Power conditioning unit with independent extreme power control for two sections of small spacecraft solar arrays

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Abstract. The article analyzes the main approaches applied in the development process of power conditioning unit (PCU) model to ensure the efficient power use of non-orientable solar arrays for small satellites operated in low Earth orbits with altitudes ranging from 300 to 1500 km. Particular attention is paid to the description of PCU structure choice, as well as the way to achieve the technical specification goals, such as efficiency factor and specific power. A conclusion is made that the optimal structure to ensure PCU efficiency and reliability is the one with a series regulator and section-by-section solar array power extreme control. It is noted that this structure will make it possible to receive power from solar array sections regardless of the difference in temperature and illumination between them. Based on the quantity and duration analysis of the solar battery charge and discharge cycles, the charge and discharge modes of the batteries are defined as basic ones, so the efficiency factor in these modes is maximized. The results of the study described in the article can be used by enterprises specialized in developing small satellites and power conditioning units as a stepping stone for developing a PCU flight model to ensure the efficient power use of non-orientable solar arrays for small satellites.

1. Introduction  
The production of modern competitive spacecraft with long lifetime and capable of meeting the customer requirements implies the use of on-board equipment with minimal weight and size characteristics, great functionality and high reliability. The fulfillment of the first two requirements is largely ensured by circuitry and layout design, the use of modern electronic components and unit design. The improvement of the equipment reliability requires a number of solutions such as the use of highly reliable component base, high-quality materials, the use of advanced technologies, thorough quality control of manufactured on-board equipment and maintaining the optimal thermal conditions of radio electronic equipment at the production stage as well as during operation in the outer space.

Since 2018, R&P Small Satellites Center LLC has been carrying out an integral part of research and development (R&D) on the subject of "Development of technical documentation and production of a power conditioning unit prototype with increased efficiency and specific output power to ensure the efficient power use of non-orientable solar arrays for small satellites".

In accordance with the general technical specification requirements R&D results shall ensure the development of power conditioning units and materials for small spacecraft (with the mass up to 300 kg) with the minimal life-time of 5 years operating in 550-600 km orbits.

The vast majority of small satellites operating in these orbits have non-orientable or partially orientable solar arrays located on the spacecraft body elements and solar panels [1]. Therefore,
spacecraft solar panels can not only have different illumination levels but also have a different temperature. All these factors have an impact on the current-voltage characteristic of the solar array panels and, thus, the maximum power parameters for each solar array panel. Moreover, the power of the solar flux incident on the solar array panels, and their temperature in the vast majority of cases are variable for each panel and will change during the spacecraft revolution around the Earth.

Hence, it is advisable to build a spacecraft electric power system (EPS) using a PCU with independent extreme power control for each solar array section.

2. Materials and methods

The main PCU production problem is to determine the structure of the spacecraft EPS incorporating PCU. The determination of the optimal structure influences the choice of technical solutions for obtaining high specific mass characteristics of both PCU and spacecraft EPS as a whole, as well as the implementation of some necessary service functions to ensure efficiency and lifetime.

The author assumes that PCU structural composition shall be first of all determined by choosing the method of stabilizers integration. A comparative study of structures based on shunt and series stabilizers as well as the analysis of the influence of their advantages and disadvantages on the achievement of the characteristics specified in the technical specifications were made. After that a comparative analysis of the target characteristics of structures based on the selected stabilization method was carried out.

According to the analysis results a structure with a sequential stabilizer integration was selected, which performs the functions of both extreme power regulation of the solar array and the battery charge and discharge.

3. R&D results

The choice of PCU structure is a multi-criteria task. This choice is determined by the set of requirements for the EPS of the spacecraft and for the spacecraft as a whole. Based on the general specification requirements and the requirements for R&D integral part, the following basic requirements for PCU were established:

- operational orbit type is circular, with the altitude of 550-600 km;
- the spacecraft life time is 5 years;
- PCU specific output power is up to 60 W/kg;
- PCU efficiency is up to 98%;
- voltage rating of the output bus is 27.00 ± 0.81 V.

There are two ways to stabilize the solar array voltage in PCU in the existing systems: in parallel or in series. The use of parallel structures (if the voltage drop on the internal PCU elements is neglected) provides that the solar array output voltage is limited to the load voltage level, which is important when the solar array temperature varies in a wide range due to the alternation of illuminated areas and Earth shadows in the spacecraft orbit. This enables to use in PCU the electronic components with a lower maximum permissible voltage compared to PCU based on a serial structure.

Higher efficiency of the power generated by the solar array can be achieved by the use of the solar array extreme power control mode [1, 2] which consists in tracking the point of optimal voltage in the current-voltage characteristic that corresponds to the maximum generated power of the solar array. Extreme power control of the solar array can be implemented in both structures. But since the solar array voltage in the parallel structure will be lower than in the serial one, the current will be higher provided that the power is the same, and therefore the power loss on PCU elements will be higher. Moreover, the parallel structure will have a higher current of the solar array at both minimum and maximum load power. In a sequential structure, the solar array current will be proportional to the load power.

The specified power of the shunt stabilizer must be equal to or exceed the difference between $P_{solar\ array\ max}$ and $P_{load\ min}$ and depends both on the change in the load power and on the solar array power. At the same time, the specified power of semiconductor devices installed in a series stabilizer structure depends only on the load power. This does not impose any limits on power increase of the solar array and, therefore, it can be chosen taking into account degradation under various operating conditions, i.e.
for a wide range of objects.

The structure with a series solar array voltage stabilizer having identical mass/size and power characteristics is more preferable [3] as it provides the greatest multipurpose use and complies with the concept of the system model design to a greater extent.

**Increased reliability**

Due to inconsistent radio visibility and considerably long spacecraft life-time it is impossible to issue a control command from the ground control complex at any time of the spacecraft operation, therefore EPS and PCU of such satellites shall have high reliability and require operator intervention only in abnormal situations.

To ensure high reliability of PCU, it was necessary:
- to minimize the complexity of PCU involving a large number of power converters;
- to eliminate multiple power conversions.

These activities will also help to increase PCU efficiency.

Significant simplification of the PCU structure is provided when the battery is used in the buffer mode. In this case, the charge and discharge units are excluded from the PCU structure. The block diagram of such PCU is given in Figure 1.

![Block Diagram of PCU with Buffer Battery](image)

**Figure 1.** The block diagram of PCU with buffer battery

In this structure, the function of the charge and discharge unit is performed by the voltage regulator of an unstabilized power bus. When the voltage of the unstabilized power bus is lower than the open-circuit voltage of the battery, the battery is discharged. When the voltage of the unstabilized power bus is higher than the open-circuit voltage of the battery, the battery is charged. If the battery charge or discharge is not required, the voltage of the unstabilized power bus sets the level of the open-circuit voltage of the battery. In addition each voltage regulator has the function of extreme power control of the solar array section.

**Specific power**

PCU shall have minimal mass provided that the requirements for PCU mechanical strength, temperature conditions of electronic components and its resistance to outer space factors are strictly met.

In accordance with the common method for calculating PCU specific power at the spacecraft level, PCU power is determined by the maximum value of the load connected to it. In this case, PCU specific
power will be 60 W/kg for PCU mass is 6.8 ± 0.2 kg and the load power of the spacecraft is 408 W.

By changing the redundancy in the power units of the voltage regulators and extending the cross section of the output buses, PCU output power can be increased up to 1400 watts. In this case, PCU specific power will be at least 200 W/kg for PCU mass is 6.8 ± 0.2 kg.

Further improvement of PCU specific power is a very difficult task, and it is achieved by the use of specific integrated circuits and power microassemblies providing the increase the functional load of the units while reducing the surface area occupied by the components within the unit.

Another way to reduce the mass and, therefore, to increase the specific power is to transfer a larger volume of functions to PCU computing device while reducing the list of tasks solved at the hardware level [4, 5]. The feasibility of using these circuit solutions depends on the conditions of a particular case and is the subject of a separate analysis.

Efficiency
PCU efficiency values are of interest for the main design case of the spacecraft energy balance — one-turn (or daily) energy balance [6]. PCU as the part of spacecraft operating in these orbits will operate both in the shadow of the Earth and in the illuminated part of the orbit during the spacecraft lifetime.

For 550-600 km orbits the one turn around the Earth is 95.65-96.68 minutes. In this case, the eclipse maximum duration at one orbit turn can reach 35.68 minutes [7]. For these orbits with a maximum eclipse duration, the battery charges and discharges alternately throughout the entire revolution. Therefore, the charge and discharge modes of the batteries were determined as the main ones [8], PCU efficiency factor in these modes is increased to the maximum.

In "Battery Key" unit, 2P7229A2 transistors were used as power transistors. The factor determining the efficiency in the applied method for turning on transistors is the resistance of the transistor channel in the on-mode. The equivalent resistance of the redundant switch of the discharge device in the applied circuit (three parallel chains of two series-connected transistors) does not exceed 43.3 mOhm. PCU efficiency will reach 98% at the battery voltage of 26 V with a charge and discharge current of 12 A, as well as at the battery voltage of 32.8 V with a charge and discharge current of 15 A. It is possible to increase PCU efficiency in the "discharge device" mode by excluding transistors from the discharge unit, but this will significantly reduce the survivability of EPS and spacecraft as a whole.

Small spacecraft operating in low orbits, in the vast majority of cases, have non-orientable or partially orientable solar arrays located on the the spacecraft body elements and hinged panels [9]. The analysis showed that the integration of a sectional extreme power regulator of the solar array in PCU is of the greatest importance for increasing EPS efficiency. The sectional extreme power regulator will allow to obtain the maximum available power from each solar array section, regardless of the differences in temperature and illumination between them.

Under the solar array power limitation mode when the solar array power is higher than the total PCU load power and the battery charge power, the requirement to increase the efficiency loses its significance, since in this case there is an excess of the solar array power and it must be limited.

It is possible to increase PCU efficiency to the value of above 98% in the operating modes in the daylight portion of the orbit by eliminating the voltage regulator of the unstabilized power bus (in this case the battery will perform the functions of the unstabilized bus voltage regulator). However, in the first place, it will significantly reduce the efficiency of using the available solar array power; secondly, it will increase the battery cycling. Furthermore, it will require an increase of the solar array surface area and of the battery capacity, and as a result, it will lead to the overall EPS mass increase.

4. Conclusion
Within the framework of the activities on the integral part of R&D, a PCU model was designed and manufactured, the dedicated electrical tests were conducted to check the compliance with the technical specification requirements. Resistance to outer space factors and reliability were analyzed, patent studies were carried out, which confirmed the possibility of developing a PCU flight model with the specified characteristics.
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