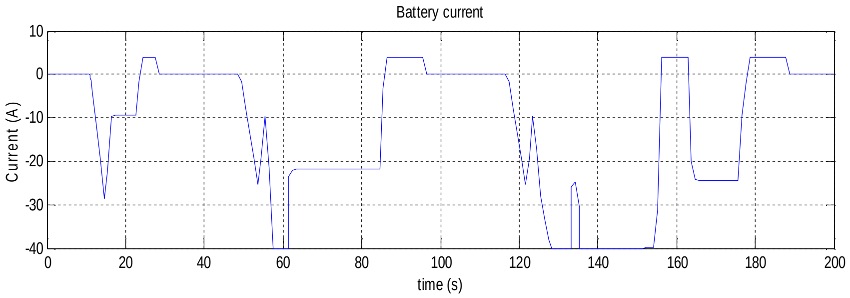


Fig. 11 – Battery current.

Fig. 12 illustrates the power of battery and supercapacitor. It can be noted that the SC discharges during acceleration phases and recovers energy during deceleration mode and the total power demand is shared between battery and supercapacitor, while the supercapacitor provides the peaks power demand, as it can be seen in Fig. 13.

In the Fig. 13 with red is the total power demand, with blue is the battery power and with green is represented the supercapacitor power.

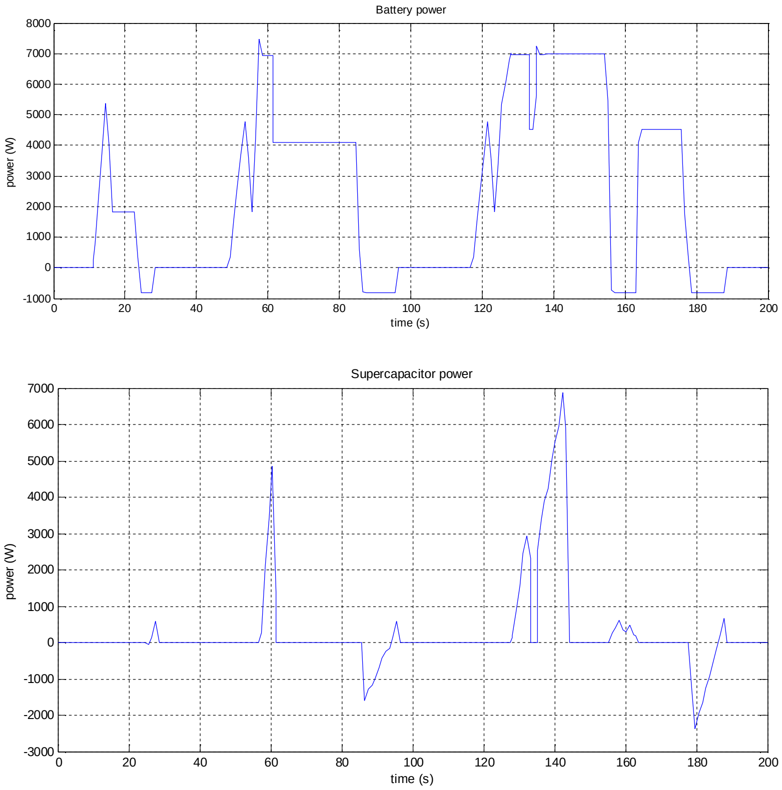


Fig. 12 – Battery and SC power.

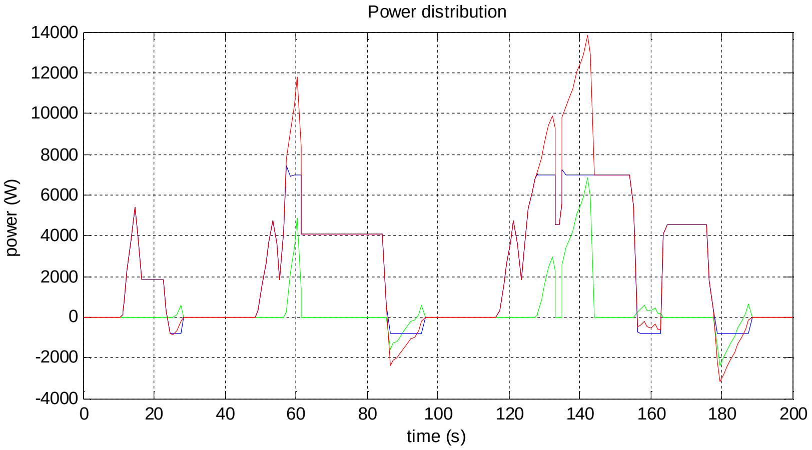


Fig. 13 – Total power sharing between energy sources.

5. Conclusion

In this work are presented the advantages of combining the battery with a supercapacitor in order to form a hybrid energy system for improving the performances of the vehicle, as well as to increase the lifetime of energy storage devices. The simulation results show that supercapacitor operates very well at high, peaks power needed for short times corresponding to transient operation. Also, the supercapacitor stores the energy recovered during regenerative braking, resulting in longer lifetime for battery.

REFERENCES

Buchmann I., *Part Two*, 2003, http://www.batteryuniversity.com/parttwo-34.htm.

Fleurbaey K., *Analysis of the Energy Storage Systems in Series Plug-in Hybrid Electric Vehicles*, Vrije Universiteitn Brussel, Master of Science, 2013.

Gao L., Liu S., Dougal R.A., *Dynamic Lithium-Ion Battery Model for System Simulation*, IEEE Trans. Compon. Packag. Technol., **25**, 495-505 (2002).

Hongyi L.U., Benteng H.E., *Application of the Supercapacitor in a Micro Grid*, Automation of Electric Power Systems, **33(2)**, 87-91 (2009).

Jackey R.A., *A Simple Effective Lead-Acid Battery Modeling Process for Electrical System Component Selection*, The Math Works, Inc., Natick, 2007.

Michalczuk M., Grezesiak L.M., Ufnalski B., *A Lithium Battery and Ultracapacitor Hybrid Energy Source for an Urban Electric Vehicle*, Przeglad Elektrotechniczny (Electrical Review), **R.88, 4b** (2012).

Mikkelsen K., *Design and Evaluation of Hybrid Energy Storage System for Electric Powertrains*, University of Waterloo of Applied Science, Ontorio, Canada, 2010.

Xiu Y., Cheng L., Chunyan L., *Research on Hybrid Energy Storage System of Supercapacitor and Battery Optimal Allocation*, J. of Internat. Council on Electrical Engineering, **4(4)**, 341-347 (2014).

Yu H., Lu R., Wang T., Zhu C., *Battery/Ultra-Capacitor Hybrid Energy Storage System used in HEV,* J. of Asian Electric Vehicles, **8(1)**, 1351-1356 (2010).

Zhang X., Dong Z., Crawford C., *Hybrid Energy Storage System for Hybrid and Electric Vehicles: Review and a New Control Strategy*, ASME 2011, Internat. Mechanical Engineering Congress and Exposition, November 11-17, 2011, Denver, Colorado, USA, **4**, 91-101.

Zheng M., Oj B., Du X., *Dynamic Model for Characteristics of Li-Ion Battery on Electric Vehicle*, 4th IEEE Conf. Industrial Electronics and Applications, 2009, Xi'an, China, 2867-2871.

Zubieta L., Bonert R., *Characterization of Double-Layer Capacitors for Power Electronics Applications*, IEEE Trans. Ind. Appl., **36(1)**, 199-205 (2000).

HIBRIDIZAREA BATERIE CU SUPERCAPACITOR – SOLUȚIE PENTRU ÎMBUNĂTĂȚIREA EFICIENȚEI SISTEMULUI HIBRID

(Rezumat)

In vehiculele electrice hibride, sistemul de stocare a energiei poate fi utilizat ca un buffer (tampon) pentru a absorbi excesul de energie, în timpul frânării, şi poate furniza un supliment de energie necesar în timpul accelerării. Cu alte cuvinte, dispozitivul de stocare a energiei trebuie sa aibă capacitate de încărcare rapidă pentru a se putea folosi frânarea recuperativă şi, cel mai important, trebuie să prezinte capacitate mare de vârfuri de sarcină. Cea mai utilizată sursă de energie la momentul actual o reprezintă diversele tipuri de baterii, de la cele de tip plumb-acid sau metal-hibrid şi până la cele de tip litiu-ion. Deşi, tehnologia bateriilor a crescut semnificativ în ultimul timp, ele nu pot satisface în totalitate puterea cerută a sistemului vehicular în anumite circumstanțe. O solutie viabilă ar fi cuplarea bateriei cu un alt sistem de stocare a energiei cu o putere specifică mai mare. În acest fel, se obține un sistem hibrid de energie (SHE) care combină cele două surse de bază, una cu energie specifică mare şi cealaltă cu putere specifică mare. În lucrarea de față sunt analizate aspectele unui sistem hibrid de energie cu baterie şi supercondensator, model elaborat cu ajutorul mediului Matlab/Simulink. Simulările, efectuate pe parcursul unui ciclu de drum predefinit, au arătat validitatea modelului în ceea ce priveşte utilizarea eficientă a fiecăreia dintre cele două surse.