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# DETERMINATION OF THE DIGITAL CONTROLLER'S CHARACTERISTICS OF THE SWITCHED-MODE POWER CONVERTERS

A. A. Lopatin, A. A. Druzhinin*, A. S. Asochakov, A. V. Puchkov

JSC Academician M. F. Reshetnev Information Satellite Systems
52, Lenin St., Zheleznogorsk, Krasnoyarsk region, 662972, Russian Federation
*E-mail: Alex-Druzh@mail.ru

*The development of spacecrafts equipment is on the way to digitalization. In particular, energy spacecraft conversion devices are being modernized by introducing digital automatic control systems instead of analog ones. This leads to an increase in the efficiency of the power supply system, but at the same time, there is a need to create methods to determine characteristics that will confirm with a high degree of accuracy and conformity of the manufactured sample with the technical requirements specified during its design. The article describes the features of functioning and methodology for determining digital control channel of a pulse voltage converter's characteristics. The proposed approach is a toolkit for verifying the correct implementation of both the hardware parts of the control channel and the controller, which is a program code implemented on digital control devices. The technique is based on determining the degree of responses correspondence to typical external influences of a hardware-implemented control channel and its model. Based on the transfer functions of the IIR and FIR digital filters, using standard built-in models, the control channel of the pulse voltage converter corresponding to the tested hardware-implemented device is simulated in the package Matlab Simulink. The basic principles of building the software architecture experiment are described. A block diagram of the test complex has been developed, including sources of external influence, control channel, and a test management tool (in this case, a personal computer). An example of applying such a technique to verify the parameters of the developed PID controller is given. Operability and accuracy of the proposed method to determine characteristics of the control channel by reaction to a sequence of rectangular pulses, and by constructing the AFCL are experimentally shown. Application of this verification method to production conditions will allow a complete check of individual central control units (CCU) of energy-converting equipment with closed feedbacks even at the stage of devices development, which will eliminate errors in the implementation of regulators in control loops.*

*Keywords: testing, pulse voltage converter, digital controller, reference model, response, typical input.*

# ОПРЕДЕЛЕНИЕ ХАРАКТЕРИСТИК ЦИФРОВЫХ РЕГУЛЯТОРОВ ИМПУЛЬСНЫХ ПРЕОБРАЗОВАТЕЛЕЙ НАПРЯЖЕНИЯ

А. А. Лопатин, А. А. Дружинин*, А. С. Асочаков, А. В. Пучков

АО «Информационные спутниковые системы» имени академика М. Ф. Решетнева»
Российская Федерация, 662972, г. Железногорск Красноярского края, ул. Ленина, 52
*E-mail: Alex-Druzh@mail.ru

*Развитие космического приборостроения идет по пути цифровизации. В частности, энергопреобразующая аппаратура космических аппаратов модернизируется путем внедрения цифровых систем автоматического управления взамен аналоговых. Это приводит к повышению эффективности системы электропитания, но в то же время возникает необходимость в создании способов определения их характеристик, которые позволят с высокой степенью точности подтвердить соответствие изготовленного прибора заданным при проектировании требованиям технического задания. В статье описаны особенности функционирования и предложен способ определения характеристик цифрового канала управления импульсным преобразователем напряжения. Предложенный подход представляет собой инструментарий для проверки правильности реализации как аппаратных частей канала управления, так и самого регулятора, представляющего собой программный код, реали-*

*зованный на цифровых управляющих устройствах. Метод основан на определении степени соответствия откликов на типовые внешние воздействия аппаратно реализованного канала управления и его модели. На основе передаточных функций цифровых фильтров с бесконечной импульсной характеристикой и конечной импульсной характеристикой, с использованием типовых встроенных моделей, в пакете имитационного моделирования Matlab Simulink смоделирован канал управления импульсным преобразователем напряжения, соответствующий испытываемому аппаратно-реализованному устройству. Описаны основные принципы построения программной архитектуры обеспечения эксперимента. Разработана структурная схема испытательного комплекса, включающая источники внешнего воздействия, сам канал управления и средство управления проведением испытаний (в данном случае персональный компьютер). Приведен пример применения такой методики для верификации параметров разработанного пропорционально-интегрального дифференциального регулятора. Экспериментально показана работоспособность и точность предложенного способа определения характеристик канала управления по реакции на последовательность прямоугольных импульсов и путем построения логарифмической амплитудно-фазовой частотной характеристики. Применение такого метода верификации в условиях производства позволит обеспечить полную проверку отдельных цифровых управляющих устройств энергопреобразующей аппаратуры с замкнутыми обратными связями еще на этапе разработки приборов, что позволит исключить ошибки в реализации регуляторов в контурах управления.*

*Ключевые слова: тестирование, импульсный преобразователь напряжения, цифровой регулятор, эталонная модель, отклик, типовое воздействие.*

**Introduction**. Operation of space technology devices has its own specific features, which combine high cost of failure, inability to repair, and a long period of continuous operation under conditions of outer space radiation exposure. In this regard, all devices that are designed for space technology go through a full cycle of checks and tests, which differ in terms of regulations, physical nature, and magnitude of disturbing effects. To ensure reliability and quality of the equipment produced, a multi-stage verification of the device is applied, which includes tests according to a hierarchical system [1]. This is how the parameters of all electrical components used are checked, tested for compliance with technical specifications requirements: first the individual units of the device, then the device autonomously as a part of the spacecraft (SC). Today, space technology is actively developing and modernizing. In this regard, development of methods for testing onboard equipment remains an important task.

One of the lines of space technology development is modernization of power supply system, and, in particular, energy-converting equipment. Improvements of microelectronics and electronic component base allowed to start introducing microprocessor systems to control the processes of voltage and current stabilization and regulation of the power bus. Digital control systems (CS) have a number of advantages over analog systems, among them the flexibility of setting parameters and independence of characteristics from external climatic influences [2], which is an important property for long-term operation in conditions of external impact factors of outer space.

Introduction of digital controllers in microprocessor systems sets the task of developing methods for determining their characteristics. Methods for characterizing analog regulators are widely known. Analog regulators are operational amplifiers with external feedback reactance. Elements used for regulators undergo input control of parameters and a series of electrical and temperature tests aimed at revealing the drift of parameters. The regulator is then subjected to electrical and functional tests. A digital controller, in contrast to an analogue one, is a program code for a digital control device (DCD), consisting of the operations of storing the values of variables, multiplications by constants and additions [3]. While a microprocessor system is used to control a pulse voltage converter, the input signal – a feedback signal (feedback) for a digital controller is converted using an analog-to-digital converter (ADC), and the output signal is formed using a digital pulse-width modulator (DPWM). Since the approach to the physical implementation of digital and analog controllers is significantly different, the test methods applied to the control channel of an analog system are not suitable for testing the microprocessor system.

In this regard, this work proposes a method for determining characteristics of a switched-mode power supply (SMPS) control channel. The proposed method was verified during IIT prototype testing.

First, a description of the test object will be given, which is a control channel of a SMPS, its features will be highlighted based on which the approach to its testing is developed. Next, the method for determining parameters is explained – which software is needed to implement the proposed method, and features of the test complex functioning are explained. The next step is results of experimental verification of the proposed method, by determining the degree of correspondence of the hardware-implemented control channel of the IIT characteristics with the results of simulation.

**Test object.** The object of testing is the channel of SMPS digital control system, which is shown in fig. 1.

The control channel consists of a sensor, an analog-to-digital converter, an error signal generator, a digital controller and a pulse-width modulator [4].

Operation of control channel can be described as follows. A signal representing the value of physical quantity is coming from the sensor. This signal is digitized by the ADC and fed to the input of the error signal generator. The digitized signal is subtracted from the reference signal, resulting in an error signal. The error signal is processed by a digital controller which calculates the control signal. The control signal goes to the digital pulse width modulator (DPWM).

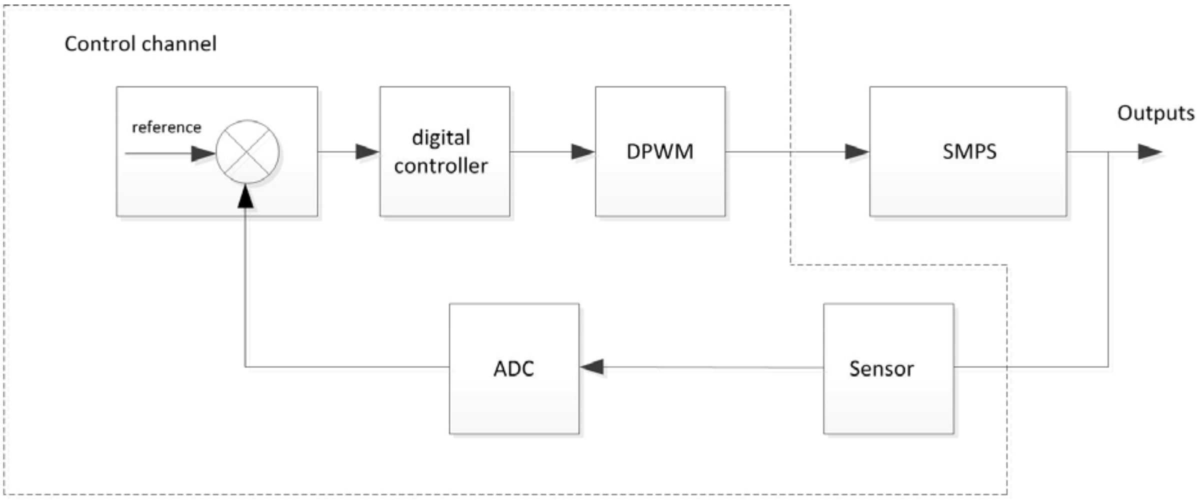


Fig. 1. Pulse converter control channel

Рис. 1. Канал управления импульсным преобразователем

There are several ways to implement a control channel [5]. It can be a microcontroller or digital signal processor (DSP) with built-in ADCs, regulators and DPWMs, or it can be a field-programmable gate array (FPGA) on which the regulator and DPWMs are made, and the ADC is an external device. However, the testing approach will be identical.

The main testing element is the digital regulator. As a mathematical object, the regulator is a digital filter with an infinite impulse response (IIR – filter), or a digital filter with a finite impulse response (FIR – filter) [6]. Formulas of transfer functions IIR (1) and FIR (2) filters in general form are given below.

$$D(z)=\frac{\sum_{i=0}^{N-1} b_i \cdot z^{-i}}{1+\sum_{k=1}^{M-1} a_k \cdot z^{-k}}, \quad (1)$$

$$D(z)=\sum_{i=0}^{N-1} b_i \cdot z^{-i}, \quad (2)$$

where $b_i$, $a_k$ are regulator coefficients, $z^{-i}$ is the delay element per cycle of the regulator operation.

The digital filter, depending on the structure and values of coefficients, has a number of static and dynamic characteristics that are unique for a given filter [7]. This property is well manifested by determining the response to typical inputs, including stepwise, impulse and harmonic effects. All outputs will also be unique to this filter. Based on this property, a methodology for checking the control channel will be built.

Since the controller is a program code consisting of the simplest arithmetic operations, it can be simulated in the Matlab Simulink simulation system. The methods for modeling digital filters in this program are well known and have shown their efficiency [8]. Also, with a given accuracy in this program, an ADC can be modeled in the form of a transmission coefficient, and external typical disturbance signals. Thus, with the help of simulation, it is possible to obtain an accurate response of the digital filter to typical inputs.

According to the described hardware-implemented control channel, a model was developed in Matlab Simulink (fig. 2). In the model, a PID – regulator is used as a regulator, and the FPGA block designates a signal source that represents a signal received from the model of the IIT control channel.

The block diagram of the hardware measuring the response of a digital filter to typical inputs is shown in fig. 3.

The source of disturbance is a serial connection between a constant voltage source and a signal generator. In this case, the controller includes an integral component, therefore, the presence of a DC component in the error signal will lead to saturation of the digital controller, which will not allow obtaining a response to any action. Thus, for correct operation it is necessary to select a source voltage and a generator signal amplitude in such a way that relation [9] is fulfilled.

$$\int_0^T (Ref - Udsup - Udgen)dt = 0, \quad (3)$$

here Ref is the reference signal, Udsup, Udgen are the digitized values of the voltage source and the generator signal, respectively, at the sensor input, T is the generator signal period.

In accordance with fig. 3, the total voltage of the source and generator is converted by the sensor and fed to the ADC input. The signal from the ADC output is used to receive the control error signal and is fed to the digital filter input. An interface connection is established between the digital control device, where the digital filter is implemented, and the personal computer [10]. Matlab is also used to obtain measurement results. Details about the program for the control center and its interaction with a personal computer will be described in detail in the next section. As a result of the experiment on a personal computer in the Matlab environment, graphs are displayed that represent the input signal of the hardware-implemented controller and its response to this signal.

As a result, in one simulation environment responses to typical inputs of the designed control channel model and responses to similar typical actions obtained during testing of the hardware-implemented control channel will be obtained. By comparing the received signals, it is possible to make an unambiguous conclusion about whether the IIT control channel is correctly implemented. If the control channel is working correctly, the signals must match.

**Software.** Digital control systems can be based on digital signal processors (DSP), universal microcontrollers or field-programmable gate array (FPGA).

Modern universal microcontrollers have ample opportunities for the formation of a control action and support digital signal processing (DSP) operations, which makes it possible to use them in control systems of power converters [11]. The most common general purpose microcontrollers are embedded 32-bit microcontrollers.

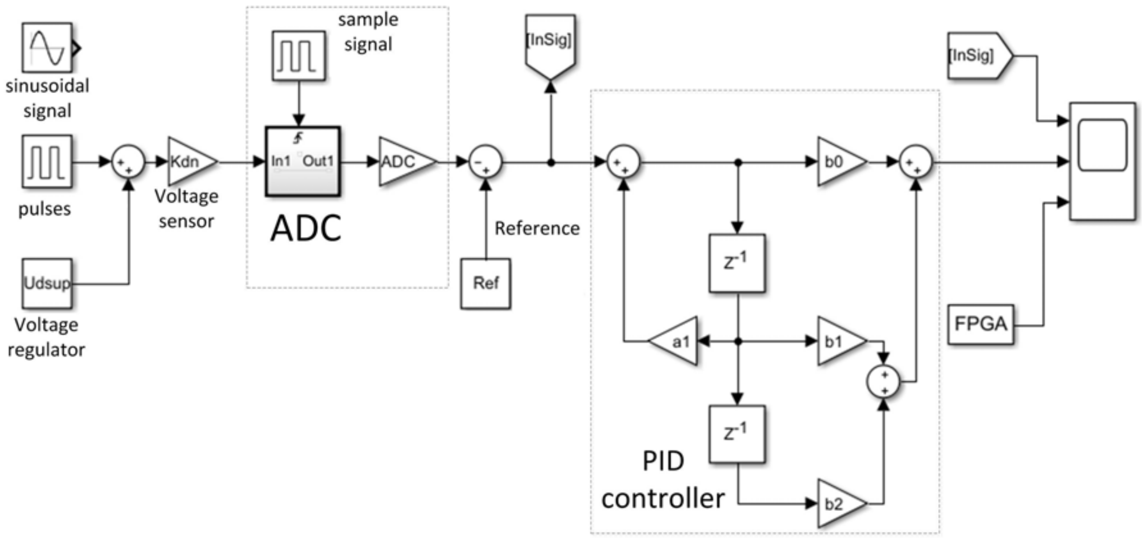


Fig. 2. Control channel model in Matlab Simulink

Рис. 2. Модель канала управления в Matlab Simulink

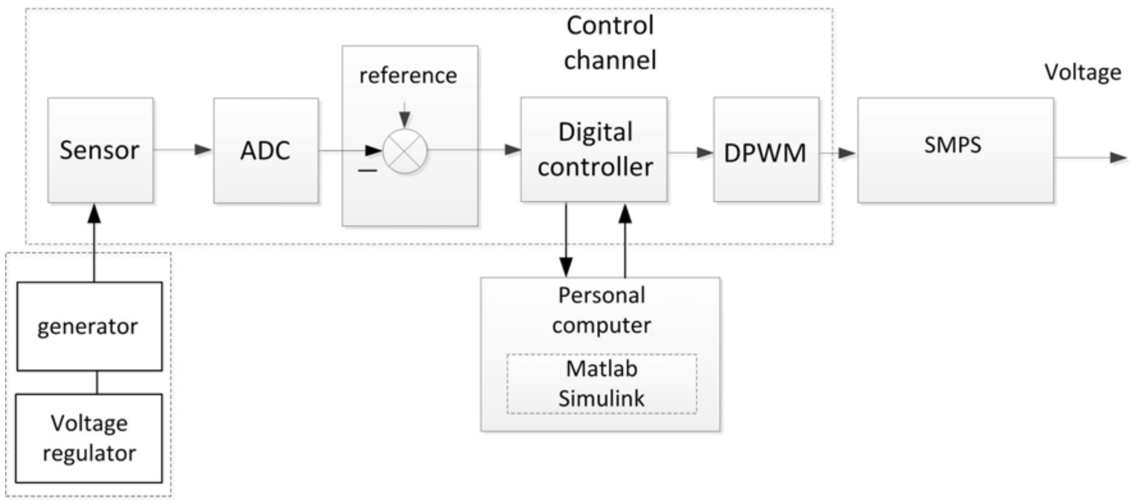


Fig. 3. Scheme of experimental determination of control channel characteristics

Рис. 3. Схема экспериментального определения характеристик канала управления

These processors include the STMicroelectronics 32-bit STM32 microcontroller. In space technology, the Milandr 32-bit 1986BE8 microcontroller is widely used to provide resistance to external influences.

Digital signal processors, in comparison with general-purpose microcontrollers of general use, ensure to maximally speed up the execution of typical tasks of digital signal processing, such as digital filtering, Fourier transform, signal search, etc. [12]. Therefore, signal processors are optimized for speed to perform just such operations. DSP processors TMS320 or specialized microcontrollers UCD3138 from Texas Instruments are widely used in power converters.

FPGAs are well suited for devices such as radar systems, electronic intelligence systems, image processing systems, signal processing devices, etc. they are primarily intended for those devices in which signal processing and vector or matrix calculations are performed. Due to the ability to perform cumbersome parallel computations, FPGAs have become widely used in complex applications [13]. Operating at relatively low clock rates of the order of hundreds of MHz, they can perform tens of thousands of calculations per clock cycle and still consume much less power than microprocessors with the same performance.

FPGA cyclone IV (EP4CE22F17C6N) [14] from Altera, which is an indirect analogue of the domestic Rad-Hard FPGA 5578TS064 manufactured by VZPP-S, and a 12-bit ADC128S022 ADC with a digital SPI interface from Texas Instruments were used in the IIT layout. The FPGA implements an ADC control unit via the SPI interface and a regulator in structure and coefficients similar to the model.

The block diagram of the program is shown in fig. 4.

Since for calculating the controllers in the used FPGA it is necessary to perform floating point calculations, the FPGA used computing units according to the IEEE 754 standard [15].

With the frequency of 100 kHz, the values are captured from the ADC and the regulators are calculated. The ADC data and regulator responses are transferred to the FPGA's internal RAM.

After experiment completion the data is transferred to the computer via the UART interface to the Matlab simulation system and output to the virtual oscilloscope for comparison with similar signals measured in the simulation model.

In the course of the work, three types of controllers were implemented and their performance and resources used were evaluated when implemented on a specific FPGA (EP4CE22F17C6N). The parameters are presented in the tab. 1.

**Experiment.** A digital regulator has been developed for the SMPS. In this case, it is a proportional-integral-derivative (PID) controller made by the method of integration according to the Euler method. This regulator was converted into an IIR – filter, the structure corresponds to formula 1, and has the coefficients presented in tab. 2.

The response to rectangular pulses signal type makes it possible to assess the correspondence of the regulator coefficients in terms of the output signal overshoot, as a result of the response to a change in the level of the disturbing pulse, and in the rate of change in the regulator output signal as a result of integrating the control error. In this experiment a signal of the type of a sequence of pulses with a peak-to-peak value of 3 V (from 0 to 3 V), a frequency of 100 Hz and a duty cycle of 0.5 was selected as a disturbance signal. Thus, at the input of the PID-controller there will be a numerical equivalent of pulses with voltage from –1.5 to +1.5 V with a zero constant component, which is necessary to fulfill condition (3).

Fig. 5 shows the results of an experiment on a pulse sequence. The dashed line indicates the disturbance signal at the filter input, and the solid line indicates the response at the filter output. The top graph shows the signals obtained on the simulation model, and the bottom graph shows the signals obtained as a result of testing the hardware-implemented control channel.

As you can see from the graphs, the responses are identical with minor differences. The differences are explained by the presence of distortion and noise in the signal of the generator, as well as by the errors of the real ADC.

The controller in the feedback loop is designed based on the requirements for characteristics in frequency and time domains of the control object. It must adjust the frequency response of the open loop of the control object so that it meets a number of requirements, such as crossover frequency and phase margin. This means that the key characteristic of the designed controller is its Logarithmic Amplitude-Phase Frequency Response (LAFC). LAFC is determined from the response to harmonic influences at different frequencies. To construct the LAFC, harmonic signals with an amplitude of 1.5 V and frequencies of 100, 250, 500, 1000, 2500, 5000 and 10000 Hz were selected as disturbing influences. From the responses of the regulator, obtained as a result of tests for harmonic influences at the declared frequencies, a piecewise-linear IIR-filter LAFC was built and compared with the continuous theoretical characteristic of the developed regulator.

In fig. 6, the solid line with highlighted points denotes the frequency response obtained as a result of the experiment, and the dashed line – calculated from the TF of the controller.

According to fig. 6 it can be concluded that the dynamic properties in the investigated frequency range of the implemented controller correspond to the calculated ones with the required accuracy.

Thus, from the totality of the experiment results carried out comparing the responses to the typical inputs of the control channel model and the real tested control channel, we can make an unambiguous conclusion that the control channel is implemented correctly and its characteristics correspond to the calculated ones.

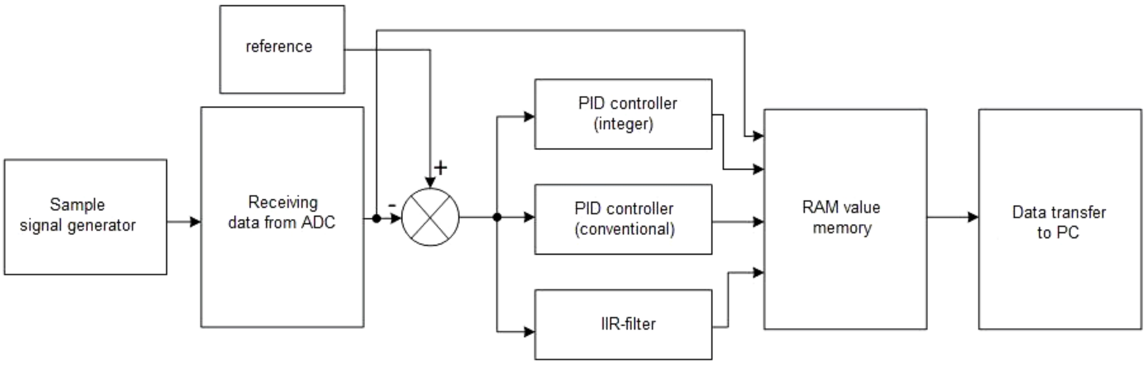


Fig. 4. Block diagrams of the program on the FPGA Cyclone IV

Рис. 4. Структурные схемы работы программы на ПЛИС Cyclone IV

*Table 1*

**Comparison table of implemented regulators**

| Parameters \ Controller | Integral controller | Standard PID-controller | IIR filter |
|---|---|---|---|
| Base frequency, MHz | 40 | 40 | 40 |
| Conversion time, ns | 350 | 1500 | 2000 |
| Number of occupied logical elements, pcs. | 1393 | 2314 | 1452 |
| The number of used DSP blocks, pcs. | 10 | 7 | 7 |

*Table 2*

**IIR filter coefficient values**

| Coefficient | Value |
|---|---|
| $a_1$ | –1 |
| $a_2$ | 0 |
| $b_0$ | 2.647745 |
| $b_1$ | –5 |
| $b_2$ | 2.354 |

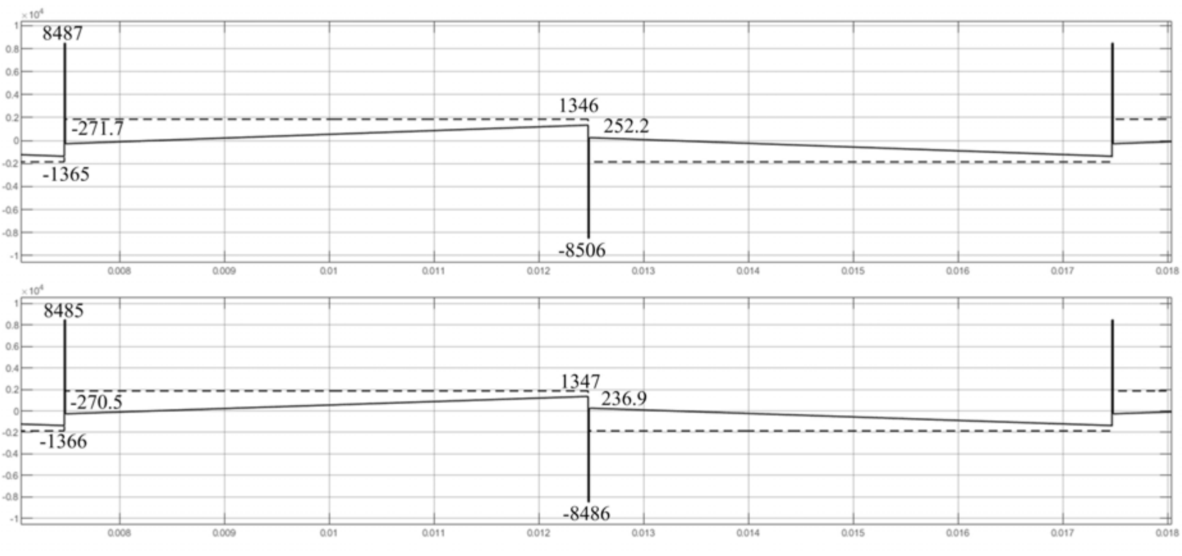


Fig. 5. Responses of the model and CCU to the impact of sequence of impulses type

Рис. 5. Отклики модели и ЦУУ на воздействие типа «последовательность импульсов»

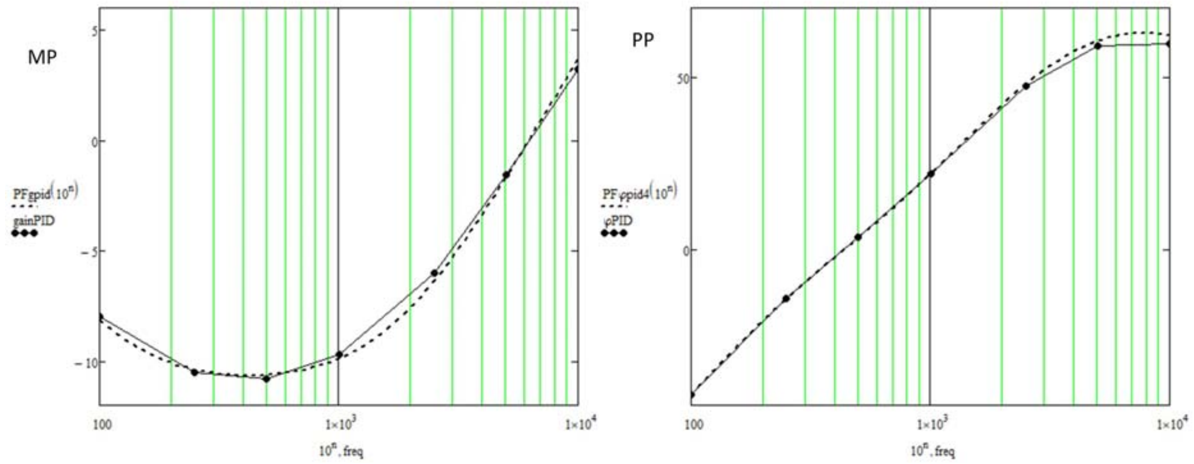


Fig. 6. Calculated from the TF filter, and obtained as a result of a full-scale experiment,
Log-magnitude and Phase diagrams

Рис. 6. Расчетные из ПФ фильтра и полученные в результате натурного эксперимента ЛАЧХ и ФЧХ

**Conclusion.** As a result of the work done, a method for determining the channel characteristics of a digital control system of a SMPS was proposed and tested, based on the comparison of control channel responses  and its model to typical disturbance signals and LAFC removal. An example of the application of such a technique for verifying the parameters of the developed PID controller is given. In the course of the study of the CCU of the IIT layout, it was confirmed that the responses to the sequence of rectangular pulses coincide, and the LAFC of the model and the physical control channel also coincided.

The proposed technique can be used to test a digital control channel of not only switched-mode power supply, but also other control objects; for testing itself any necessary disturbance signals, including non-periodic signals of a complex shape, can be used.

Introduction of this testing technique in production conditions will allow a complete check of individual control centers of power converters with closed feedbacks before the final assembly of the device and power on, which will eliminate errors in the implementation of control loop regulators, leading to undesirable non-stationary modes of operation of power converters.

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**Lopatin Aleksandr Aleksandrovich** – Cand. Sc., head of design section power supply and conversion equipment; JSC Academician M. F. Reshetnev Information Satellite Systems. E-mail: lopatin@iss-reshetnev.ru.

**Druzhinin Aleksandr Aleksandrovich** – design engineer; JSC Academician M. F. Reshetnev Information Satellite Systems. E-mail: Alex-Druzh@mail.ru.

**Asochakov Arseniy Stepanovich** – design engineer; JSC Academician M. F. Reshetnev Information Satellite Systems. E-mail: arseniy.asochakov@yandex.ru.

**Puchkov Aleksandr Vital'yevich** – design engineer; JSC Academician M. F. Reshetnev Information Satellite Systems. E-mail: puchok_95@mail.ru.

**Лопатин Александр Александрович –** кандидат технических наук, начальник сектора разработки силовой бортовой аппаратуры; АО «Информационные спутниковые системы» имени академика М. Ф. Решетнева». E-mail: lopatin@iss-reshetnev.ru.

**Дружинин Александр Александрович** – инженер-конструктор; АО «Информационные спутниковые системы» имени академика М. Ф. Решетнева». E-mail: Alex-Druzh@mail.ru.

**Асочаков Арсений Степанович** – инженер-конструктор; АО «Информационные спутниковые системы» имени академика М. Ф. Решетнева». E-mail: arseniy.asochakov@yandex.ru.

**Пучков Александр Витальевич** – инженер-конструктор; АО «Информационные спутниковые системы» имени академика М. Ф. Решетнева». E-mail: puchok_95@mail.ru.