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AN ONBOARD POWER FEEDING SYSTEM FOR ELECTRIC VEHICLES USING ULTRACAPACITORS

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The article describes the technique of calculating the parameters of the battery of ultracapacitors as a power source and of the electrochemical battery as an energy source for the construction of an onboard hybrid electric power system for electric vehicle. The structures of building such a system are analyzed, a variant of the automatic control of its operation is suggested, and computer simulation is carried out.

Key words: electric vehicle, onboard electric power supply system, battery of ultracapacitors, electrochemical battery.

БОРТОВА СИСТЕМА ЖИВЛЕННЯ ЕЛЕКТРОМОБІЛЯ З ВИКОРИСТАННЯМ СУПЕРКОНДЕНСАТОРІВ

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Надано методику розрахунку параметрів батареї суперконденсаторів як джерела потужності та електрохімічної акумуляторної батареї, енергії для побудови гібридної бортової системи живлення електромобіля. Проаналізовано структури побудови такої системи, запропоновано варіант системи автоматичного керування та досліджено її роботу на комп'ютерній моделі.

Ключові слова: електромобіль, бортова система електричного живлення, батарея суперконденсаторів, електрохімічна акумуляторна батарея.

PROBLEM STATEMENT. Given the environmental problems, the depletion of fossil resources and the consequent steady increase in oil prices, the world's leading car companies develop and produce electric vehicles (EV), mainly hybrid. However, the latter only partially solve this problem. Much better energy and environmental performance is observed in full EV, but the biggest problem that hinders their development is the lack of an onboard power supply system, which would be marked by high values of specific energy and power [1]. With the current state of technology, a satisfactory and reasonably priced onboard power feeding system can and should be developed for the full EV designed for urban areas.

EXPERIMENTAL PART AND RESULTS OBTAINED. Since there are no onboard energy sources that would simultaneously have high energy and high power that is necessary to ensure a satisfactory range of motion and the adequate dynamics of EV, the onboard power supply system is made hybrid: one of the onboard power sources or batteries is the source of energy, and the other one is the source of power. As a source of energy electrochemical batteries (AB) of large capacity and fuel cells are used, and as a source of power powerful electrochemical AB of small capacity, batteries of supercapacitors (SC) and ultraflywheels [1, 2] are used. The hybrid onboard power feeding system, consisting of electrochemical high-capacity AB and the battery of SC, has, in our view, the best price/quality ratio. There are a number of publications relating to the development of hybrid control systems of onboard plants of such or similar types [3-5]. However, given the novelty of the branch of EV development, the search for a successful solution to the problem of designing a hybrid onboard power plant continues.

The purpose of this study is to develop the method of calculating the necessary parameters of the hybrid onboard power system for EV using electrochemical AB and SC battery, analysis of the functional schemes of such a system, development of an automatic control system and computer simulation of the created onboard power supply system.

Since the tasks of the two components of the hybrid onboard power supply system for EV are different, the approaches to their calculation are different too: the parameters of the electrochemical AB must provide the specified range of motion S in the urban environment, and the parameters of SC battery must provide an EV acceleration to maximum speed in the city $V_{\mathrm{t.max}}$ and the regeneration of energy when EV breaks from the initial speed $V_{\mathrm{t.start}}$ to the final $V_{\mathrm{t.end}}$, at which it is still more appropriate to use electrical braking.

When traveling with constant speed V_{t} on the road without incline the propulsion EV force consists of the force of road rolling resistance F_{r} and the force of aerodynamic resistance F_{ad}:

$$F_{\mathrm{p.st}} = F_{\mathrm{r}} + F_{\mathrm{ad}} = m_{\mathrm{EV}}\, g\, k_{\mathrm{r}} + 0{,}5\rho_{\mathrm{a}}\, k_{\mathrm{ad}} A_{\mathrm{f}} \left(V_{\mathrm{t}} + V_{\mathrm{w}}\right)^2 , \quad (1)$$

where $m_{\rm EV}$ is the mass of EV, $k_{\rm r}$ is the rolling resistance coefficient, $\rho_{\rm a}$ is the density of air, $k_{\rm ad}$ is the coefficient of aerodynamic resistance, $A_{\rm f}$ is the frontal area of EV, $V_{\rm w}$ is the projection of wind speed on the direction of motion.

Under acceleration or braking to propulsion, EV force (1) adds great force of прискорення $F_{\rm a}$ or $F_{\rm b}$ speed:

$$F_{\rm p.a} = F_{\rm p.st} + F_{\rm a}\,; \qquad F_{\rm p.b} = F_{\rm p.st} + F_{\rm b}\,, \qquad (2)$$

where $F_{\rm a} = m_{\rm EV} a_{\rm a.max}$, $F_{\rm b} = m_{\rm EV} a_{\rm b.max}$, $a_{\rm a.max}$ and $a_{\rm b.max}$ are the maximum acceleration of EV in accordance with gathering speed and braking.

Constant power, which the electric drive consumes from onboard power feeding system, in motion with constant velocity $V_{\rm t}$ is:

$$P_{\rm el.st} = \frac{F_{\rm p.st} V_{\rm t}}{\eta_\Sigma}\,. \qquad (3)$$

Maximum values of power will be at the end of acceleration to speed $V_{\rm t.max}$ and at the beginning of the braking from the speed $V_{\rm t.start}$, respectively

$$P_{\rm el.a.max} = \frac{F_{\rm p.a} V_{\rm t.max}}{\eta_\Sigma}\,; \; P_{\rm el.b.max} = \frac{F_{\rm p.b} V_{\rm t.start}}{\eta_\Sigma}\,, \qquad (4)$$

where $\eta_\Sigma = \eta_{\rm m} \eta_{\rm el}$ is the total efficiency of the mechanical transmission and electric propulsion system.

Calculation of SC Battery. Electrical energy, which is necessary for EV gathering to speed $V_{\rm t}$ with acceleration $a_{\rm a.max}$, is

$$W_{\rm a} = \frac{F_{\rm p.a} S_{\rm a}}{\eta_\Sigma} = \frac{F_{\rm p.a} V_{\rm t}^2}{2 a_{\rm a.max} \eta_\Sigma}\,. \qquad (5)$$

Electricity that can regenerate in SC is equal to the difference of the kinetic energy released during braking from EV braking from speed $V_{\rm t.start}$ to speed $V_{\rm t.end}$ and the energy spent on overcoming the resistance of movement during braking:

$$W_{\rm b} = \frac{1}{2}\left(m_{\rm EV} + \frac{J_\Sigma}{r_{\rm w}^2} - \frac{F_{\rm p.a}}{a_{\rm b.s}} \right)\left(V_{\rm t.start}^2 - V_{\rm t.end}^2 \right)\eta_\Sigma\,, \qquad (6)$$

where J_Σ is the moment of inertia of all rotating parts of EV respect to the axis of rotation of the wheel, $r_{\rm w}$ is the radius of the wheel, and $a_{\rm b.s}$ is the average EV acceleration during braking.

From the obtained values of energy (5) and (6), one should select the greater as the required affordable energy of SC battery $\Delta W_{\rm SC}$. This is the power the SC battery should have in reserve for possible acceleration and must be capable of taking in this much power when braking occurs.

We will designate the working range of voltage variation of the battery SC in pu as $U_{\rm SC}^* = 0.5 \div 1.0$. Given that energy of the SC battery is equal $W_{\rm SC} = 0.5 C_{\rm SC} U_{\rm SC}^2$, the operating range of SC energy will be $W_{\rm SC}^* = 0.25 \div 1.0$. To ensure $\Delta W_{\rm SC}$ both with the sign + and with the sign -, the working point of SC battery should be chosen in the middle of the given range – $W_{\rm SC.r}^* = 0.625$. Then

$$\Delta W_{\rm SC} = 0.375 W_{\rm SC.max}\,. \qquad (7)$$

Under this, the operating point of the SC battery voltage (the point of its reference for the control system) will be $U_{\rm SC.r}^* = \sqrt{0.625} = 0.79$. A SC battery consists of *m* enabled parallel branches, each of which has $n_{\rm SC}$ serially connected individual SC, the permissible operating voltage of which is $U_{\rm SC.1} = 2.3$ V [1]. Then the maximum SC battery energy and its maximum voltage respectively constitute

$$W_{\rm SC.max} = 0.5\, m\, n_{\rm SC}\, C_{\rm SC.1} U_{\rm SC.1}^2\,; \qquad (8)$$

$$U_{\rm SC.max} = n_{\rm SC}\, U_{\rm SC.1}\,. \qquad (9)$$

Substituting (8) in (7), we obtain the expression that defines the required number of serially connected SC in the battery branch:

$$n_{\rm SC} = \frac{\Delta W_{\rm SC}}{0.1875\, m\, C_{\rm SC.1} U_{\rm SC.1}^2}\,. \qquad (10)$$

Expressions (9) and (10) make it possible to form for EV a battery for the desired voltage from $m n_{\rm SC}$ SC. The capacity of this battery will be $C_{\rm SC} = m\, C_{\rm SC.1} / n_{\rm SC}$. This SC should allow the maximum current, the values of which for the cases of acceleration and deceleration will be achieved at $U_{\rm SC} = 0.5 U_{\rm SC.max}$:

$$I_{\rm SC.a.max} = \frac{2 P_{\rm el.a.max}}{m\, n_{\rm SC} U_{\rm SC.1}}\,; \qquad I_{\rm SC.b.max} = \frac{2 P_{\rm el.b.max}}{m\, n_{\rm SC} U_{\rm SC.1}}\,.$$

Calculation of Electrochemical AB. The electrical energy, required for a given distance of movement *S*, while moving with constant speed $V_{\rm t}$ on the road without incline is

$$W_{\rm AB.st} = \frac{P_{\rm el.st}\, S}{\eta_\Sigma V_{\rm t}}\,. \qquad (11)$$

It is known that in the urban environment about 2/3 of the road vehicle's energy is spent on acceleration regimes and the overcoming of the incline. In the case of EV, a part of this energy (with the exception of double losses in the electric drive and the mechanical transmission) can be returned to the SC battery and then to the AB. In this case, the required energy of AB will be

$$W_{\rm AB} = W_{\rm AB.st} + 2 W_{\rm ABst}\left(1 - \eta_\Sigma^2 \eta_{\rm AB}\right) = W_{\rm AB.st}\left(3 - 2\eta_\Sigma^2 \eta_{\rm AB}\right), \qquad (12)$$

where $\eta_{\rm AB}$ is the charging efficiency of AB.

To improve the work of semiconductor power DC-DC converter, it is better to choose for the voltage of AB something higher than the maximum voltage of SC battery. Then the number of serially connected AB will be

$$n_{\rm AB} = {\rm int}\left(\frac{U_{\rm SC.max}}{U_{\rm AB.1}} \right) + 1\,, \qquad (13)$$

and the AB voltage will be $U_{\rm AB} = n_{\rm AB}\, U_{\rm AB.1}$, where $U_{\rm AB.1}$ is the voltage of one battery in the AB.

The capacity of one battery in the AB will be equal $C_{\rm AB} = W_{\rm AB} / U_{\rm AB}$.

Since the AB will provide the compensation of SC battery energy that is used when EV is moving with constant velocity, the AB should allow the following maximum current: $I_{AB.max} = P_{el.st}/U_{AB}$.

With the initial EV parameters $m_{EV} = 1300$ kg, $V_{t.max}$ = 80 km/h, V_t = 60 km/h, $a_{a.max} = a_{b.max}$ = 1.5 m/s^2, S = 80 km, $V_{t.start}$ = 80 km/h, $V_{t.end}$ = 20 km/h, η_Σ = 0.8 we obtained the following while using the abovementioned method:

$F_{p.st}$ = 281 N, $F_{p.a}$ = 2230 N, $F_{p.b}$ = -1670 N;

$P_{el.st}$ =5850 W, $P_{el.a.max}$ = 46460 W,

$P_{el.b.max}$ = 46390 W;

W_a = 258.1 kJ, W_b = 257.8 kJ.

With $\Delta W_{SC} = W_a$ and using the SC PC7220 of company Maxwell Technologies ($C_{SC.1}$ = 2700 F, $U_{SC.1}$ = 2.3 V) as the best option for the SC battery for EV, the battery should be composed of two parallel branches with 49 serially enabled SC in each. The parameters of the obtained SC battery are: $U_{SC.max}$ = 112.7 V, C_{SC} = 110.2 F, $I_{SC.a.max}$ = 412.2 A.

The electrochemical AB should be built with separate AB-type Ni-MH at voltage 12 V (10 batteries connected in a series). Whereas η_{AB} = 0.75, according to (12), AB energy should be W_{AB} = 14.9 kW·h and under (13) the number of batteries connected in a series must be equal to n_{AB} = 10. Then the AB voltage will be U_{AB} = 120 V, the capacitance of AB should be no less than C_{AB} = 124 A·h, and their allowable maximum current should be $I_{AB.max} \geq 48.8$ A.

Analysis of the Functional Schemes of the Onboard Power Plant. The most viable solution is a cascade connection of AB and SC batteries through a DC-DC converter, and the SC battery as the more powerful element must be fitted closer to the propulsion electric drive system (ED). For the best quality of the ED operation, it is usually fed from the source of constant voltage (Fig. 1, a). As the voltage of the SC battery during operation varies in the range of 2:1, the continuity of voltage on the capacitor C, to which the ED system is connected, may be provided by the pulse power semiconductor converter DC-DC 2. However, this converter must be designed for the maximum power of ED, so it is quite an expensive device. Because the ED system must include a power semiconductor converter, which regulates electric voltage, the system of the onboard power of EV can be significantly simplified through excluding the converter DC-DC 2 and connecting the ED system directly to the SC battery, as shown in Fig. 1, b. This ED system in some modes of high speed does not have enough voltage. However, the propulsion ED in EV should provide a wide range of adjustment of the angular speed of the electric motor, which is achieved by the broad second area where the excitation of the motor is weakened and the ED work is done with a constant power. At low voltage the second zone should begin at lower angular speed of the motor. Thus, the simplification and cost reduction of an onboard EV power feeding system can be achieved by developing special systems of two-zone speed control of the propulsion motor.

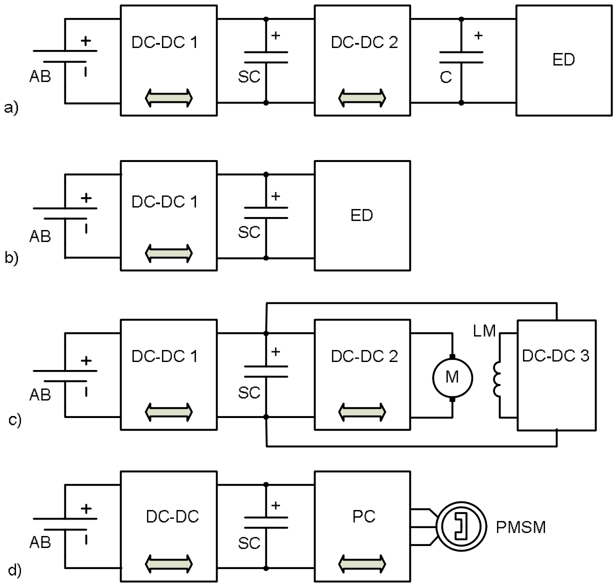

Figure 1 – Variations of the functional schemes of the onboard power supply systems and ED for EV

Fig. 1, c and d show as examples the functional schemes of connection to the hybrid onboard power feeding system, which consists of AB, SC battery and a low-power DC-DC converter (DC-DC 1), the propulsion ED systems of EV based on: c) collector DC motor M with pulse-width converters for regulation of voltage of the armature DC-DC 2 and voltage of the excitation winding DC-DC 3; d) brushless motor with permanent magnets PMSM, which is adjusted by the power semiconductor converter PC.

Development of the Control System of the Hybrid Onboard Plant. In the example of constructing the control system of the hybrid onboard EV power system and the propulsion ED on the basis of the electrical DC motor (Fig. 2), there are two automatic control systems that are built on the principle of the subordinate coordinate regulation: 1) voltage control of the SC battery, 2) two-zone speed regulation of the driving motor M. The first control system with an internal control loop of AB current and the external voltage control of the SC battery (current regulator CR1 and voltage regulator VR, sensors of current CS1 and voltage VS1) performs the task of permanent regulations through the exchange of electric power by pulse voltage converter DC-DC1 with the aim of regulating the voltage of the SC battery to the optimum level $U_{SC.r} = 0.79 U_{SC.n}$. The value of the maximum AB current is limited to acceptable level $I_{AB\,max}$. The second control system with an internal control loop of current of the motor M and the outer control loop of its speed (current regulator CR2 and speed regulator SR, sensors of current CS3 and speed SS) with the system of regulation of engine EMF in the second zone (not shown in the Figure 2) performs the function of speed control of the driving motor at a specified level ω_r . The switching voltage converters DC-DC2 and DC-DC3 are the executive power devices in this control system. The value of the maximum motor current is limited to acceptable level $I_{\mathrm{M\,max}}$. Also, with the help of the negative delayed feedback from the current that is implemented using the current sensor CS2 and the nonlinear element NE, this control system limits the allowable current of the SC battery.

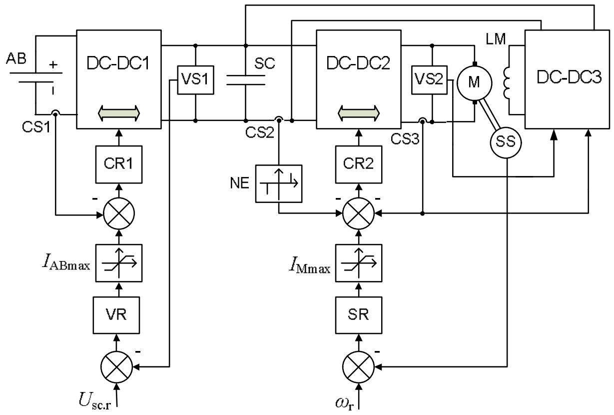

Figure 2 – The variant of the control system of the propulsion ED and hybrid onboard power feeding system for EV

Based on the scheme shown in Fig. 2, the computer model which allows simulating the operation of propulsion ED with onboard hybrid power feeding system for EV with the above parameters was developed in the MatLab/Simulink. To enable the simulation of long time, switching voltage converters DC-DC1 and DC-DC2 was simulated without PWM and operate on smooth functions by power transmitted feedback, and the possibility of change of direction of its transmission.

In Fig. 3 given the responses obtained on the model of the system during 33 s. EV start-up to 80 km/h for 15 s, and then, starting from 20 s, the EV break down to 10 km/h (Fig. 3,a). Thus to the speed of 60 km/h (angular velocity of the DC motor equals 150 s^{-1}) the motor is a full excitation, and a further increase in speed is due to the weakening of excitation (Fig. 3,b), accompanied by a decrease of starting torque (Fig. 3,c).

In the time interval 6.5 - 14.5 s the motor torque is also reduced due to limitations of SC current at an acceptable level of $I_{\mathrm{SC.a.max}}$ = 500 A (Fig. 3,d). During acceleration of EV the SC battery discharges and its voltage drops from 110 V to 55 V, and then braking it again charged to a voltage of 84 V (Fig. 3,e). Since the control system is configured to maintain the voltage of SC battery at $U_{\mathrm{SC.r}}$ = 89 V, then until time 6.3 s the SC battery discharged on AB (Fig. 3,f), and then begins to charge her. Herewith the control system maintains a maximum AB current of $I_{\mathrm{AB.max}}$ = 50 A (Fig. 3,g).

CONCLUSIONS. On the basis of a hybrid power source consisting of electrochemical battery AB and SC battery, one can build an onboard power supply system for EV, which can provide the necessary values of energy and power for operating in the urban environment. The method of calculating the parameters of elements of the hybrid onboard power supply system and the proposed structure of its automatic control make it possible to design these systems for full EV of different classes and purpose.

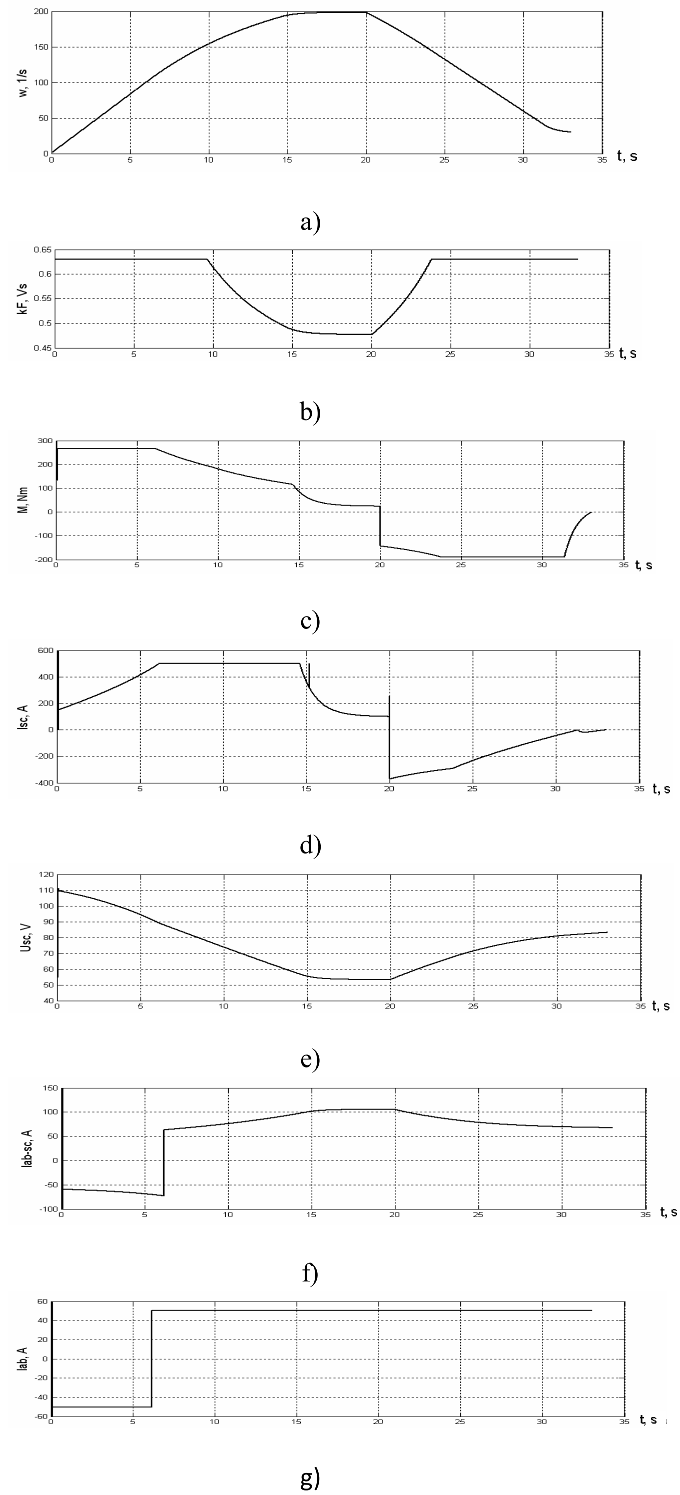

Figure 3 – The responses of the main coordinates EV obtained on the computer model:
a) angular speed of DC motor; b) excitation coefficient; c) motor electromagnetic torque; d) current of SC battery from the side of ED; e) voltage of SC battery; f) current of SC battery from the side of AB; g) current of AB

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БОРТОВАЯ СИСТЕМА ПИТАНИЯ ЭЛЕКТРОМОБИЛЯ С ИСПОЛЬЗОВАНИЕМ СУПЕРКОНДЕНСАТОРОВ

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Представлена методика расчета параметров батареи суперконденсаторов в качестве источника мощности и электрохимической аккумуляторной батареи в качестве источника энергии для построения гибридной бортовой системы питания электромобиля. Проанализированы структуры построения такой системы, предложен вариант системы автоматического управления, и исследована ее работа на компьютерной модели.

Ключевые слова: электромобиль, бортовая система электропитания, батарея суперконденсаторов, электрохимическая аккумуляторная батарея.

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