Beata JAKUBIEC

Politechnika Częstochowska, Instytut Telekomunikacji i Kompatybilności Elektromagnetycznej

doi:10.15199/48.2016.12.15

Computer model of electric vehicle drive system fed from hybrid energy storage system

***Abstract**. The paper presents a model of the drive system of an electric vehicle with a hybrid energy storage system. Electric drive consist of a permanent magnets synchronous motor supplied by a battery and a supercapacitor. Bi-directional DC/DC converter shall be responsible for transfer of energy from a power supply unit to the motor and its recovery during braking. The time characteristics of motor electromechanical values and parameters of power supply system were recorded during simulation testing carried out for various conditions of operation.*

***Streszczenie.** W pracy przedstawiono model układu napędowego pojazdu elektrycznego z hybrydowym magazynem energii elektrycznej. Napęd elektryczny stanowi silnik synchroniczny z magnesami trwałymi, dla którego źródłem zasilania jest bateria akumulatorów oraz superkondensator. Dwukierunkowa przetwornica DC/DC odpowiada za transfer energii ze źródła zasilania do silnika i jej odzysk podczas hamowania. Podczas badań symulacyjnych, przeprowadzonych dla różnych warunków pracy, rejestrowano charakterystyki czasowe wielkości elektromechanicznych silnika oraz parametry układu zasilania. (**Model napędu pojazdu elektrycznego z hybrydowym zasobnikiem energii**).*

Keywords: hybrid energy storage system, battery, supercapacitor, electric vehicle
Słowa kluczowe: hybrydowy zasobnik energii, bateria akumulatorów, superkondensator, pojazd elektryczny

Introduction

Popularity, intensively promoted both throughout Europe and the world, of energy efficient and ecological transport provided with electric vehicles, depends to a large extent on the quality of operation of the vehicle drive system and its supply system, which shall ensure the satisfactory length of road that can be travelled with the charged energy storage, which at the same time shall be durable [1,2,3]. These aims can be achieved due to improving construction of motors and applying electronic elements, or owing to the selection of appropriate control algorithms and the application of more efficient power supply units [4,5,6,7,8]. The range of an electric car is influenced by the capacity of an energy storage system, and primarily energy density that is the quantity of energy accumulated in a mass unit and power density proving the dynamics and current-carrying capacity of the power supply unit. Moreover, from a user perspective, the life cycle of the energy storage, understood as a number of cycles of full charge and discharge which do not substantially affect the total capacity, is also very important indicator, as currently the energy storage is one of the most expensive elements of an electric vehicle. Unfortunately, the applied batteries undergo considerably sped up degradation, because they are charged with large energy which especially occur in city driving (frequent acceleration and braking) [9,10]. To improve the properties of this energy source are proposed solutions in the form of hybrid energy storage systems HESS, in which battery cooperates with other energy storage. One of the proposals is cooperation of a battery with a supercapacitor. The battery is still the main power supply unit, however the supercapacitor, owing to its properties, shall ensure energy when demand is increased (acceleration) and provide energy storage generated at braking (recovery braking). Therefore, application of the hybrid energy storage system in an electrical vehicle shall allow achieving satisfactory vehicle range and sustainable operation of energy storage, even while driving characteristics are dynamic [11,12,13].

The paper presents a computer model of the drive system of the electric vehicle provided with hybrid energy storage system. The purpose of the simulation is to monitor the operation of the hybrid power system for the drive.

Properties of batteries and supercapacitors

Currently, electrochemical cells: lead-acid accumulators, nickel-metal-hydride accumulators and lithium-ion accumulators are the most likely applied in electric cars. In this group Li-Ion batteries are specified with the greatest energy density, but they are rather expensive. The cheaper technologies, which store less energy, shall fail to ensure satisfactory ratio, or cause the increase of total vehicle mass. Besides, they require the longer charging time (even up to a dozen or so hours), and their durability amount to approximately 5 years. Temperature impacts the parameters of the rechargeable batteries, as well. Supercapacitors, also called ultracapacitors feature a large capacity, high durability and less sensitivity to the temperature. Their main advantage is high power density, what allows their charging and discharging with high currents in a very short period of time [5,13,14]. The characteristics of charging and discharging of the battery and the supercapacitor are provided in figure 1. They illustrate in simplified way the differences in operation of the referred energy sources. Table 1 provides a statement covering the primary parameters which enables presentation of the properties of the various types of accumulators and a supercapacitor.

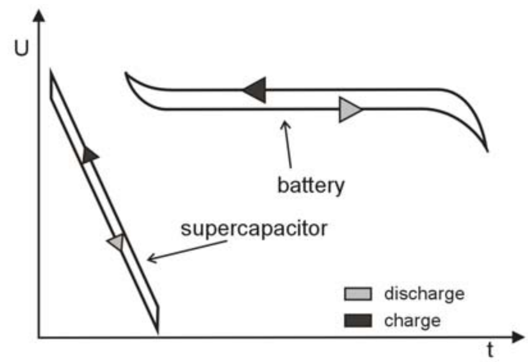

Fig.1. Charge/discharge curves of battery and supercapacitor

Topologies of the hybrid energy storage system

The energy storage system which consists of a battery and a supercapacitor may be of diverse topology. The literature advices many ways to combine the both energy sources, what influence on to a size and a number of

DC/DC converters applied (Fig. 2). In general, two types of structures: the passive and active one can be signalized. The passive structure, where an battery and a supercapacitor are directly connected to the drive unit. It is a simple construction, however, it is not the best solution owing to non-optimal power distribution between the referred energy storages resulting merely from internal parameters of the sources themselves (Fig.2a). The examples of active hybrid energy storages are the systems presented in figures 2b÷2h. The referred structures, provided with one (semi-active topology) or two DC/DC converters (active topology), determine the drive power strategy and power distribution that is battery and supercapacitor charge level. And thus, it improves the life cycle of the hybrid energy storage system, however it increases expenses and the extent of complexity of the drive system [11,13,15].

Table 1. Parameters of the batteries and the supercapacitor [10,11]

Parameter	Pb	NiMH	Li-Ion	SC
Cell voltage [V]	2	1,2	3,7	2,7 V
Capacity	***	**	**	*
Internal resistance [mΩ]	15÷25	40÷60	25÷75	0,2÷6
Efficiency	70%	80%	90%	84÷95%
Specific power [W/kg]	80	1000	3000	10000
Specific energy [Wh/kg]	40	80	200	5
P/E [W/Wh]	6	2,7	36	1200
Charge/discharge cycles (to 80 %)	400	800	1000	1 mln
Operating temperature [°C]	-30 ÷ +60	-20 ÷ +45	-20 ÷ +60	-40 ÷ +80
Charge time	6÷12h	6h	1÷6h	0,3÷30s
Charge current	0,1C	0,1C	3C	500 A
Life time [years]	2÷5	4	3	5÷10
Self-discharge [% per month]	10	40	10	50

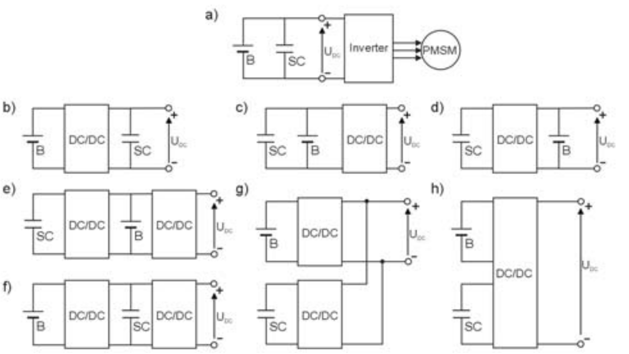

Fig.2. Examples of the topology of the hybrid energy storage system [13,14]

Computer model

Figure 3 provides the computer model of the vehicle drive. Simulation parameters were selected in order to reflect the primary technical data of the drive unit for i-MiEV car (tab.2). Application of the hybrid energy storage system is the basic difference in comparison to the Mitsubishi electric vehicle. Thus, the modelled drive of the electric vehicle consists of three-phase permanent magnets synchronous motor fed by Li-Ion battery and the supercapacitor. Bidirectional DC/DC converter shall be responsible for transfer of energy from a power supply unit to a motor and its recovery during braking [15,16].

Table 2. Selected parameters of the computer model i i-MiEV [17]

Parametr	Model	i-MiEV
Power of PMSM [kW]	38	35
Li-Ion capacity [kWh]	5	16
Supercapacitor capacitance [F]	330	-
Rotational speed of the motor [rpm]	8500	8000

In the computer model of PMSM the mathematical relations as (1)÷(4) dependences have been applied [6,18,19].

(1) $$u_d = R_s i_d + L_d \frac{di_d}{dt} - L_q i_q \omega$$

(2) $$u_q = R_s i_q + L_q \frac{di_q}{dt} + L_d i_d \omega$$

(3) $$T_e = J\frac{d\omega}{dt} + B\omega + T_L$$

(4) $$T_e = 1{,}5\,p[\psi_f i_q + (L_d - L_q) i_d i_q]$$

where: u_d,u_q – dq axes components for the stator voltage, i_d,i_q – dq axes components for the stator current, L_d,L_q – dq axes inductances, R_s – phase stator resistance, ψ_f – magnetic flux induced by the permanent magnets of the rotor, ω – angular speed of the rotor, T_e – electromagnetic torque, J – moment of inertia, B – viscous friction factor, T_L – external load torque, p – number of pole pairs.

The components of the hybrid energy storage system: i.e. of Li-Ion battery and a supercapacitor can be presented in a form of mathematic expressions which describe the voltage at the terminals of battery U_{bat} (5,6) and its charge level SOC_{bat} (7), as well as the capacitance of supercapacitor C in the function of its voltage u_{sc}(t) (8) and the charge level of the supercapacitor SOC_{sc} (9) [20,21,22,23].

(5) $$U_{bat} = E - R_{bat} I_{bat}$$

(6) $$E = E_0 - K\frac{Q}{Q - \int idt} + A\exp\left(-B\int idt\right)$$

(7) $$SOC_{bat} = 100\left(1 - \frac{\int_0^t idt}{Q}\right)$$

where: E – controlled voltage source, R_{bat} – battery internal resistance, E_0 – no load battery voltage, I_{bat} – battery current, Q – battery capacity, K – polarization constant, A – exponential zone amplitude, B – exponential zone time constant inverse.

(8) $$C(u_{sc}(t)) = C_0 + k u_{sc}(t)$$

(9) $$SOC_{sc} = \frac{E_{sc}}{E_{sc\max}} = \frac{U_{sc}^2}{U_{sc\max}^2}100\%$$

where: C_0 – supercapacitor capacitance for 0V, k – capacity coefficient as a function of the voltage, E_{sc},E_{scmax} – remaining energy and maximum energy of the supercapacitor, U_{sc},U_{scmax} – voltage and maximum voltage of the supercapacitor.

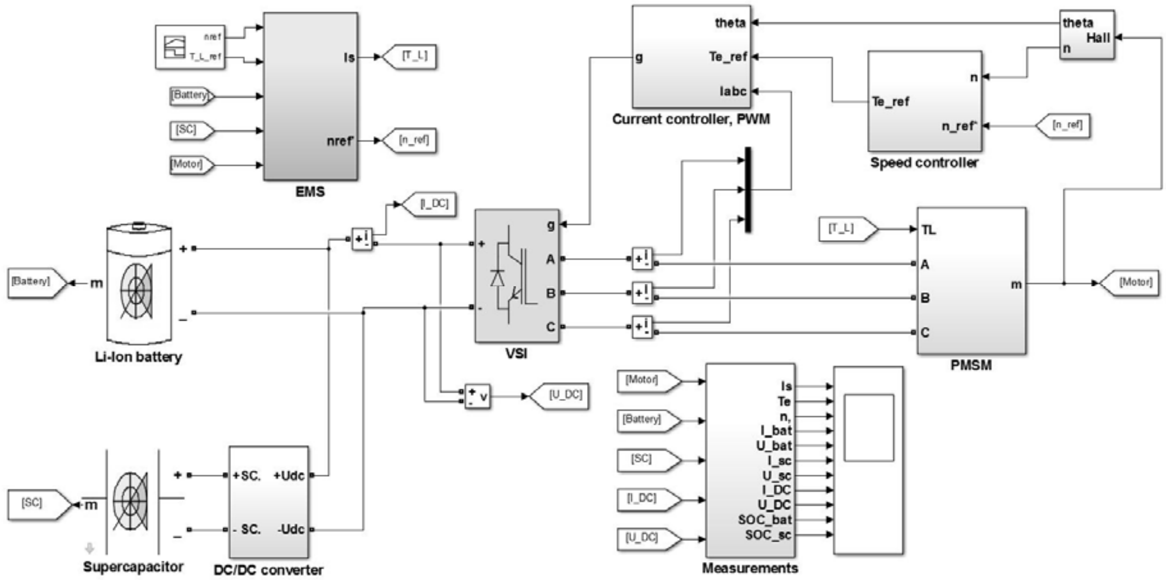

Fig.3. The simulation model of the electric vehicle drive with hybrid energy storage system

Simulation tests

Simulation testing was performed for the computer model for prescribed values corresponding to various operating conditions of the drive. The time characteristics of motor electromechanical values and parameters of power supply system – the hybrid energy storage system - were recorded. Figures 4 and 5 present: one of the stator phase current, rotational speed and electromagnetic moment of PMSM motor for the prescribed speed motor and for various load torques corresponding to the vehicle acceleration and braking. The current and voltage time characteristics on the DC-link, of the battery and the supercapacitor are, respectively, provided in figures 6, 7 and 8. The next figures present the curve to state of charge of both energy storages resulting from the prescribed nature of the motor load (Fig. 9,10).

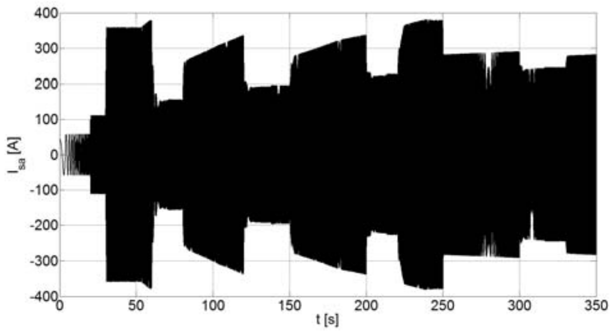

Fig.4. Time characteristic of the stator phase current

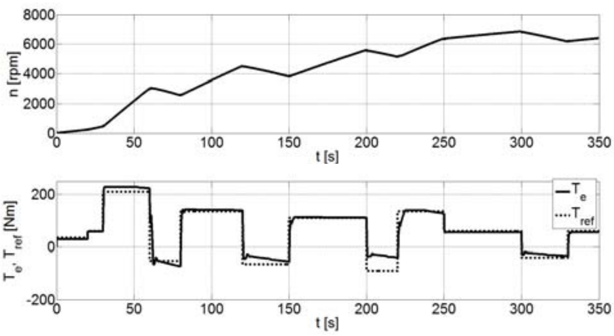

Fig.5. Time characteristics of the rotational speed and the electromechanical torque

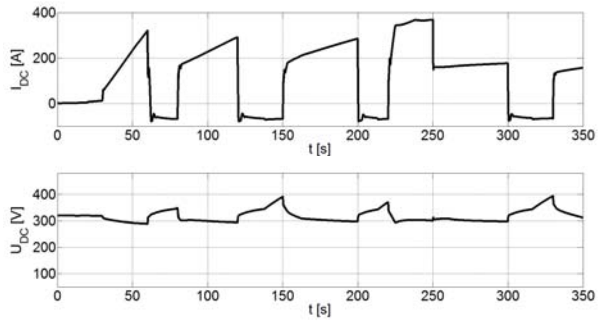

Fig.6. Time characteristics of the DC-link current and the DC-link voltage

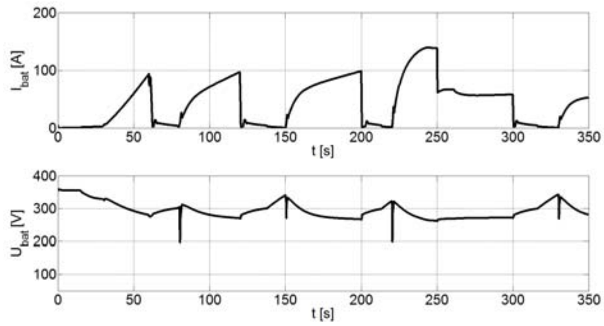

Fig.7. Time characteristics of the battery current and the battery voltage

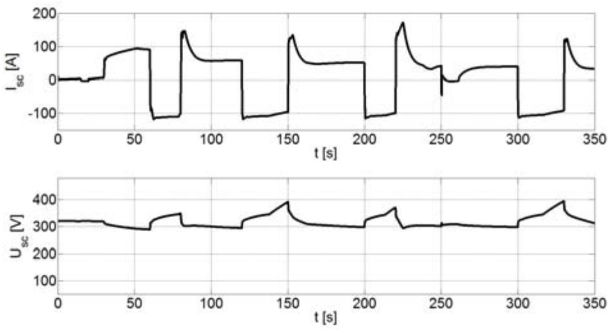

Fig.8. Time characteristics of the supercapacitor current and the supercapacitor voltage

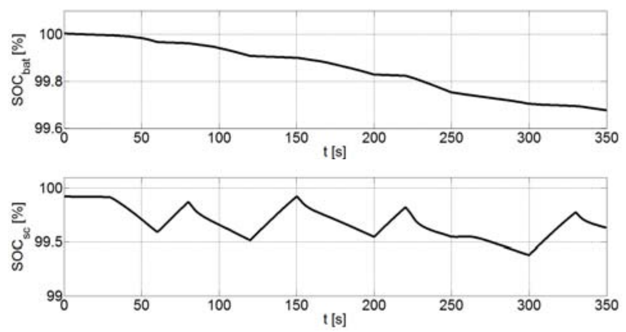

Fig.9. State of charge of battery and supercapacitor

For comparison, for the same prescribed conditions, simulation was performed where supply for the drive system was provided from the battery (16kWh), only. The graphs of state of charge and battery current are presented in figure 10. In this case, the drive must be supply for battery with a larger capacity. During operation the battery is higher current discharged/charged. This is very adverse for the battery.

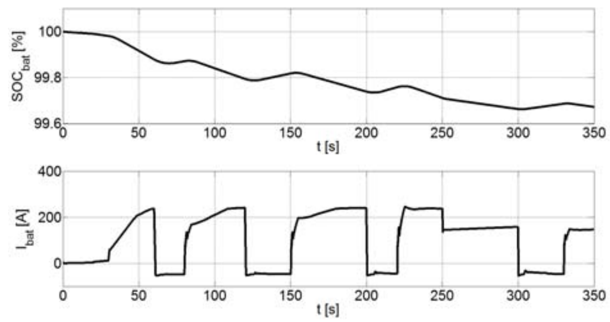

Fig.10. Time characteristics of the battery current and state of charge of battery (16kWh)

Conclusions

The computer model of electrical drive system provided with hybrid energy storage system (battery and supercapacitor) shall allow initial monitoring of the quality of cooperation of such a power source and the drive system, for example depending on a change of the charge and dynamics of motor operation. Therefore, the simulating model may be a tool assisting in the preliminary selection of the energy storage depending on the operating conditions of an electric vehicle drive. The use of semi-active energy storage system shall enable to apply an battery with less capacity, and in practice it may constitute a compromise between the drive system complexity as well as cost and the profit resulting from the using the braking energy.

***Author**: dr inż. Beata Jakubiec, Politechnika Częstochowska, Instytut Telekomunikacji i Kompatybilności Elektromagnetycznej, Zakład Energoelektroniki, Robotyki i Jakości Energii, al. Armii Krajowej 17, 42-200 Częstochowa, E-mail: beja@el.pcz.czest.pl*

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