Analysis of structures of energy conversion complexes of spacecraft power supply systems in development of their digital control systems

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Abstract. The paper discusses the principle of construction of automatic control systems for the energy conversion complex of a spacecraft with a digital control system. It is shown that the proposed digital control system is able to solve all the tasks assigned to it. The results are tested on an experimental model.

1. Introduction
The modern level of energy-converting complexes (ECC) of spacecraft (SC) is characterized by the use of combined control systems (CCS), which include a digital part, providing general control and telemetry for ECC, and an analog part that implements high-speed feedback loops. Modern ECC provide minimum weight and dimensions, high reliability, accuracy and speed. However, the CCS, or rather its analog part, is subject to aging of elements, and it is difficult to implement complex adaptive control algorithms on it. The constant increase in the requirements for the ECC forces us to look for new solutions that will improve the listed quality indicators. One of these solutions, in our opinion, is the implementation of fully digital CS (DCS) of ECC.

Digital control systems (DCS), in which direct digital control of power keys from microcontrollers is implemented, are just beginning to be used in some new products [32]. This is due to the absence of publications and positive examples of implementation proving the necessity and expediency of transferring the ECC to the DCS. In addition, a new digital element base suitable for use in space radioelectronic equipment appears on the market with some lag.

It is known that direct replacement of an analog control system of a pulse converter with a digital one leads to a decrease in its dynamic characteristics and accuracy due to delays and a quantization effect associated with the operation of digital PWM, ADC and digital corrective element [25]. However, the DCS, in comparison with the analog system, has a number of advantages, which are noted in the works [25–28]. Comparison of analog and digital control systems of pulse converters has been given in [28]. Comparing them with combined control systems, we will present the comparison results in table 1.
Table 1. Comparison of analog, digital and combined control systems of pulse converters.

| Characteristic          | Analogue CS | DCS | CCS  |
|-------------------------|-------------|-----|------|
| Overall dimensions      | -           | +   | +/-  |
| Programmability         | -           | +   | +    |
| Ability to change structure | -         | +   | +/-  |
| Ability to change operation modes | -       | +   | +    |
| Departure of parameters | -           | +   | +/-  |
| Possibility of telemetry| -           | +   | +    |
| Reliability             | -           | +   | +/-  |
| Accuracy                | +           | -   | +    |
| Speed performance       | +           | -   | +    |
| Complexity              | +           | -   | +/-  |

We briefly comment on some of the characteristics given in table 1.

Programmability and the ability to change is a property of remotely changing the structure of the control system and the algorithm of operation without changing the hardware.

The ability to change modes of operation is a property of a remote change in the course of a laid-down algorithm of operation, for example, in flight in the event of emergency situations.

Departure of parameters – this characteristic is associated with changes in the parameters of elements over time. Analogue CS are strongly affected by aging parameters. Since CCS include the analog part, they are also subject to aging.

The possibility of telemetry is the ability to remotely monitor the operation of the CS.

For ECC of SC, the most important characteristics are: mass and dimensional parameters, the ability to change operating modes, the departure of parameters, the possibility of telemetry, reliability, accuracy and speed of CS. The ability to change the modes of operation and telemetry are fully possessed by the ECC implemented using the CCS. Improvement of the remaining characteristics can be achieved only with the use of the DCS.

Improving the weight and dimensions of the DCS is achieved due to a higher degree of integration of the digital element base with respect to analog one. The use of digital microcircuits of a high degree of integration allows creating systems on a chip [29].

Modern spacecrafts have an active lifetime (ALT) up to 15 years. The departure of parameters during the aging of elements leads to a significant deterioration in the accuracy of measured parameters. For example, super-precision in terms of long-term stability, thin-film resistors C2-29C have a resistance stability ± 0.25% for 25,000 hours of operating time. Such resistors are used in measuring circuits and corrective links. In digital control systems, corrective links of feedback loops are implemented using digital signal processing methods and, as a result, have higher temporal stability indicators.

The accuracy of the digital control system is determined by the level of discretization of the analog signal. Modern high-speed ADCs, for example, ADC128S102QML-SP with a sequential approxima-
tion, have a digit capacity of up to 12 bits, a signal conversion rate of 1 MHz and a maximum conversion error of ± 2 LSB. The accuracy of such ADC is ± 0.05% of the full scale of measurement, which is five times as accurate as the stability of a single resistor. Therefore, it can be argued that the accuracy of the DCS for unattended systems with a large ALT is significantly higher than the accuracy of analogue and combined CS.

The reliability of the control system is determined by the failure rate of its constituent elements and the amount of failures. For example, the failure rate of resistor C2-29B is $20 \times 10^{-9}$ 1 / h, and the failure rate of programmable logic integrated circuits (PLIC) is in the range from $10.3 \times 10^{-9}$ 1 / h to $74.6 \times 10^{-9}$ 1 / h, depending on design standards CMOS technology [30]. Comparisons of these values show that the failure rate of a single resistor and an PLIC containing thousands of logic elements are comparable. Therefore, the implementation of CS on digital element base allows to reduce the number of discrete elements and, accordingly, to increase the reliability.

The implementation of control systems on a digital element base requires an analysis of the tasks of control systems in a selected ECC structure, such as uniform current division in energy-converting ECC modules, ECC reliability, ensuring the output voltage stabilization performance when developing disturbing influences, and ensuring the energy balance of primary sources and load with a minimum number of charge cycles / discharge of energy storage devices (batteries).

2. Structure of the DCS and the uniformity of the division of currents in the energy-converting modules of ECC

The increase in power of the power supply system (PSS) of spacecraft (SC) is conducted primarily due to the parallel connection of energy conversion modules (ECM) of the energy-converting complex (ECC), which is confirmed by block diagrams of ECC, leading manufacturers of platforms for spacecraft [1, 2, 3, 4, 5]. The parallel inclusion of the ECM provides the possibility of technical implementation of the modular structure of the ECC, which allows to increase the efficiency and durability of the ECC. However, the implementation of, for example, a discharge device (DD) in the form of parallel-connected switching power supplies (modules), poses the task of uniformly distributing the current between the modules to ensure uniform thermal conditions, which ensures an increase in the lifetime of the switchgear.

The task of uniform current distribution between parallel-connected pulse converters can be solved in various ways, and is considered in the works [6–11, 24]. In [6], the most complete classification, review and comparison of methods for uniform current distribution between parallel-connected pulse converters is given. In [7], the issues of uniform current distribution are interpreted in terms of the foundations of the theory of electrical circuits and the theory of automatic control, which makes them physically more understandable and makes it possible to outline additional ways to solve them. Obviously, not all solutions considered in [6, 7] satisfy the requirements imposed on a spacecraft power supply system (SC PSS).

The analysis showed that, at present, for the SC ECC, two variants of control organization of parallel operating converters are most widely used. The first version of the organization of control in accordance with the work [6], corresponds to the class of combined systems: “Systems with a falling output characteristic, united by regulation on the external current loop” (Outer Loop Regulation & Voltage Droop Via Output Current) [8, 9, 10, 11, 24]. Let's name it for brevity ACS (automatic control system) with the falling characteristic presented in figure 1. These systems are also characterized by the adjustment of the reference voltage by signals from the internal and external current loops.
Figure 1. Structural scheme of the ACS with a falling characteristic.
ACS with the falling characteristic consists of N of energy-converting modules (ECM1-ECMN) connected by output in parallel to the load L via the CSS current sensor, the signal of which is reduced to the average current of one ECM. At the input, all the ECM are connected to their own power sources PS1 - PSN. In general, all the ECM at the input can be connected to one or several PSs, depending on their power. All energy-converting modules ECM1..ECM N, through the CSS current sensor are covered by common feedback on average current, which, together with all ECM, forms an external circuit for correcting the reference voltage. All energy-converting modules ECM1..ECM N, through the CSS current sensor are covered by common feedback on average current, which, together with all ECM, forms an external circuit for correcting the reference voltage. Each ECM has its own voltage feedback loop, an independent reference voltage Uref and an internal circuit for adjusting the reference voltage. The feedback loop for the voltage of each of the ECM includes a voltage sensor VS, an adder A1, a corrective short circuit element CE and a pulse voltage converter PVC. The internal circuit of the correction of the reference voltage is formed by the current sensor CS, the adder A4, the nonlinear element NE, the amplifier Amp, the adders A3, A2 and includes a voltage feedback loop subordinate to the internal circuit of the current reference voltage correction. The external circuit for the correction of the reference voltage includes the current sensor CSS and the internal circuits for the correction of the reference voltage for the current of all the ECMs, which are also subordinates to this circuit.

The internal circuit of the correction of the reference voltage allows to provide a falling output characteristic of an ECM with a short-circuit current limitation, and an external one allows the currents to be equalized between the energy-converting modules of the ECM1 .. ECM N.

The alignment of the output currents ECM1..ECMN by external circuit correction of the reference voltage is as follows. If the output current of a single ECM exceeds the average value of the load current, the reference voltage of the Uref1 voltage stabilization circuit decreases, leading to a decrease in the output voltage and a decrease in its current.

Power sources with a falling output characteristic can work in parallel, the equality of the currents flowing through the sources will be determined by the slope of their output characteristics. The signal from the external current sensor CSS additionally ensures the equalization of the currents of each pulse converter.

The second version of the organization of control by parallel-working converters, according to [6], corresponds to the ACS class with a subordinate current loop (Inner Loop Regulation) [12], shown in figure 2.

The structure of the ACS with a subordinate current loop also consists of N of energy converting modules (ECM1..ECMN), connected in parallel to the load L. Each ECM is also powered by its own power source PS1 .. PSN. The parallel operation of pulsed power sources is provided by two feedback loops: internal current subordinate circuits for each ECM and external voltage loop. The internal subordinate feedback loop for current is implemented by a current sensor CS, an adder A1, a correcting link for the current CLC, and a pulsed voltage converter PVC. The external feedback loop for voltage is implemented by the voltage sensor VS, the main error amplifier MEA, and a subordinate loop current of each of the ECM. The main error amplifier MEA consists of the adder A2, the correction link for the voltage CLV and the reference voltage source Uref.

Internal subordinates of current circuit transform each of the ECM into a controlled current source. The driving signal for the output voltage at the load L is the common reference voltage source Uref, and the driving signal for the current I1 of each PVC is the output signal of the correction link in the voltage CLV. The equality of the currents of all the ECM is ensured by the accuracy of stabilization of their internal current feedback loops.
In [6], it is noted that the lack of a ACS with a falling characteristic is a possible instability in transient conditions and, because of this, the magnitude of the gain of the internal open-loop feedback circuit due to the voltage of the ECM is limited. This has a negative effect on the accuracy of stabilization of the output voltage of an ECM when exposed to any of the disturbing factors. In these structures, the accuracy of the division of currents between the modules is in conflict with the accuracy of the stabilization of the output voltage.

With high demands on the accuracy of the output voltage, a definite preference is given to ACS with a subordinate current loop. The issues of ensuring the accuracy and dynamics of the ACS with a subordinate current loop are the subject of numerous studies, e.g. [13,14].

3. **Structure of DCS and ensuring the reliability of ECC**

The disadvantages of ACS with a subordinate current loop are low structural reliability, which is explained by the fact that in this structure the voltage feedback channel, which includes the voltage sensor VS and the main error amplifier MEA, is common to the entire system. The failure of any of the elements of this channel leads to the failure of the entire system.

The main disadvantage of ACS with a subordinate current loop is eliminated by the implementation of multi-channel negative voltage feedback. To do this, all the channels, each of which

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**Figure 2.** Structural scheme of the ACS with a subordinate current loop.
includes its own voltage sensor and the main error amplifier MEA are connected to the input in parallel. Their outputs are connected to the "majority" element (ME) [15] with the required number of inputs, which selects one signal from three (all) signals of each of the negative voltage feedback channels and transmits this signal to all the ECM. In this case, the common element of the entire system becomes the ME, which should have a high degree of reliability.

In foreign literature, the unit combining all channels of voltage feedback, called the Main Error Amplifier (MEA) while the ME is not included in this unit. The algorithm for selecting the ME signal (one of three or more) and its scheme in the ECC review are not discovered.

In work [16], four algorithms for the selection of the ME signal are distinguished: the majority choice, the choice by the median, the choice by the mean value, and the choice by the principle of pluralism.

Majority choice of a signal corresponds to the algorithm of choosing a signal by majority vote. The choice of the signal by the median corresponds to the algorithm for sorting the values of the input signals in ascending order and choosing such an input signal whose value will be in the middle.

The choice of the signal by the mean value corresponds to the algorithm for determining the average value from the values of all input signals and the choice of such an input signal, the value of which has the minimum deviation from this average value.

The choice based on the principle of pluralism corresponds to the algorithm for choosing such an input signal, the value of which was most often encountered during the previous operating time of the ME. For a single sample of input signals, the algorithm of choice according to the principle of pluralism will give the same result with the majority choice, for many samples the result will be different. In [16], it is argued that the algorithm of choice on the basis of pluralism has the highest probability of choosing the right value from a set of samples. In this case, the sample is understood as the values of analog signals at a particular point in time. Its disadvantage is the need to memorize the prehistory of the samples and complex technical implementation.

Of the four algorithms considered for selecting one signal from among a variety of input analog signals, in our opinion, only two of them are suitable for the structure of spacecraft power supply system - this is the choice by the median and the choice by the mean value.

The implementation of the selection algorithm by the median at the level of principal schemes is presented in the works [17, 18, 20, 21, 22, 23].

Thus, in the ECC, which is presented in [15], the only non-reserved functional unit is the ME, which reduces the reliability of the ECC control system. At the same time, in the work [15] the possible technical solutions for the reservation of this ME are not indicated.

One of the options for improving the reliability of the ECC control system, due to the degree of reservation of the ME, is to increase the number of MEs to the number of modules connected in parallel, and to construct the MEs in each of the modules. In this case, the reliability requirements for the ME will be significantly reduced. The proposed version of the control system with the reservation of the ME is presented in figure 3.

The ACS scheme with the reserved ME repeats the ACS structural scheme with a subordinate current loop. The difference is that in each of the energy-converting modules of ECM1..ECMN, the majority element ME is included, and the total voltage feedback is implemented by the three main error amplifiers MEA1..MEA3. It should be noted that in each MEA there is its own reference voltage source U_{ref}, and the variation in the magnitude of this voltage will affect the divergence of the MEA output signals during their operation.
Figure 3. Structure of scheme ACS with reversed ME.

4. DCS structure and speed
The decrease in the dynamic characteristics of the stabilization circuit of the ACS, due to the transition to digital control systems, can be compensated for by the simpler implementation of adaptive control algorithms in the DCS [33].

In paper [31], one adaptation algorithm is proposed, which assumes stabilization of the loop gain coefficient of the open-loop circuit for the voltage of the ECC which varies, depending on the number of concurrently working modules of the discharge devices of the ECC. The positive influence of the chosen adaptation algorithm on the dynamic characteristics of the converter and the output impedance is noted. It is shown that the output impedance of the system does not change when the number of working modules of the discharge devices changes.

However, the loop gain coefficient depends not only on the number of working modules of the discharge device in the ECC, but also on the parameters of the primary power sources. For example, the coefficient of loop amplification of an open circuit by voltage when operating on the current branch of a solar battery (SB) is proportional to the SB current. And the coefficient of loop amplification of the subordinate current circuit is proportional to the voltage of the battery (B). These parameters of power sources and energy storage devices in the course of work vary over a wide range from 0 to $I_{\text{max}}$ for SB, and from $U_{\text{min},A}$ to $U_{\text{max},A}$ for B. Accordingly, a change in these parameters also
leads to a significant change in the loop gain factors, and hence to a change in the dynamic properties of the system. At the same time, the corrective links of the analog and combined control systems ensuring the stability of the automatic control system are adjusted to the mode of the SB maximum current and the maximum voltage of the B and have the maximum speed and the specified stability margin. By reducing these characteristics, the performance of the ACS is reduced and a decrease in the stability margin is possible.

The implementation of the stabilization algorithms for loop gains in the DCS will allow us to obtain the dynamic characteristics of the ECC, which in some modes are no worse than those of analogue CSs, while in others they are significantly superior.

5. ECC structure and energy balance

One of the main tasks of the control system of ECC is to maintain the energy balance of primary sources and loads with a minimum number of charge / discharge cycles of the battery (B). At the same time, the ECC should maximize the energy generated by the solar battery (SB), transferring it to the load and to the B, in order to maintain the B in the maximum charged state. And only if the power of the load exceeds the power of the SB, the battery B can be discharged. This task is performed by the zone control method based on the error signal (the foreign term “Three-Domain Control”), which is implemented by a buffer amplifier [19].

Figure 4 shows the structural scheme of the ACS of ECC with DCS, which provides a solution to all the problems considered.

The proposed ACS of ECC with DCS is composed of N of modules of voltage stabilization MVS1..MVSN, five-channel digital controle module DCM, power sources SB1..SBN, energy storages B1..BN, five-channel digital communication interface CI which connects all control modules of ACS.

Each MVS includes: bit channel (BC), charger channel (CC) and energy conversion channel of SB (CSB), majority element ME with five inputs, and five-channel digital communication interface receiver (DCI).

All energy conversion channels consist of a pulse voltage converter (PVC) and buffer amplifier (BA). Energy conversion channels CC and CB, besides a buffer amplifier and PVC, also have their current sensor (CS), adder A and correcting link for the current CLC, implementing the subordinate charge / discharge current control loop of the B.

The function of reserved MEA is performed by five channels of digital control module (CDCM1..CDCM5). Each channel of DCM (CDCM1..CDCM5) consists of a voltage sensor VS, analog-to-digital converter ADC, adder A, voltage reference source Uref, correction link for the voltage CLV and a single channel digital communication interface transmitter (DCI).

The operation principle of ACS of ECC with DCS is as follows. Output voltage of ECC is transmitted to the voltage sensor into all five channels of DCM (CDCM1...CDCM5). Further, this voltage is transformed by the ADC into a numeric form. Each channel of DCM independently calculates the required signal of control action (SCA1..SCA5) in the numeric form and transmits it through the transmitter DCI via five-channel communication interface CI into all receivers of DCI of all MVS.

The DCI transmitters add a checksum to the packets of transmitting SCA to eliminate errors during data transmission. Signals of control action (SCA1..SCA5) are received by the DCI receivers of each MVS and transmitted to the inputs of the majority element ME, which selects one of the incoming SCAs and transmits it to the buffer amplifiers of all the MVS energy conversion channels. Buffer amplifiers of energy conversion channels determine the sequence of operation of these channels, realizing the zone principle of control by the error signal.

The control algorithms incorporated in the buffer amplifiers guarantee the absence of the mode of simultaneous operation of the charger channel (CC) and the bit channel (BC), by the fact that these channels operate alternately. This ensures the minimum number of charge / discharge cycles of the battery (B) and the maximum efficiency of using the energy generated by the SB.
Figure 4. Structural scheme of ACS of ECC with DCS.
In the particular case, all ECC modules can be implemented in separate structural units, which makes it easy to increase the output power and increase the degree of reservation of the ECC. In this case, all the blocks designed to control all the pulse voltage converters of all the MVS channels can be implemented in a single digital integrated circuit of the large integrated circuit (LIC), programmable logic integrated circuits (PLIC) or on a specialized microcontroller. Such a microcircuit will play the role of the MVS control system.

Figure 5 shows the model of the ECC with two energy-converting modules MVS and a five-channel digital control module DCM.

Figure 5. Model of ECC with DCS.

6. Conclusions
– The proposed structural scheme of ACS of ECC with DCS and its implementation in the model showed the possibility of using digital control systems in the ECC.
– The use of digital control systems fundamentally allows to solve all the tasks imposed on the SC ECC.
– The undoubted advantage of digital control systems is the possibility of implementing complex corrective links that adapt to external disturbing influences due to changes in illumination and SB degradation, voltage changes on the battery (B), as well as a wide range of load changes and failure of both ECC modules and other nodes of power supply system of SC.

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