Methodology to synthesis of digital regulator for solar battery energy conversion channel in the spacecraft power supply system.

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***Abstract*— The methodology to synthesis of a digital regulator for a solar battery energy conversion channel in a spacecraft power supply system is presented. The mathematical model of a shunt converter in the basis of commutation function has been developed, it is linearized and simplified. Simulation modeling power supply system with digital control has been carried out in solar battery energy converter operation mode.**

Keywords— digital controller synthesis, technical optimum, simulation modeling, shunt converter, power supply system, spacecraft

I. Introduction

The methodology to synthesis of a digital regulator for a solar battery energy conversion channel in a spacecraft power supply system is presented. The mathematical model of a shunt converter in the basis of commutation function has been developed, it is linearized and simplified. Simulation modeling power supply system with digital control has been carried out in solar battery energy converter operation mode.

Keywords: digital controller synthesis, technical optimum, simulation modeling, shunt converter, power supply system, spacecraft.

One of the most important onboard systems of automatic spacecraft is a power supply system which is a combination of primary and secondary current sources, energy conversion and output voltage stabilization equipment with the necessary automatic devices of monitoring and control [1].

In developing a spacecraft power supply systems, it is necessary take into consideration many factors (load resistance and power sources capacity changing, primary energy sources degradation, etc.), which define the static and dynamic quality characteristics of the output voltage and this leads to the need to build a control system that ensures stable system operation over the entire frequency range.

At present, the analogue control systems are widely used in the spacecraft power supply systems. In solving the increasing reliability task of power supply system, while improving its mass-scale and functional characteristics, it is obvious that the control systems are reach the physical limit of the possibility improving the electrical parameters and mass-scale characteristics [2].

The next stage in the development of the spacecraft power supply systems is the transition to digital control. The digital control in comparison with an analogue control will provide: higher reliability, the mass and dimensions reduction of the power supply system (including the cable network), control signal transmission noise immunity, small delays in the control loop and delays in transmitting information, etc. [3].

In addition, the digital control will provide flexibility, wide functionality, modifiability, simplify the integration of the power supply system into the structure of various devices, and also allow data exchange with the on-board control system via a high-speed data transfer interface.

The purpose of this work is to develop the methodology to synthesis of a digital regulator for a solar battery energy conversion channel in a spacecraft power supply system.

The following algorithm is proposed to solve the task:

1. The control object mathematical model construction in the basis of discontinuous commutation functions;
2. Linearization of the obtained model;
3. Finding the transfer function of the system;
4. Check the adequacy of the model;
5. The frequency characteristics family construction of an open uncorrected control system at the extreme operation points;
6. The regulator synthesis, allowing tuning the system to the technical optimum.
7. The simulation model construction and the regulator verification;

II. Mathematical model of the SB channel

The control object is the voltage stabilization module of the energy-conversion complex, which includes three types of energy conversion channels:

- “*SB channels*” designed to convert the onboard solar batteries energy;
- “*AB channels*” designed to convert the onboard accumulator batteries energy;
- “*CD channels*” necessary to charge the onboard batteries with a specified stabilized current.

Energy conversion channels are high-frequency power converters with the necessary electronic elements for their functioning.

In this article, only the *SB* conversion channel, based on the shunt converter, is considered (Fig. 1). Since the solar battery operates on the current branch of its current-voltage characteristic, in this circuit it was represented as a current source. The signal from the voltage sensor located at the *SB* channel`s output is converted into a digital form by the *ADC*, subtracted from the reference voltage signal and then through the corrector, the modulator and the driver is fed to the converter power switch. As a modulator, we use a first-order pulse width modulator (*PWM 1*) with a one clock cycle delay of the sweep signal. Such a modulator is implemented in digital control systems based on microcontrollers. The current source simulates the load current disturbing effect. The filter *C1, C2, R1* is necessary for smoothing the voltage pulsations on the solar battery [4].To synthesize a correcting unit, it is necessary to construct an energy conversion channel mathematical model in the basis of discontinuous commutation functions (Fig. 2). In the block diagram shown, that a switching function signal $F_k(t)$ is a signal from a modulator output to the input of which comes a control signal $X(t)$. The modulator realizes a converting function $f(X(t))$ a input control signal $X(t)$, into a commutation function $F_k(t)$. The control signal $X(t)$ is a correction unit output signal W_{K3}. The correction unit W_{K3} determines the control signal $X(t)$ value based on the error signal, which is the difference between the reference signal $u(t)$ and the feedback signal. The feedback signal is the voltage signal on the capacitor *C2*. The mathematical model presented in Figure 2 has two types of nonlinear units: multiplication blocks and a modulator block *(M)*. The linearization methodology description for these units is described in [5]. In the linearized model, the modulator was replaced by a delay unit (Fig. 3), so it is impossible to mathematically calculate the regulator parameters for tuning the system to the technical optimum. The linearized mathematical model of the shunt converter can be simplified to the model shown in Fig. 4, using equivalent transformations methods of the automatic control systems structural schemes.

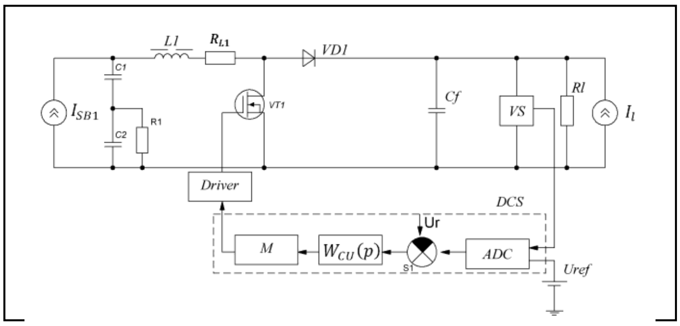

Fig. 1. The shunt converter`s scheme with digital control system.

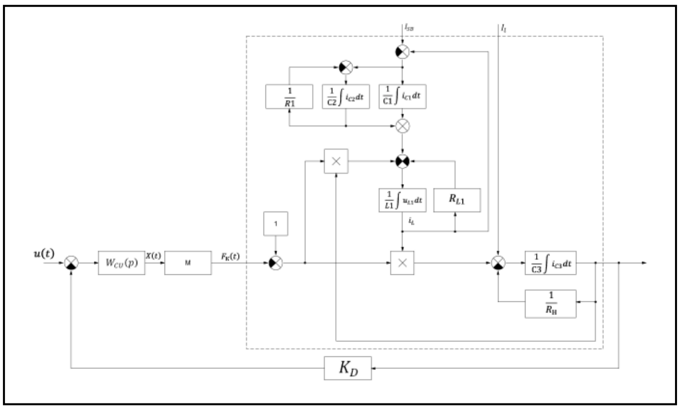

Fig. 2. The shunt converter`s mathematical model with input filter and control system.

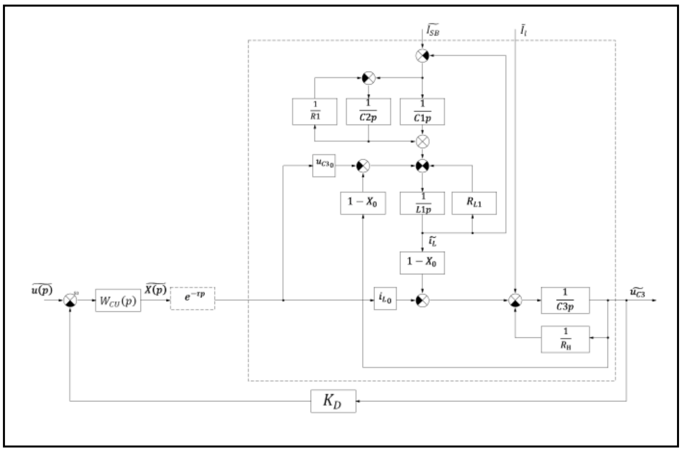

Fig. 3. The shunt converter`s linearized mathematical model with input filter and control system.

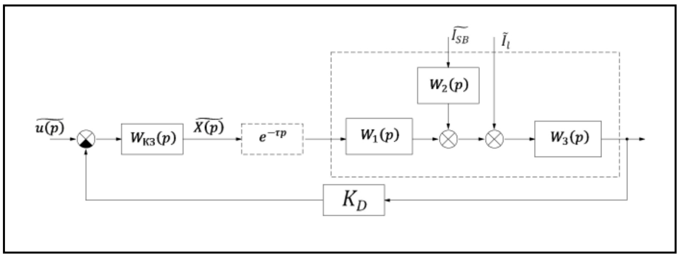

Fig. 4. The shunt converter`s simplified linearized mathematical model with input filter and control system

Formulas 1-3 represent the units’ transfer functions shown in Fig. 4.

$$W_1(p)=\frac{u_{C30}\times\frac{1}{R_{L1}}\times\frac{1}{\frac{L1}{R_{L1}}p+1}(1-X_0)}{\frac{1}{R_{L1}}\times\frac{1}{\frac{L1}{R_{L1}}p+1}\times\left(\frac{1}{C1p}+\frac{R1}{R1C2p+1}\right)+1}-i_{L0}\quad(1)$$

$$W_2(p)=\frac{\frac{1}{R_{L1}}\times\frac{1}{\frac{L1}{R_{L1}}p+1}\times\left(\frac{1}{C1p}+\frac{R1}{R1C2p+1}\right)\times(1-X_0)}{\frac{1}{R_{L1}}\times\frac{1}{\frac{L1}{R_{L1}}p+1}\times\left(\frac{1}{C1p}+\frac{R1}{R1C2np+1}\right)+1} \quad (2)$$

$$W_3(p)=\frac{\frac{R_H}{R_H C3\times p+1}\times\left(\frac{1}{R_{L1}}\times\frac{1}{\frac{L1}{R_{L1}}p+1}\times\left(\frac{1}{C1p}+\frac{R1}{R1C2\times p+1}\right)+1\right)}{\frac{R_H}{R_H C3p+1}\times\frac{1}{R_{L1}}\times\frac{1}{\frac{L1}{R_{L1}}p+1}\times(1-X_0)^2+\frac{1}{R_{L1}}\times\frac{1}{\frac{L1}{R_{L1}}p+1}\times\left(\frac{1}{C1p}+\frac{R1}{R1C2p+1}\right)+1} \quad (3)$$

For mathematical model adequacy experimental verification, one can use the method described in [6]. Since the nonlinear system`s response to a harmonic signal is the signal` harmonics spectrum, the first harmonic amplitude will be much larger that the higher harmonics amplitude, it is proposed to use as the amplitude-frequency characteristic the system responce first harmonic amplitude ratio dependence of the of the system response to the input action amplitude in the steady-state mode. The check results are shown in Fig. 5.

The dependencies shown in Fig. 5, confirm the reliability of the mathematical model. To determine the correcting unit parameters, it is necessary to construct the HF-family of an open uncorrected system at the extreme operating points (Fig. 6).

Based on the described mathematical model frequency characteristics, the correcting unit`s type and coefficients were selected to ensure the necessary stability stocks (16 dB, 35 degrees):

$$W_{кр}(p)=K_{кр}\frac{T_1p+1}{p(T_2p+1)}\times\frac{1}{p}, \quad (4)$$

$$K_{кр}=800, T_1=0.16, T_2=6.41e-5.$$

The resulting transfer function corresponds to an analog corrector. To determine the discrete circuit transfer function parameters, it is necessary to replace in the analog prototype [7]:

$$W_{кр}(z)=W_{кр}(p)\Big|_{p=\frac{2(z-1)}{T(z+1)}} \quad (4)$$

T – sampling period.

On *DSP* controllers, the maximum possible sampling frequency T is no more than the *PWM* modulator frequency when the *ADC* operation and the calculation of the signal at the correcting unit (control signal) output are performed once during the sampling period.

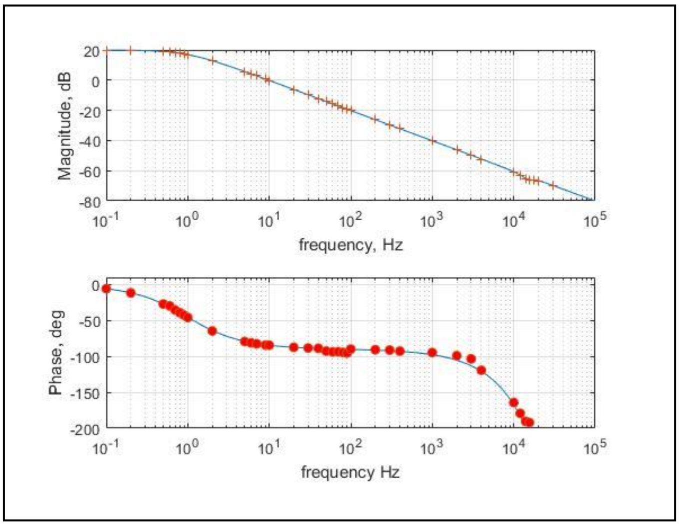

Fig. 5. LAFR and LPFRof the simulation ('+') and mathematical (blue line) models.

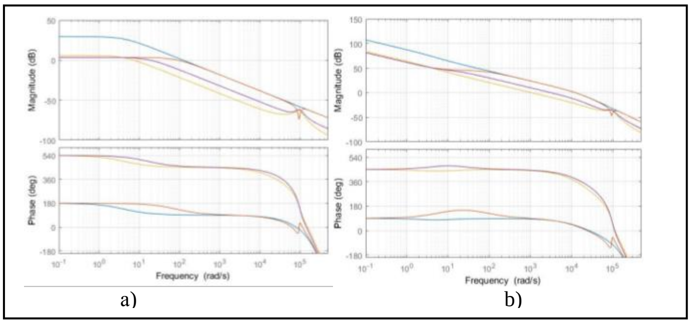

Fig. 6. Frequency characteristics: a) open uncorrected system, b) open corrected system.

III. Imitation model of the SB channel

Also in the Simulink package of the *Matlab* development environment a *SB* channel simulation model was constructed (Fig. 6a). The model parameters are shown in Table 2, the *PWM I* block internal structure is shown in Fig. 6b, the subsystem T1 structural diagram is shown in Fig. 6c.

TABLE I. ELEMENTS PARAMETERS OF THE SHUNT CONVERTER SIMULATION MODEL.

Elements	***Value***	***Elements***	***Value***
C1	1 μF	Rl	13.5 … 135 Ohm
C2	1 μF	IBS	7.4 A
R1	10 Ohm	Il	0 …4 A.
L1	170 μH	Diode1, Switch 1	Ideal
RL1	33 mOhm	F	100000Hz
C3	1200 μF	Ur	100V

Fig. 7 shows the *BS* channel operation diagrams obtained with the simulation model help.

The simulation result analysis showed that the steady-state voltage on the load power bus is 100±1 V when the load changes in the range of 5-95% of the maximum value. The diagrams show that when quick changes load resistance the voltage pulsation does not exceed the permissible range, overshoot for load shedding is 8.125%, the transient duration is 486μs.

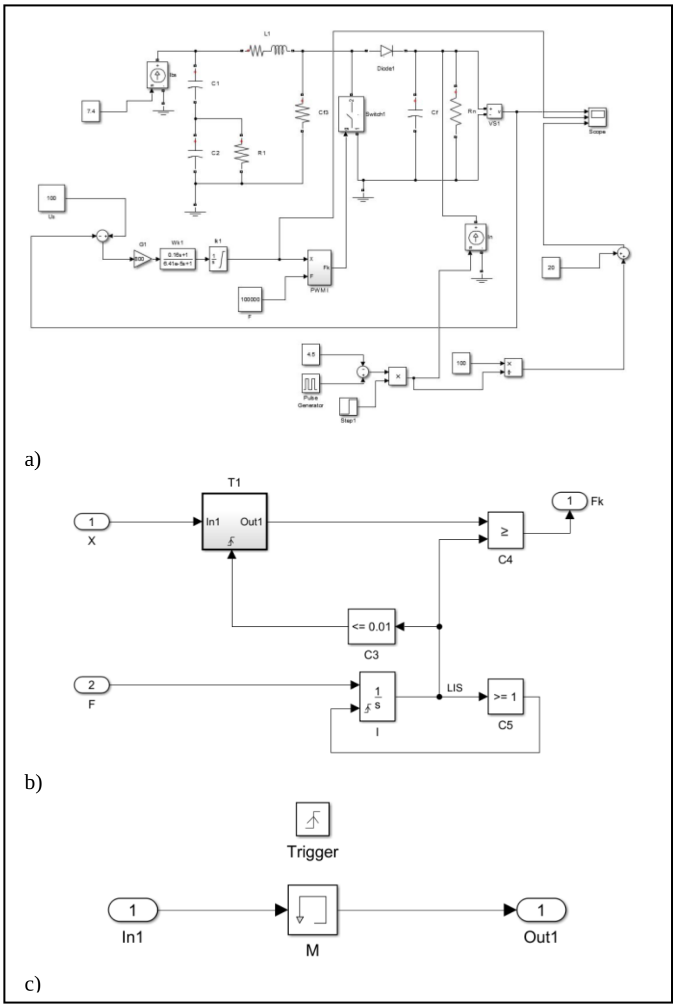

Fig. 7. Fig. 6. Simulation model: a) SB energy conversion channel, b) PWM1 subsystem model, c) T1 subsystem model.

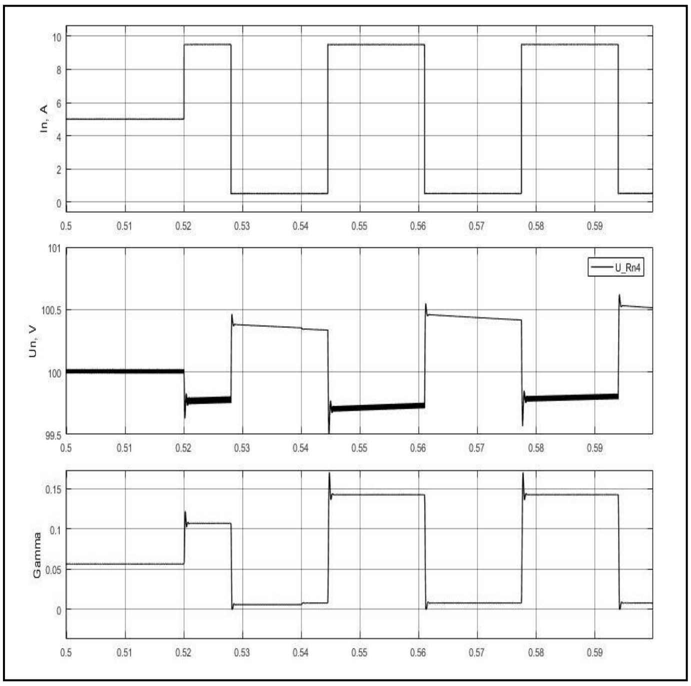

Fig. 8. Diagrams load voltage (Un), the control signal at the SB channel PWM modulator (Gamma BS) input and load resistance (Rn)

IV. Using the Template

In the course of research the methodology to synthesis of a digital regulator for a solar battery energy conversion channel in a spacecraft power supply system is developed.

The mathematical model of a shunt converter in the basis of commutation function has been developed, it is linearized and simplified. By comparing the frequency characteristics of the simulation and mathematical model, the adequacy of the mathematical model was proved.

Based on the described mathematical model frequency characteristics, the correcting unit`s type and coefficients were selected to ensure the necessary stability stocks, using the simulation model it was proved that at such the coefficients` values, stable operation of the system is ensured throughout the declared range of load changes.

The correcting unit`s parameters are chosen so that the system`s characteristics are close to the technical optimum settings. However, accurate parameters calculation of the correcting unit is not possible due to the fact that the system contains a delay unit. Parameters selection should be done experimentally [8].

The simulation results showed that the output voltage stabilizes in a given range, the voltage pulsation amplitude during load current pulsations does not exceed 1V.

It was proved that, despite the delays presence in the feedback channel, it is possible to create a digital control system for the spacecraft power device that meets the requirements.

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