

Modelling the EDLC-based Power Supply Module for a Maneuvering System of a Nanosatellite

A A Kumarin¹ and I A Kudryavtsev¹

¹ Space research department, Samara University, Samara, Russia

E-mail: alky_samara@mail.ru

Abstract. The development of the model of the power supply module of a maneuvering system of a nanosatellite is described. The module is based on an EDLC battery as an energy buffer. The EDLC choice is described. Experiments are conducted to provide data for model. Simulation of the power supply module is made for charging and discharging of the battery processes. The difference between simulation and experiment does not exceed 0.5% for charging and 10% for discharging. The developed model can be used in early design and to adjust charger and load parameters. The model can be expanded to represent the entire power system.

1. Introduction

The development of modern electronic components allows to implement more and more complex missions via light classes of space vehicles. Nanosatellites (NS) have become widespread, mostly because of the introduction of CubeSat platform which unifies the requirements to launching containers. One of the crucial systems of a satellite is a power system (PS). It normally consist of an energy generator (usually a solar battery), electrical storage device (usually Li or Ni battery) and a control system.

Modeling is an essential part of design which allows to avoid some mistakes in early design. In this phase some parameters of the system are uncertain. Therefore, simulations allow to adjust parameters of a designing system. In this paper a model of a power supply module for a maneuvering system (MS) of a nanosatellite is described.

The MS is a propulsion engine for using in a nanosatellite. It is used for orbit correction. It create thrust by expelling reaction mass through the nozzles. Working mass is a mix of water and ethanol and is stored at low initial pressure of about 3 atm, which is not enough to create a suitable thrust. That is why the liquid flows through a heater where it partly vaporizes. It leads to the increasing pressure which creates greater thrust. The main problem of such concept is the high value of peak electrical power needed in the heater. It cannot be provided by regular PS unit.

Most PS of NS nowadays are based on Li batteries. Most of them cannot sustain current greater than 2C, where C denotes the capacitance in Ah, without permanent damage, which would result a reduction of the capacitance. Thermal calculations of the MS shows that the PS have to provide at least 200W peak power and 4kJ total energy. The maximum voltage of Li-Ion battery (LIB) is 4.2V which means, that the minimum capacitance of the battery would be around 24 Ah. For a battery of LIB with maximum voltage 8.4V the capacitance would be around 12 Ah, for 16.8V – around 6 Ah. Each case is unacceptable. That is why a buffer storage device is used in this paper.



Electrical double layer capacitors (EDLC) are used in this work [1, 2]. Their main features are higher energy density than of ordinary electrolytic capacitors and higher discharge current than of chemical batteries. However, they cannot be used as primary battery because their energy density is lower than of Ni-Mh batteries.

2. Methods

2.1. EDLC selection

An analysis of components of the shelf (COTS) EDLC was made for the developing system. The choice was based on such criteria as energy density, maximum current and the amount of cells in battery to fit energy requirements. Only EDLC for power applications were taken into account. The data from manufacturer's datasheets was combined in table 1.

Table 1. COTS EDLC characteristics

Partnumber	Capacitance, F	Maximum current, A	Length, mm	Diameter, mm	Stored energy, J	Cells in battery	Mass, g	Battery volume, cm ³	Energy density, J/g
BCAP350	350	34	61	33	1276	4	252	209	17.4
BCAP650	650	88	52	61	2369	2	320	320	12.8
BCAP1200	1200	110	74	61	4374	2	520	520	14.5
BCAP1500	1500	140	85	61	5468	1	280	280	16.8
BCAP2000	2000	170	102	61	7290	1	360	360	17.5
BCAP150	150	40	50	25	547	9	288	288	14.7
SCCV60B107MRB	100	53	60	18	365	13	260	260	15.7
SCCX50B207VSB	200	96	50	22	729	7	280	280	15.7
SCCY62B307VSB	300	104	62	35	1094	5	385	385	14.3
SCCY68B407VSB	400	174	68	35	1458	4	348	348	14.5

As can be seen from the table, different models have similar energy densities. The EDLCs with lower values of capacitance are impractical because of large amounts of cells in batteries, which are difficult to install. Cells with high capacitance are also impractical because of problems with installation. Thus, BCAP350 were chosen. The battery consists of 4-5 cells, because usable energy is lower with non 100% depth of discharge.

2.2. Math model

The math model is based on experimental data. A measurement equipment was designed to conduct the experiment. It is based on pulse current source. It charges the EDLC with constant current and monitor the voltage (U) on its terminals over the time.

Differential capacitance is determined by equation (1).

$$C = I \left(\frac{dU}{dt} \right)^{-1} \quad (1)$$

Since the current was maintained constant, it was only necessary to measure the value of the time derivative of the voltage. It is averaged during small time periods, where it can be considered constant. The value is obtained using least square linear regression method for N experimental data points as shown in equation (2).

$$\frac{dU}{dt} \approx \frac{N \sum_i U_i t_i - \sum_i U_i \sum_i t_i}{N \sum_i U_i^2 - \left(\sum_i U_i \right)^2} \quad (2)$$

Averaging results of multiple experiments shows that the capacitance depend on voltage linearly. A measurement, based on single charging process can give bias at about 3% from average as shown on figure 1. This is happening most likely because of difficulty for ions to penetrate pores of an activated

carbon pores [3]. These processes cannot be predicted, therefore, the dependence is modeled as linear function – equation (3). Numerical values may significantly differ from cell to cell.

$$C = A_C U + B_C \approx 62.0U + 268.6. \quad (3)$$

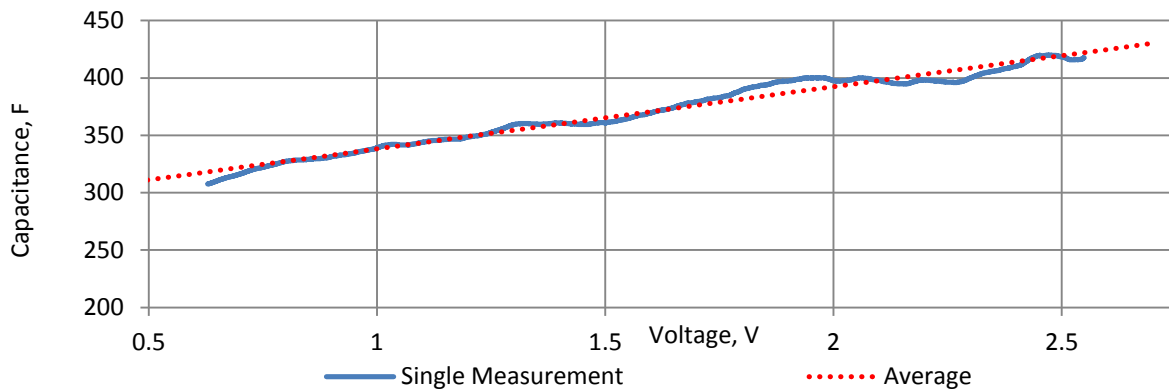


Figure 1. Capacitance over voltage of BCAP350

The ESR of the EDLC is considered to be constant in this paper since its value is lower than any other resistances in the circuit (about 3mOhm) and its dependence on voltage can be neglected [4].

Another factor in every process with EDLC is leaking. It is modelled in this paper via leak power which depends on the voltage of the cell. Experimental data shows that it could be approximated with exponential function. The data was acquired by measuring open circuit voltage (U) of the cell. The measurements were taken each 4 seconds during 35 hours. The cell leaked from 2.64V to 2.30V which corresponds to approximately 25.5% of total energy. Calculated values of leak power are represented on figure 2. Approximation function used for simulation is shown in (4).

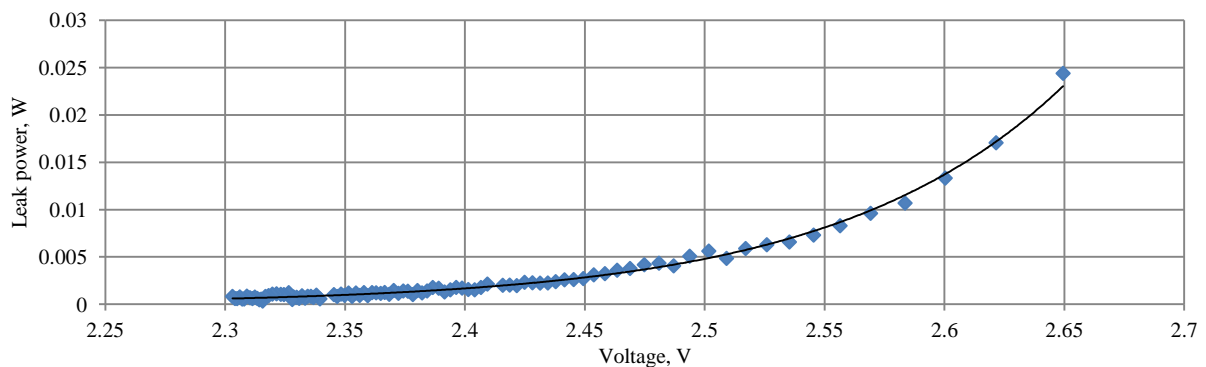


Figure 2. Leak power over voltage of BCAP350

$$P_l = A_l e^{B_l U} \approx 2.33 \cdot 10^{-14} e^{10.42U} \quad (4)$$

The finite element method is used to solve the problem. The time step is defined to fit the following condition: relative difference in voltage of the EDLC at the beginning and in the end of the time step should not exceed a predefined value ε . In this paper 10^{-4} was used as the value and equation (5) – as the time step estimation. Thus, the voltage of the EDLC can be considered constant with error estimation. Time step is variable, therefore processes with low current can be calculated faster with same accuracy.

$$\Delta t = \varepsilon \frac{U \cdot C(U)}{I}, \quad (5)$$

The state of EDLC is considered to be a function of the cell open circuit voltage. That is suitable since current changes slowly in all processes. Transition processes can be neglected because they last

for less than a second while other processes last for minutes or even hours. Therefore, the inductance does not affect the results significantly [5]. Thus, the open circuit voltage of the EDLC on the next time layer is described by equation (6).

$$U_{oc}(t + \Delta t) = U_{oc}(t) + \left[\frac{I(t)}{C(U)} - \frac{P_t}{U \cdot C(U)} \right] \Delta t. \quad (6)$$

The voltage on the terminals of EDLC depends on current, because there is a voltage drop in internal series resistance r . The dependence is described by equation (7).

$$U(t) = U_{oc}(t) + rI(t). \quad (7)$$

Equations before described a single EDLC cell. However, MS is supposed to have a series battery of EDLC. Therefore, for estimation simulations voltage can just be multiplied by the number of cells in the battery. The current I is the difference between current from charger and current of load defined by Ohm law. The value of current I_{in} from satellite's power grid with voltage U_{in} can be obtained using charger current I_c , EDLC voltage and the efficiency η of charger via equation .

$$I_{in} = \frac{I_c U}{\eta U_{in}}. \quad (8)$$

The electrical load of the system is a heater. Its resistance depends on temperature. The dependence is considered linear and the temperature resistance coefficient is used. The temperature of the heater is defined by equation (9). It was acquired by simple reworking of Fourier's law and the law of conservation of energy.

$$T(t + \Delta t) = T(t) + \left(\frac{U^2}{R(T(t))C_h} - \lambda(T(t) - T_{amb}) \right) \Delta t, \quad (9)$$

where U – heater voltage, R – heater resistance, C_h – heater thermal, λ – fixture thermal conductivity, T_{amb} –temperature of the fixture.

2.3. Experiment

The propriety of simulation results has to be proven by verification. Therefore, an experiment was conducted. The electrical scheme of experimental setup is represented in figure 3.

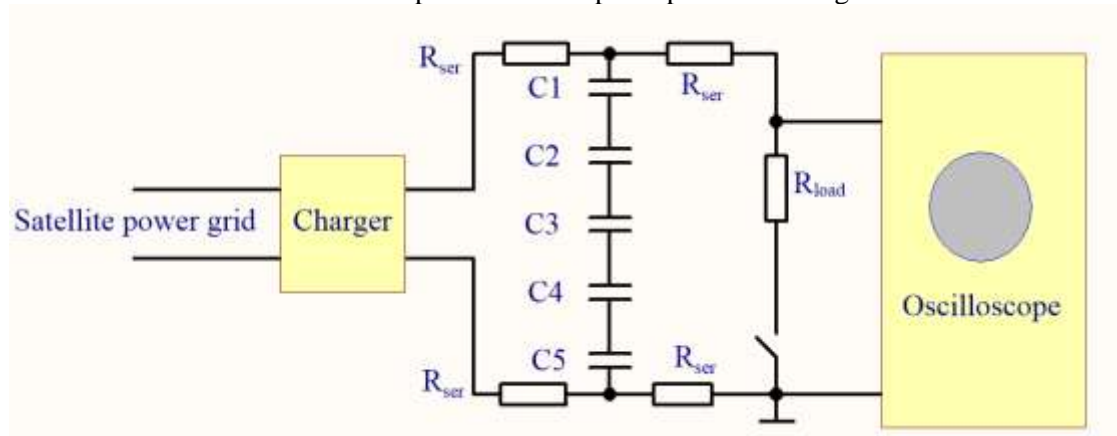


Figure 3. Electrical scheme of the experimental setup

The first mode of the setup is charging: the switch is closed, regulated current flows from charger to the battery. The second mode is discharge: the switch is open and current flows from battery to load. In both cases charging/discharging current does not flow through measurement circuit. An oscilloscope GWInstek GDS-72304 is used to measure voltage. The measurement error with respect to averaging sample does not exceed 0.2%.

2.4. Modeling results and verification

Simulation and experiment data for charging process are represented in figure 4. Relative error is shown in figure 5. The data for discharging process is shown in figure 6, relative error – figure 7.

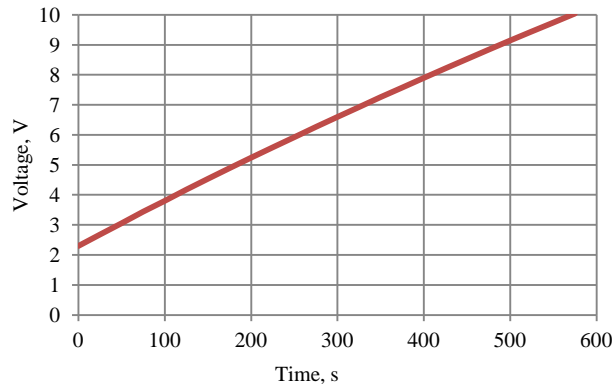


Figure 4. EDLC voltage in charging process

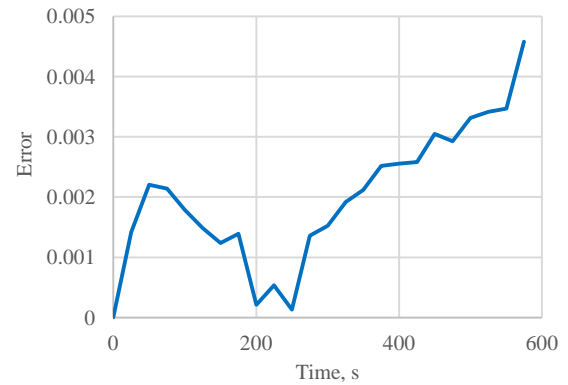


Figure 5. Relative error of simulation of charging process

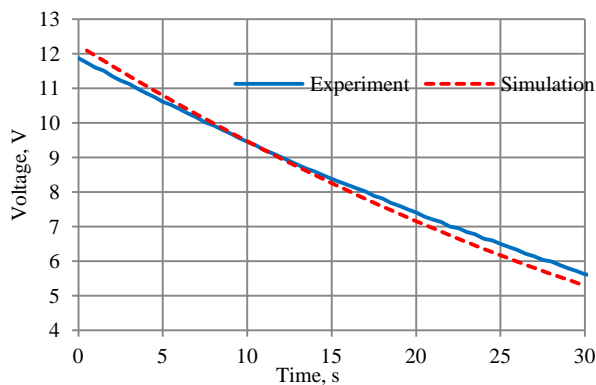


Figure 6. EDLC voltage in discharging process

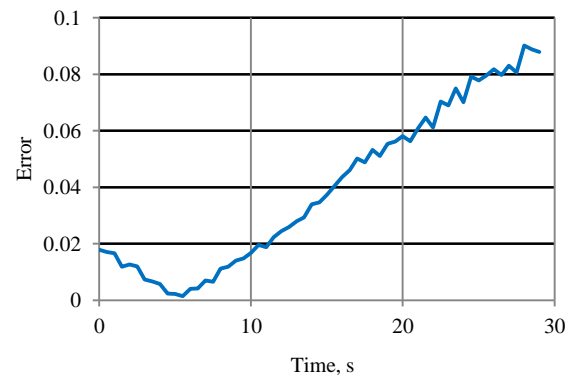


Figure 7. Relative error of simulation of discharging process

3. Discussion

The paper discuss power supply module for maneuvering system for a nanosatellite. The aim of creating a model was an opportunity of simulation of the processes in a module with set parameters. This could help to reduce the amount of mistakes in early design and in addition, to adjust the parameters of heater and charger to fit desired characteristics.

A comparison of simulation and experiment data has shown, that relative error does not exceed 0.5% for charging process, which allows accurate charger parameters adjust.

Relative error of discharging process does not exceed 10%. Such error is probably due to the difference between table values of thermal resistance coefficient, heat capacity and most importantly heat conductivity and their real values. These values have to be obtained from experiment or by detailed thermal modelling with respect to design features of the heater. However, 10% is an acceptable error for estimation simulations during early design, which was the purpose of the study.

The described model can be integrated in a model of the whole power supply system, which would allow to adjust all important parameters.

References

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