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ANALYSIS OF TOPOLOGIES OF HYBRID ON-BOARD ENERGY STORAGE SYSTEMS FOR ELECTRIC VEHICLES

Introduction. Recently, all the world's leading automotive companies have been developing and serially producing electric vehicles (EVs). The EVs are certainly the most efficient ones from the environmental and energy points of view. However, due to a lack of on-board storage or power generation systems that would have high specific energy performance, for now only small full EVs are being produced. For the same reason, only hybrid EVs can truly compete on the market with traditional cars. However, even these vehicles have the problem of creating an effective on-board power system with high levels of energy and power density. Since there are practically no onboard energy sources that would simultaneously have high energy and high power, which is necessary to ensure a satisfactory range of motion and EV dynamics respectively, the onboard energy storage systems are made hybrid (HESS)—various energy sources with complementary properties are combined. For example, one of the on-board battery power sources is the source of energy, and the other the source of power. As a source of energy, the electrochemical batteries (Bs) of large capacity and fuel cells are used, and as a source of power, powerful Bs of low capacity, batteries of supercapacitors (SCs) and flywheels are used [1].

Analysis of Recent Research and Publications. Along with the development of on-board power supply sources, a lot of research is being done towards building effective HESSs [1, 2]. The qualities of these systems influence considerably technical and especially operational performance: energy density, power density, cycle life, security, cost, etc. Such studies are important not only for EV production, but also for other industries that use stand-alone power systems: for telecommunications and alternative energy based on renewable energy, etc. [2, 3]. There are two main problems for HESS creation: technical and economic explanation of efficient power circuit topology, and development of the structure and synthesis of the control system [4]. Despite the large quantity of research and publications (see the review [5]), research that would make it possible to assess the impact of HESS topologies on its performance with the same structure of the control system—in order to make informed decisions about the building of HESS—remains relevant.

Problem Statement. The purpose of this paper is to analyze the variations of the power circuit topologies of HESSs with sources of energy and power and to conduct comparative studies by computer simulation of alternative HESSs with the proposed effective control system.

Explication of the Main Material. We conduct a comparative study of HESS which consists of an electrochemical high-capacity B and battery of SC because such a hybrid on-board system, in our view, has currently the best price/quality ratio. Although A and SC are electrochemical devices, their characteristics significantly differ and complement each other (Table 1): B have a relatively high specific energy density and a relatively small cycle life, while the SC have high power density and a large cycle life. These properties are the basis for building HESS: B should work with a light load on EV and in order to maintain the state of charge of SC, while the SC must operate with a large load – acceleration, braking, driving uphill.

Since both B and SC are a source of direct voltage and are designed to supply a direct voltage on-board network, all possible topologies of HESS power schemes are based on combining these battery power sources and DC-DC converters of various types. All power elements of HESS – B, SC and DC-DC converters – are characterized by high cost, which makes the price issue of topologies very important.

Table 1 Characteristics of Batteries and Supercapacitors [2]

Chemistry		Nominal Voltage	Energy Density	Power Density	Cycle life
		V	Wh/Kg	kW/Kg	Times
B	Lead-Acid	2	30-40	0.18	Up to 800
	Ni-Mh	1.2	55-80	0.4-1.2	Up to 1000
	Li-Ion	3.6	80-170	0.8-2	Up to 1,200
	Li-Polimer	3.7	130/200	1.0-2.8	Up to 1,000
	Li-Iron Phosphate	3.2/3.3	80-115	1.3-3.5	Up to 2,000
SC		2.5/2.7	2-10	4-10	Over 1,000,000

The simplest topology of HESS is the so-called passive one [4], when both power sources are connected in parallel to the board power supply grid (Fig. 1a). However, this topology depends on B and SC units with commensurate power and its performance and lifetime are low.

All options of active HESS topologies, in which power-driven DC-DC converters used, are

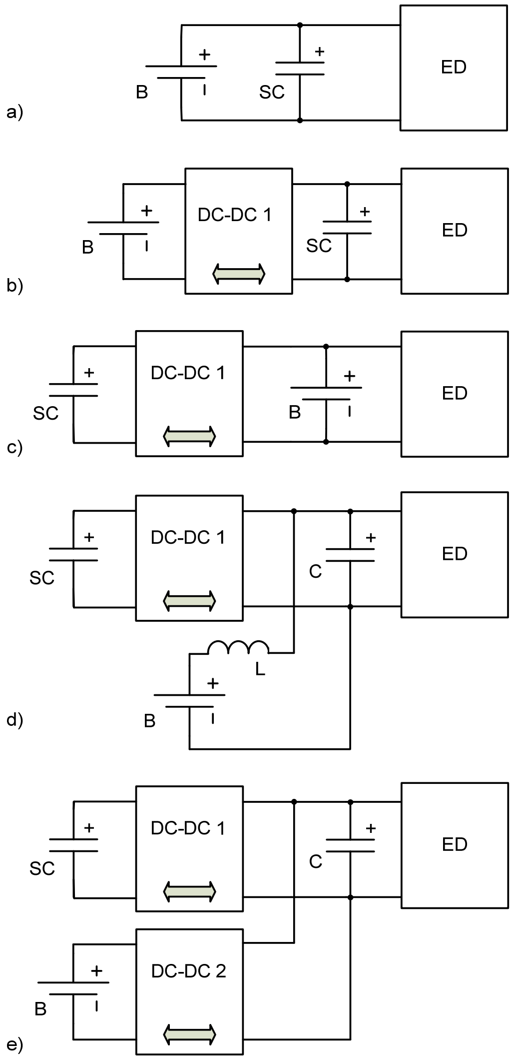


Fig. 1 The variations of the power circuit topologies of HESSs

shown in Fig. 1 b-d. They have one or two power sources separated from board network by DC-DC converters, which are usually boost-type and bidirectional. The DC-DC converter, which separates the B, is of significantly smaller power, and therefore cost, than the one that separates the SC.

For the aforementioned reason, the topology in Fig. 1b is cheaper than other active topologies. It was investigated in our study [6]. However, in this topology the SC determines the voltage of on-board network, which can vary in a range in relative units U^*_{SC} = 0.5 ... 1.0. This limits the possibility of EV drive system: power, speed adjustment range in the first zone and the second one with the flux weakening. Of course, this drawback can be minimized by reducing operating range of voltage change of SC battery, but this is only possible if its capacity and cost are increased. In view of the above, this topology can be recommended for low-power EV with low maximum speed.

Given the disadvantage of the previous topology, it can be concluded that the SC should be separated from the board network by a DC-DC converter, in spite of its power and cost. It would also reduce the operating voltage of SC battery, which can resolve the difficult task of aligning the state of charge of separate SC [7].

In the topology shown in Fig. 1c, the voltage of the board network already defines the B, the voltage of which changes slightly during work. It will partly take on itself the pulse currents in the dynamic modes of electric drive, which will adversely affect its service life. To reduce this factor, the B should be separated from the board network by LC filter as shown in Fig. 1d. However, in both cases, the efficiency of this topology will significantly depend on the control response of the DC-DC converter. Another drawback of this topology is the high B voltage, which is determined by the power of EV electric drive system. While the number of series connected batteries increases, the problem of aligning its state of charge becomes more complicated.

Considering all of these shortcomings, the most advanced topology is shown in Fig. 1e. Through the use of two DC-DC converters the SC and B voltages can be reduced, and the voltage of board network is provided by the control system. Required capacitance of the separate capacitor bank C depends on the quality of work of this control system, under the same other conditions (type and power of electric drive, the voltage of on-board network, the value of the carrier PWM frequency). However, the drawback of this topology is its comparatively high cost.

Thus, as a result of this analysis the most promising topologies for powerful EVs and hybrid EVs are the topologies shown in Fig. 1 d,e. They will be examined by computer simulation.

As we know, DC-DC step-up converter is a non-linear non-minimal phase dynamic link, which complicates the development of the control system based on it. In order to reduce the negative impact of this phenomenon, we suggest building a control system of HESS according to the structure shown in Fig. 2. Its peculiarity lies in three aspects: 1) the resolution of the work of two control systems – continuous control of board network voltage using converter DC-DC 2, and detainee control of dynamic current of the electric drive system through the converter DC-DC 1; 2) using two current sensors CS1 and CS2 for rapid regulation of large dynamic currents of SC, 3) relay control of the SC voltage.

The proposed control system of HESS works as follows. After it is turned on, the SC is being charged

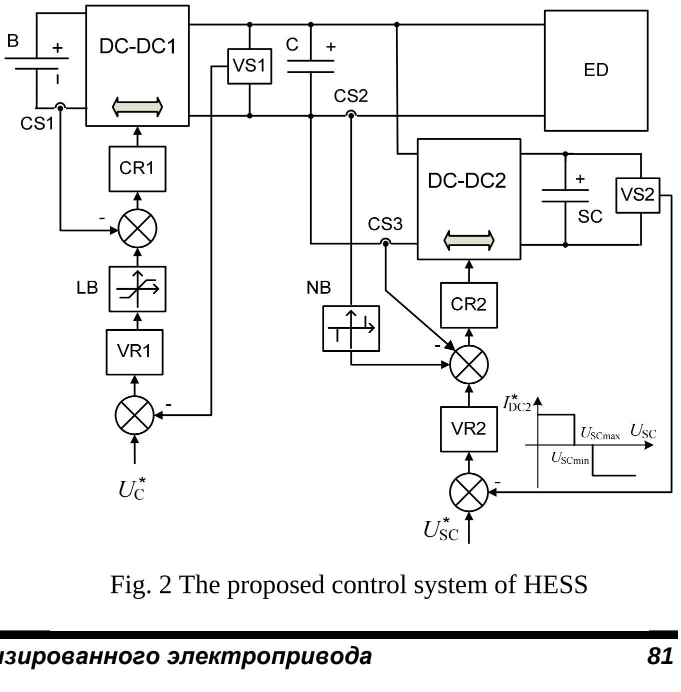


Fig. 2 The proposed control system of HESS

for some time to the reference voltage from the B through the board network. The current is consumed through the converter DC-DC 2 from the capacitor C, and the converter DC-DC 1 charges this capacitor from B. The board network voltage is close to the nominal level due to the choice of the reference currents in the limitation blocks LB and the relay voltage regulator VR2, respectively I_{LB} and I^{*}_{DC2}, for both current control systems according to the equation $I_{\mathrm{LB}} = I^{*}_{\mathrm{DC2}} \cdot U_{\mathrm{B}} / U_{\mathrm{Cn}}$, where U_{B} is the B voltage, and U_{Cn} is the board network voltage. When the SC voltage reaches the lower limit of the dead zone U_{SCmin}, which is set by relay voltage regulator VR2, the charging of the SC is complete. In the same way the SC is charged and discharged during EV operation. If the SC voltage is in the dead zone of the voltage regulator $U_{\mathrm{SCmin}} < U_{\mathrm{SC}} < U_{\mathrm{SCmax}}$, the power exchange between SC and B does not occur. During the light load of EV, when the electric drive current does not exceed the value $i_{\mathrm{load}} \le I_{\mathrm{B.d.max}} \cdot U_{\mathrm{Cn}} / U_{\mathrm{B}}$ or braking current does not exceed the value $i_{\mathrm{load}} \le I_{\mathrm{B.c.max}} \cdot U_{\mathrm{Cn}} / U_{\mathrm{B}}$, where $I_{\mathrm{B.d.max}}$ and $I_{\mathrm{B.c.max}}$ are the maximum values of B discharging and charging current, the electric drive system is powered by B. In the case of larger loads or intensive braking, if the above conditions are not met, the non-linear block NB is triggered, and consumption or generation current of the EV electric drive will be worked off by the SC subsystem. In a topology with a single DC-DC converter (Fig. 1 d), the system works similarly, but the B current is no longer limited at a given level, and is limited only by the work of the LC filter.

To construct computer models, the appropriate mathematical models of dynamic processes in the studied HESS topologies should be developed. Given the need for simulation of systems for a long time, it is advisable to replace switching variables during the work of DC-DC converters by corresponding average values, which can be obtained through duty cycles of transistors' pulse control of converters: μ1 and μ2 respectively for DC-DC 1 and DC-DC 2. Using this approach for boost type DC-DC converters, we received the following mathematical models in the normal Cauchy form, which describe the work of the studied topologies of HESS:

- For the topology shown in Fig. 1d

$$L_{\mathrm{DC1}} \frac{\mathrm{d}i_{\mathrm{SC}}}{\mathrm{d}t} = u_{\mathrm{SC}} - u_{\mathrm{C}}$$

$$C_{\mathrm{SC}} \frac{\mathrm{d}u_{\mathrm{SC}}}{\mathrm{d}t} = -i_{\mathrm{SC}}$$

$$L \frac{\mathrm{d}i_{\mathrm{B}}}{\mathrm{d}t} = u_{\mathrm{B}} - i_{\mathrm{B}}\left(R_{\mathrm{L}} + R_{\mathrm{B}}\right) - u_{\mathrm{C}}$$

$$C \frac{\mathrm{d}u_{\mathrm{C}}}{\mathrm{d}t} = i_{\mathrm{SC}}\left(1 - \mu_1\right) + i_{\mathrm{L}} - i_{\mathrm{load}}$$

- For the topology shown in Fig. 1e

$$L_{\mathrm{DC1}} \frac{\mathrm{d}i_{\mathrm{SC}}}{\mathrm{d}t} = u_{\mathrm{SC}} - u_{\mathrm{C}}$$

$$C_{\mathrm{SC}} \frac{\mathrm{d}u_{\mathrm{SC}}}{\mathrm{d}t} = -i_{\mathrm{SC}}$$

$$L_{\mathrm{DC2}} \frac{\mathrm{d}i_{\mathrm{B}}}{\mathrm{d}t} = u_{\mathrm{B}} - i_{\mathrm{B}} R_{\mathrm{B}} - u_{\mathrm{C}}$$

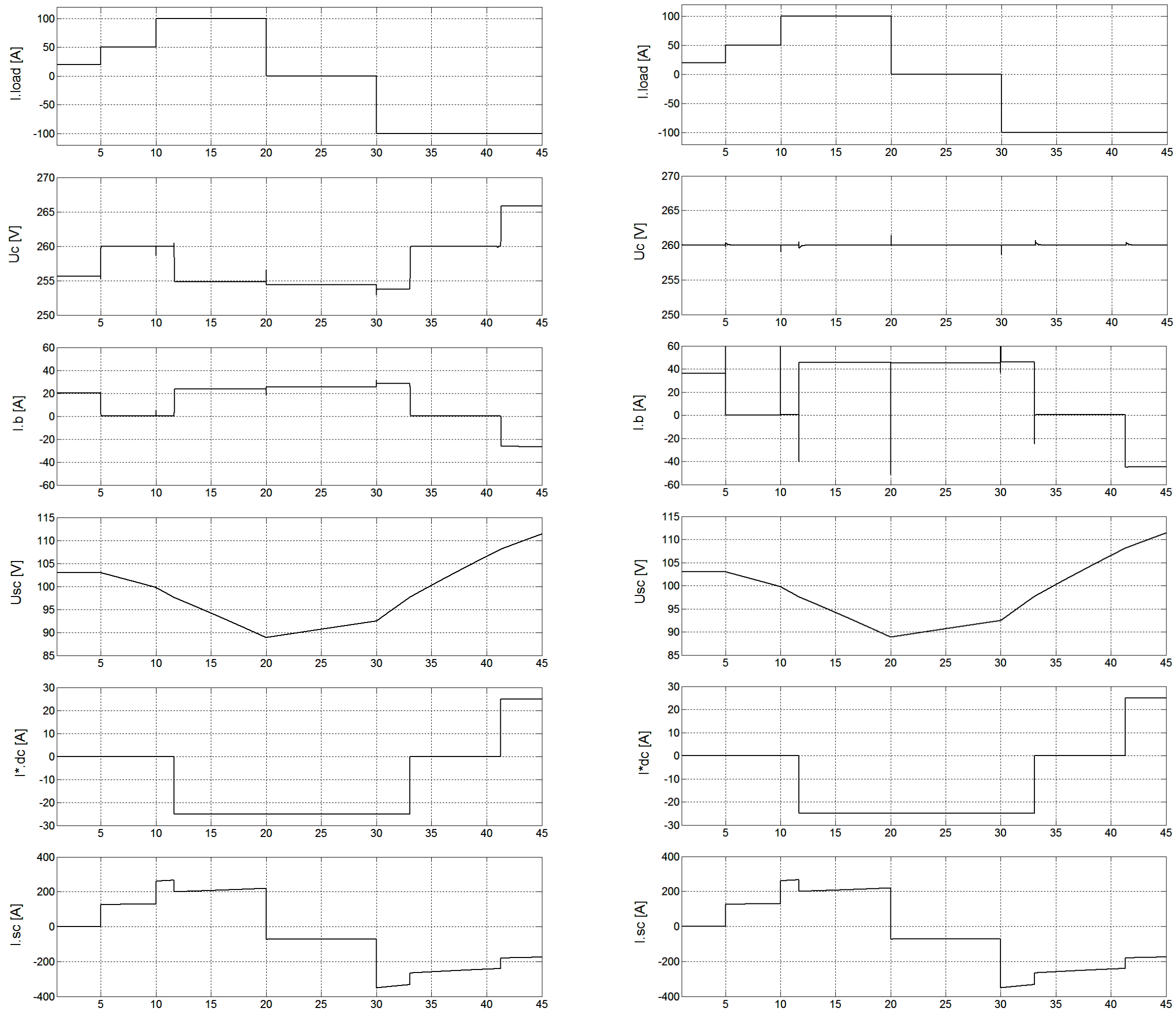
$$C \frac{\mathrm{d}u_{\mathrm{C}}}{\mathrm{d}t} = i_{\mathrm{SC}}\left(1 - \mu_1\right) + i_{\mathrm{B}}\left(1 - \mu_1\right) - i_{\mathrm{load}}$$

where L_{DC1} and L_{DC2} are the inductances of the converters DC-DC 1 and DC-DC 2 respectively, C_{SC} is the capacitance of the SC, L and C are the inductance and capacitance of the LC filter, u_{SC} and i_{SC} are the voltage and current of the SC, u_{B} and i_{B} are the voltage and current of the B, u_{C} is the voltage of the capacitor C, i_{load} is the load current of EV electric drive, R_{L} and R_{B} are the resistances of the L and B respectively.

On the basis of these models according to the functional scheme presented in Fig. 2, computer models of the two topologies of HESS were built. Their work was compared at the same test signal, which simulates the operation of EV electric drive.

In the models the following nominal values of the HESS parameters were selected: U_{AB} = 144 V, $I_{\mathrm{B.d.max}} = I_{\mathrm{B.c.max}}$ = 80 A, $U_{SC.n}$ = 130 B, U_{Cn} = 260 V. According to the procedure described in [6], the relative value of the operating voltage of SC battery should be $U^{*}_{\mathrm{SC.r}} = \sqrt{0.625} = 0.79$, which provides the same energy capacity for the possible charging or discharging that may follow. Then $U_{\mathrm{SC.r}} = U^{*}_{\mathrm{SC.r}}\, U_{\mathrm{SC.n}}$ = 103 V, and 10% to SC energy dead zone of the VR can be set as follows: $U_{\mathrm{SCmin}} = \sqrt{0.9}\, U_{\mathrm{SC.r}}$ = 97.7 V, $U_{\mathrm{SCmax}} = \sqrt{1.1}\, U_{\mathrm{SC.r}}$ = 108.0 V. Simulation begins with the charged SC battery to $U_{\mathrm{SC.r}}$. Then the test load of EV electric drive is simulated, which includes both light and heavy load in the modes of traction and braking. The results of simulation as basic coordinate responses are shown in Fig. 3. Up to 5 s drive powered by epy B, and more – from the SK. Within the interval 12-33 s SC charges from B, and after 41 s gives energy to B.

Conclusions. At the current level of technological development, energy efficient and reliable on-board power supply EV system can be built by combining sources with high energy and high power, the electrical coordinates of which are regulated by step-up DC-DC converters. As a result of our analysis, two promising topologies using one and two DC-DC converters were selected and the mathematical models describing the dynamic processes in them were developed. The structure of the HESS control system was proposed and its efficient performance was confirmed by computer simulation. According to the simulation with the same load test, both studied HESSs satisfactorily perform their functions. However, HESS with two DC-DC converters provides a better stabilization of electric supply voltage and allows it to regulate, thus reducing the loss of electric drive.



a) b)

Fig. 3 The results of simulation of HESSs with the topology shown in Fig. 1d (a) and in Fig. 1e (b) as basic coordinate responses (from top to bottom): i_{load}, u_{C}, i_{B}, u_{SC}, I^{*}_{DC2}, and i_{SC}

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