Development of High Efficiency Power Processing Unit for Hall Thruster.

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Abstract: Today, an integral part of most satellites is the propulsion system. The propulsion system allows to solve a whole range of tasks such as maintaining the orbit, maneuvering in orbit, moving a satellite into a disposal orbit at the end of its life. Improving the electronic components allows us to create highly efficient and reliable power supplies and controls for electric propulsion systems. In the TUBITAK UZAY was completed the development a HETs with a power level of 300W and 1500W. At the same time, PPUs were developed for these thrusters. The PPUs are designed for use in satellites with 100V power bus for 1500W HET and 28V power bus for 300W HET. As a result, two propulsion systems were obtained, capable of solving a wide range of tasks for LEO and GEO satellites. This article describes the stages of PPU designing and shows the achieved characteristics.

Nomenclature

HET = Hall Effect Thruster
PPU = Power Processing Unit
PPCU = Power Processing and Control Unit
V = Volt
A = Ampere
W = Watt
CTR = Current Transfer Ratio
LEO = Low Earth Orbit
GEO = Geosynchronous Equatorial Orbit
TÜBİTAK = The Scientific and Technological Research Council of Turkey
UZAY = Space Technologies Research Institute
HALE = Hall Effect Propulsion System Development Project

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I. Introduction

For many decades, the direction of electric propulsion systems for satellites has been developing all over the world. Gradually, electric propulsion systems will force out chemical ones. This is due to the higher efficiency of electric propulsion systems. Chemical propulsion systems have traditionally been used for many years as engines on satellites due to their simplicity and reliability. However, modern electronics allows creating reliable power sources and control systems for electric motors. Hall thrusters, which are being developed in-house in the scope of HALE project. One thruster operates at a power of 200-300 W (called HALE-200) while the other one has a power level of 1-1.5 kW (called HALE-1500). The 1500W and 300W propulsion systems will be used in the TUBITAK UZAY satellites and will allow solving a wide range of tasks in orbit. When developing these propulsion systems, the development team had to solve a numerous problems, starting with the selection of components and ending with the testing of the system. In this material you can get acquainted with the development of the Power Processing Unit for HET based propulsion system.

II. PPU Design

A. Analysis of the task and building a block diagram of PPU

Before starting any work it is useful to analyze in detail the task and the additional conditions according to which it was solved. Baseline for the development of PPU can be the characteristics of the engine and the parameters of the power supply network of the satellite. This can be considered the main input and output parameters. Analyzing a task the desired dimensions and mass of the PPU should be taken into account, and also a whole set of requirements for ensuring reliability and electromagnetic compatibility.

Input and output electrical parameters		
1500W system		300W System
HET parameters		
Thruster Discharge Voltage	300V	250V
Thruster Discharge Current	<5A	<1A
Cathode Voltage	<20V	<20V
Cathode Current	2.5A	2.5A
Magnet Voltage	-	<5V*
Magnet Current	-	<0.5A*
Satellite Bus Voltage	100V	28V

Table 1. PPUs Input and output electrical parameters.

The main parameters of the technical specifications are summarized in the table. Let us dwell on them in more detail. In the beginning, consider a system that is a load for developing PPUs. Such a load is a propulsion system based on the Hall Effect Thruster (HET). In this article we only schematically consider the propulsion system device. The propulsion system consists of the HET and the cathode. The discharge voltage is applied between the anode - one of the elements of the HET and the cathode. An element of the Hall thruster also are external and internal solenoids - sources of a magnetic field. Besides we must provide the necessary power for cathode.

Ggenerally, a universal PPU should include a discharge voltage source, power sources for external and internal solenoids, and cathode power sources. In our case, the task is somewhat simplified by the fact that both the engine itself and the cathode are developed by TUBITAK UZAY specialists.

In the joint development of PPU and HET, great attention was paid to their mutual coordination.
For example, the parameters of the internal and external solenoids were calculated in such a way that their operating current was equal to the discharge current. This allows to power the solenoids from a discharge power source and not have separate power sources for the solenoids.

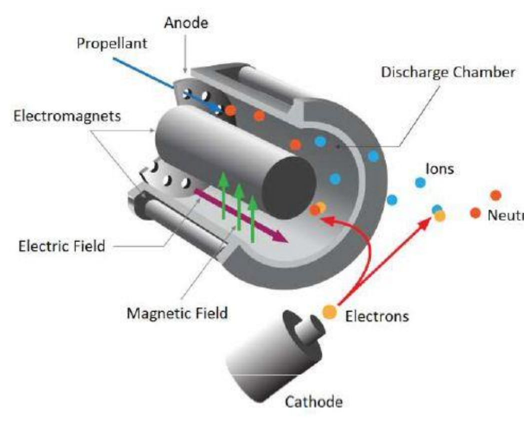

Figure 1. Hall Effect Thruster Propulsion.

The advantages of this solution are obvious. But there are some difficulties. With insufficiently careful calculation of the magnetic system of the engine, a decrease in operating parameters during throttling is possible. Therefore the isolation of the solenoids should be designed to work at high discharge voltage.

Using an original design cesium cathode allows to have only one power source for the cathode in the PPU.

Thus, only two power sources are required for the 1500W PPU: a discharge voltage source and a voltage source for the cathode.

The situation with PPU for a 300W system is slightly different. At the beginning of PPU development, the issue of solenoids for a 300W thruster was not resolved. Thus, it was decided to include a solenoid power source to the system for safety reasons. And the decision on its necessity must be made after the design and testing of the engine.

Thus, the 300W PPU includes a discharge power source, a solenoid power source, and a cathode power source.

We have decided on the composition of the power sources. The PPU also includes an input filter and Inrush Current Limiter.

Now it is possible to draw a PPU block diagram. We must also include a control and telemetry module in to the diagram. A detailed description of this module is beyond the scope of this article, but we must remember that this is an important part of the Power Processing and Control Unit. [1]

At the design stage of the PPCU, it was decided that the control and telemetry module should provide automatic operation of the propulsion system and require a minimum of external command actions from the on-board computer. A step-by-step mode is also provided, but it is not the main one and will be used only in case of emergency situations.

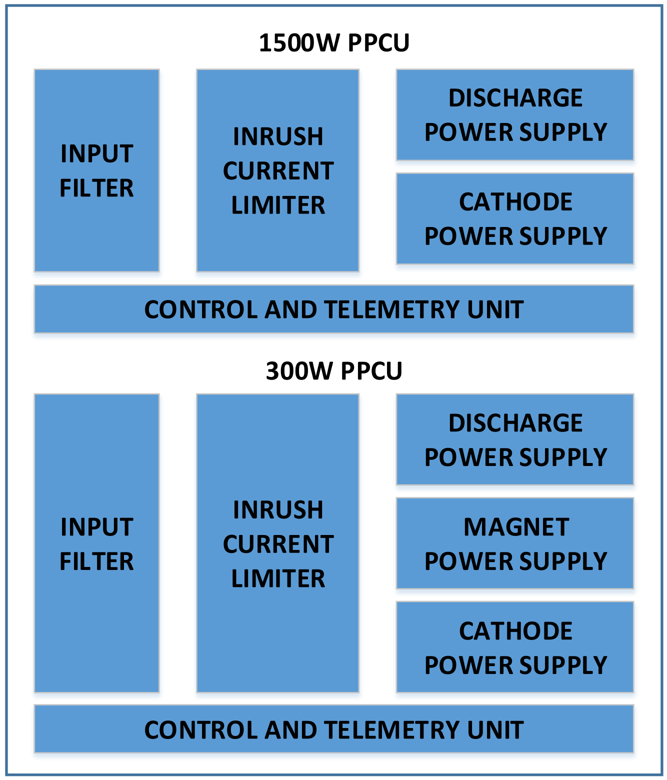

Figure 2. Block Diagram of 1500W and 300W PPUs.

Thus, the main mode of operation of the PPCU is automatic. All subsystems must be covered by telemetry for timely diagnosis and reliable operation with the satellite.

After compiling the block diagram we can start drawing a schematic of each block and start selection of components. Let's consider components of which PPU consists in more detail.

B. Discharge Power Supply.

Consider a discharge voltage source. This is the most powerful source in our system. And its parameters will make a decisive contribution to the characteristics of the system as a whole. Therefore, we need to pay special attention to the design of this power source. Consider the general principles of designing such power sources. This device will be operated in the outer space. This imposes certain restrictions on the choice of components. Thus, we will focus on solutions that have become classic. Since in this case we will have a minimum difficulties with the components. The general requirement for power supplies as part of PPUs is full galvanic isolation of the output voltages from the input supply line. The requirements of galvanic isolation are fully met by transformer converters.

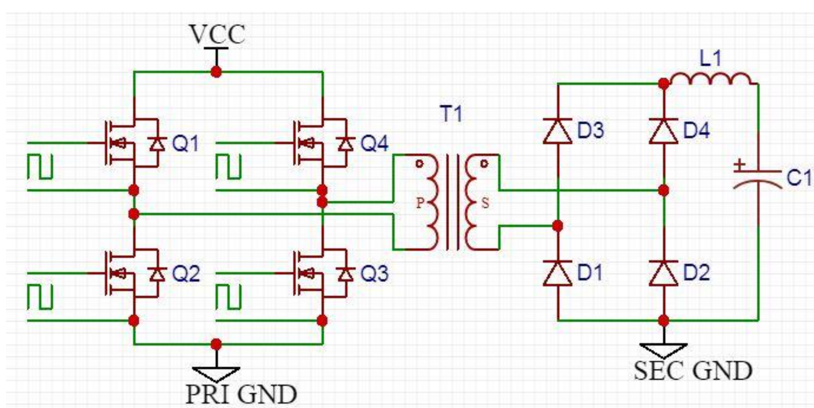

Figure 3. Full Bridge Power Converter Diagram.

For a power source of hundreds and thousands of watts, push-pull topologies are well suited. For the sources of discharge voltage of 1500W and 300W, the full bridge transformer topology was chosen. A voltage source with current protection is required to power the HET.
The mission does not require control of the thruster operating point due to a change in the discharge voltage. Thus, voltage adjustment during operation also is not required. This greatly simplifies development.

Consider a possible structural diagram of such a power source.

The necessary control signals are generated by the DCDC controller. We chose the integrated DCDC controller. The bridge transistor control signals are further amplified by gate drivers.

The required output voltage is generated by a step-up transformer, rectified and filtered. Parameters such as input and output voltage and current are converted into feedback signals, as well as transmitted to the control and telemetry module.

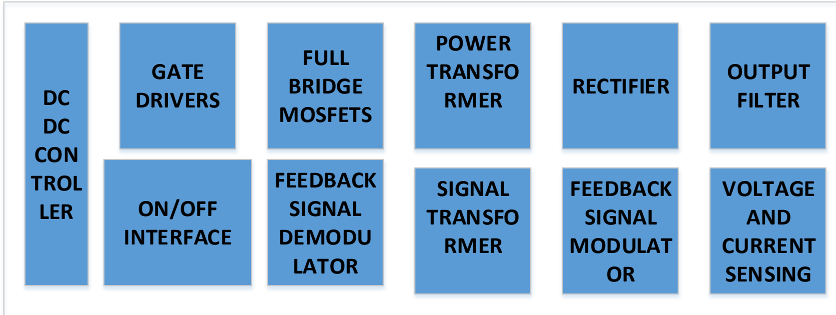

Figure 4. Discharge Power Supply Block Diagram.

It should be noted the inapplicability in the feedback loop of optocouplers, such popular in ground-based applications. Changing their CTR under the influence of outer space factors makes it impossible to use them in the feedback circuit. Since the CTR of the optocoupler is included in the feedback transfer function, its large changes can lead to unstable operation of the power source. In this development, transformer feedback is used in all power supplies. For its implementation, it is necessary at first modulate the feedback signal, and then demodulate after the decoupling signal transformer. For this design, a transformer feedback circuit was developed and tested, which showed good results during testing.

An additional ON / OFF interface is used to turn on and off the source according to the commands from the control and telemetry module.

The UC1825-SP from Texas Instruments for the 300W PPU project and the Intersil IS-1825 for 1500W PPU was chosen as the DCDC controller. This choice was dictated by the necessity to use components with a given radiation grade. The gate drivers used are RIC7S113L4. The use of an integrated driver simplifies the design. A bridge output rectifier is a compromise. Losses on 4 diodes are higher than when using a full-wave rectifier, however, this solution allows the using of a simpler transformer with 1 primary and 1 secondary windings. In the graph below, you can see the resulting efficiency of the 1500W converter at an output voltage of 300V and an input 100V at different load currents.

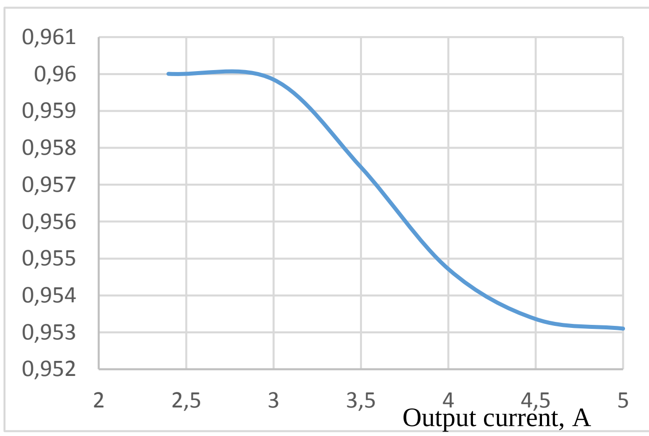

Figure 4. Discharge Power Supply efficiency

The 300W discharge power source was designed according to similar structural and circuit diagrams. It should be noted that the supply voltage of this source is 28V. This makes it possible to apply another widely used Push-Pull topology. However, this would require the use of a transformer with two primary windings. To avoid this, it was decided to apply the Full Bridge topology to use a simpler transformer. The components used in these projects are also available for commercial and industrial use or have direct analogues. In developing and testing, can be used the numerous best practices and recommendations from manufacturers and open source materials from third-party developers. This fact greatly facilitates the development.

C. Cathode Power Supply

As we noted earlier, an innovative cesium cathode was used as part of the propulsion system [4, 5, 2]. Only one power source is required for its operation. The graph shows the characteristics of the cathode at different stages: switching on from the "cold" state, initialization, ignition, and operating state. As we see, when power is applied, the cathode successively passes through all stages from the "cold" state to the operating state at constant current. The voltage applied to the cathode changes. Thus, the cathode power supply must be a constant current source with output voltage limitation. As can be seen from the graph, the cathode current remains unchanged and does not require adjustment during operation. This means that the cathode power supply also does not need to be adjusted during operation. The working current of the cathode is 2A for a 300W propulsion system and 2.5A for a 1500W propulsion system. The voltage during operation varies from 5-6V long-term to 20V at the start-up phase. Thus, the long-term power of the cathode power supply will be 12-18W and up to 50W at startup.

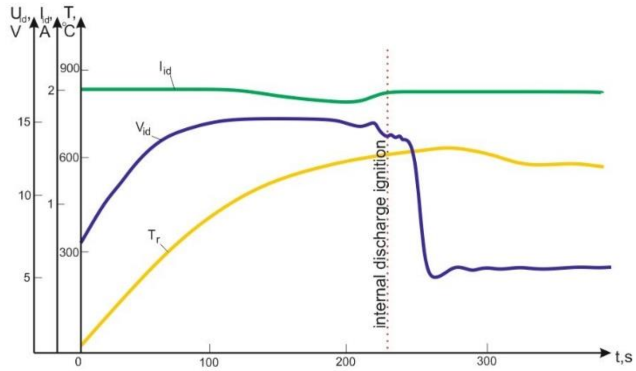

Figure 5. . Time variation of the discharge voltage V_{id}, discharge current I_{id}, and Cesium reservoir temperature T_r at cathode startup.

The cathode power supply can be performed on a single-ended circuit. A suitable topology would be Flyback. The advantages of this topology include ease of implementation and the absence of a choke in the output circuit. The current in the primary circuit of the flyback is limited by a current-sensitive resistor, the power in the secondary circuit is limited by the energy stored in the transformer. Also, the transfer of energy to the transformer and the transfer of energy from the transformer to the load occur at different time phases. Thus, the flyback has good stability when working with loads from free running to short circuit. Which is in good agreement with the cathode power supply requirements.

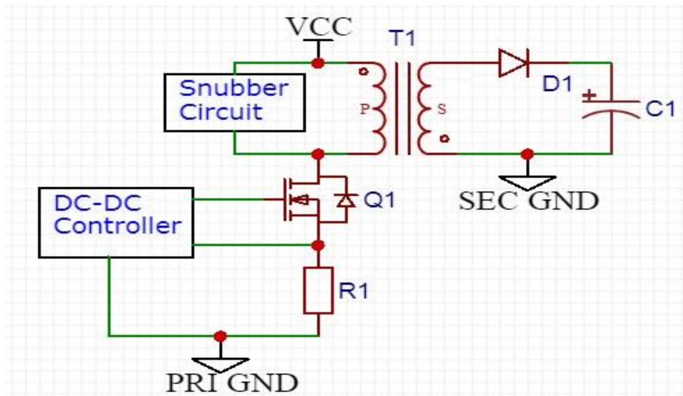

Figure 6. Flyback Power Converter Diagram.

Consider a possible structural diagram of such a power source. As a matter of fact, there is much in common with the block diagram of a discharge voltage source. There is an ON / OFF interface, because it requires the ability to control on and off the source by commands from the control and telemetry module. A transformer feedback circuit is also implemented, similar to a discharge voltage source. The module also contains voltage and current control circuits for protection against abnormal operation and telemetry.

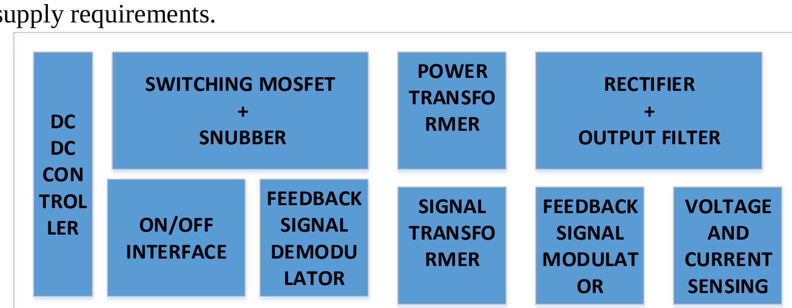

Figure 7. Cathode Power Supply Block Diagram.

But there are significant simplifications. So the DCDC controller usually has a built-in gate driver for the key transistor. The output filter circuit is also simplified.

One of the disadvantages of the Flybackk topology is the impossibility of a simple implementation of a synchronous rectification circuit. This negatively affects the efficiency when working with low output voltages and high currents. The diagram shows the efficiency of the cathode power supply for output voltages in the operating range and current 2.5A. As you can see, the efficiency is relatively small, but due to the small, in comparison with the discharge power source, own power, the negative contribution to the efficiency of the whole PPU is small. And in general, the positive qualities of this solution outweigh the relatively small efficiency.

Flyback is also a well-studied and widespread topology. During development, you can use a large number of reference materials and ready-made design solutions.

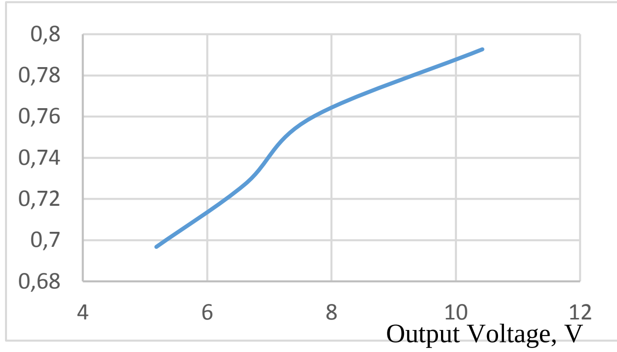

Figure 8. Cathode Power Supply efficiency

The UC1843-SP from Texas Instruments was chosen as the DCDC controller for the 300W PPU project and Intersil ISL78843 for the 1500W PPU. A feature of this power source is the using of a power switch with a high operating voltage and snubber, triggered by pulses of large amplitude. During normal operation, the snubber is practically not involved. Its limiting properties are manifested only under abnormal cathode operating conditions. This solution slightly increases the level of EMI radiation from the source, but can significantly reduce the heat emission from the snubber elements. The use of the IRHM7460 transistor with an operating voltage of 500V provides the necessary voltage margin for reliable operation of the converter in all modes, including emergency.

D. Magnet Power Supply

As shown earlier, an additional solenoid power supply is needed only for operation with a 300W propulsion system. To maintain a given level of the magnetic field, it is necessary to power the solenoid from a constant current source. The requirements for the power source of the solenoids are the same as for the power source of the cathodes. Differences will be only in the required levels of output current and maximum voltage. Therefore, we will not consider in detail the construction of this source.

Let's look at possible options to power the HET solenoids. The differences between these options will affect the output parameters of the solenoid power source, and therefore the choice of components. Figures 9.A, 9.B, and 9.C show three of the possible options for connecting a Hall thruster to a PPU.

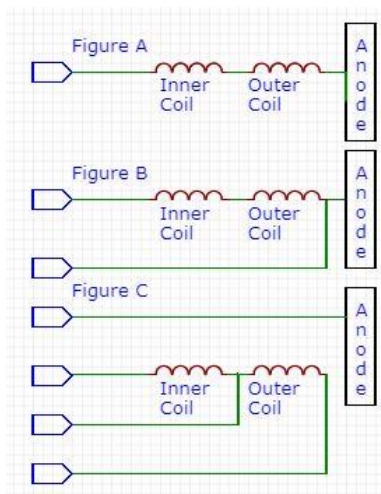

Figure 9. Various options for powering Hall Effect Thruster solenoid coils.

Figure 9.C shows the inclusion, which can be called classic. Anode voltage is connected directly to the anode. Solenoids have their own connection points. To power the solenoids can be used as two independent power sources, as one common. The first option allows you to power the solenoids of different magnitude current. Also, this option somewhat facilitates the design of the engine, since the solenoids can be under a small potential relative to the housing and the requirements for their insulation are relatively small. The advantage of this option is the independence of the solenoid current and discharge current. This allows you to change them over a wide range if necessary to adjust engine conditions. The disadvantage is the need to have additionally one or two solenoid power sources.

Figure 9.A shows a variant in which the solenoids are connected in series with a discharge voltage source. This option simplifies the design of PPU, because there is no need for separate power supplies for the solenoids and all the elements of the control system and telemetry associated with them.

However, this solution requires increased attention to the design of the magnetic system of the motor, because it is necessary to achieve equality of the currents of the solenoids to the discharge current in the operating mode. But such a solution presents increased requirements for the isolation of solenoids relative to the motor housing. In this case in this case, the solenoids will be at a high potential source of discharge voltage. The impossibility of deep regulation of the motor also can be considered a disadvantage, since the discharge current and the solenoid current, in this case, are interconnected. But, the advantages of this solution make it attractive and it is this inclusion that was applied in the 1500W propulsion system.

Figure 9.B shows the serial connection of the solenoids to the anode of the engine, but with an additional outlet. A similar necessity may arise in two cases.

1. When developing the engine for some reason, it was not possible to achieve equality of the discharge current to the current of the solenoids.

2. When operating the engine, I want to have a possibility to some change in the current of solenoids relative to the current of the anode.

Consider the first situation on the example of a 300W propulsion system.

The development of the PPCU for the 300W propulsion system began at the same time as testing the prototype 300W HET. During this testing of the thruster, one feature was revealed: to obtain the optimal parameters of the magnetic field, a solenoid current of several hundred milliamperes higher than the discharge current was required. The required current can be reduced by increasing the number of turns of the solenoids. But, it was not possible for the inner coil due to geometric restrictions. The prototype of thruster showed high productivity. Optimization of the solenoid current required a redesign of the thruster design, and it was decided to lay an additional solenoid power supply in the 300W PPU design. In case of a successful change in thruster design, the components of this additional source will not be installed.

Why was design mode 9.B selected instead of 9.C? After all, we still have an additional power source. It's all about the low efficiency of this source. This issue was discussed in detail when considering the cathode power source. It is possible to reduce the negative contribution from low efficiency by reducing the power of the source itself. In option 9.B, the main current of the solenoids is provided by a source of discharge voltage, which has a much higher efficiency. The power source of the solenoids is used only as a source of additional magnetizing current and can have a small power of several watts.

But such a solution has a disadvantage. All the components of the secondary circuit of the solenoid power supply will be under the potential of the anode. This must be taken into account when designing the source and its power transformer. When designing the PPU circuit board, the components of the secondary circuits of the solenoid power supply were placed near the components of the output filter of the discharge voltage source. The power transformer was designed with increased insulation between the primary and secondary windings.

E. Input Filter and Inrush Current Limiter

The input filter is an important component of the PPCU. It is the input filter that will largely determine the normal operation of the PPCU in conjunction with other systems. PPCU is a powerful load in the onboard power network. In some cases, it is the most powerful device on board. When designing, special attention should be paid to the issues of electromagnetic compatibility.

A good solution is to use a certified filter that complies with the MIL-STD-461 standard. However, this is not always possible. There can not be a filter for the required operating current. Or its dimensions can not satisfy the developers. In this case, the input filter should be developed in conjunction with the development of other PPCU submodules. Such a solution provides great flexibility in the design of PPCU, but requires a lot of attention from the developer in the design. Since the low filter parameters or its unsuccessful design can adversely affect the electromagnetic compatibility of the propulsion system as a whole.

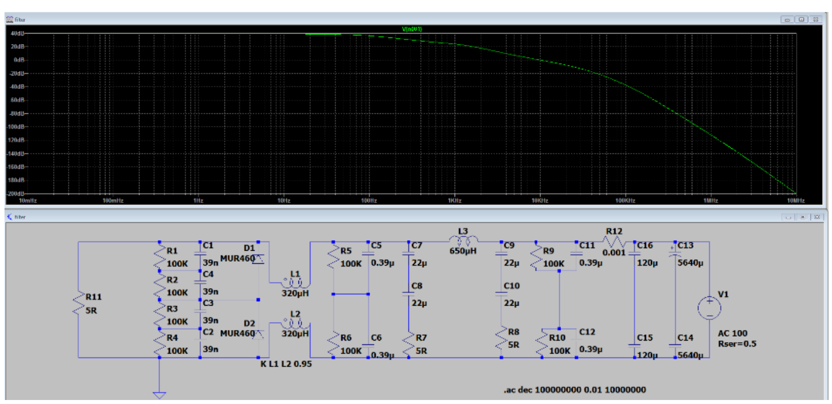

Figure 10. Computer modelling of input filter

A filter was developed with a working current up to 20A and the necessary attenuation parameters. The operating voltage of the filter can be either 100 or 28 volts, depending on the components used. Thus, this filter can be used for 1500W PPU and for 300W PPU with minimal changes.

The filter model showed attenuation of 20dB at a frequency of about 1 KHz and 40dB at a frequency of about 10 KHz.

Further EMI / EMC tests of the PPCU confirmed the acceptability of the filter and the system as a whole.

Inrush Current Limiter has an inrush current protection function when the PPCU is turned on. Short-term inrush current can exceed a hundred amperes when turning on such a powerful load as PPU and can be dangerous both for the onboard power supply network and for nearby satellite systems. Therefore, the input current must be limited to acceptable values. During operation, the input current is constantly measured by the monitoring and telemetry system and it will be automatically turned off in case of an abnormal increase in PPU. When turned on, you can protect yourself from the inrush by applying a stepwise turning to the power input. The easiest way to enable this is to use two relays with normally open contacts and a resistor.

This circuit is installed between the input filter and the PPU power supplies. First, on command from the control module and telemetry, the contacts of relay SW1 are closed. Current flows into the circuit through a limiting resistor R1. After the end of transients, a command is issued to close the contacts of SW2. As such, PPU is ready for operation.

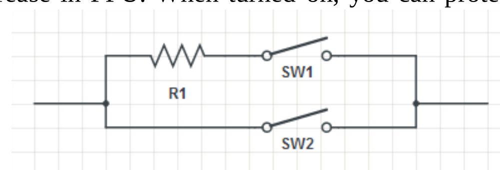

Figure 11. Inrush Current Limiter Diagram

III. Conclusion

Power Processing and Control Units (PPCUs) are designed in the TUBITAK UZAY are responsible for controlling of Hall Effect Thruster, supplying the necessary power to each equipment of the subsystem (including XFU heaters and a fuel tank) and establishing an interface with the rest of the satellite.

PPCU consists of a submodule of discharge power sources, cathode and solenoids, a submodule of control and telemetry, auxiliary DC-DC converters for powering PPCU components, a filter board and a housing. 1500W PPCU has a completely redundant design, in one case there are two independent submodules of power supplies, control and telemetry modules and input filters with auxiliary power supplies. Together with a redundant propulsion system, this solution allows you to have a highly reliable system of widespread use.

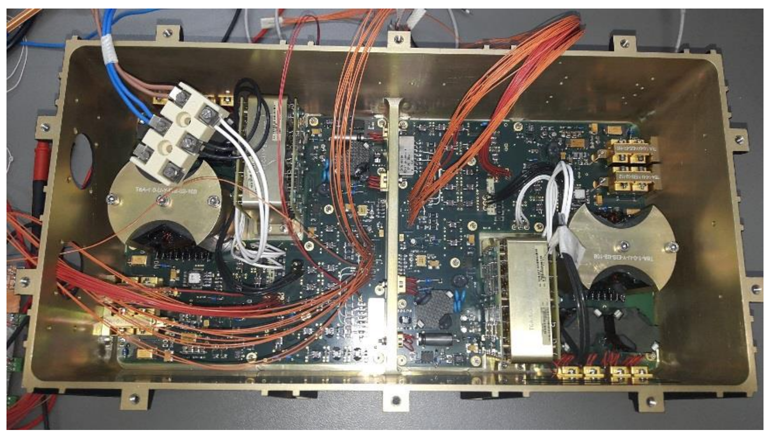

Figure 12. Primary and Redundant 1500W PPU in the case. Functional test after mounting.

The unit is subjected to qualification test campaign including functional-performance, vibration, EMC, thermal-vacuum and shock tests in 2019.

PPCU for 300W propulsion system has a different construction, due to the characteristics of a specific task. The on-board equipment is responsible for the temperature conditions of the propulsion system and the PPCU does not include control and heater control channels. Also, the 300W PPCU design contains only one set of submodules for power, control and telemetry, a filter module and auxiliary power sources. Redundancy is done at the system level by installing two PPCUs.

The unit is completed to qualification test campaign including functional-performance, vibration, EMC, thermal-vacuum and shock tests in 2019 -2020.

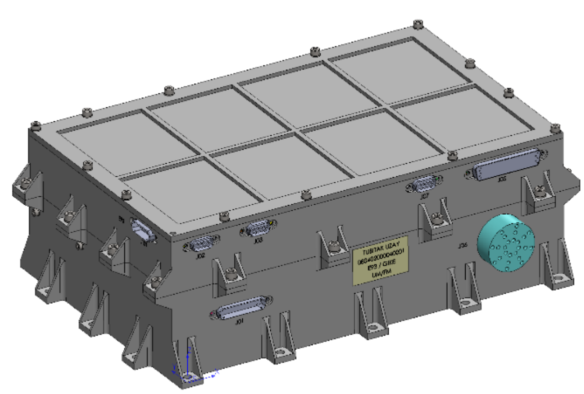

Figure 13. 300W PPCU.

Acknowledgments

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