CETRA 2016

4th International Conference on Road and Rail Infrastructure
23–25 May 2016, Šibenik, Croatia

Road and Rail Infrastructure IV

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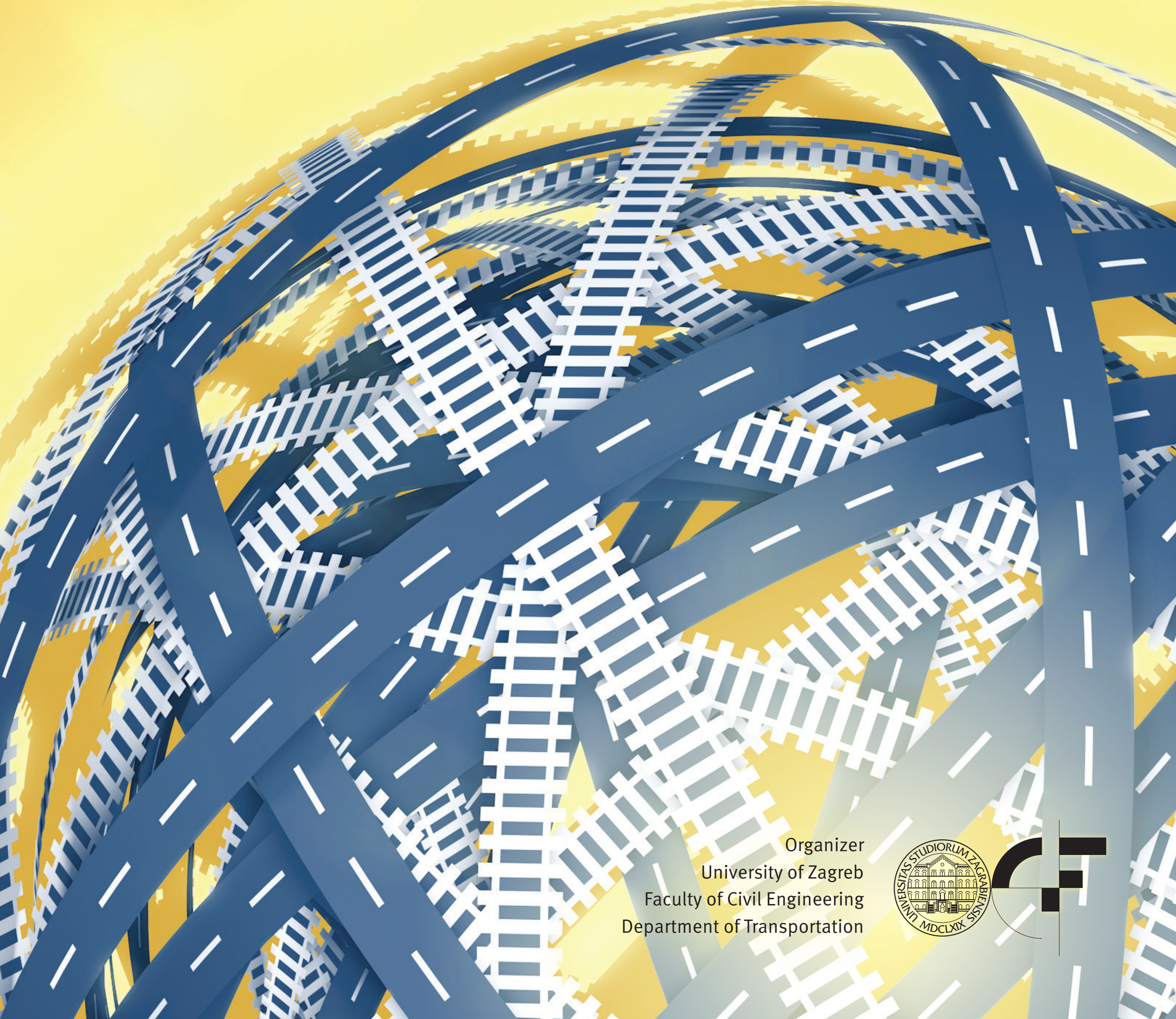

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POWER CONTROL ALGORITHM OF HYBRID ENERGY STORAGE SYSTEM FOR VEHICULAR APPLICATIONS

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Abstract

In the paper, a new power control algorithm for hybrid energy storage system (HESS) is proposed. The algorithm is dedicated for vehicular applications. The aim is to enable connecting any number of energy storage devices or generators to the system and providing universal input for energy management strategy. Described system is based on multiple converter configuration with all devices connected to one DC link. Half-bridge DC/DC converters are used to interface between device and DC link. Theoretical analysis and simulations for the system composed of lithium-ion batteries, supercapacitors and photovoltaic panel were carried out.

1 Introduction

Energy storage systems (ESS) are becoming one of the most important elements that improve overall performance of applications ranging from power supply system and electric vehicles all the way to mobile electronic devices. ESS used in traction system allow redistribution of regenerative braking energy and support catenary during voltage decrease [1]. In power system ESS with a power of approximately MW are used to equalize the load and improve power quality [2]. Research and development of electrochemical batteries, especially lithium-ion (li-ion) technology, indicate the possibility to increase specific energy, which now is approximately 200 Wh/kg, by 300%. Nevertheless, they are not able to match fossil fuels (diesel – 13000Wh / kg). Instead they become a serious alternative for vehicles operating in big cities, where range is not priority, or, in case of restrictions on access to the oil supply and in an era of rapid climate change. Currently available ESS have several limitations regarding not only specific energy but also specific power, cycle life, price etc. Using the multitude of technologies currently available on the market and the differences in the characteristics of different types of ESS, it is possible to create a hybrid energy storage system (HESS). HESS is a combination of two or more types of trays in one system. This solution allows to use the advantages of the various energy storage devices in a single system.
There are a lot of connection configurations of a HESS described in a literature [3], [4]. In electric vehicles the most often proposed HESS is arrangement of a li-ion battery and a supercapacitor. This is justified by high specific power and cycle life of a supercapacitor on one side and high specific energy of a li-ion battery on the other. The battery is used as main energy source for the vehicle and the supercapacitor provides peak power during acceleration and regenerative breaking.
The constantly growing number of vehicles and the dynamic development in the field of photovoltaic leads us to propose the use of vehicles surface as distributed sources of renewable energy. This approach can significantly contribute to increasing the efficiency of energy conversion by vehicles and to reduce air pollution in urban areas. Currently, it is also considered the use photovoltaic (PV) panels in charging stations for electric vehicles [5].

To allow for a power control of each device and connection of additional devices we selected a configuration in which all the sources are connected to one DC link. The paper focuses on the power control algorithm that allows connection of any number of devices to the system and input for energy management strategy. The simulation study was conducted for HESS consisting of li-ion battery, supercapacitor and PV panel.

2 HESS model

The scheme of the simulated HESS is presented in Figure 1. The devices models – supercapacitor, li-ion battery and PV panel – are connected to the DC link (DC link capacitor C_{DC} = 100 mF) with half-bridge, IGBT, buck-boost converters. The current smoothing inductances L1 = L2 = L3 = 5 mH are connected in series to devices. The load was modeled as controlled current source.

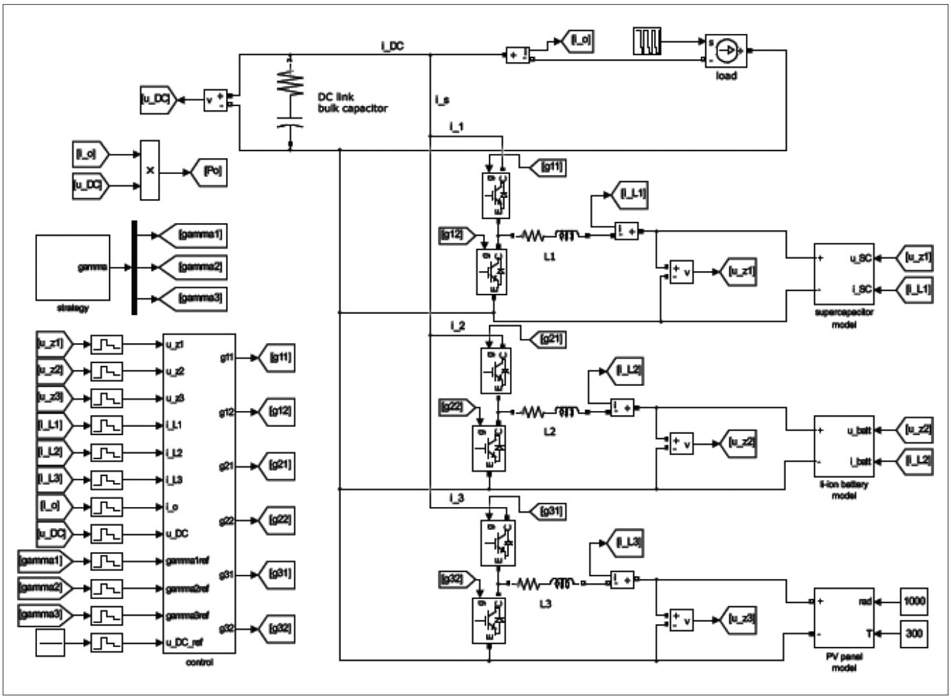

Figure 1 Scheme of the studied HESS.

In the Figure 2 the power control loop, which is placed in the control block in Figure 1, is presented. The system is designed to keep fixed controlled voltage on DC link. Using the measurements of devices currents i_L1, i_L2, i_L3, devices voltages u_Z1, i_Z2, i_Z3, DC link voltage u_DC, load current i_o and reference values of DC link voltage u_DC_ref and power split coefficients gamma1ref, gamma2ref, gamma3ref the control system is obtaining the modulation coefficients references m1_ref, m2_ref, m3_ref for each DC/DC converter. Those references are than used in PWM generators. The power of each device is described by (1).

$$P_1 = \text{gamma1ref} \cdot P_0$$
$$P_2 = \text{gamma2ref} \cdot P_0 \qquad (1)$$
$$P_3 = \text{gamma3ref} \cdot P_0$$

Where P_0 denotes load power. Therefore, defining the energy management strategy comes down to defining the values of gamma1ref, gamma2ref, gamma3ref, which sum should be always equal to 1 to meet power demand and keep fixed DC link voltage.

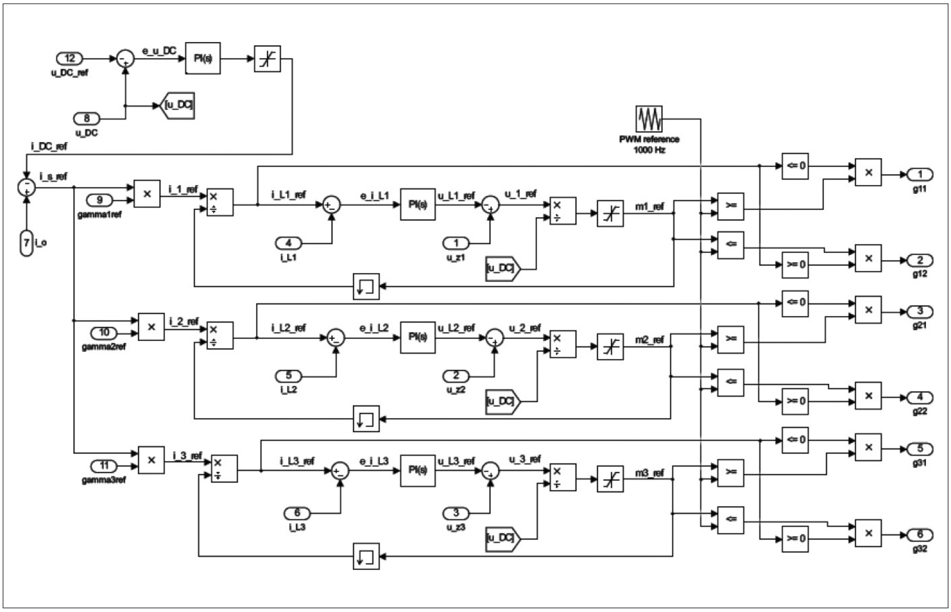

Figure 2 Scheme of the power control system.

3 Devices models

The scheme of the supercapacitor model used in the study was presented in Figure 3b, where C_{SC} and R_{s_SC} are respectively the capacity and equivalent series resistance of the element. The li-ion battery model was adopted basing on [6]. The scheme of the battery is shown in Figure 3a. It consists of controlled voltage source which variable is state of energy of the battery and series resistance R_{s_batt}. The last modeled device is PV panel. In the study the simulation model developed in [7] was adopted. The panel equivalent circuit is shown in Figure 3c. The parameters of the devices used in the analysis were given in Table 1.

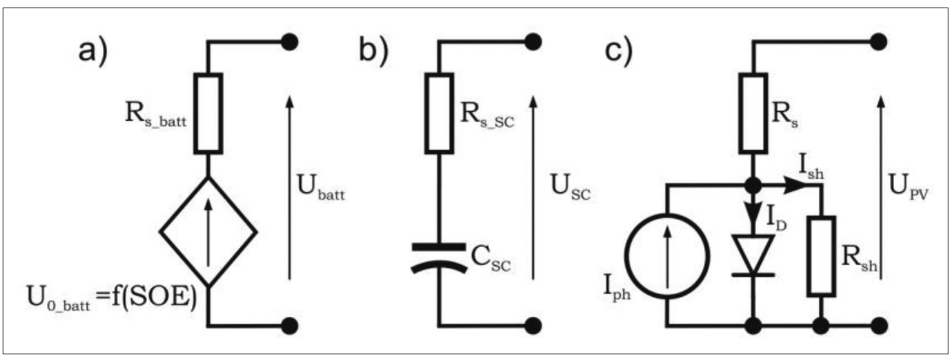

Figure 3 Equivalent circuit of a) the li-ion battery, b) the supercapacitor and c) the PV panel.

Table 1 Devices parameters.

	Parameter	Value	Unit
supercapacitor	Nominal voltage U_{N_SC}	48	V
	Series resistance R_{s_SC}	6	mΩ
	Capacity C_{SC}	165	F
	Maximum constant current I_{N_SC}	130	A
	Mass M_{SC}	14.2	Kg
li-ion battery	Nominal voltage U_{N_batt}	48	V
	Capacity	60	Ah
	Series resistance R_{s_batt}	55	mΩ
	Nominal power P_{N_batt}	4,5	kW
	Mass M_{batt}	124	kg
PV panel	Open circuit voltage Uoc_PV	48	V
	Nominal power PN_PV	120	W
	Radiation	1000	W/m^2
	Temperature	300	K

4 Energy management strategy

There are number of energy management strategies for HESS described in literature. Some of the most interesting were presented in [3], [8], [9]. In this study focused on the control algorithm we proposed simple strategy described in Table 2.

Table 2 Vehicle operation modes.

	CONDITIONS	SUPER-CAPACITOR	LI-ION BATTERY	PV PANEL	
standstill	SOE_{SC} = * SOE_{batt} < 1 v = 0; a = 0; P_0 = 0	gamma1ref = 0 i_1_ref = 0	gamma2ref = 0 i_2_ref = –i_3_ref	gamma3ref = 0 i_3_ref = P_{PVmax}/U_DC	mode 1
	SOE_{SC} < 1 SOE_{batt} > 0 v = 0; a = 0; P_0 > 0	gamma1ref = 1 – gamma2ref – gamma3ref	gamma2ref = P_{batt_limit}/P_0	gamma3ref = P_{PVmax}/P_0	mode 2
acceleration	SOE_{SC} > 0 SOE_{batt} > 0 v > 0; a > 0 $P_0 > P_{batt\_limit}$	gamma1ref = 1 – gamma2ref – gamma3ref	gamma2ref = P_{batt_limit}/P_0 – gamma3ref	gamma3ref = P_{PVmax}/P_0	mode 3
	SOE_{SC} = * SOE_{batt} > 0 v > 0; a > 0 $P_0 \leq P_{batt\_limit}$	gamma1ref = 0	gamma2ref = 1 – gamma3ref	gamma3ref = P_{PVmax}/P_0	mode 4
constant speed	SOE_{SC} = * SOE_{batt} > 0 v > 0; a = 0 $P_0 \leq P_{batt\_limit}$	gamma1ref = 0	gamma2ref = 1 – gamma3ref	gamma3ref = P_{PVmax}/P_0	mode 5
regenerative breaking	SOE_{SC} < 1 SOE_{batt} = * v > 0; a < 0; P_0 < 0	gamma1ref = 1	gamma2ref = – gamma3ref	gamma3ref = P_{PVmax}/P_0	mode 6
	SOE_{SC} = 1 SOE_{batt} < 1 v > 0; a < 0; P_0 < 0	gamma1ref = 0	gamma2ref = 1 – gamma3ref	gamma3ref = P_{PVmax}/P_0	mode 7

**Any value*

The gamma coefficients depend on current state of the vehicle, where v denotes vehicle's velocity and a its acceleration, and state of the energy of the supercapacitor SOE_{SC} and the battery SOE_{batt}. The PV panel power should be as high as possible regardless of the vehicle conditions. Due to that, the panel is equipped in maximum power point tracking (MPPT) system. In Table 2, seven possible modes of HESS operation were specified.

5 Results and discussion

The operation of the proposed system was verified on the example of an electric car, which parameters are given in Table 3. The car performs theoretical drive cycle that allows to examine all HESS operation modes. The load current during the cycle is shown in Figure 4.

Table 3 Vehicle parameters.

Parameter	value	Unit
Mass M	1500	kg
Drag coefficient C_x	0.4	–
Frontal area A	4	m^2
Rolling resistance coefficient I C_0	0.008	–
Rolling resistance coefficient II C_1	$6*10^{-6}$	$(s/m)^2$
Power train efficiency n_d	0.8	–
Air density ρ	1	kg/m^3

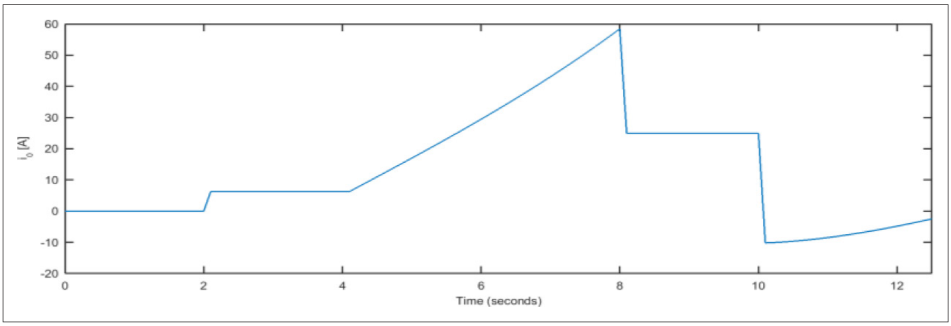

Figure 4 Load current plot.

The programmed strategy was correctly executed by the control system (Figure 5). In mode 1 the battery is charged by PV panel. Next, in mode 2, while the load power is greater than zero due to the car's auxiliary power (assumed 500W), which means that the car will be accelerating soon, the battery and PV panel are charging the supercapacitor. During an acceleration the battery is covering the power demand to the previously set limit P_{batt_limit}. The power that exceeds the limit is covered from supercapacitor (modes 3 and 4). At the same time the PV panel power is added to storage devices power. While the car is driving with constant speed the power demand is fully covered from battery and PV panel (mode 5). During a regenerative braking whole energy is gathered by supercapacitor, while it is also charges from PV panel (mode 6). The 12V overvoltage can be noticed while switching from mode 5 to 6. It is caused by fast change of the load current. The load current is dropping but the devices currents are still higher as the controller did not react yet, so the DC capacitor is charged by devices currents. If the supercapacitor is fully charged the whole braking energy is gathered by battery while is also charged by PV panel (mode 7).

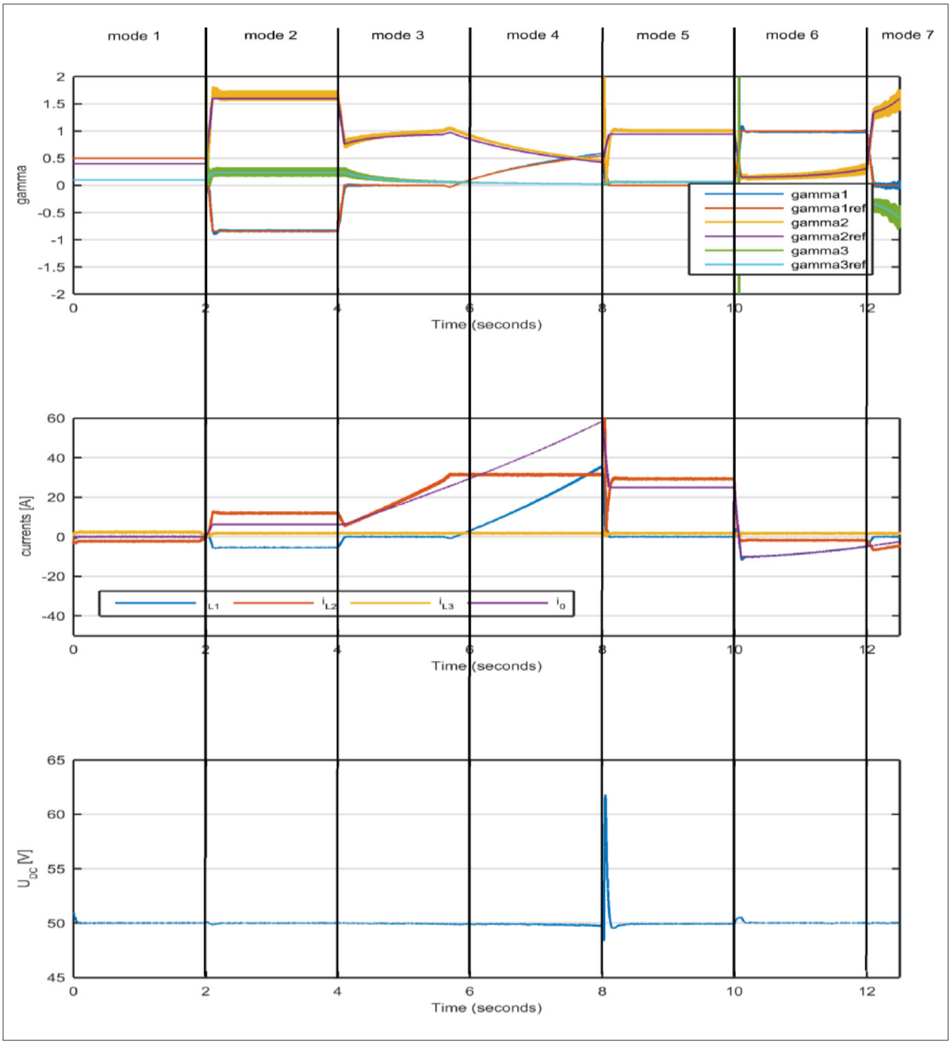

Figure 5 The plots of the gamma coefficients, device currents and DC link voltage during the drive cycle.

6 Conclusions

The proposed control system allows connecting any number of devices to HESS. The power of devices is easily controlled using gamma coefficients. An optimization of the energy management strategy is one the most important issues in HESS. Well designed strategy can improve the overall system performance. The optimization process can be focused on system's efficiency, durability or power performance. It has also strong influence on sizing of the elements of the system. The proposed HESS uses renewable sun's energy in electric vehicle. The simulations show that the power of PV panel are fully used during the vehicle operation. Taking into account the growing number of electric cars it can come out as more beneficial solution than stationary solar charger, because the car is not forced to stop.

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