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CONTROL OF CHARGE OF SUPERCAPACITOR'S BATTERY AS DEVICE WITH DIFFUSION PROPERTIES

Victor Busher
Odesa National Polytechnic University

Abstract. There has been analyzed the charge processes in a battery of series-connected supercapacitors and developed the fractional differential-aperiodic regulator for a model of fractionally-integrated section for SIMULINK with high accuracy and fast performance at the fixed calculation step. The proposed model is an improved version of the supercapacitor that takes into consideration the diffusive processes and parameters' variation on change of the current polarity.

Key words: control, supercapacitor's battery.

1. Introduction

The supercapacitor (SC) based on the creation of a dual electrical layer (DEL) is described by fractional calculus [4, 5] when in a dynamic mode. Taking into consideration the properties of DEL as well as the experimental studies of transient processes and the Nyquist diagram of supercapacitors, the model of the supercapacitor has been proposed. It consists of series-connected traditional elements – capacity C and internal resistance R and also a fractionally-integrated section, which simulates the processes of diffusion and adsorption (Fig. 1) [2]. The impedance of the supercapacitor in this model is calculated on the basis of a transfer function between Laplace images of a current $I(p)$ and a voltage $U(p)$ in the following form:

$$H(p)=\frac{U(p)}{I(p)}=R+\frac{1}{Cp}+\frac{1}{Bp^{\mu}}, \qquad (1)$$

where μ is the fractional order of integration, its value ranges within the limits $0<\mu<1$; B is a parameter, caused by the diffusion $\left[Ohm/s^{\mu}\right]$.

The experimental studies show that the parameters of the supercapacitor are changing in charge and discharge modes. This may be caused by a thin layer of dipoles at the electrode- electrolyte boundaries, generated by polar bonds between the surface of the electrode and oriented adsorbed atoms and molecules of the electrolyte and the solvent [1]. This layer can change all parameters of supercapacitor due to a certain additional potential jump, sensitivity to the quality of processing the surface of the electrode, and the composition of an environment. However, conducting the measurements of this layer's parameters is practically impossible. But being independent of the physical causes, it is possible to examine the groups of parameters during the charge of R_+, C_+, B_+, μ_+ and discharge of R_-, C_-, B_-, μ_-. The parameters also depend on heat losses in a diffusion layer W_b: the changes in the capacity anount to $\pm 0.3\%$, those of the effective resistance do $\pm 4\%$, but those of diffusion parameters do $\pm 20...\pm 50\%$ (fig. 1).

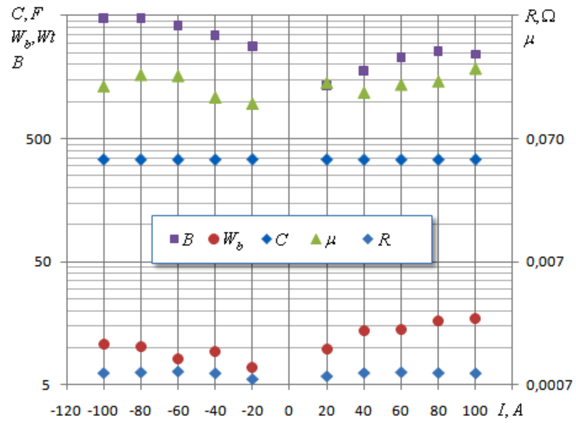

Fig. 1. Dependence of the parameters of SC on the current and the heat losses in the diffusion layer

SCs are usually low-voltage devices connected in series in batteries. If we use a SC with the large deviation of the parameters, then the speed of their charging will be different. Exceeding the maximum permissible voltage on one of the SC will be the consequence of this. As a result the electrical breakdown of this SC will arise and subsequently that of the entire battery.

Therefore, the task of determining the permissible variations of the parameters of the SC for the serial connection and developing a regulator for safe control of charging the supercapacitors battery is actual.

With the serial connection of the n SCs up to the moment $t_{ch} \approx (U_{\max}-U_{\min})C_{bat}/I_{ch/dch}$ (the end of charging the battery by a direct current $I_{ch/dch}$) when $U_{bat}=\sum_{i=1}^{n}U_{sc_i}$, $1/C_{bat}=\sum_{i=1}^{n}1/C_i$ the voltages of separate SC U_{sc_i} are determined from the formulas:

$$U_{sc_i} = U_{\min_i} + I_{ch/dch}\left(\frac{t_{ch}}{C_i} + R_i + \frac{1}{\Gamma(1+\mu_i)B_i}t_{ch}^{\mu_i}\right). \quad (2)$$

But at the end of the diffusion processes the voltages of the SCs are determined only by the relationship of the capacities C_i and they can differ significantly from the results of calculations according to (2).

Figure 2 illustrates the change in the voltages of SCs in the charge mode with relay voltage regulation of the battery (by model in SIMULINK), composed of SCs with distinguishing parameters and the nominal voltage $U_{SCnom} = 2.5V$.

Therefore, for the selection of the maximum permissible voltage of the battery after selection the SCs it is necessary to carry out testing according to the formula (2) taking into account a possible parameter spread. SCs with the smaller capacity and B, by the increased value of μ can prove to be charged to the inadmissible voltages.

For the compensation of parasitic properties of supercapacitors the regulator of battery charging must have the following transfer function:

$$H_{reg}(p) = \frac{1}{R_{bat} + \dfrac{1}{B_{bat}p^{\mu}}} = \frac{B_{bat}p^{\mu}}{R_{bat}B_{bat}p^{\mu} + 1}. \quad (3)$$

If we ignore the fractional component, we obtain a proportional regulator

$$H_{reg\_stat}(p) = \frac{1}{R_{bat}}.$$

Let us compare these regulators. Figure 3 shows transient processes in the battery (the same as in Fig. 2) with the proportional regulator. It is obvious that the proportional regulator decreases only insignificantly the overvoltages on the SC.

Figure 4 shows transient processes with the fractional differential-aperiodic regulator. This regulator completely protects the battery from the overvoltages on the SC.

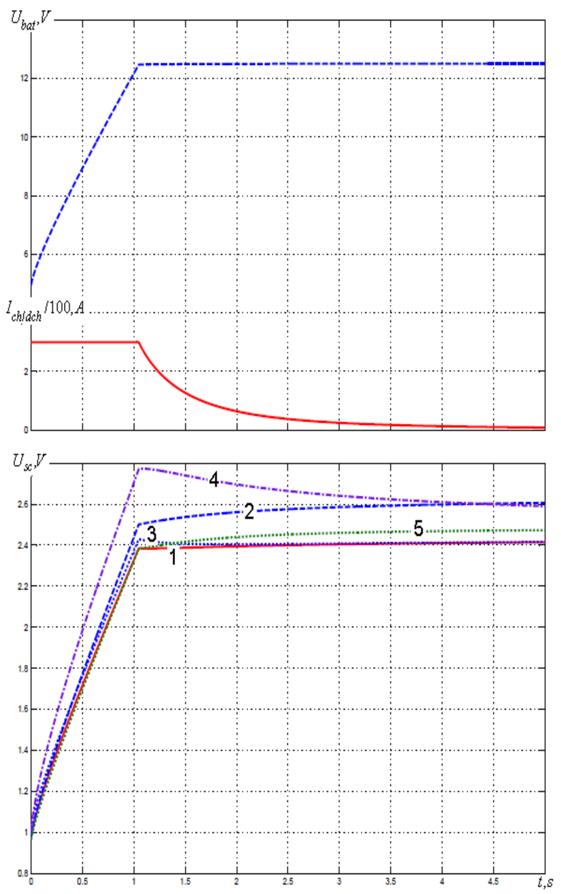

Fig. 2. Time-response characteristics $U_{bat}(t), I_{ch/dch}(t), U_{sc_i}(t)$ in the charge mode of the battery by a relay current regulator

(Here and throughout: 1 – SC with nominal parameters, 2 – C-10%, **3 –** R+10%, **4 –** B-50%, **5 –** μ-20%)

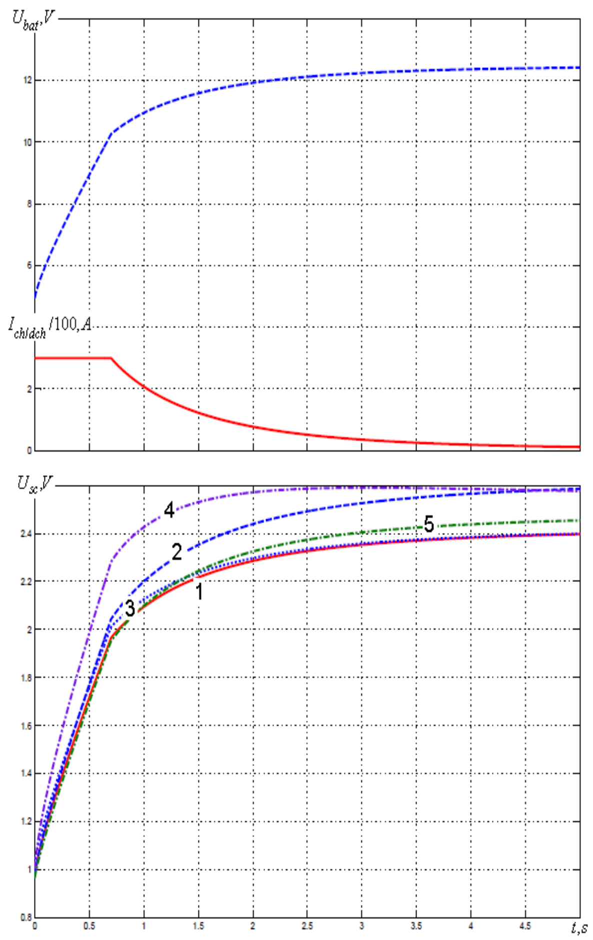

Fig. 3. Time-response characteristics in the charge mode of the battery with a proportional regulator

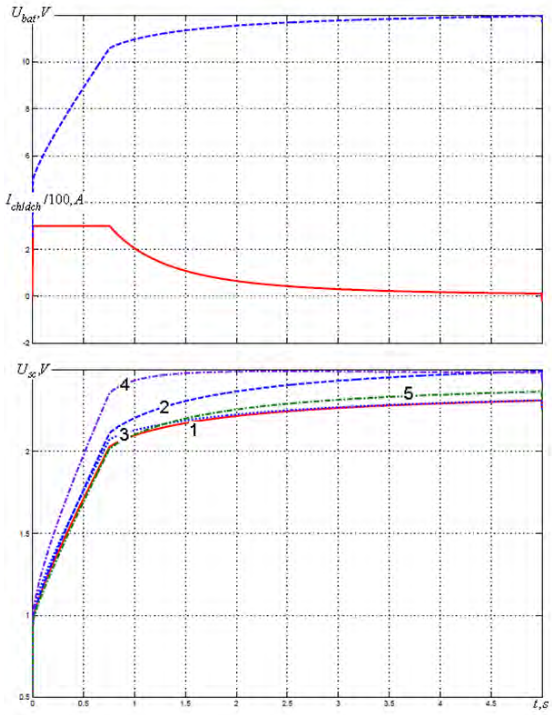

Fig. 4. Time-response characteristics in the charge mode of the battery with a fractional regulator

The implementation of the fractional regulator may be based on the modified form of Riemann-Liouville for step time fractional order calculus [3] and a block diagram of the regulator according to Fig. 5:

$$I^{\mu} f_i = \frac{\Delta t^{\mu}}{\Gamma(\mu)} \sum_{j=1}^{i} f_{i-j} k_j^{\mu},$$

$$k_j^{\mu} = \frac{j^{\mu+1} - (j-1)^{\mu+1}}{\mu(\mu+1)} - \sum_{n=1}^{j-1} k_n^{\mu}, \qquad (4)$$

$$D^{\mu} f_i = \frac{I^{1-\mu} f_i - I^{1-\mu} f_{i-1}}{\Delta t}.$$

where Δt – the step of calculation.

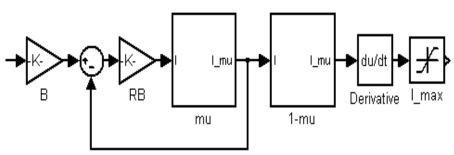

Fig. 5. The block diagram of the fractional regulator

Conclusions

The analysis of the charge mode of the supercapacitor's battery has showed that for the safe work of the battery the fractional differential-aperiodic regulator is necessary. It provides protection of separate SCs from the overvoltages independent of the parameter spread of the diffusion layer.

The proposed block diagram and analytical expressions for enumerating the signal of this regulator make it possible to implement it in the microprocessor control systems in the electro-mechanical devices, with the supercapacitors integrated in (but not limited to) the drives of electric cars with kinetic energy recovery systems.

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КЕРУВАННЯ ПРОЦЕСОМ ЗАРЯДЖАННЯ БАТАРЕЇ СУПЕРКОНДЕНСАТОРІВ ЯК ПРИСТОРОЮ З ДИФУЗІЙНИМИ ВЛАСТИВОСТЯМИ

В. Бушер

Проведено аналіз процесу заряджання батареї, що складається з послідовно злучених суперконденсаторів, та розроблено для SIMULINK дробовий диференційно-аперіодичний регулятор високого ступеня точності та швидкодії з фіксованим кроком для моделі дробово-інтегрованої секції. Запропонована покращена модель суперконденсатора, що враховує дифузійні процеси та зміну параметрів внаслідок зміни полярності струму.

Victor Busher – graduated from Odesa Polytechnic Institute. Since that time he has been working at the Department of Electrical Drives and Automation of Industrial Enterprises of the institute. PhD, associate-professor, leader of educational-scientific "Systems of automation of industrial buildings and living quarters and home appliances". Research interests: control systems of technological processes with fraction-integral and fraction-differential properties.