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Electric propulsion system SPS-25 with Hall Thruster

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Abstract

The electric propulsion system SPS-25, designed by Space Electric Thruster Systems (SETS) is presented. The system has 150 – 250 W input power, and consists of: Hall thruster ST-25; Xenon storage and feed system (XFS) and Power processing unit (PPU). At the referenced input power (150 – 250 W) ST-25 provides a thrust 5 – 11 mN, specific impulse up to1200 s and efficiency in the range 26 – 32%. The feature of the ST-25 structure is that in order to reduce of electric power for the formation of a radial magnet field in the acceleration channel, a permanent magnet in the central magnet pole was used. Xenon storage and feed system consists of the tank from polymeric composition materials for storage of working substance, providing storage of Xenon at pressure 150 bar; high-pressure unit, that provides the decline of pressure in an accumulator tank to the level 1.0-1.2 bar and the low-pressure unit, that provides the feed of working substance from the accumulator tank to the anode unit and hollow cathodes with the set level of mass flow rates. For the structure of the storage and feed system of working substance, the SETS Company have designed the valves of high (up to 200 bar) and low pressure (up to 5 bar). For providing of the set mass flow rate of working substance to the anode and hollow cathode by a company SETS corresponding flow restrictor were developed. The Power processing unit consists of a few independent sources of power supply: the discharge power supply for the anode unit; the source of current for electromagnets of the thruster; source of current of hollow cathode heater; source of voltage for the feed system. The Power processing unit contains also the control unit of the propulsion system that gets on-off commands for propulsion system, provides work of the propulsion system and forms the telemetry signals about subsystems status of the propulsion system and signals transmission to control system.

Keywords: Electric propulsion system, Hall thruster, magnet system with permanent magnet, Xenon storage and feed subsystem, power-processing unit

1. Introduction

One of the modern trends in the development of space technology is the reduction in the mass of spacecraft and, accordingly, the decrease in electric power on board. This implies the task of creating electric propulsion systems with the relatively small (200 - 300 W) electric power. For create the electric propulsion thruster with the input power 150-200 watts, SETS suggested using a permanent magnet as part of the Hall's magnetic system. As a result, the ST-25 Hall thruster was developed, which became part of the SPS-25 electric propulsion system.

Electric thruster system SPS-25 consists of following subsystems:

- Hall thruster ST-25 with input power 100 – 200 W;
- Xenon storage and feed subsystem (XFS), ensures the mass flow rate feeding and control to anode and cathodes of the thruster;
- Power processing unit (PPU), ensures the transform of onboard power supply energy to voltages and currents, which are needs for the electric propulsion subsystems operating.

2. ST-25 Hall Thruster

Specific of the ST-25 structure (Fig. 1) is that in order to reduce the cost of electric energy for the formation of a radial magnetic field in the accelerating channel of the thruster in the area of the central magnetic circuit, a permanent magnet is used [1, 3].

The permanent magnet is fabricated from material SmCo (YXG32M), Curie point of it is 650 – 700°C, that is why such permanent magnet can be used at operating temperature about 350°C. As the external electromagnets, four of the traditional electromagnets were used. Direct referenced current is passed through electromagnets from separate direct current power supply. The main ST-25 parameters are presented in Tab. 1.

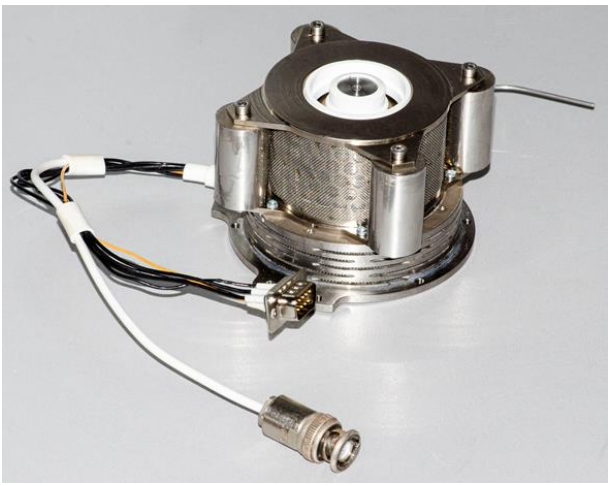

Fig. 1. ST-25 Hall thruster (without cathode)

Table 1. ST-25 Hall thruster parameters

Parameters	Values
Working substance	Xenon
Cathode	Preheated Hollow Cathode
Discharge Power, W	100 – 200
Thrust, mN	5 – 11 (depends from input power)
Specific impulse, s	Up to 1200
Anode mass flow rate, mg/s	0.70 -1.00
Cathode mass flow rate, mg/s	0.08
Power for electromagnets, W	5
Power for cathode pre-heating	50
Efficiency, %	Up to 30
Mass of the thruster, g	750
Dimensions, mm	139x92.5x78
Life-time, hours (estimated)	No less 3000

3. ST-25 Thruster laboratory testing

Laboratory testing of ST-25 executed by two ways. At the first stage, ST-25 was tested with the laboratory discharge voltage power supply. Dependences of the thrust from discharge voltage, discharge power and specific impulse from discharge voltage were obtained. The values of anode mass flow rate in a range 0.5 – 0.9 mg/s with step 0.1 mg/s were used.

At the second stage ST-25 was tested with the discharge power supply in structure PPU. Specific of this discharge power supply that this power supply has characteristics as source of power.

3.1 Results of ST-25 testing with laboratory discharge voltage power supply

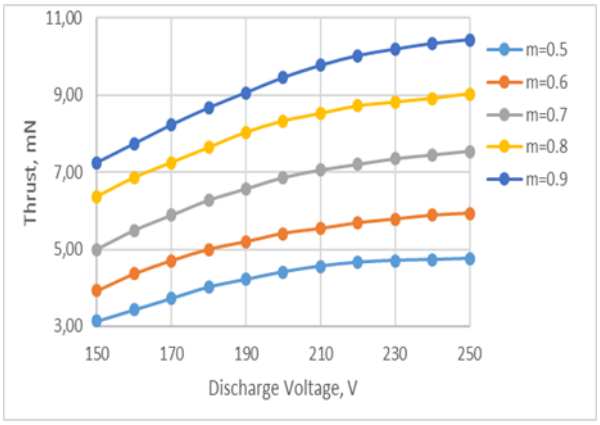

Fig. 2. Dependence of thrust on discharge voltage (Lab Discharge Supply)

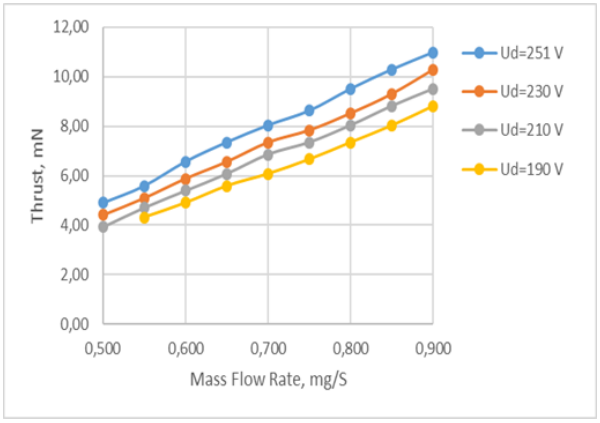

Fig. 3. Dependence of thrust on mass flow rate (Lab Discharge Supply)

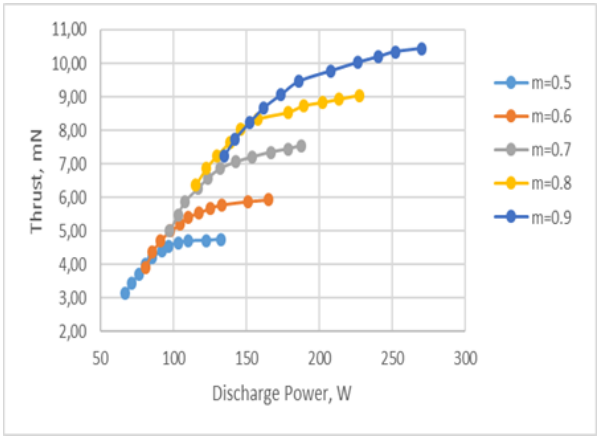

Fig. 4. Dependence of thrust on discharge power (Lab Discharge Supply)

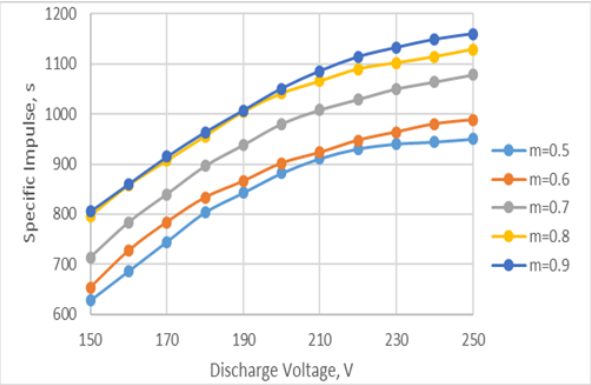

Fig. 5. Dependence of specific impulse on discharge voltage (Lab Discharge Supply)

3.2 Results of ST-25 testing with PPU discharge power supply

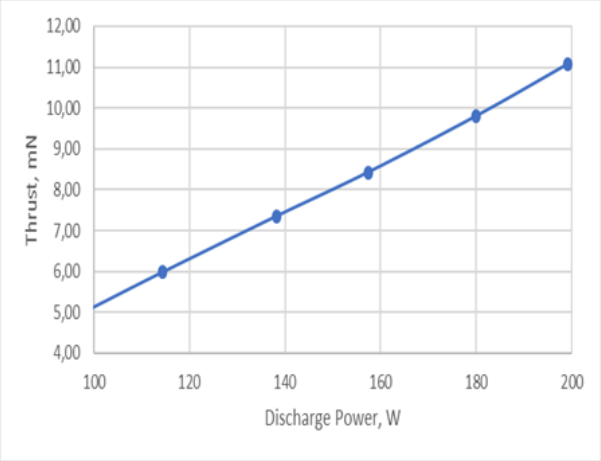

Fig. 6. Dependence of thrust on discharge power (PPU Discharge Power Supply)

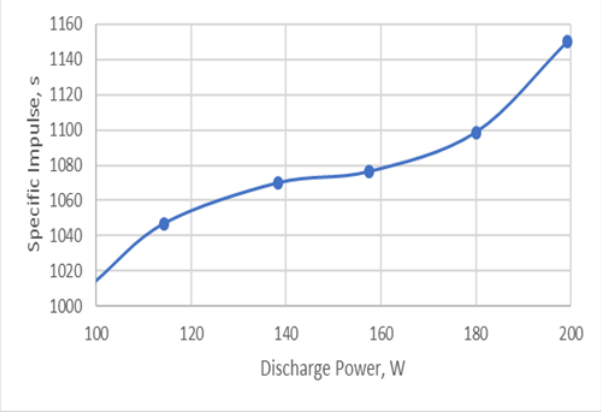

Fig. 7. Dependence of specific impulse on discharge power (PPU Discharge Power Supply)

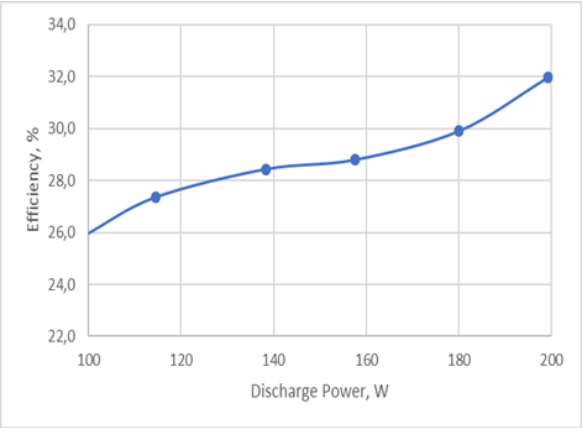

Fig. 8. Dependence of efficiency on discharge power (PPU Discharge Power Supply)

3.3 Results of the ST-25 thrust vector deviation measurement

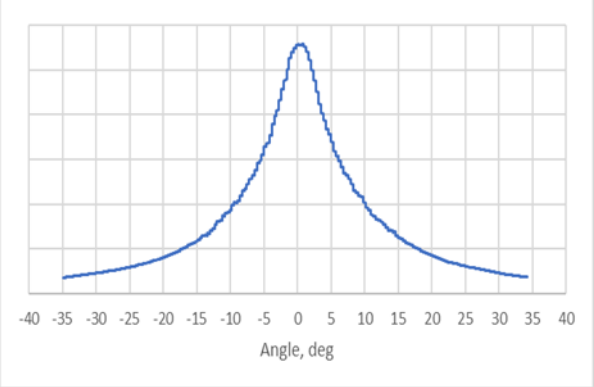

Fig. 9. ST-25 thrust vector deviation

4. Xenon storage and feed subsystem

Fig. 10. Xenon storage and feed subsystem

The Xenon storage and feed system (Fig. 10) contains a tank from polymer composite materials that provides storage of Xenon at a pressure of 150 -160 bar

(not shown in the figure); High pressure part, which reduces the pressure in the accumulator tank to 1 ± 3% bar and the Low pressure part, which supplies the working gas from the accumulator tank to the anode and hollow cathodes of the thruster with a referenced flow rates.

The structure scheme of XFS for the propulsion system with one ST-25 thruster application presented in Fig. 11.

At design of the Xenon feed system, SETS developed, high (up to 200 bar) and low (up to 25 bar) pressure valves, which have actuations number more than 1 million. For pressure measurement at referenced points of the XFS, the pressure transducers with high accuracy of pressure measurements were used - PHE867 (L'essor Francais Electronoque).

For ensure a predetermined the mass flow rates of the working substance to the anode unit and the hollow

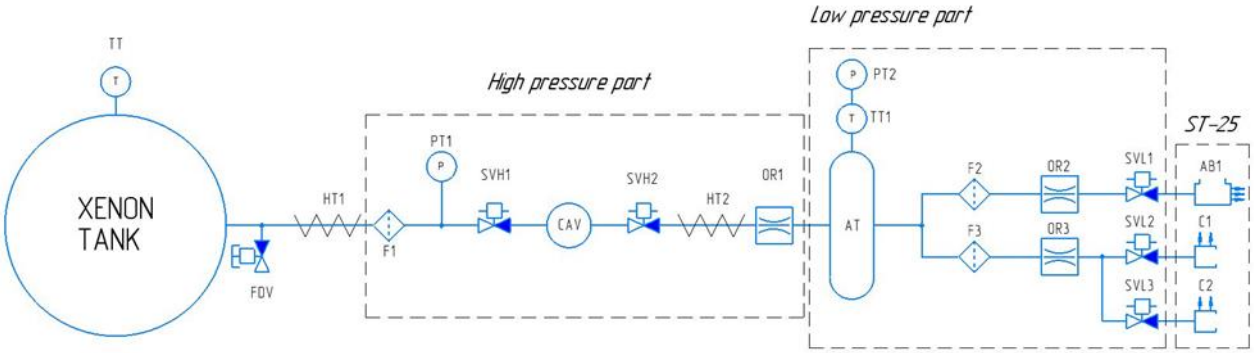

Fig. 11. Xenon feed system structure

In Fig. 11 presented following abbreviations:
TT, TT1 – Temperature Transducers.
HT1 – Heater.
FDV – Fill and Drain Valve.

High-pressure unit

High-pressure unit (HPU) is designed to reduce the pressure of the working substance in the AT to a working pressure of 1…2 bar. HPU includes the following elements:
PT1 – Pressure Transducer.
F1 – Filter.
SVH1, SVH2 – High Pressure Solenoid Valves.
CAV – Cavity,
HT2 – Heater.
OR1 – Flow Restrictor.

Low-pressure unit

Low-pressure unit (LPU) has an inlet pressure of 1...2 bar, provides mass flow to the anode unit and cathodes. The LPU includes the following elements:
AT – Accumulator Tank.
TT1 – Temperature Transducer.
PT2 – Pressure Transducer.
F2...F3 – Filters.
OR2...OR3 – Flow Restrictors.
SVL1...SVL3 – Low Pressure Solenoid Valves.

ST-25 – Hall-effect thruster

AB1 – Anode unit.
C1, C2 – Cathodes.

The accuracy of setting the mass flow rates of the working gas is set by stabilizing the pressure in the receiver-tank and is ± 3%.

The main technical parameters of designed XFS are presented in Tab. 2.

Table 2. Xenon Feed System specification

Parameters	Values
Working substance	GXe, GAr, GKr
Maximum storage pressure, bar	150
Pressure in accumulator tank, bar	1 ±3%
Anode flow rate, mg/s	0 to 10 ±3%
Cathode flow rate, mg/s	0 to 1 ±3%
Pressure transducer's accuracy, %	±0.35%
Pressure transducer's accuracy, %	±1%
External leakage, sccs of GHe	$<1\times10^{-6}$
Internal leakage, sccs of GHe	$<1\times10^{-3}$
Inlet filter rating, μm filtration	≤ 4
Mass (without tank), g	≤ 950
Dimensions, mm	105x100x100
Operational temperature range, ºC	0 to +40
Non-operating temperature range, ºC	-20 to +65

5. Power Processing Unit

The Power-processing unit of the propulsion system provides on-board electrical energy conversion and

consists of independent power sources: the power source of the thruster discharge circuits; a current source of coils of electromagnets of the anode unit; the hollow cathode heater current source; voltage source for supplying the components of the XFS.

The power-processing unit also contains a control unit for control of the propulsion system, which receives commands to turn the propulsion system on and off, provides operation of the propulsion system and generates telemetry signals about the current state of the propulsion system subsystems and transmits these signals to the spacecraft control system [2, 4, 5].

The universal PPU structure diagram, which provides the operation of one or two ST-25 thrusters and one ST-40 thruster developed by SETS, shown in Fig. 12.

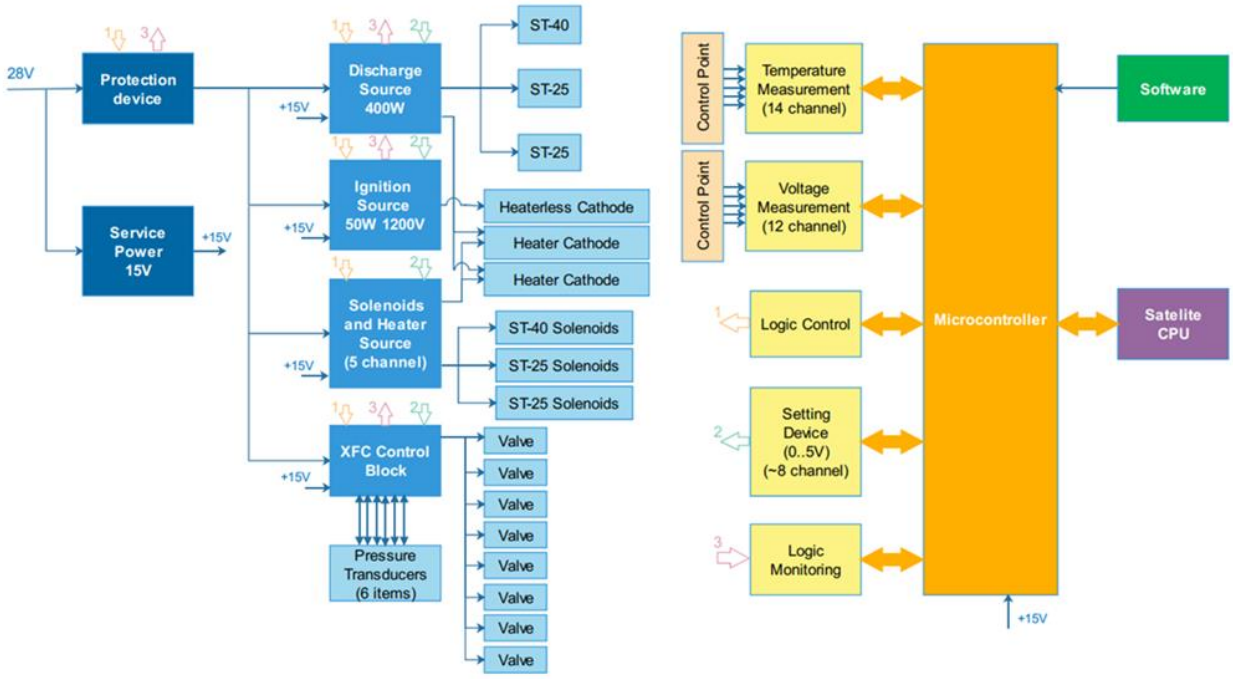

Fig. 12. Universal Power-processing Unit structure

Power Processing Unit designed by SETS intended for operation with a spacecraft on-board power supply at output voltage in a range + 20…36 V. Maximum input power for PPU is 400 W.

Power Processing Unit consists of following power supplies:

5.1. Discharge Power Supply:

- Maximum output power – 300 W;
- Discharge voltage – 150…400 V;
- It's possible changing limited output power from 150 to 300 W by step 50 W.

5.2. Ignition Power Supply for heater less hollow cathode ignition:

- Maximum output power – 50 W;
- Ignition voltage – 150…1200 V.

5.3. Power Supply for 3 electromagnets of Hall-effect thrusters and 2 hollow cathodes heaters:

3 channels of supply electromagnets of Hall thrusters:

- Maximum output voltage – 15 V;
- Maximum output current – 5,0 A;
- insures control and stabilization of output current.

2 channels of supply hollow cathodes heaters:

- Maximum output voltage – 15 V;
- Maximum output current – 3,0 A;
- insures control and stabilization of output current.

5.4. Power Supply for control of 8 valves of Feed System of working substance:

- Voltage – 12 V (switch on of valves); 7 V (keeping of valves);
- Maximum current – 0,5 A (for high-pressure valves);
- Maximum current – 0,2 A (for low-pressure valves).

Efficiency of electric power transformation PPU (at maximum input power) – not less 95%.

Power Processing Unit includes following logical units:

5.5. XFC control unit:

- Provides control of the valves of the working substance supply system. Also contains normalizing

amplifiers for pressure sensors (6 pcs.) and a power source for pressure sensors - 15V.

- A two-stage voltage supply is used for control the valves. First, the valve starting voltage (12 V), then the holding voltage (7 V).
- To form voltages for valve control, the unit contains pulse converters for 12 and 7 V.
- Each valve control channel (8 pcs.);
- Commands to turn valves on and off the Microcontroller will sent through the Logic Control unit.

5.6. Temperature Measurement Unit:

- It includes 16-bit ADC.
- Two types of sensors used to measure temperature - K-type thermocouple and a platinum thermistor;
- Thermocouples measure the temperature of the thrusters (2 channels) and cathodes (2 channels), and the thermistors measure the temperature of the cold junction of thermocouples (3 channels), the temperature of the PPU (3 channels), and the temperature of the feed system (2 channels);
- All channels provided with overvoltage protection.

5.7. Voltage Measurement Unit:

- This unit made with the same ADC as the Temperature Measurement Unit.
- It used to measure operating voltages (4 channels) and currents (8 channels) in PPU nodes;
- All measured voltages and currents in PPU with the help of normalizing amplifiers are reduced to the range of 0…5 V;
- All channels provided with overvoltage protection.

5.8. Logic Control Unit:

- Logical control signals generated for PPU nodes.
- These signals provide switching on and off nodes (sources of voltages and currents), modes switching of nodes operation (Discharge Source) and control of the supply system;
- The outputs of the formers have an open collector and protected from overvoltage.

5.9. Setting Device Unit:

- This unit is used for generate analog control signals to set the output power, voltages and currents at the PPU nodes;
- Control signals are generated with a range of 0…5 V;
- Formers convert PWM (Pulse-Width Modulation) signals (16 bits) to voltage, and then voltage reduced to the required range by normalizing amplifiers;
- Total 8 channels are used. All outputs provided with overvoltage protection.

5.10. Logic Monitoring Unit:

- It used by Microcontroller to receive logical signals of the state of PPU nodes including emergency;
- The inputs of the unit designed for connecting open collector outputs. Total 19 inputs used;
- All inputs protected against overvoltage.

As showed on Fig. 12, in structure PPU the microcontroller is included. This component of PPU ensures communication between PPU and on-board subsystems of spacecraft, setting and control of the propulsion system regimes of operation, measurement of the propulsion system parameters for creation of the control signals and telemetry signals.

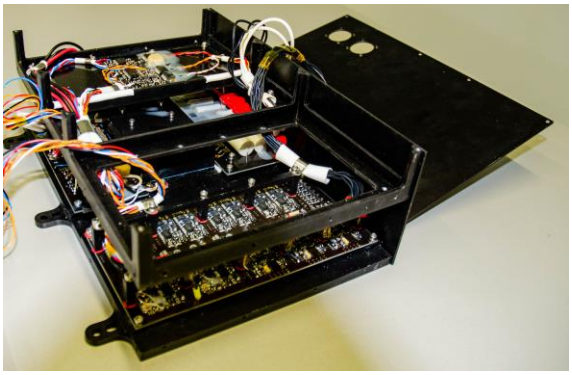

Fig. 13. Universal Power-processing Unit PPU-400

6. Discussion

Design and development of the electrical propulsion system SPS-25 has confirmed the effectiveness of the use of a permanent magnet in magnetic systems of low-power Hall thrusters in order to reduce energy costs for the formation of a magnetic field in the accelerator channel.

The power processing unit uses a discharge power supply, which has the properties of a power stabilizer. The use of such a discharge power supply ensured reliable thruster start and its stable operation.

6. Conclusions

As a result of the development of the ST-25 Hall thruster, Xenon storage and feed system, and an Power processing unit and control system, it was possible to create a prototype of an electric propulsion system SPS-25 that can be used to solve specific space tasks.

Acknowledgements

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