Design and Manufacturing of Control Unit for low and medium power Hall Effect Thruster.

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Abstract: Plasma rocket thrusters based on the Hall Effect are actively used as sustainer, side and orbit-correcting thrusters on geostationary satellites. Maintaining the engine operating point, monitoring the status and processing commands from the flight computer is performed by the control and telemetry unit. The purpose of this article is to describe the general way to designing a Control System for small and medium-sized thrusters with TID up to 100krad, highlights some of the problem of component selection, redundancy, grounding strategy, and power system configuration are considered. Special attention is paid to development of a subsystem maintaining the operating point of a HET[4]. An attempt to improve the operational parameters and reduce the cost of the finished system required an integral approach to design. As a result of which thruster control system was combined with telemetry module and Xenon Feeding Unit system control module, monitoring aids of integrity of modules are added, the subsystems were reserved. Research is carried out as part of the TURKSAT6A project [1] . Integration with power supply system, testing and qualification of control system components is planned to be completed by the end of 2019 [2][3].

Nomenclature

TUBITAK	=	The Scientific and Technological Research Council of Turkey
UZAY	=	Space Technologies Research Institute
HALE	=	Hall Effect Propulsion System Development Project
HET	=	Hall Effect Thruster
XFU	=	Xenon Feed Unit
PPCU	=	Power Processing and Control Unit
TURKSAT 6A	=	The first indigenous GEO satellite of Turkey
FC	=	Flight Computer
GEO	=	Geostationary Equatorial Orbit
LEO	=	Low Earth Orbit
TT	=	Technical Task
PWM	=	Pulse Width Modulation

I. Introduction

The development of the satellite propulsion platform control system begins with the overall description - the technical task (TT). The analysis of which allows to describe the initial source data for the subsystems included in the platform. The scope of TT is determined by the customer and can be specified based on technical capabilities

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and expediency. The platform for the HET thruster includes the following components: HET thruster, cathode unit [8], Xenon Feeding Unit (XFU), Power Processing Unit (PPU) [5], control and monitoring unit. This article attempts to systematize the process of developing a control and monitoring system, as well as to unify the design process for low and medium power HET platforms. The obtained material can be considered as a design technique for more advanced control systems with improved characteristics and increased reliability.

II. Control Unit design

The design of the control system consists in determining the formal qualities of the constituent elements, creating structural and functional links based on the analysis of the task in order to obtain a given functional. In the following presentation, design elements will be considered one by one and a synthesis of the project will be performed.

A. Technical task analysis

Baseline data for the development of Control Unit can be the characteristics of the thruster and the satellite power bus parameters. This can be considered the main input and output parameters. The baseline data for the development of platforms for HET of small and medium power are shown in Table 1.

Table 1. Baseline data for development platform.

System type	1500W	300W
HET power	1.35…1.5 kW	300W
Thruster Discharge Voltage	300V	250V
Thruster Discharge Current	3.5A…5A	0.8A
Thrust	70-80mN	13mH
Specific Impulse	1500-1680 s	1000 s
FC interface type	MIL-STD-1553B	CAN
Input bus Voltage	100V	28V
Input bus Current	15A	15A
TID	100 krad	-

Technical specifications are supplemented by time constraints. TT determine the lifetime on orbit. In the case of designing a control system, it transforms into a more usable form - the probability of fault-free work. The in-orbit lifetime for medium-power platforms is 10–25 years, small-power 7–10 years. Probability of fault-free work for Control Unit is normalized at the level of 0.958-0.992.

The electronic components of the platform are temperature sensitive. To evaluate the operating temperature range, a thermal analysis is performed. As a result of which there is an additional criterion for choosing the components of the HET Control Unit - the range of operating temperatures of each component. For systems operating in a GEO, this parameter is informative, since the components used are Military or Space grade, which have an operating temperature range of -55ºC...+ 125ºC. The range of operating temperatures is more important for the LEO platforms, since it becomes possible to use components that have an Industrial grade. This leads to a significant reduction in the cost of the platform and improvement of its technical characteristics.

B. Interfaces

From the point of view of PPCU, there are two types of interfaces: internal and external. Internal are used to transfer control information and telemetry data between platform units. External are used for communication between the PPCU and the FC. By the type of transmitted data, the interfaces can be divided into: analog and digital (discrete). Data is transmitted via analog interfaces by setting an arbitrary voltage or current level in a given range; in a discrete interface, information is encoded by two voltage or current levels - high and low. Digital interfaces are divided into serial and parallel. The main difference is the amount of data transferred per unit of time. The main advantages of analog interfaces are their simplicity and a wide range of transmitted values, high data rate, and high resolution. As disadvantages, high sensitivity to interference and low stability over time can be noted. Discrete interfaces are devoid of these disadvantages, however, they have their own, in particular limited resolution, lower data transfer rate, the need to use expensive FPGA's or DSP for data processing.

The following types of interfaces are most suitable for communication between the FC and PPCU: MIL1553, MIL1773, ARNIC429, SpaceWire. Each of them has high reliability, noise immunity. The possibility of redundancy is provided by the interface. As internal interfaces, it is advisable to use simpler CAN, RS422, RS485, as well as analog and discrete lines.

C. Control object structure

To design a control system, it is necessary to determine the structure of control objects, their quantity and parameters[1][7]. Also, make a classification in order to unify objects for platforms of low and medium power.

Control objects for HET control system are:

1) XFU valves that can be of the MEMS type or of the electromagnetic type [6]. These types of components are discrete type. The design of the selected valves may include feedback sensors to control actuation. The presence of these sensors simplifies the control system, since it does not require the analysis unit of valve response by indirect indications as part of the software. As indirect indicators of operation, it is possible to use pressure sensors, usually having an analog output. The selected valves are electromagnetic and have a coil resistance of 178 Ohms for the latch valve and 195 Ohms for isolating valve at a supply voltage of 24-28V.
2) Flow rate controllers. It controls the flow of xenon into the anode unit and the cathode unit. Flow controllers can be considered as analog devices, however, from the point of view of a control system, they can be discrete (PWM) or fully digital if they contain control electronics with a digital interface. The selected flow controller has a supply voltage of 28V and a power consumption of up to 10W. Flow restrictors for the cathode unit have a supply voltage of 28V and power consumption up to 5W.
3) Power Processing Unit. In order to simplify the propulsion platform, a change in the operating point of the thruster is not provided. This allows using only a discrete type of PPU control. An indicator of the operation and integrity of the power supplies is the output voltage and output current when the load is connected. It is convenient to transfer these data to the control system in analog form. It is convenient to use discrete interfaces to control power supplies.
4) Heaters. They are analog executive devices; however, a discrete interface for PWM implementation can be used for control. As feedback, signals and temperature sensors are used, forming a point of temperature control. XFU have several heaters, the power consumption of each of them does not exceed 10W.

The quantity and type of control objects is selected from the design requirements of the propulsion platform[1][7].

D. Block diagram of Control Unit

To build a block diagram of the Control Unit, need to select the list of the desired components of the final system. From the point of view of the functionality of the control system, all components can be divided into two groups: minimally sufficient, without which the functioning of the HET is not possible, and additional, which improve the operational characteristics and functionality of the final system.

The <u>minimum list</u> of Control Unit components required for HET control:

1) Flow control unit. This unit should provide xenon flow regulator control. This unit should provide a given level of xenon flow supplied to the anode and cathodes. Depending on the type of flow controller used, either a discrete output in PWM mode or a digital parameter setting via a digital interface is used. To maintain at a given level of xenon flow in the cathode unit, a flow restrictors is used, which is a heater with temperature feedback from the point of view of the control system. The control function is to maintain a stable temperature of the flow restrictors. As the operating temperature, a value is selected that exceeds the maximum operating temperature of the XFU obtained as a result of the initial thermal analysis of the platform.
2) Power Processing control unit. The unit performs switching of the power sources necessary for the operation of the HET thruster according to the specified algorithm, ensuring the correct and timely switching on and off of the power supplies in the process of HET control. Also, the blocking of forbidden combinations is carried out and the output of the power supplies parameters from the operating modes is controlled. In case of emergency, the module

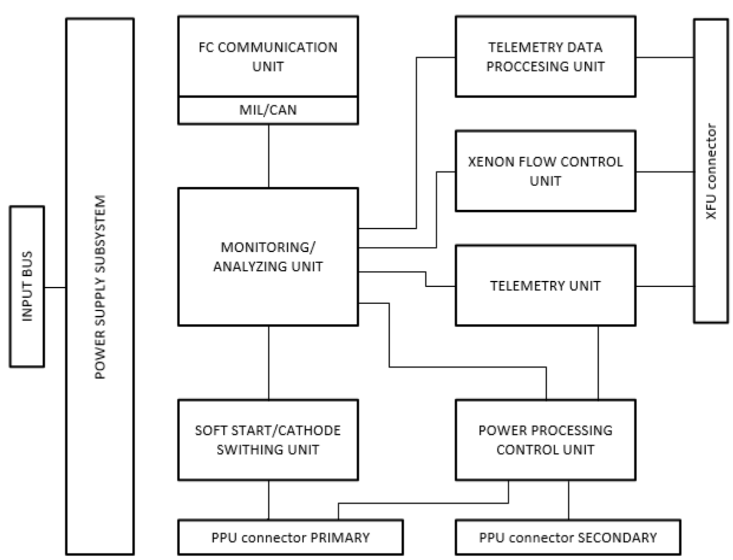

Figure 1. Control Unit block diagram

must provide an appropriate indication.

3) FC communication unit. The module decrypts the commands coming from the FC, their execution and the transfer of information about the status and integrity of the platform and its elements.

The extended list. The implementation of these units in the control system allows expanding the functionality of the propulsion system, reduces its dependence on FC software, simplifies the interface with the satellite:

4) Telemetry data collection and processing unit. The task of this unit is to collect and analyze the parameters of the HET platform and transmit extended information to the FC about the integrity of the units, the operating modes of the thruster. The unit helps the ground station in deciding on the need to use backup systems, and also collects primary data for further work on improving the propulsion system.
5) Soft start control unit. The unit is an extension of the Power Processing control unit. Turning on the Power Processing unit begins with the charge of the capacitors and causes a short surge of current of large amplitude, which can negatively affect the satellite's on-board network. To reduce stress loads, a system for limiting the charge current of filtering capacitors is used. Charging parameters can be changed by this unit.
6) Cathode switching unit. The use of this unit allows extending the life of cesium cathodes due to the periodic activation of the cathode, which is in cold reserve. An equally important function is the indication of cathode integrity for the analysis and control module.
7) Unit for monitoring and analyzing the integrity of platform components and switching to backup systems. This unit collects and analyzes information from the previous units in order to adjust the control algorithm and inform the FC about emergency situations.

The overall dimensions of the systems and the implemented high integration of nodes made it possible to realize the full functionality of the system. The block diagram of the obtained Control Unit is shown in Figure 1.

E. Redundancy

To ensure a high failure-free operation throughout the entire life of the satellite, it is necessary to use special methods to increase reliability. One of the most effective measures is the use of system redundancy. On platforms running on GEO, the issue of reliability is most relevant due to the presence of ionizing radiation. From the design point of view, this means the need to place an excessive number of units in the project. Triple modular redundancy (TMR) has very high reliability indexes. However, along with high reliability indexes, the implementation of TMR under the conditions of using the Military and Space components also has a high cost. To reduce which it is advisable to use the backup of only the most important parts of the circuit. For example, the indicator "PPCU case temperature" is not involved in the process of controlling the operation of the HET, and a simplified implementation of the measurement channel for this parameter is acceptable. In turn, the parameter "FR temperature" is much more critical and it is recommended to use more than one sensor in the thermal monitoring system of this unit.

F. Transition from platform TT to control system TT.

Having all of the above information, it is possible to formulate primary data for the design of the HET control system. Table 2 indicates the minimum number of output and output interfaces of the control system for HET low and medium power. The interface type of the monitored parameter is also described.

Table 2. Technical task for Control Unit.

Parameter	Output	Input
Latch valve interface	4 (discrete)	-
Isolation valve interface	3 (discrete)	-
Flow restrictor interface	2 (discrete)	2 (analog)
Pressure measurement interface	-	3 (analog)
Pressure regulator Heater	1 (discrete)	1 (analog)
Xenon Flow Controller*	1 (discrete)	3 (analog)
Thruster Discharge Voltage	-	1 (analog)
Thruster Discharge Current	-	1 (analog)
Cathode Voltage	-	1 (analog), 1 (discrete)
Cathode current	-	1 (analog)
Supply voltage	-	1 (analog)
Supply current	-	1 (analog)
Coil voltage	-	1 (analog)
Coil current	-	1 (analog)

* Xenon flow controller is used in analog control mode.

Analog channels can be divided into 4 groups: measurement of pressure, current, voltage and temperature. Temperature channels are divided into high-temperature (-60 ... 600 C) and low-temperature (-40 ... + 125). The use of high-temperature channels is necessary to control the temperature of the anode unit, which is significantly higher than the operating temperature of the remaining units.

General requirements for two systems: presence of RS422 interface for internal communication and FPGA for the implementation of the control functions. It is also necessary to provide for FPGA power supply systems, clocking and reset circuits. According to the terms of reference, the XFU for low power HET and medium power HET systems has the same structural diagram [6]. This is due to the desire for unification.

Different for the two systems will be: the communication interface with the FC (MIL-STD-1553B for the medium power system and CAN for the low power system), the presence of the ON/OFF interface (in the case of the low-power system it is not provided for by TT), the input bus voltage (100V and 28V). The difference in the measuring ranges (for example, Thruster Discharge voltage) is compensated by the design of the normalization circuit of the input analog parameters.

In order to unify discrete outputs, an implementation using the same type of circuit solutions is proposed. Measurement of analog parameters is performed using signal normalization schemes and digitalization using ADCs.

G. Power supply subsystem for Control Unit, structure, parameters

The power supply provides stable voltage to the components included in the control unit. Its design begins with the selection of the number and levels of supply voltage. To supply FPGA, sources with an output voltage of 1.5V are needed to power the core and 3.3V to supply input and output FPGA buffers. The choice of 3.3V level is due to the ease of connection with external (for FPGA) devices. The power level of analog circuits is determined based on the choice of available op amps. For example, we can choose the level +5V. The selection of a unipolar source simplifies the selection and purchase of a DC/DC converter in the future. Since the structure of the measuring part of Control Unit implies measuring the input and output characteristics of an isolated power source, for normal operation, two +5V sources isolated from each other are necessary. A +24V power supply is also needed to power the XFU parts. To reduce the design time, it was decided to use the mass-produced DC/DC converters.

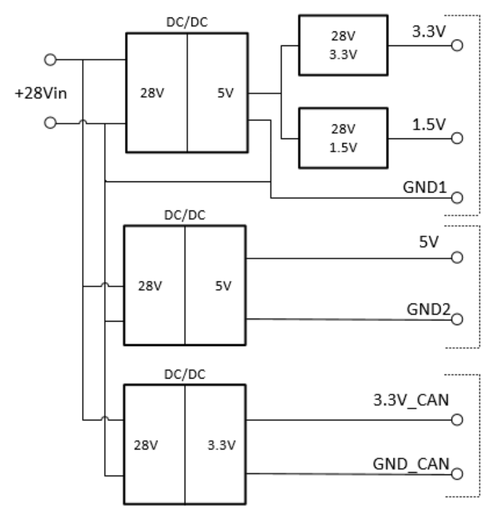

Figure 2. Power subsystem for low power HET

Further analysis of the base line data and the desire for unification of circuit solutions leads to the separation of the 100V to 28V converter for systems powered by 100V buses with a power of 40-80W necessary for powering XFU devices. For systems powered by a 28V bus, a +24V power supply is not required and the XFU components can be powered directly from the input bus. A preliminary analysis of the current consumption led to the creation of a block diagram of the power sources for low-power control systems (Figure 2) and for medium-power HET control systems (Figure 3). The main difference between them is the use of an additional low-power DC/DC converter for powering external interface circuits (CAN), which, according to TT, must have galvanic isolation from the control

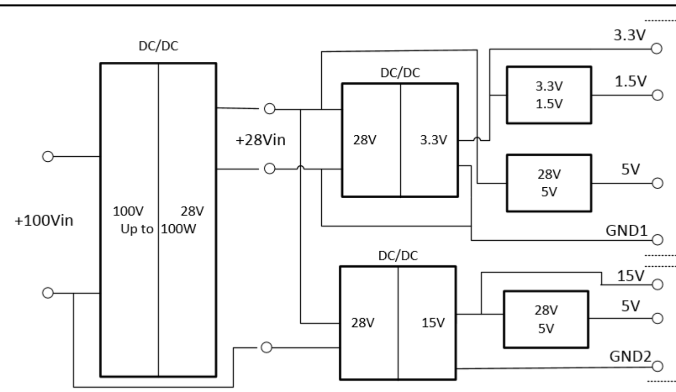

Figure 3. Power subsystem for mid power HET

system.

The choice of grounding strategy in systems with multiple power supplies is the most complex and controversial issue. The choice of the wrong topology of the grounding can lead to the formation of “earthen loops” and, as a result, increased sensitivity to interference, or lead to a complete system failure. At the time of the start of design, the grounding topology was not agreed upon, so it was decided to use the complete galvanic isolation of the primary and secondary sides using galvanic isolation and the use of additional power sources. Also on the boards was the possibility of arbitrary connection of earth points in order to reduce the level of stray currents. Grounding topology optimization was performed after the control system was assembled before the start of EMI/EMC tests.

H. Selection of electronic components

In addition to electrical characteristics, important factors such as price, delivery time, and the minimum quantity for the order become important criteria for choosing. The following are additional criteria for selecting components according to their type.

1) FPGA. Optimal choice of FPGAs are Microsemi devices. For GEO missions, RTAX1000 chips are suitable; for LEO missions that do not require radiation immunity, the FPGAs of the Axelerator family are the best choice. Both families have identical cases as part of families, which allows prototyping without changing the PCB trace for different models (EM, QM, FM). These FPGAs are one-time programmable, which allows to obtain high reliability and long life of control systems operating in extreme conditions.
2) Operational amplifiers. When choosing, preference is given to radiation hardened op-amps that can operate from a unipolar power source and have rail-to-rail inputs and outputs. The optimal choice is the choice of devices of the LM158 series. However, when designing circuits, it is worth considering their features. If the design requires strict compliance with the requirements of Rail-to-Rail, then the RHR61 series devices are well suited.
3) Valve drivers. As switching elements, the use of AAHS298B integrated drivers in conjunction with the LX7710 for implementing discrete outputs with partial redundancy is a good choice. A distinctive feature of these devices is connecting with FPGA outputs without the use of level shifters. The microcircuits provide an output current of 700mA, switch voltages up to 50V, and have Internal Ground Clamp Diodes.
4) ADC. The requirements for choosing an ADC are small - it is preferable to work with one power source, the presence of an integrated multiplexer. Operation with 3.3V and 5V power is preferred. The ADC128S102QML-SP instruments that are suitable for two projects are fully suitable for such requirements. These ADCs have a resolution of 12 bits, a sampling rate of up to 1 MSPS, and a built-in multiplexer provides switching of eight channels. Another important feature of it is the serial output, which allows you to reduce the number of FPGA pin involved.
5) Galvanic isolation. The use of optocouplers as a galvanic isolation in radiation conditions increases the probability of failure in operation due to the temporary degradation of semiconductors under the influence of radiation. As an alternative to optocouplers, the use of the ADUM7442S chip, which can perform the function of level matching, can be recommended. This chip is a 4-channel isolator, provides data transfer at speeds up to 25 MBPS.

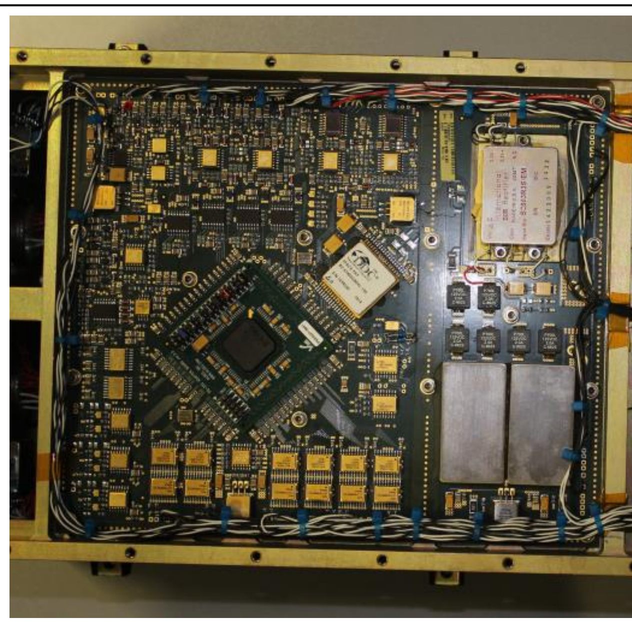

Figure 4. Control Unit for HET 1500W

6) Interface ICs. As transceivers MIL-STD-1553b, products of the DDCs company BU-67402F80HL were used, which had two transceivers and a transformer in their composition. To implement the RS422 interface,

LVDS/RS422 receivers and transmitters HX422R and HX422D are applicable. CAN interface implemented using SN55HVD233-SP transceiver. All transceivers are compatible with 3.3V logic and can be directly connected to the FPGA.

7) DC/DC converters. The choice of converters is quite large. The choice of a specific can is determined by the possibility of purchase and the acceptability of delivery times. The baseline data for the order is the level of input and output voltage, as well as power.

8) As resistors and capacitors, any components intended for use in space are applicable.

I. The resulting control system

After selecting the electronic components, a schematic design was created, measuring circuits were designed and calculated. According to the requirements of ECSS, the design of the circuit board was completed. The TUBITAK UZAY production department completed the installation in accordance with ESCC requirements.

The photo of the medium-power thruster Control Unit is shown in Figure 4. The size of the 12-layer board is 205x244 mm.

The PCB of the low power thruster Control Unit is shown in Figure 5. At the time of publication of the article, the board is at the assembly stage. The dimensions of the obtained 10-layer board are 312x200 mm.

Technical characteristics of the resulting systems are listed in Table 3.

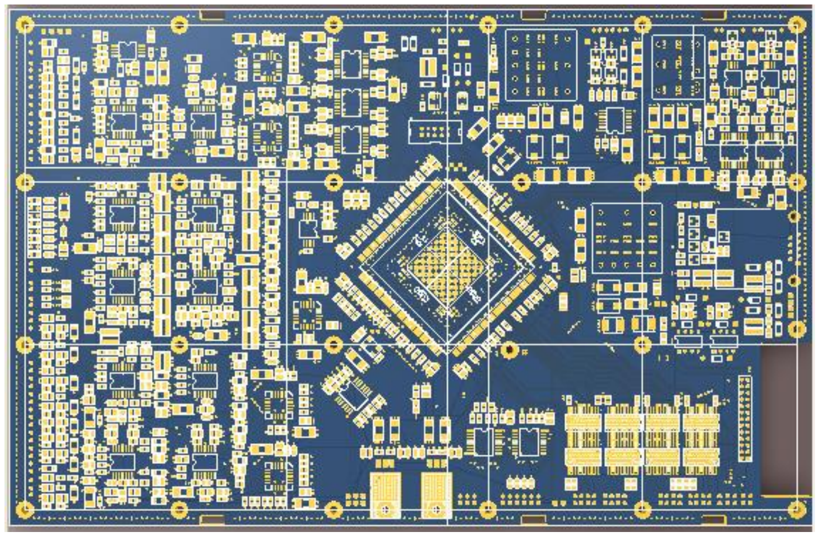

Figure 5. Control Unit for HET 300W

Table 3. Technical characteristics of the resulting systems.

Parameter name	1500W system	Value range	300W system	Value range
Discrete Outputs	27	24V, 700mA	17	24V, 700mA
Discrete Inputs	1	24V	1	24V
Number of channels for measuring high temperature	4	-60...+600ºC	2	-60...+600ºC
Number of channels for measuring low temperature	16	-40...+125ºC	9	-40...+125ºC
Number of channels for measuring high pressure	1	0..200 bar	1	0..200 bar
Number of channels for measuring low pressure	4	0..6 bar	4	0..6 bar
Discharge voltage	1	0..350V	1	0..300V
Discharge current	3	0..6A	2	0..2A
Cathode voltage	1	3..30V	1	3..30V
Cathode current	1	0..3A	1	0..3A
Input bus voltage	3	0..130V	3	0..35V
Input bus current	1	0..20A	1	0..20A
Magnet voltage	-	-	1	5V
Magnet current	-	-	1	1A
Additional analog input	2	0..2.5V	1	0..2.5V
Supply voltage		86..135V		16V..40V
Internal Interface	4	RS422	4	RS422
FC interface type	1+1	MIL-1553B	2	CAN
ON/OFF	1		1	
TID		100krad		50krad

At the beginning of the design of the Control Unit, it was not possible to select the operating modes of the low-power thruster, so an additional magnet power supply was implemented. This led to the need to implement a magnet voltage and magnet current measurement unit in the system.

J. Maintaining HET thruster operating point.

Maintaining the thruster operating point is the main task of the control system. The control of the operating point is possible by changing the parameters of the discharge power supply or by controlling the xenon flow regulator in the anode unit. It is also necessary to maintain a stable xenon flow into the cathode unit. Supply voltage adjustment is not provided. Cathode flow rate is fixed.

Figure 6 shows the dependence gas flow of temperature in cathode flow restrictor. Calibration was performed using argon instead of xenon. This explains the difference between the claimed flow rate and the resultant from the experiment.

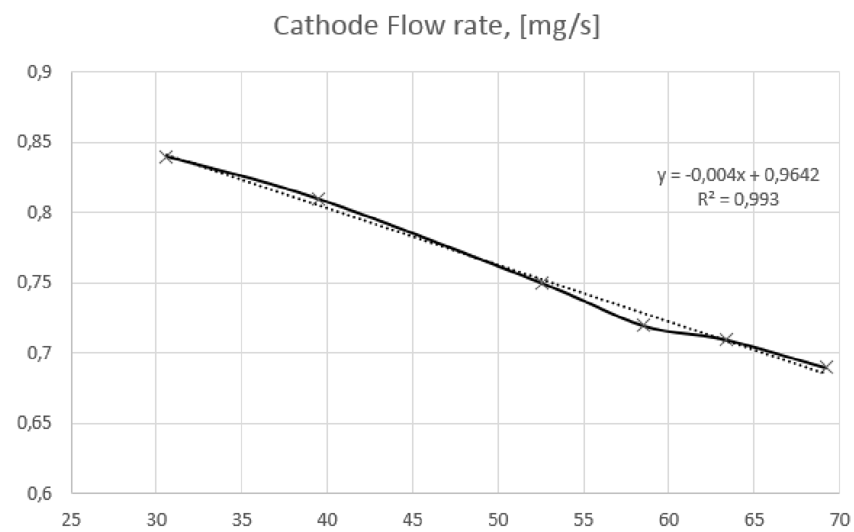

Figure 6. Cathode flow rate

The flow control in the cathode unit is carried out by a flow restrictor. The task of the control system is to maintain a stable temperature of the flow restrictor. For this, at the moment, the control system has implemented the function of a proportional controller that maintains the set temperature of 60°C ± 1°C. The temperature sensor used in feedback has redundancy.

At the time of publication of the article, work on the development of an algorithm for controlling the flow in the anode unit is being completed.

III. Conclusion

The control system designed by TUBITAK UZAY for medium power HET provides control of all units of the HET platform, as well as communicates the platform with the FC. The mid-power HET propulsion platform control system is finally to qualification test campaign including functional-performance, vibration, EMC, thermal-vacuum and shock tests in 2019.

The control system of the low power HET platform is at the assembly stage. After which the qualification test campaign including functional-performance, vibration, EMC, thermal-vacuum and shock tests in 2019-2020 will be completed.

The main tasks for this period will be: calibration of the system’s sensors, development of control algorithms, as well as work on the platform’s control system by the FC side.

Acknowledgments

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