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OPTIMIZATION OF HYBRID ENERGY STORAGE SYSTEM FOR ELECTRIC VEHICLES*

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Abstract: The paper deals with improvement of efficiency of energy storage devices for electric vehicles. The benefits and features of the hybrid energy storage system based on the batteries and ultracapacitors are described. The possible topologies and common schematics of bi-directional DC/DC converters for energy storage are analyzed in terms of efficiency, reliability and battery maintenance. An algorithm for optimization of its parameters is developed, analyzed, shown and explained in detail. The surfaces, which show the dependence between required battery and ultracapacitors' capacities, energy storage cost and battery discharge ratio are obtained and analyzed. Conclusions are drawn concerning optimization strategy and results of optimization with possible further improvements.

Keywords: *electric vehicle, battery, ultracapacitor, hybrid storage system, optimization, DC/DC converter, topology*

1. INTRODUCTION

Despite on the obvious benefits of electric and hybrid vehicles regarding their low emission, high reliability, dynamic and comfort aspects, the market still grows slowly because of one major challenge – the performances of the energy storage systems. At present, almost all pure electric vehicles (PEVs) are equipped with galvanic electrochemical batteries, which have lower energy density (J/m^3 or J/kg) compared to petrol [1]. While high-end cars like Tesla model X provide more than 450 km travel range, the average-cost electric vehicles can drive far less than conventional cars [2]. There is even a special term – "range anxiety", describing the fear that electric vehicle can run out of charge before reaching its destination or recharging point [3], [4].

This problem is partially solved in hybrid electric vehicles (HEVs) equipped with conventional internal combustion engines, hydrogen engines or fuel cells.

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However, such hybrid traction systems, unlike those in pure electric vehicles, cannot effectively utilize regenerative energy during braking. Neither can it be captured in pure electric vehicles during intense decelerations because of low power density and fast degradation of the cells in the battery under high charging currents. These losses of the braking energy substantially reduce the travelling range of the vehicle. The current surges under acceleration in the urban driving cycles also significantly reduce the lifetime of the batteries. Even when using the battery management systems that directly control the charging and discharging rate, cell's state of charge (SOC), voltage and temperature, the lifetime of the common traction batteries does not exceed 4–5 years. Meanwhile, the battery is the most expensive part of electric vehicle.

To solve the above-mentioned problems, different variations of the hybrid energy storage systems (HESS) were proposed by researchers during the last decade [5]–[11]. The main idea of hybrid energy storage system is to combine different energy storage technologies (e.g., batteries, fuel cells, solar panels, ultracaps, etc.) into the coherent system with special control strategy, which can use the advantages of each energy source in order to improve overall performances. Special attention should be given to the battery-ultracapacitor systems, in which energy-dense battery serves as an energy source for long-range travelling, while ultracapacitor pack is used as a peak power source, providing bursts of power for acceleration and capturing regenerated energy during braking. Very high power density, big number of charging/discharging cycles and wide operating temperature range of the ultracaps make them ideal "assistants" for galvanic batteries in electric vehicles.

The efficiency of the battery-ultracapacitor hybrid energy storage systems was proved by many researchers on theoretical models and practical prototypes [8], [10], [11], but due to significantly different operational parameters of ultracapacitors and batteries there is still an open question of optimal combination of their parameters. There are many topologies of the battery-ultracapcitor hybrid energy source systems, each has its advantages and disadvantages, and researchers are still seeking an optimal solution.

In this article, we shall try to analyze most common topologies from the viewpoint of their efficiency, cost and reliability. Another important point that is often overlooked is the optimal sizing of the hybrid energy storage system components. If the ultracapacitors are undersized and there is a situation when they are empty and cannot provide required acceleration of the vehicle, the necessary current will be drawn from the battery; it will shorten its service life. Another aspect of undersizing is a loss of energy during braking, which might otherwise be captured and stored in the ultracapacitor. On the other hand, the excessive capacity beyond required would overprice the system. Moreover, increasing capacity means increasing vehicle weight, which, in turn, will demand more power for acceleration. Taking into account all these factors, we shall try to find the optimal ratio of capacities.

2. TOPOLOGIES OF THE BATTERY-ULTRACAPACITOR HYBRID ENERGY STORAGE SYSTEMS

While galvanic batteries operate at relatively constant voltage, it is known that depending on the level of charge, the voltage of ultracapacitor changes from zero to nominal value. That is why hybrid systems usually have power DC/DC converters to match voltage levels and regulate power flows [5], [6].

The topology of the HESS with direct parallel connection of storage units without any DC/DC converter (Fig. 1), despite of the obvious simplicity and reliability, has many limitations and cannot provide proper operation of the system, neither can it save the battery from surge charging/discharging currents.

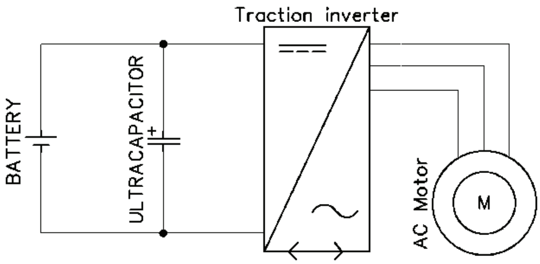

Fig. 1. Basic parallel topology of the HESS

The power flows between the UCs and battery in this configuration depend only on the internal resistance of the storage unit and cannot be controlled. Because of the parallel connection, the voltage of the DC-link and UCs are equal to the voltage of the battery $U_{DC} = U_{UC} = U_B \sim$ const, which is relatively constant. The effective energy provided by ultracaps storage is determined by the equation

$$E_{UC} = \frac{C(\Delta U_{UC})^2}{2} . \tag{1}$$

In basic parallel configuration the ΔU_{UC} tends to be zero, so the effective energy, which can be used from UCs unit, also tends to zero. That is why, to provide high efficiency of the HESS, a DC/DC converter is required.

Four topologies of HESS with DC/DC converters (Fig. 2) should be examined in detail [10], [11].

In these configurations, each storage unit is connected to the DC-link of the traction inverter by its own DC/DC power converter. Although such topologies can provide full regulation of voltage, current and power in order to obtain greater overall efficiency, they must have at least one DC/DC converter that is rated according to the full traction power of the vehicle, which increases the cost of the system.

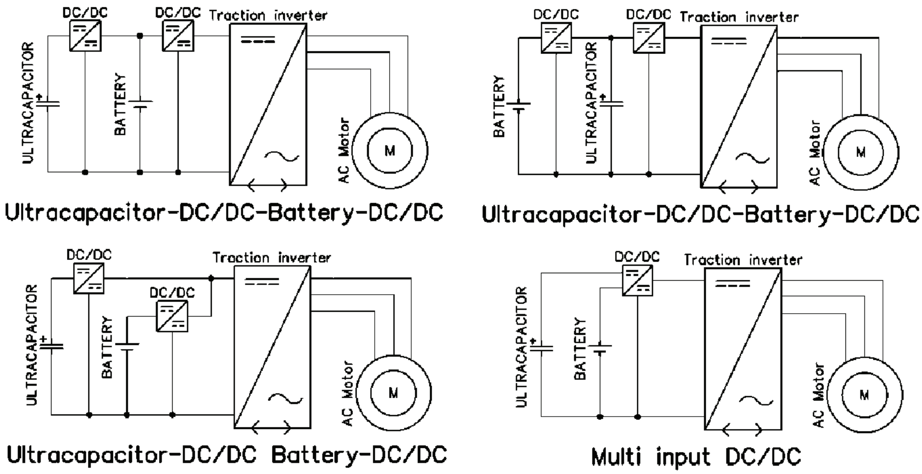

Fig. 2. Topologies with several DC/DC converters

That is why two configurations are now most common (Fig. 3) [10], [11]. In these two topologies, there is one DC/DC converter, which can be less powerful than traction system of the vehicle.

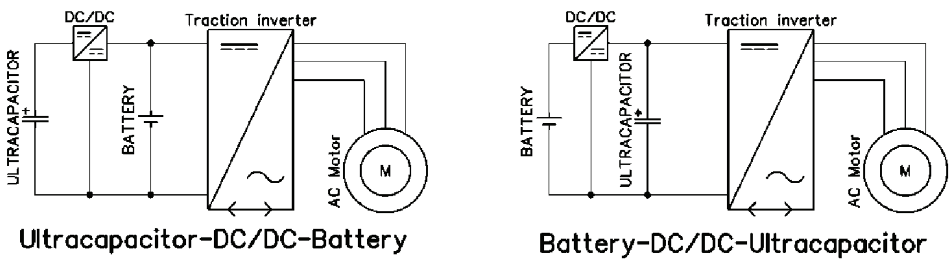

Fig. 3. Topologies with single DC/DC converter

In the UC-DC/DC-Battery topology, the UCs unit is connected through the bidirectional DC/DC converter to the DC-link, while the battery is connected directly parallel to it. This configuration is the most common variant of hybrid storage, since the DC/DC converter can sustain the voltage of DC link during the discharging of ultracapacitors and thus fully utilize the energy stored in them [5]. However, if we want to use all benefits of UCs, namely large power density for acceleration and regenerative braking and high number of charging/discharging cycles, the power of DC/DC converter must match the power of the UCs unit, which again leads to the increased cost of the power electronic components. This problem is aggravated by the fact that with discharging, the voltage of the UCs drops by non-linear dependence. Therefore, in order to supply the same level of energy at low voltage levels, the

DC/DC converter must provide higher current. And since the energy stored in capacitor is proportional to the voltage in the second degree ($W \sim U^2$), the drop of voltage will require quadratic increase of current. In addition, since the battery is connected directly to the DC-link there is possible situation when battery will suffer from the bursts of charging/discharging currents, for example, due to the lagging in the DC/DC control circuitry or when the UCs are fully charged.

Nevertheless, in terms of reliability, this topology has obvious benefits, since the traction drive can be supplied directly from the battery (like in conventional EV) even in the case of DC/DC failure. This feature is also useful for long accelerations, when all energy from the UCs is drained.

In the Battery-DC/DC-UC configuration, the UCs unit is connected directly to the DC-link, while the battery is connected through the DC/DC converter. In this configuration, the current of the battery can be fully controlled by the bi-directional converter in any driving condition in order to protect the battery from the bursts of charging/discharging currents. The voltage of the DC-link is equal to the voltage of the UCs and varies during vehicle acceleration and deceleration, but modern traction drive for vehicle application can provide peak level of motor current in wide ranges of input voltage. For example, the BRUSA's traction controller "DMC5" [12] can operate in $U_{\min} = 200$ V – $U_{\max} = 450$ V voltage range with full load current capacity, so from equation (1) the available energy from UCs unit can be calculated by

$$E_{\mathrm{av}} = \frac{\dfrac{CU_{\max}^2}{2} - \dfrac{CU_{\min}^2}{2}}{\dfrac{CU_{\max}^2}{2}} = \frac{U_{\max}^2 - U_{\min}^2}{U_{\max}^2} \approx 80\% \,. \tag{2}$$

Due to the quadratic dependence between the stored energy and voltage of the UCs unit, almost all stored energy (~80%) can be utilized in the operating range of traction drive input voltage. Therefore, direct connection of the UCs unit to the DC-link provides peak power for acceleration as well as effective utilization of braking energy.

Another key advantage, which is attributed to the Battery-DC/DC-UC topology, is that the converter can have lower power than it is required in the UC-DC/DC-Battery topology [10] because ultracapacitor will absorb most of the power surges. However, it should be mentioned that ultracapacitors could be quickly depleted in case of long driving at high speeds; in such cases all required power will be drawn from the battery through the DC/DC converter.

Figure 4 illustrates the diagram of vehicle speed in the Worldwide Harmonized Light Vehicles Test Procedure Cycle (WLTP) and required power for mid-size passenger car. The WLPT cycle simulates the urban driving cycle with frequent accelerations and decelerations for evaluation of the energy consumption.

As is seen from Fig. 4, the graph of consumed power has a lot of spikes with maximum value $P_{\max} = 43.7$ kW, and minimum value $P_{\min} = -30$ kW. Despite that the average level of consumed power over the whole cycle is equal to P_{av} = 4.88 kW, there is a big period between 1100 and 1300 sec where the vehicle moves at high speed and consumes approx. 40 kW.

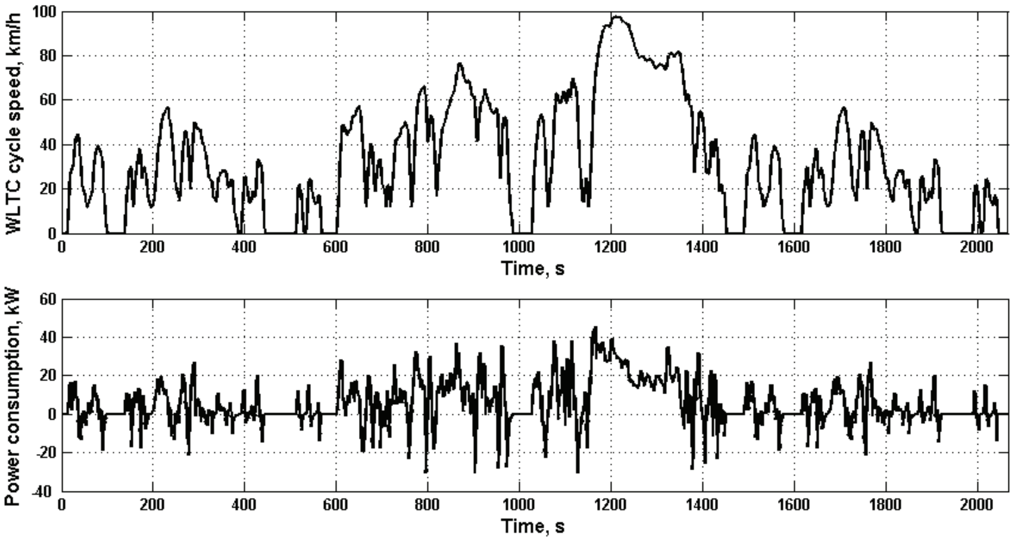

Fig. 4. Speed and required power for mid-size vehicle on the WLTP cycle

Therefore, the battery capacity, UCs capacitance and DC/DC converter's rated power must be properly sized taking into account the aforementioned constraints.

Special attention should be given to the schematics of the DC/DC power converter in the chosen HESS topology.

The most common bi-directional DC/DC converter uses a half-bridge buck-boost schematic, shown in Fig. 5 [5], [6], [9].

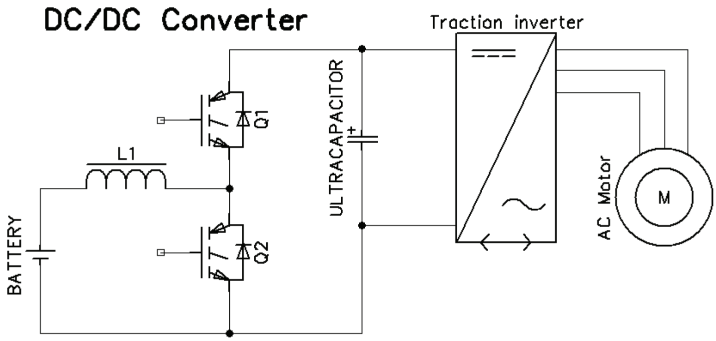

Fig. 5. Half-bridge bi-directional DC/DC converter schematic

The high-side switch Q1 with inductance L1 and body diode of the transistor Q2 constitutes a usual step-down buck converter that can regulate the battery charging current, when the power flows from the UCs unit to the battery during regenerative braking of the vehicle. On the other hand, the transistor Q2 with the choke and body diode of the transistor Q1 represents a step-up boost converter, which can consume constant and limited current from the battery and charge the UCs with higher voltage.

Because of the body diode of the transistor Q1 a special situation can occur in this circuit. When the UCs unit is completely discharged, it can be assumed as short circuit, since the internal resistance of the UCs unit is very small. The charging current then will flow through the battery L1 and body diode of Q1 transistor without any regulation or limiting and probably destroy other components (high frequency choke L1 cannot limit the current because of its low inductance). Therefore, this schematic needs additional low-power pre-charging converter for UCs unit.

In practice, this body diode of Q1 transistor can act as a self-regulating element of the HESS. Until the voltage of the UCs unit is higher than battery voltage, the resulting voltage across body diode of the Q1 is reverse so it does not conduct. In cases when stored in the UCs unit energy may not be enough for extended vehicle acceleration and the voltage of the UCs unit will drop to the rated battery voltage, the diode opens and connects the battery directly to the DC-link like in conventional schematic, so the vehicle can continue acceleration. The results of HESS with half-bridge DC/DC converter modeling in Simulink® software are shown in Fig. 6. The input parameters are listed in Table 1. Considering this, the high side switch should be rated for the maximum vehicle traction power, or additional high power ultra-fast (faster the body diode) valve should be connected in parallel with transistor Q1.

Table 1. Parameters of HESS taken for simulation
of half-bridge converter

Parameter	Value
Battery capacity	$C_B = 40$ Ah
UCs capacity	$C_{UC} = 50$ F
Load power	$P_{\text{load}} = 15$ kW
Battery discharge ratio	$DR_B = 1\ C_B$
Battery rated voltage	$V_B = 190$ V
UCs initial voltage	$V_{UC,\text{init}} = 250$ V
DC/DC conv. voltage threshold	$V_{DC/DC} = 230$ V
Battery fully charged voltage	$V_{B,\max} = 221$ V

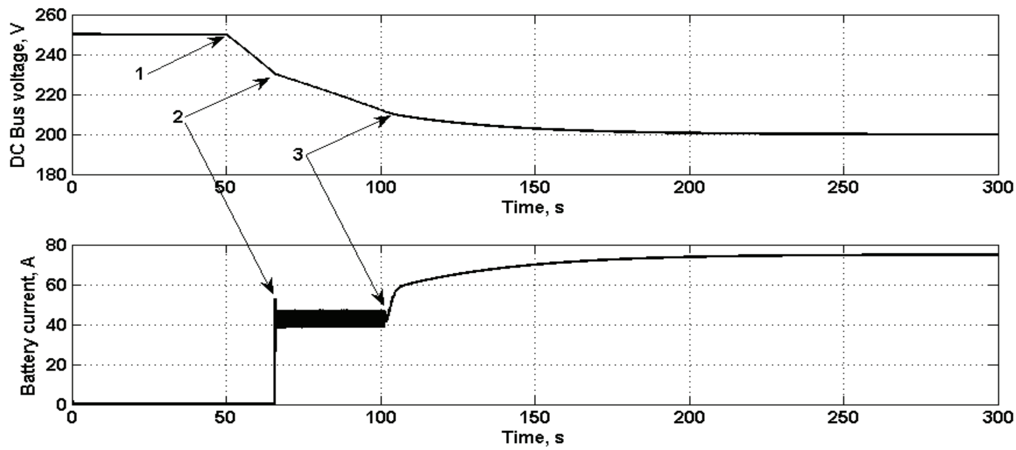

Fig. 6. Modeling of the HESS with half-bridge DC/DC converter:
(1) switching-on the constant power load; (2) discharging battery with constant current via DC/DC converter; (3) opening the body diode of the high-side switch

Although the half-bridge schematic of the DC/DC power converter is practically useful, the influence of the not-controlled additional battery current through the body diode of the high-side switch should be excluded. Therefore, for optimization of the capacity parameters, the scheme of DC/DC converter (Fig. 7) should be used.

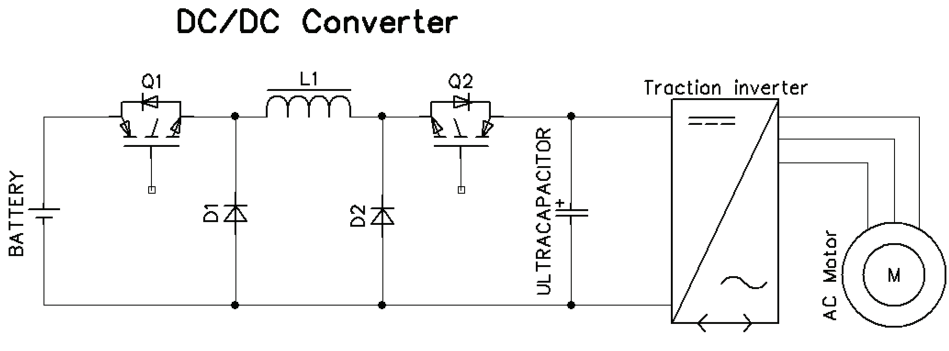

Fig. 7. Schematic of DC/DC converter for HESS parameters optimization

The principal electric connection diagram, shown in Fig. 7, represents two buck converters with common choke, connected in counter directions. The path of current flow during discharging and charging of the battery is shown in Fig. 8. As is seen in Fig. 7, there is always one switch in current flow circuit, which provides full control of the battery charging or discharging current.

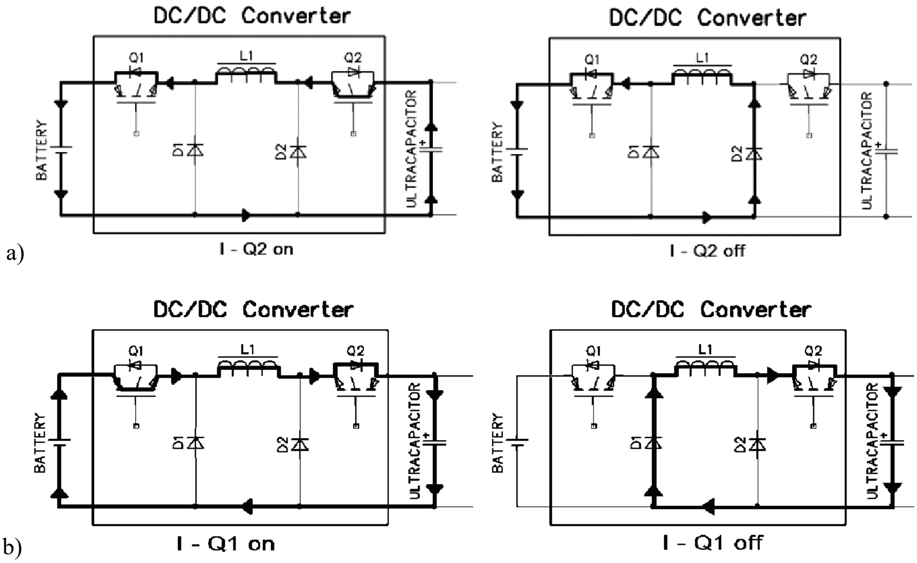

Fig. 8. Curent flows in DC/DC converter:
(a) battery charging from UCs; (b) UCs charging from battery

The waveforms of power distribution, DC Bus voltage and vehicle speed in the HESS with proposed common choke buck converter topology are shown in Fig. 9. The figure represents results of simulation of vehicle movement in the normalized test cycle procedure (e.g., WLTC) from the 100th to the 400th second.

The relay regulators of DC/DC power are tuned according to the DC bus operating range, the system has the following settings:

1. DC bus operating range – 200–300 V.
2. Battery discharging switch-on threshhold – 220 V.
3. Battery discharging switch-off threshhold – 240 V.
4. Battery charging switch-on point – 260 V.
5. Battery discharging rate – $2C_B$, where C_B = 60 Ah – capacity of battery unit in the simulation.
6. Battery charging rate – 1 C_B.
7. Ultracaps unit capacity – C_{CAP} = 10 F.

Let us illustrate some specific points that describe operation of HESS with proposed type of power converter. At point 1 the voltage of DC bus drops below 220 V, since the vehicle accelerates and consumes the power from UCs unit ($P_{CAP} > 0$). At this time, the power converter turns on and charges the UCs up to 240 V at constant battery power (which improves the battery operation condition and increases its lifetime), since the UCs unit cannot provide sufficient amount of energy for vehicle acceleration.

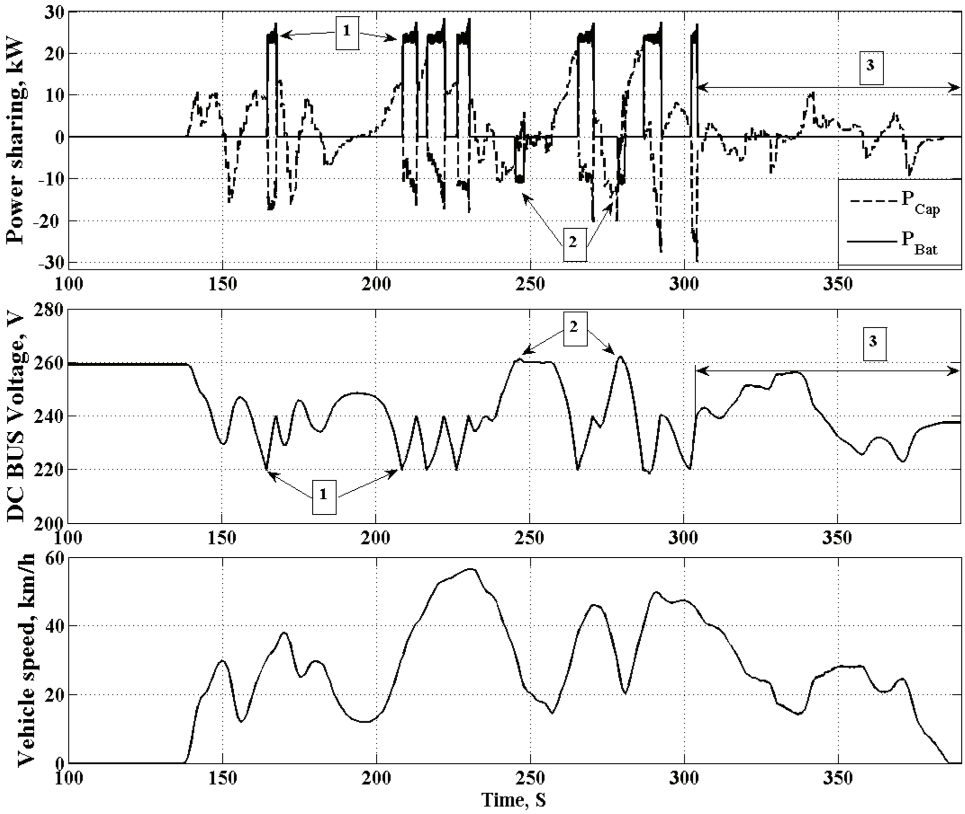

Fig. 9. Distribution of power flows and key signals in the EV's hybrid energy storage system

At point 2 under vehicle's regenerative braking, the voltage of DC bus rises above 260 V, and the DC/DC converter begins to transfer the energy into the battery at constant charging current (P_{BAT} = const) for long-time storage. However, if the voltage of DC bus does not exceed the thresholds of regulators (U_{DC} = 240–260 V), like it is shown on the Interval 3, the vehicle can accelerate and brake only with the help of UCs unit ($P_{BAT} = 0$, $P_{CAP} <> 0$).

Such an algorithm of HESS operation provides simple and effective power flow management. System's performances may be adjusted by thresholds of relay regulators. At the same time, this DC/DC converter topology completely protects the battery from current surges.

Thus, of all the topologies examined, the Battery-DC/DC/-UC configuration looks the most adequate trade-off due to the lower cost, higher reliability, fully controlled battery current and efficient utilization of the ultracapacitors' advantages. In the next section of the article, we shall optimize the parameters of the energy storage system.

3. OPTIMIZATION OF THE HESS COMPONENTS' PARAMETERS

The model of HESS parameters optimization in Simulink Software is shown in Fig. 10. The aforementioned schematic of DC/DC converter is supplemented with two relay current regulators, which turn on and off the charging or discharging part of scheme, depending on the DC-link voltage, and limit the battery currents. According to recommendations of the manufacturers, the charging current or charge ratio (*CR*) of the battery is defined by the battery capacity C_B and limited at the $CR = 1\ C_B$ value. The discharging ratio (*DR*) of the battery is changed during optimization and can vary in $DR = 1 \div 4\ C_B$ range.

The DC-link is loaded onto ideal current consumer, and the current consumption is determined by the required power for mid-range vehicle in the WLTP driving cycle. The range of DC-link voltage variation is chosen according to recommended voltage for the traction converters and common EVs battery packs voltage. The voltage of the DC-link can vary in the $V_{DC} = 200 \div 300$ V range. The relay regulators of DC/DC converter are configured to stabilize the average voltage at $V_{AV} = 250$ V, therefore they switch battery charging or discharging when the deviation of the DC link voltage exceeds 5% of the average value. If the voltage of the DC-link during simulation of the system on the WLTP cycle is changing beyond the recommended range, the parameters of the system are rejected, since HESS with these parameters cannot provide or consume required energy at limited battery current.

Another important parameter, which should be considered in HESS optimization, is the cost of the system. Although it is a very relative value, which in real life can be affected by many factors, we shall take it as a main criterion in the HESS parameters optimization. Setting constrains on battery charge/discharge current and DC bus voltage limits the range of battery capacity and UC's capacitance. We shall seek a combination of these two parameters, which provides the lowest price of the system.

The price of lithium battery and UCs units depends on the capacity and capacitance. According to the current prices on electric components, the specific price of the standard Li-Ion batteries is $P_{rB} \approx 150$ \$/kWh. As for the ultracapacitors, they can store far less amount of energy, it is actually convenient to measure this energy in Joules. The price of the UCs was taken as $P_{rUC} \approx 0.004$ \$/J according to the manufacturers' data [5]. However, in order to operate with single units, we shall stick to kWh: $P_{rUC} \approx 14400$ \$/kWh.

It is important to note that economic indicators of EV construction and maintenance are by no means limited by components' prices. Installation of Ucaps will reduce surges of battery currents and hence prolong battery's service life. We shall not evaluate such side effects but it should be kept in mind that hybridizing energy storage brings additional benefits.

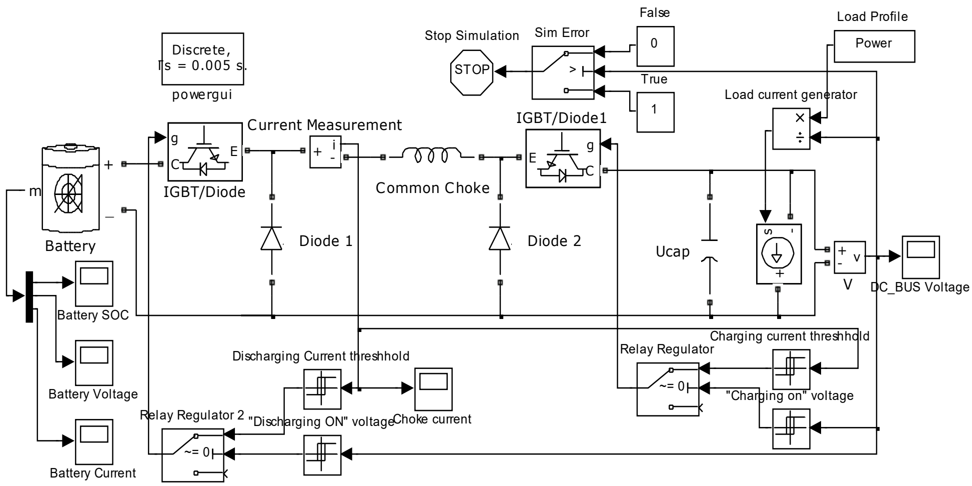

Fig. 10. Model of the HESS for storage unit's capacity optimization

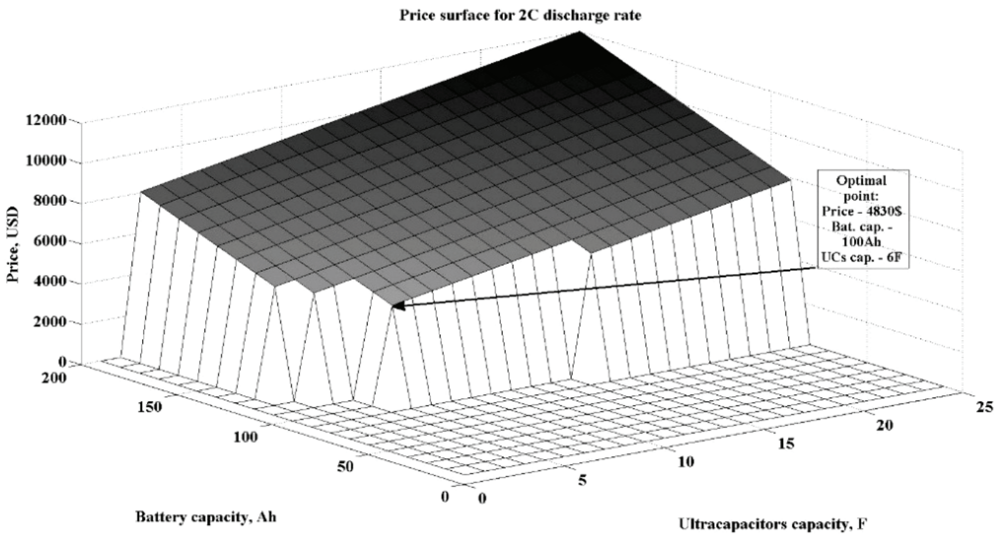

Fig. 11. Price surface for discharge ratio $DR = 2C_B$; the point of optimal operation is $C_B = 100$ Ah, $C_{UC} = 6$ F, $PR = 4830$ \$

Finally, the simplest method was chosen for optimization – cycles through the capacity parameters. The main idea of this method is to update cyclically the input parameters (capacity of units) of the Simulink® model, calculate the price of the HESS with these parameters (if HESS operation meets the above-mentioned constraints) and choose the best cost-effective set of parameters. Although this method takes much longer time than various gradient methods, it allows the full map of capacity-price dependence to be obtained and gives opportunity to analyze the system behavior in all calculated parameters of capacity. The capacity of battery during optimization was varied within $C_B = 10 \div 200$ Ah range, while the capacity of UCs was in $C_{UC} = 1 \div 25$ F range.

The price surfaces with optimal points of capacity parameters for battery discharge ratio $DR = 2\ C_B$, $3\ C_B$, $4\ C_B$ are shown in Fig. 11, Fig. 12 and Fig. 13, respectively. The white squares represent the parameters of the system, which do not meet the limitations.

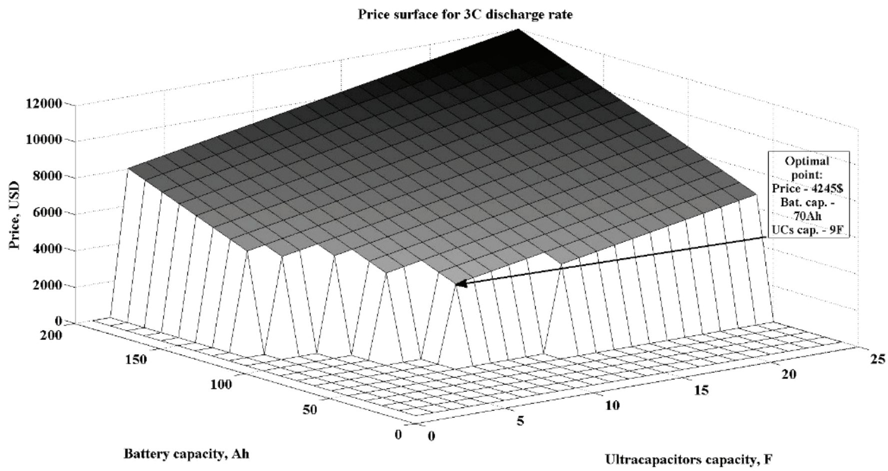

Fig. 12. Price surface for discharge ratio $DR = 3C_B$; the point of optimal operation is $C_B = 70$ Ah, $C_{UC} = 9$ F, $PR = 4245$ $

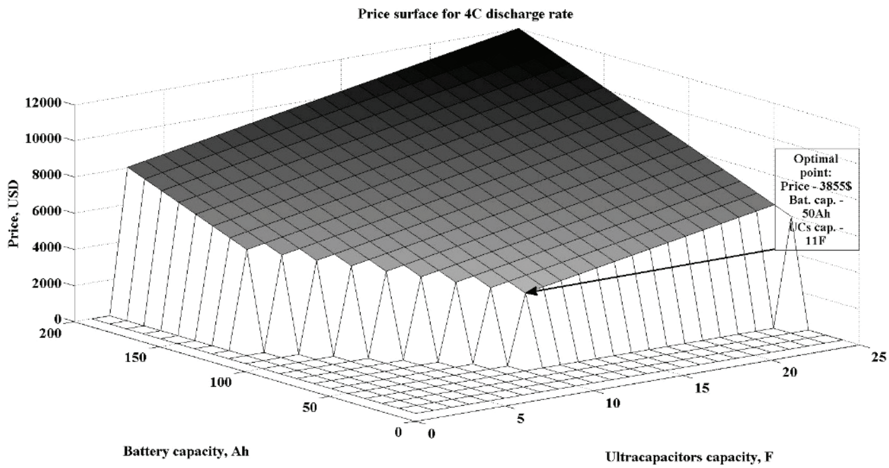

Fig. 13. Price surface for discharge ratio $DR = 4\ C_B$; the point of optimal operation is $C_B = 50$ Ah, $C_{UC} = 11$ F, $PR = 3855$ $

As we can see, the obtained characteristic can be described as a linear monotonically increasing function of HESS price, which is limited by the hyperbolic dependence of battery capacity and UC capacitance. The capacity of galvanic battery is directly proportional to the average consumed in the cycle energy as well as to discharge ratio. When surges and spikes of the speed curve are mitigated by ultracapacitors, the battery capacity can be calculated taking into account the two parameters only.

With given discharge ratio, the UC capacitance is inversely proportional to the battery capacity, and this dependence has hyperbolic character. However, essential decrease of battery capacity and relatively small increase of UCs unit capacity in the systems with higher battery discharge rates leads to lower overall prices.

4. CONCLUSIONS

Adding ultracapacitors to the energy storage of electric vehicle improves vehicle's dynamic performances and allows the battery of less capacity to be installed. Ultracapacitors also smooth currents flowing from and to the battery, thus improve its operating conditions. It is proven that among various "battery plus ultracapacitor" schematic solutions, the most practically feasible is "battery–double buck DC/DC converter–ultracapacitor" configuration. The optimal ratio of battery and ultracapacitor's capacitances should be sought taking into account limitations regarding DC-link voltage drop. As was shown by simulation, the optimal by resulting price point lies on the limiting curve, for the mid-size sedan and WLTP driving cycle the battery capacity should be 50 Ah, the ultracapacitor should be of 11 F.

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