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Electrical Power Supply System for a Maneuvering System of a Nanosatellite

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Abstract. Modern CubeSats has become an attractive platform for different types of missions. Some of them involve high peak power consumers. Most of them were originally meant for heavier classes of satellites. Possibility and features of using electrical double layer capacitors (EDLC) in electrical power system for maneuvering system of a nanosatellite are discussed in this paper. Results of calculation of operation are presented. A method of effective charging EDLC in series with switching balancing is described.

Keywords: EDLC, CubeSat, power system, maneuvering system, energy saving

INTRODUCTION

Modern nanosatellite payloads require more and more power to operate. Tasks of space vehicles involve power-consuming systems, some of them originally were not supposed to be used on this class of vehicles. At the same time, the size of modern satellites is limited to several CubeSat units. The CubeSat standard itself defines a row of restrictions in size and mass and development of an appropriate power supply unit becomes a problem. Typical electrical power supply system (EPS) includes solar battery, chemical battery (accumulator) and an electronic control system (CS).

The most used type of batteries are Li-Ion and Li-Polymer. They have some current restrictions, commonly 2C where C denotes the capacitance of a battery in mA*h. For example typical 2 Ah Li-Ion battery might have maximum current I_{max} = 4 A and maximum power P_{max} = 16.8 W. Connecting two batteries in series doubles these values. However, these values do not fulfill the requirements for some specific applications, which in current case is a maneuvering system. It require at least 50 W, however it works for about 10–15 s. Moreover, it has its limits of supply voltage: maximum is 5.5 V. Thus, lowering maximum current by rising supply voltage via connecting multiple cells in series is not an option in this case.

Therefore, the task standing is to find a storage device, capable of delivering high current. There is a type of capacitors known as supercapacitors or ultracapacitors or electric double-layer capacitors (EDLC), which current limit is acceptable for such a task. Their specific energy is lower than Li-Ion batteries can provide, but far greater than ordinary capacitors can. For instance, BCAP350 have been used in this study. Their capacitance is about 350 F, maximum voltage is 2.7 V, ESR is ~3 mOhm and continuous current limit is about 20 A. Therefore, maximum achievable continuous power is about 54 W/cell, though it cannot be maintained for a long period. Maximum stored energy is about 1.3 kJ. Maximum extractable energy depends on minimum acceptable voltage.

Analysis of scientific activity on this subject shows that several research groups are studying EDLC to use in nanosatellites [1]. However, most scientists are interested in using EDLC in microsatellites. Though these topics seem to be similar, they both have many specific features. Thus, the aim of this study is to find out, whether EDLC are acceptable choice for supplying maneuvering system with particular requirements, marked before.

PROBLEMS USING EDLC

EDLCs main features except high capacitance are low ESR and sensitivity to overvoltage. Allowing voltage to rise beyond 2.8 V will cause dielectric breakdown. On another hand, nearly half of energy is extracted by discharging EDLC from 2.7 to 2 V. Therefore, using just this voltage range will grant an appropriate output voltage range and appropriate energy when connecting two EDLC in series: 4 .. 5.4 V and 1152 J respectively. In addition, this will grant an energy reserve for an emergency case. Thus, the aim of EPS is to charge both capacitors to maximum voltage avoiding overvoltage. Implementation of this is not a trivial task because of the EDLCs' features.

Most common tolerance of component of-the-shelf (COTS) electrolytic capacitors in common and EDLC in particular is –20/+80 %. Therefore, capacitance can be significantly different. Even selection of EDLCs with close values of initial capacitance would not guarantee that they would not become different during operation because of degradation. The difference of capacitances when connecting EDLC in series will cause difference in voltages. Therefore, when one of the capacitors reaches maximum voltage charging must be stopped. However, another capacitor would be undercharged. In the worst case, it would contain only a half of maximum energy. To avoid such situations some kind of balancing method should be applied. The most used method of balancing EDLC is adding resistors in parallel with each cell. However, this method adds wasted power, which should be avoided in space missions. Therefore, an efficient and scalable switching method should be developed.

Thus, the main purpose of the study is to find out whether EDLCs are suitable for supplying a maneuvering system of a nanosatellite and to find a method to efficiently charge them.

MODELLING

Before designing any circuit, a basic modelling is to be done. For that purpose, a simulating program has been created, capable of modeling different scenarios. EDLCs operate just like ordinary capacitors if the voltage changes slowly [2], which is the case all the time except the beginning/ending of charging/discharging process. In addition, schematic of [2] can be simplified to one capacitance and one resistance in series due low actual value of ESR. Therefore, a formula can be defined for EDLC voltage from basic considerations:

$$U(t+dt) = U(t) + \left(\frac{I}{C} - \frac{P_L}{CU(t)} \right) dt,$$

where C – capacitance, P_L – leak power, I – input current.

Here leaks are represented as a static power, which depends on cell voltage. As this relation between leak power and cell voltage is not provided by EDLC manufacturer's datasheet, it has to be measured. Therefore, an experiment has been conducted. The target EDLC was charged and disconnected from any circuits except high impedance measurement system to avoid leaks through them. P-V diagrams represent analysis of experiment data for BCAP350 (Figure 1b). For a comparison same data is presented for EECHW0D226 (Figure 1a) − an elder model of EDLC with lesser capacitance − 22 F. In both cases relation can be approximated as exponential.

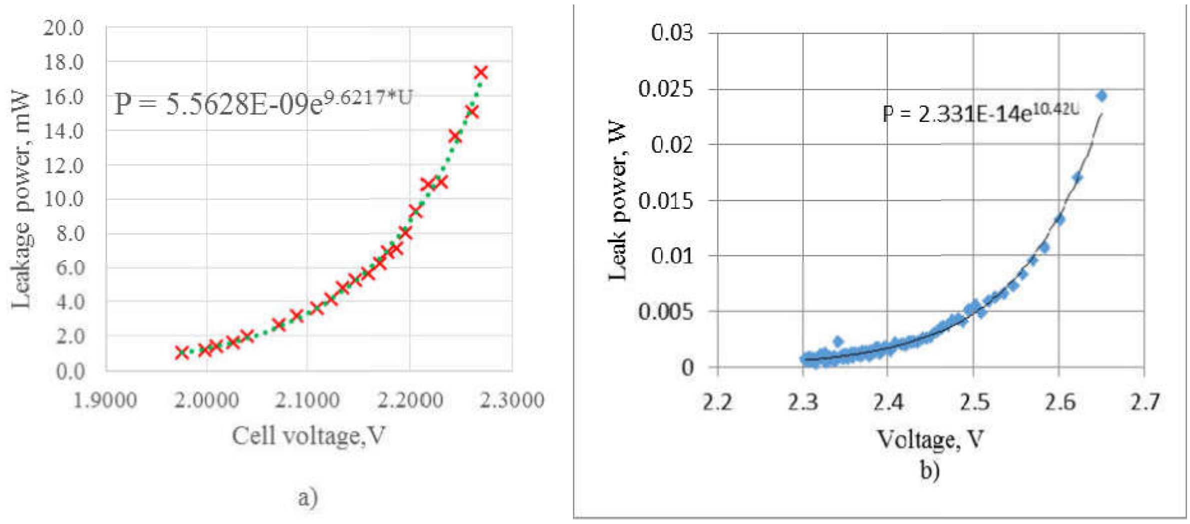

Figure 1. Leak power vs. cell voltage (a) EECHW0D226, (b) BCAP350

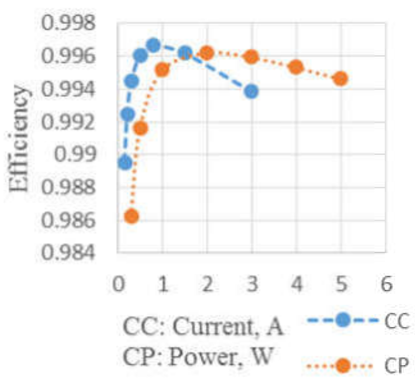

Figure 2. Charging EDLC

Using this data an operation calculation can be made for a single EDLC. First, diagrams on Figure 2 represent charging efficiency of constant current (CC) and constant power (CP) charging methods vs. the values of current and power respectively. Clearly, a wide range of currents or powers can be used to charge EDLC with charge times from 3 to 45 minutes. In addition, some special methods can be created to ensure even more fast/efficient charging if needed. However, keeping EDLC with high voltage will lead to waste of energy trough leaks. Therefore, starting time and intensity of charging is to be chosen from the considered usage time.

Similarly discharging process can be calculated. The efficiency exceeds 97% even at 15s working at resistive load with 50 W peak power, which is twice as high as the considered value. The main source of energy losses at discharging is EDLC's ESR. However, its value is ~3 mOhm, which is much less than most switches. In addition, the resistance of contacts and wires can be even greater. Therefore, ESR can be ignored for considered powers. That combined with high continuous current is a great advantage against Li-Ion, which ESR is significantly higher (about 0.2–0.5 Ohm). In addition, EDLC's cycle life is about 1 million, which is significantly greater than any rechargeable battery can provide.

Thus, the efficiency of EDLC itself exceeds 95 %. Therefore, the efficiency of EPS will mostly depend on the effectiveness of hardware implementation of charging and switching circuit.

CHARGING THE EDLC

To charge an EDLC the main EPS's battery is used as the power source (PWR). Therefore, the voltage is nominally 7.4 or 14.8 V. If charging takes place only during lighted orbit time, the main battery is not affected, the entire load is on battery charger. Since the voltage of EDLC can vary from nearly zero at the very first charge to 2.7 V for a cell, the only option is to regulate charging current. However, for space applications basic linear regulators are not suitable because of their high power dissipation. Moreover, most switching-type current source ICs, which are mostly used in LED lamps, are not suited either. This is because of their internal switching devices – Darlington transistors. Since these transistors are bipolar, their significant voltage drop makes them ineffective. Therefore, an effective step-down (buck) DC-DC voltage regulator should be applied. Effectiveness is provided by low open channel resistance MOSFET-transistor as switches. A transistor also replaces diode in buck circuit. En example of such a solution is LM46000 integrated circuit (IC) [3]. An adjustment should be made to the feedback system to make voltage regulator regulate current. Figure 3 shows a feedback schematic of the charger. An external analog signal (EXT_SIG) is added to make an opportunity to change current limit. The current is measured by measuring amplified voltage on shunt resistor Rsh.

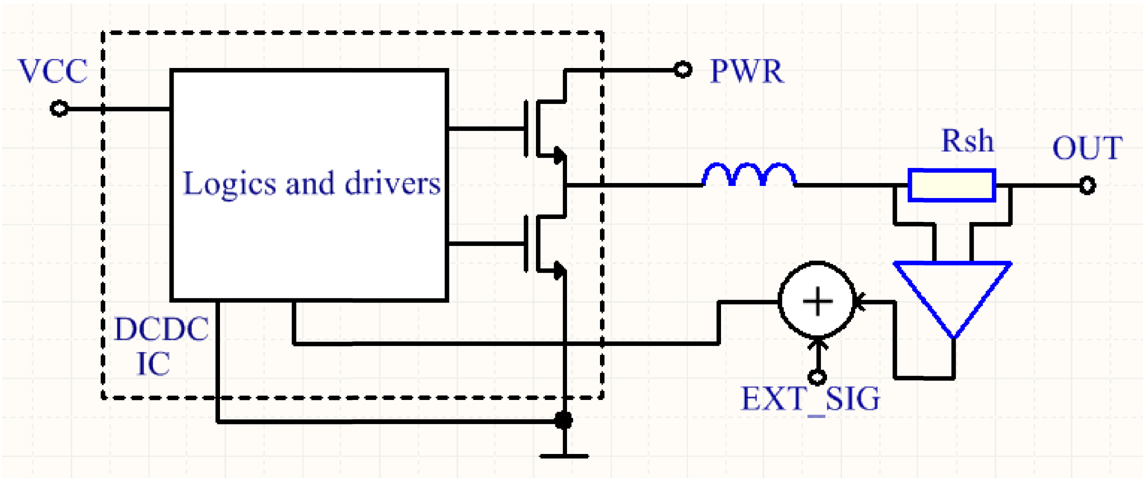

Figure 3. Feedback schematic for charger

Charging EDLC in series is another problem. As was stated before, voltage can differ for different cells [4]. Therefore, a special switching schematic has been designed for temporary switching off some of the cells. Figure 4 shows a two-cell (C1, C2) version of the schematic. The main principle is to bypass a cell, which voltage is significantly higher than others' are using SW1 and SW3. However, the bypassing method should not discharge the cell. Therefore, some device should be used to prevent current to flow in discharge direction. For a point between cells (middle point), SW2 must be used, because reverse current is to be when discharging to a load. For the top cell, a simple Schottky diode (D1) can be used. Since the charging current is considered low, this diode would have

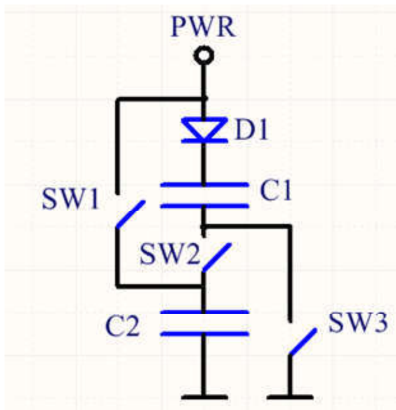

Figure 4. Series balancing schematic

acceptable power dissipation. For high charging current, the method would be the same as for a middle point.

Implementation of this schematic uses low open-channel resistance n-MOSFET transistors. Therefore, power dissipation is low. The problem is to drive a transistor with source tied to an EDLC. Since gate voltage is related to source, a higher voltage related to ground is needed to open the transistor. Therefore, there should be a voltage source capable of driving the gate of the highest transistor. For example, IRF7832 will require 3 V above the maximum output. Since the main battery's voltage is 14.8 V, it is possible to connect up to four cells without any external voltage source. In that case, the maximum output would be 10.8 V. That is suitable for current and most of future versions of the maneuvering system.

Discussion

The main aim of the study was to find out, whether EDLCs are suitable power source for supplying a maneuvering system of a nanosatellite and find a way to charge them effectively. The first criteria is mass and volume. A single cell of BCAP350 has mass about 60 g, 61.5 mm length and 33.3 mm diameter. Therefore, two cells require more volume than main batteries. However, since the maneuvering system itself fills 1U of CubeSat standard, that is suitable.

The modelling based on experimental data showed, that the efficiency of an EDLC itself in charging and discharging processes is about 95 % in extreme power operation. That is achieved because of low ESR, which mostly affects the performance during discharging, and relatively short time of charging, when the leakage effect prevails. This results combined with environmental tests [5] signify that EDLC should be suitable for an electrical power system for a maneuvering system.

A charging scheme has been made for EDLC. Since it is a switching current regulator with an external control option, almost any charging profile can be achieved. An implementation circuit determines the efficiency of charging. Choosing an IC with low open-channel resistance MOSFET switch, for example − LM46000, will guarantee performance greater than 90 %.

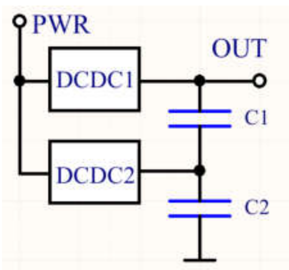

Figure 5. Alternative charging schematic

A balancing has been developed for proper charging several EDLCs in series. It seems a simple and efficient solution. Its main advantages are relatively simple circuit, scalability, low power dissipation. The disadvantages are impossibility of balancing if discharging, additional components are required to prevent short circuit in case of program error, and the switches require higher voltage to open.

Figure 5 shows an alternative balancing schematic for a comparison. Similar schemes are used in chemical batteries chargers. DCDC converters can be applied like shown or connected in series. The advantages of such scheme comparing to previous are possibility to balance cells in use, no additional ESR. The main disadvantages are the complexity of the circuit and bad scalability. The benefits do not seem to compensate the additional problems. Therefore, the first scheme seem to be the most suitable. Therefore, a suitable charging method seems to be found.

The results of this paper are to be used to design an implementation of an EPS for a maneuvering system of a nanosatellite. In addition, some of the results might be interesting for designers of EPS for a nanosatellite. Since the balancing schematic is scalable, it is possible to use more cells in series to obtain higher maximum voltage, e.g. 5.4 V, 8.1 V, 10.8 V with 2, 3, 4 cells respectively. A lower capacitance can be used to reduce mass and volume in satellites, where less energy is needed. Finally, the results of this study are not limited to space applications. They can be used in any energy harvesting system for prolonging cycle life.

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