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HIGH-EFFICIENCY DISCHARGE POWER SUPPLY FOR SPS-40 ELECTRIC PROPULSION SYSTEM

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Abstract. The structure of electric propulsion systems based on Hall thrusters includes an energy processing and control unit (PPU) that converts the electrical energy of an onboard power supply into the voltages and currents needed to operate of all the propulsion system subsystems. One of the main secondary power supplies of PPU is the discharge power supply, the parameters of which largely determine the parameters of PPU and the entire electric propulsion system. In this article, the results of the development of a high-efficiency discharge power supply for the Hall thruster ST-40, which is as component in the warehouse of the electric propulsion system SPS-40, are presented. At the discharge power supply developing, it must be taken into account that during of the Hall thruster start the big of voltage and current surges existing, that is why it's too difficult for the discharge power supply can be operated with high efficiency (93 - 95%). When choosing of the power supply principle of operation, its functional and structural scheme, it was proposed to provide stabilization of the supply output power by introducing appropriate feedbacks. The article presents the functional and structural diagrams of the discharge supply, which provides stabilization of a given value of the output power of the discharge supply. Laboratory tests of the developed discharge power supply with active load showed that the technical solutions adopted during the development process provided the possibility of stabilizing the output electric power of the supply at a given level - 200 and 400 W. The use of an electric power stabilizer as a discharge power supply for the ST-40 Hall thruster made it possible to obtain a high value of the supply efficiency (more than 93%) in a wide range of discharge voltage and current. Laboratory tests of the developed discharge supply together with the ST-40 Hall thruster showed that the thruster, after the hollow cathode temperature reaches a predetermined value, starts reliably and works stably after starting.

Keywords: electric propulsion system, Hall thruster, discharge power supply, +, Hall thruster testing

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ВИСОКОЕКОНОМІЧНЕ ДЖЕРЕЛО РОЗРЯДУ ДЛЯ ЕЛЕКТРИЧНОЇ РАКЕТНОЇ ДВИГУННОЇ УСТАНОВКИ SPS-40

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Анотація. До складу електричних ракетних двигунних установок на базі холловських двигунів входить система перетворення та управління (PPU), яка забезпечує перетворення електричної енергії бортового джерела в напруги та струми, які необхідні для роботи всіх підсистем двигунної установки. Одним з основних вторинних джерел живлення PPU є джерело електроживлення розряду, параметри якого в значній мірі визначають параметри PPU та всієї двигунної установки. В даній статті представлені результати розробки високоефективного джерела розряду для холловського двигуна ST-40, який входить до складу електричної ракетної двигунної установки SPS-40. При розробці джерела електроживлення розряду було враховано, що в процесі запуску холловського двигуна та виходу його на номінальний режим відбуваються значні стрибки розрядної напруги та струму, під час яких важко забезпечити роботу джерела з високою ефективністю (93 – 95%). При виборі принципу роботи джерела, його функціональної та структурної схеми було запропоновано забезпечити стабілізацію вихідної потужності джерела шляхом введення відповідних зворотних зв'язків. В статті представлені функціональна та структурна схеми джерела розряду, які забезпечують стабілізацію заданої величини вихідної потужності джерела розряду. Лабораторні випробування розробленого джерела розряду з активним навантаженням показали, що прийняті в процесі розробки технічні рішення забезпечили можливість стабілізації вихідної потужності джерела заданого рівня – 200 та 400 Вт. Використання в якості джерела електроживлення розряду холловськог двигуна ST-40 стабілізатора електричної потужності дозволило отримати високе значення ефективності джерела (більше 93%) в широкому діапазоні значень розрядної напруги та струму. Лабораторні випробування розробленого джерела розряду спільно з холловським двигуном ST-40 показали, що двигун після того, як температура полого катоду досягає заданої величини, надійно запускається і стабільно працює після запуску.

Ключові слова: електрична ракетна двигунна установка, холловський двигун, джерело електроживлення розряду, стабілізація потужності розряду, випробування холловського двигуна

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ВЫСОКОЭКОНОМИЧНЫЙ ИСТОЧНИК РАЗРЯДА ДЛЯ ЭЛЕКТРИЧЕСКОЙ РАКЕТНОЙ ДВИГАТЕЛЬНОЙ УСТАНОВКИ SPS-40

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Аннотация. В состав электрических ракетных двигательных установок на базе холловских двигателей входит система преобразования энергии и управления (PPU), которая обеспечивает преобразование электрической энергии бортового источника в напряжения и токи, необходимые для работы всех подсистем двигательной установки. Одним из основных вторичных источников электропитания PPU является источник электропитания разряда, параметры которого в значительной степени определяют параметры PPU и всей двигательной установки. В данной статье представлены результаты разработки высокоэффективного источника разряда для холловского двигателя ST-40, который входит в состав электрической ракетной двигательной установки SPS-40. При разработке источника электропитания разряда было учтено то, что в процессе запуска холловского двигателя и выхода его на номинальный режим происходят значительные выбросы разрядного напряжения и тока, при которых трудно обеспечить работу источника с высокой эффективностью (93 – 95%). При выборе принципа работы источника, его функциональной и структурной схемы было предложено обеспечить стабилизацию выходной мощности источника путем введения соответствующих обратных связей. В статье представлены функциональная и структурная схемы источника разряда, которые обеспечивают стабилизацию заданной величины выходной мощности источника разряда. Лабораторные испытания разработанного источника разряда с активной нагрузкой показали, что принятые в процессе разработки технические решения обеспечили возможность стабилизации выходной электрической мощности источника на заданном уровне – 200 и 400 Вт. Применение в качестве источника электропитания разряда холловского двигателя ST-40 стабилизатора электрической мощности позволило получить высокое значение эффективности источника (более 93%) в широком диапазоне значений разрядного напряжения и тока. Лабораторные испытания разработанного источника разряда совместно с холловским двигателем ST-40 показали, что двигатель после того, как температура полого катода достигает заданной величины, надежно запускается и устойчиво работает после запуска.

Ключевые слова: электрическая ракетная двигательная установка, холловский двигатель, источник электропитания разряда, стабилизация мощности разряда, испытания холловского двигателя

Introduction

The development of the electric propulsion systems (EPSs) based on the Hall thruster necessitates the development of highly efficient power supplies that are components of the power processing unit (PPU) in structure of EPS.

This unit converts the electrical energy of an on-board power source into voltages and currents that ensure the operation of all EPS subsystems. PPU consists of the following power supplies: discharge power supply, supply for the ignition electrode, power supply for electromagnets, preheating of the hollow cathode, and a source that ensures the functioning of the Xenon storage and feed system of the working substance for the Hall thruster. The PPU also includes a propulsion system control unit, which provides the receiving of EPS control signals from the spacecraft control system and the creation of control signals for all controlled secondary power supplies of the PPU.

The high requirements for mas and size characteristics, efficiency, stability and reliability of electric propulsion system on-board power supplies are existed. In some cases, the mass and dimensions of PPU are at least 40–50% of the entire electric propulsion system, and the requirements for the efficiency of power supplies exceed 93–95% [1, 2].

The discharge power supply, which is part of the PPU of a propulsion system with Hall thruster, has the maximum mass and dimensions compared to other secondary power supplies. Therefore, optimization of the discharge power supply leads to a significant improvement in the parameters of not only the PPU, but of the entire electric propulsion system as a whole.

Goals and objectives of the investigation

An actual in the design and development of the PPU of an electric propulsion system with a Hall thruster is the search for such options for constructions of a power source for the discharge circuits of the Hall thruster that ensure reliable start-up of the thruster and its stable operation in predetermined modes while ensuring high efficiency, stability and reliability values.

It's well known [1] that at the moment of the Hall thruster starting significant discharge currents occur (over 250 - 300 μs), which necessitates the use of a discharge power supply that significantly exceeds the rated mode in power. All this leads to a significant increase in the mass and dimensions of the discharge power supply for Hall thruster.

The aim of this research was to select such a structure and parameters of a secondary discharge power source for a Hall thruster, which would provide high efficiency, stability and reliability of the supply operation together with the thruster.

To achieve this goal, it was necessary to solve the following tasks:

- choose a block diagram of the discharge power supply;
- develop a functional diagram;
- make a choice of the component base, which in its characteristics and parameters corresponds to the component base for space applications;
- conduct autonomous tests of the developed discharge power supply using active load;
- conduct laboratory tests of the discharge power supply in conjunction with the Hall thruster.

The choice of structural and development of functional schemes of the supply

The main requirements for the discharge power supply for the Hall thruster are determined by the characteristics and parameters of the thruster, as well as its operating modes. From these requirements, the structural and functional diagrams of the discharge power supply follow.

The SPS-40 electric propulsion system, developed by Space Electric Thruster Systems (SETS), incorporates the ST-40 Hall thruster with a power consumption of 300 - 500 W. The appearance of ST-40 Hall thruster is shown in Fig. 1, and its main parameters are presented in Table. 1.

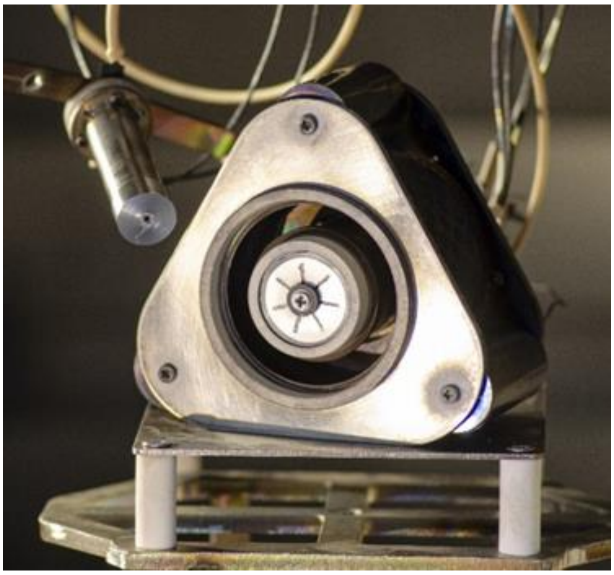

Figure 1 – ST-40 Hall thruster

Table 1

N	Thruster's parameters	Value
1	Input power, W	300 - 500
2	Discharge voltage, V	200 - 300
3	Discharge current, A	1.2 – 2.2
4	Ignition power, W	55 - 60
5	Ignition voltage, V	1200
6	Main (anode) mass flow rate, mg/s	1.3 – 2.3
7	Cathode mass flow rate, mg/s	0.1 – 0.2
8	Electromagnet current, A	1.0 – 2.1
9	Thrust, mN	14 - 35

It is known [3–4] that the start of a Hall thruster is accompanied by a significant change of the discharge voltage and current, which significantly complicates the development of a highly efficient discharge supply. In order to eliminate these disadvantages, the discharge power supply in PPU was developed as a stabilized power supply. This technical solution made it possible to ensure high efficiency of the discharge power supply (93 - 95%).

The structure diagram of the discharge power supply is shown in Fig. 2. The following notations are used in this figure: 1 - source control unit; 2 - power supply unit, providing auxiliary voltages; 3 – protection unit and defense of overheating; 4 - generator with phase regulation; 5 - output power stabilization system; 6 - system for limiting the output current and output voltage; 7 - protection unit of the power transformer to the current; 8 - rectifier bridge on field-effect transistors; 9 - power transformer; 10 - rectifier and output filter.

The developed discharge power supply is an engineering model of a flight prototype and therefore is powered by the satellite's onboard power supply equivalent to + 28 V.

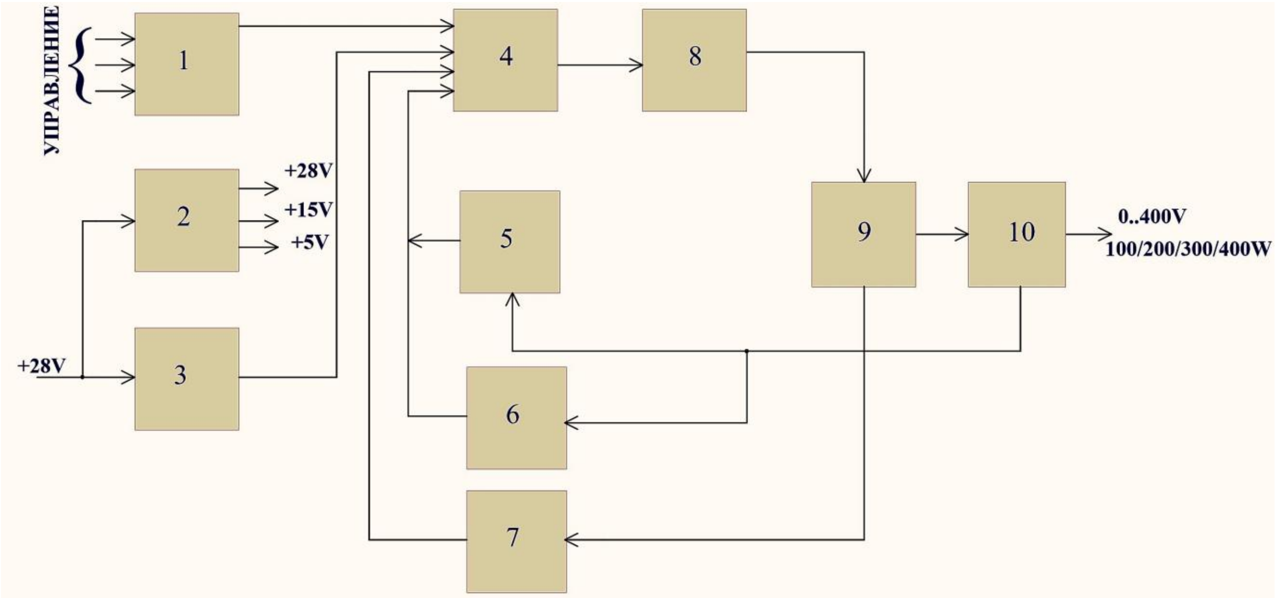

Figure 2 – Structure diagram of the discharge power supply

The developed discharge power supply provides an output voltage of 0 ... + 400 V with stabilized values of the output power, the regulation of which can be carried out smoothly, starting from 50 W.

Based on the structure diagram, a functional diagram of the source was developed, which is presented in Fig. 3.

The following notations are introduced in the presented figure:

A1 - voltage-controlled phase generator;

A2 - driver of control signals;

A3 - amplifier with a controlled gain;

A4 - power rectifier bridge;

A5, A15 - voltage filtering capacitor units;

A6 - current transformer;

A7 - power transformer;

A8 - rectifier;

A9 - output filter;

A10 - rectifier;

A11 - voltage stabilizer unit;

A12 - analog signal multiplier;

A13, A16 - amplifiers;

A14 - current / voltage converter;

A17 - voltage / voltage converter;

A18, A19 - threshold elements.

To implement the function of stabilizing the supply discharge output power, the principle of negative feedback is used with the formation of a mismatch signal by comparing the specified voltage set by the unit (A1) and the voltage obtained by multiplying the values of the output current and output voltage. Stabilization of the output power of the supply is provided by units A1, A3, A12 - A14, A16 - A19.

Converters A14, A17 generate signals proportional to the output voltage and current to stabilize the output power. Amplifiers A13, A16 are used to coordinate the received signals with an analog multiplier A12. After multiplying the signals with an analog multiplier A12, the resulting signal is put to the controlled amplifier A3, which generates a negative feedback signal.

To limit the output current and voltage, threshold elements A18, A19 are applied. The output voltage of the supply is limited to + 400 V, and the output current is 5 A.

For control of power supply the driver of control signals A2 is used, it provides for supply turn on / turn off, regulation of output power, turning off the supply at an input voltage above + 33 V or a radiator temperature above 70°C.

In the diagram presented in Fig. 3 units A11 - to form auxiliary voltages and A5, A15 - to filter the voltage of the primary power source also are used.

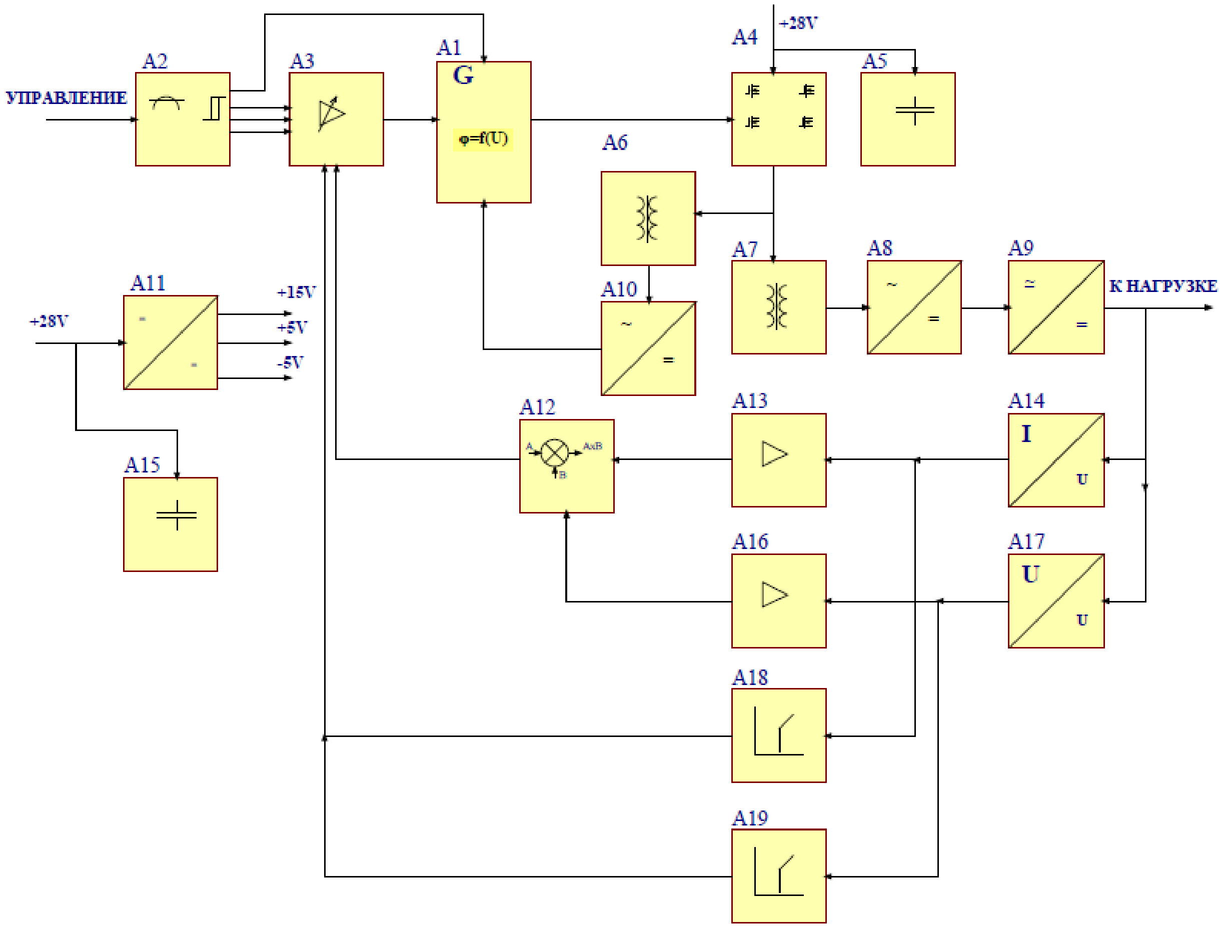

Figure 3 – Discharge power supply functional diagram

Structurally, the discharge power supply is made on a printed circuit board with dimensions of 250 x 210 mm. The power transistors of the supply have thermal contact with the radiator located on the back of the board. When developing the design of the source board, the requirements for the on-board prototype were taken into account in terms of resistance to vibration and mechanical overloading.

The developed discharge power supply was structurally included in the PPU of the SPS-40 electric propulsion system and provides electrical parameters for the discharge of the ST-40 Hall thruster, which is part of the propulsion system.

Results of the discharge power supply testing with active load

At the first stage of developed discharge power supply testing, an active load was used. These tests made it possible to obtain experimental dependences of the supply efficiency and the magnitude of the output power on the output voltage. Graphs illustrating the source's active load operation are shown in Fig. 4. Two modes of the output power stabilization of the supply - 200 and 400 W were investigated.

When stabilizing the output power of 200 W, the supply provided a given stabilization accuracy in the range of the discharge output voltage of 100 - 300 V. In this range of the output voltage, the supply showed an efficiency value in the range of 82 - 95%. Moreover, starting with an output voltage of 160 V, up to 300 V, the efficiency value does not decrease below 90%.

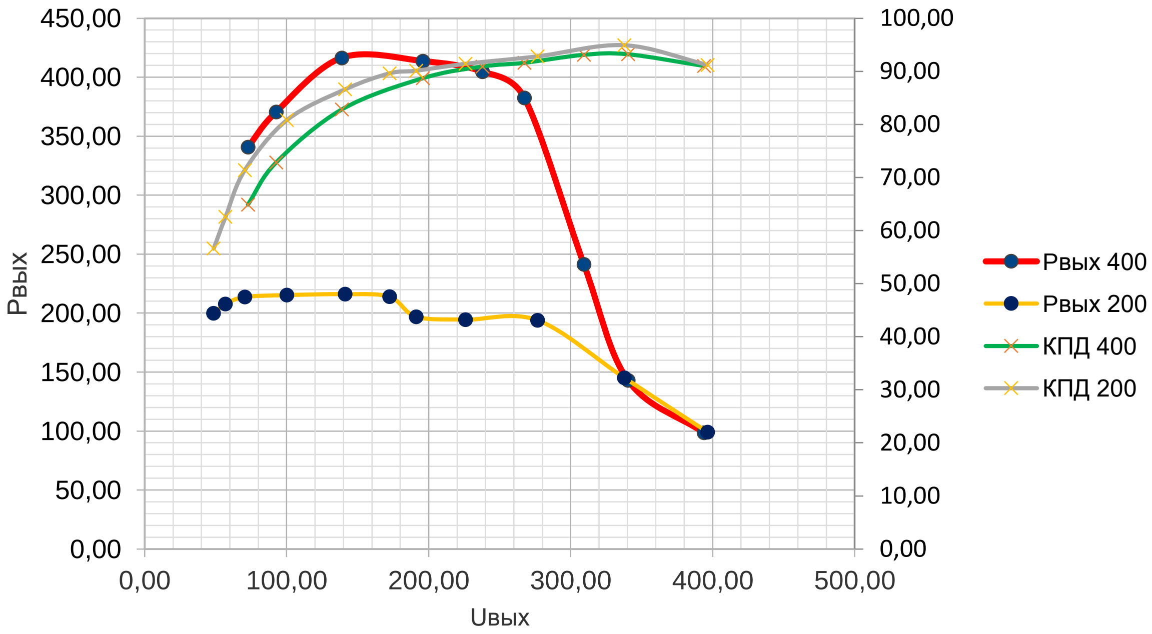

Figure 4 – Results of the discharge power supply testing with an active load

Results of designed discharge power supply testing together with ST-40 Hall thruster

At the second stage of laboratory tests of the developed discharge power supply, the Hall thruster ST-40 was used as a load, the parameters of which were presented in Table. 1.

The results of laboratory testing of the developed discharge power supply with a Hall thruster showed that the supply retains its properties and parameters that were obtained at an active load. The use of power stabilization in the developed discharge power supply led to a simplification of the Hall thruster start-up and an increase in its stable operation in stationary mode.

Graphs of changes in current and discharge voltage during the Hall thruster starting process are presented in Fig. 5. As shown in the figure, the process of the thruster starting after applying the discharge voltage takes 9 - 10 seconds, after which the thruster's parameters reach the nominal values and the thruster continues to operate stably in stationary mode.

Conclusions

As a result of design and developing the discharge power supply with stabilization of the electric power value and laboratory tests, the following conclusions can be presented:

- the use of an electric power stabilizer as a discharge power supply for the Hall thruster made it possible to obtain a high value of the supply efficiency (more than 93%) in a wide range of discharge voltage and current;

- characteristics of the discharge power supply obtained during tests with active load did not change during the operation of the discharge power supply with the Hall thruster;

- tests of the developed discharge power supply together with the ST-40 Hall thruster showed that the thruster starts reliably after the temperature of the hollow cathode reaches a predetermined value, and the thruster itself stably works after starting.

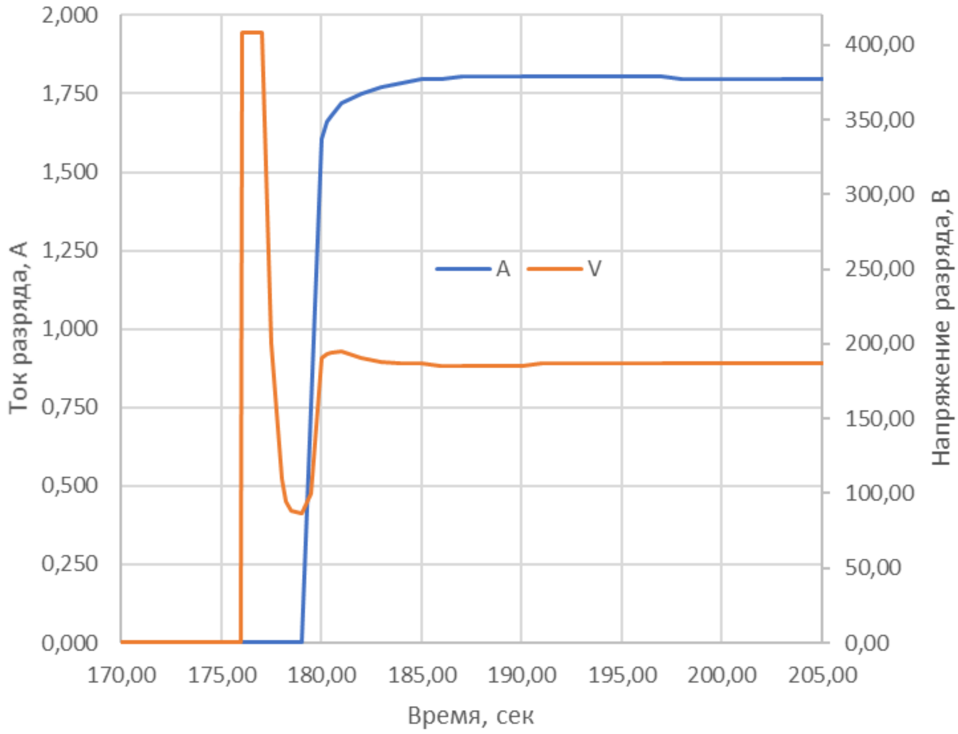

Figure 5 – Graphs of the discharge current and voltage changes in Hall thrust starting process

References

1. Gollor M. Power Processing Units - Activities in Europe 2015 [Electronic resource] / M. Gollor, A. Franke, U. Schwab, W. Dechent, G. Glorieux, M. Boss, N. Wagner, J. Palencia, P. Galatini, G. Tuccio, E. Bourguignon // Proc. Joint Conference of 30th ISTS, 34th IEPC and 6th NSAT, Kobe-Hyogo, Japan, July 4 – 10, 2015.
2. Santiago, W, Bozak, K., Piñero, L., Scheidegger, R., Gonzalez, M., Birchenough, A., Garrett, M. and Ivanov, N., "High Input Voltage, Power Processing Unit Performance Demonstration," 52nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 2016-5033, Salt Lake City, Utay, USA, July 25-27, 2016.
3. Piñero, L., Bozak, K., Santiago, W. and Scheidegger, R., "Development of High-Power Hall Thruster Power Processing Units at NASA GRC," 51st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 2015-3921, Orlando, Florida, USA, July 27-30, 2015.
4. Petrenko A.N. The problem of power processing and telemetry/control unit design for stationary plasma thruster [Electronic resource] / A.N. Petrenko, J.A. Hamley, J.M. Sankovic // Processing of the 24th International Electric Propulsion Conference, IEPC-95-126, Moscow, Russia, September 19-23, 1995.
5. Kamhawi, H., Huang, W., Haag, T., Yim, J., Herman, D., Peterson, P., Williams, G., Gilland, J., Hofer, R. and Mikellides, I., "Performance, Facility Pressure Effects, and Stability Characterization Tests of NASA's Hall Effect Rocket with Magnetic Shielding Thruster," 52st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 2016-4826, Salt Lake City, Utah, USA, July 25-27, 2016.

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