Designing, Manufacturing, and Testing of Power Processing and Control Unit for a 1.5 kW Hall Effect Thruster

IEPC-2019-346

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

A. Tsybulnyk, S. Neugodnikov, M. Ucan, B.C. Aydin, D. Ulusen, B. Solak, S. Arslan
TUBITAK UZAY Space Technologies Research Institute, Ankara, Turkey

Abstract: TURKSAT6A (T6A) communication satellite owns an experimental Electric Propulsion Subsystem (EPS) on board for east-west station keeping maneuvers. A Power Processing and Control Unit (PPCU) is designed throughout HALE project at TUBITAK UZAY facilities which is responsible for controlling the thruster operation, supplying necessary power to each subsystem equipment (including heaters on XFU and Propellant Tank) and establishing an interface with the rest of the satellite.

Nomenclature

HALE	=	Hall Effect Thruster Development Project
T6A	=	TURKSAT6A Communication Satellite
EPS	=	Electric Propulsion Subsystem
PPCU	=	Power Processing and Control Unit
XFU	=	Xenon Feed Unit
HET	=	Hall Effect Thruster
GSU	=	Ground Support Unit
GEO	=	Geostationary Equatorial Orbit
ADC	=	Analog to Digital Converter

I. Introduction

Electric propulsion has become a key technology for space applications over the years due to the advances in electronics and the need to build compact and lightweight satellites. Turkey' first electric propulsion system development project, HALE, not only aimed to found a development facility but also develop a Hall thruster propulsion system (EPS) [1,2]. HALE project's outcomes, including a 1.5 kW Hall Effect Thruster (HET), a Xenon Feed Unit (XFU), a Propellant Tank, and a Power Processing and Control Unit, are planned to be used experimentally onboard TURKSAT 6A platform for east-west station keeping maneuvers [1-4]. This paper focuses on the design, manufacturing, and testing activities of the Power Processing and Control Unit (PPCU)

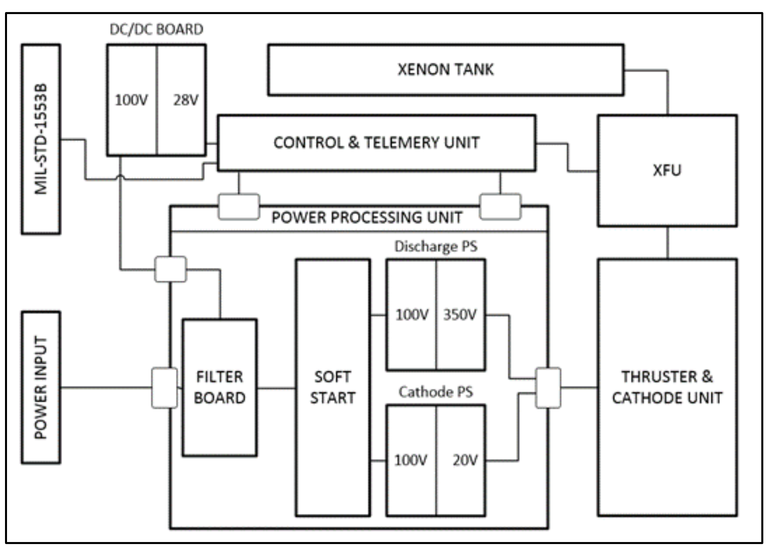

Figure 1 Electric Propulsion Subsystem

to power and control the EPS on TURKSAT 6A. The block diagram presenting the physical architecture of the EPS with its all internal and external interfaces is given in Figure 1.

II. PPCU Design

In the EPS system, the Thruster and Cathode Unit (THU) has two thrusters each with two cathodes (for redundancy) and the Xenon Feed Unit has two identical but independent braches to feed each thruster. Therefore, the mechanical structure of the PPCU houses two identical modules, each of which consists of one Power Processing, one Control and one DC-DC board to power and control one THU and one XFU. A common Filter board located in the PPCU mechanical structure is used by these two identical modules. Electronic and mechanical design of the PPCU boards are presented in detail in the following sections.

A. Power Processing Board

The main function of the Power Processing Board is to supply necessary voltages to the elements of the propulsion system. The board is designed for reliable operation under geostationary orbit conditions. Radiation grades of the electronic components are up to levels of 100K RAD. The unit consists of an input filter with an inrush current limiting circuit, a discharge power source, a cathode power source, and a communication interface with the Control Board [5]. The discharge voltage source is the most powerful converter in the unit and supplies power to the anode of the HET for plasma discharge. The cathode voltage source provides the necessary voltage and current for the cathode [6] operation.

All input and output voltage and current telemetry is received by the Control Board. These parameters are used for continuous and healthy HET operation. The telemetry is also transmitted to the on-board computer on request. In addition, each of the power supplies has an on and off interface for commands from the Control Board. The block diagram of the unit is given in Figure 2. The characteristics of Power Processing Board are summarized in Table ***1***.

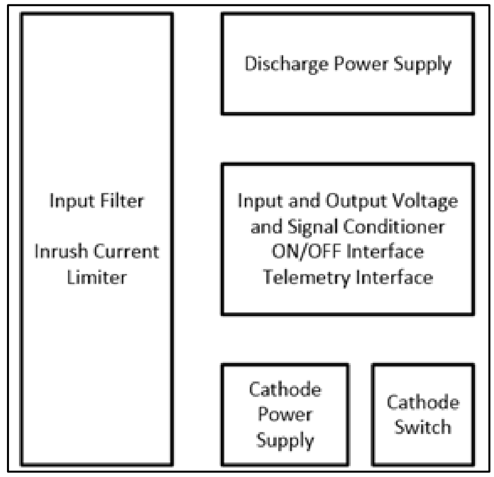

Figure 2 Power Processing Board Block Diagram

The discharge voltage source has a full bridge topology. This is an effective solution for an output power of 1500W. The source has current protection as well as input and output voltage control both on the primary and secondary circuits. The transformer circuit of the converter provides full galvanic isolation between the input supply voltage and the load.

High reliability and high efficiency are the top priorities in the development process of the power supplies. Furthermore, the cathode power source shall comply with the cathode's different operating modes [6]. A current source with output voltage limitation should be used as a cathode power source. In the process of starting, the voltage of the source can vary from 15-20 Volts to 5-6 Volts while the current has to be kept at 2.5A. Therefore, the power supply is 50 W during startup and decreases to 15 W during HET operation. Taking into account these features, the cathode power supply is designed according to a single-cycle fly-back topology. This solution is well suited for a low power converter operating in a wide range of loads. Furthermore, relatively low efficiency of this converter does not have a significant impact on the overall efficiency of the PPCU as its power is low compared to overall power. The Power Processing Board is shown in Figure 3.

Table 1 Power Processing Board Characteristics

Module	Voltage	Current	Efficiency
Discharge Power Module	300V	Up to 5V	> 95%
Cathode Power Module	5-20V	2.5A*	70-80%

Figure 3 Power Processing Board

B. Control Board

The Control Board constitutes the interface with the spacecraft, controls the Xenon Feeding Unit, controls the Power Processing Board, collects telemetry data, and provides temperature control of the XFU and Xenon tank. Continuous monitoring of the EPS components is also performed in order to identify and report malfunctions. The design of the Control Unit is carried out for operation on GEO missions under radiation levels up to 100krad. Power characteristics of the Control Unit are shown in Table 2. The block diagram of Control Unit is showed in Figure 4. The control system is divided into several logical modules [7]:

a) XFU control module. It performs control of the XFU valves according to a given algorithm, maintains the operating temperature conditions of the flow restrictors, and communicates with the xenon flow control valve. It also monitors the pressure of the high and low pressure sides of the XFU and adjusts the control algorithm in the event of erroneous situations during the thruster operation.

b) Telemetry collecting and analysis module. The function of this module is to collect information about the current state of the system and transfer the necessary data to the spacecraft. It is also possible to analyze the information received in real time in order to quickly respond to emergency situations. Due to the presence of galvanic isolation, the module has the ability to receive information from the primary side of the platform (from the spacecraft) and from the secondary side (thruster side). A complete list of measured parameters and the measurement range are given in Table 3.

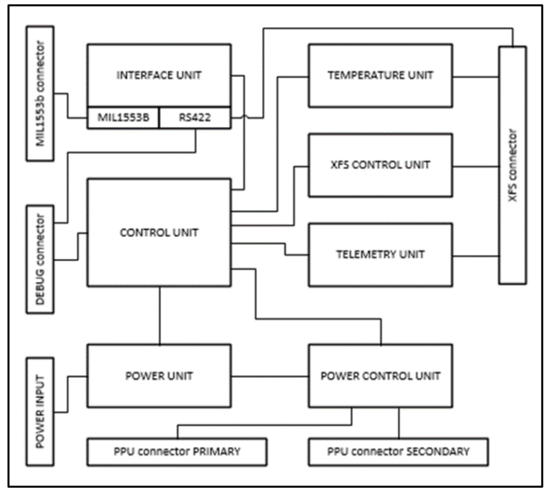

Figure 4 Control Board Block Diagram

c) Interface module. The module consists of two parts. The external communications part is designed to transfer data to the spacecraft and receive control commands and parameters from it. The interface used is MIL-STD-1553B. For internal communications in PPCU, as well as debugging operations, the four-channel LVDS / RS422 interface is used.

d) Power Processing board [5] control module. Performs switching of the anode power source and the cathode power source in a given sequence, and also performs the blocking of forbidden sequences. In addition, the module performs cathode switching and soft start processing.

e) Temperature control module. The module monitors and stabilizes the temperature of the XFU components within a limited operating temperature range by heaters. The components include flow restrictors, xenon tank, pressure regulator, and the XFU base plate [8].

f) Submodule of power supplies. Designed for generating FPGA supply voltages (+3.3V, + 1.5V), two Analog Front End supply voltages (+5V), and a redundant power source for the primary circuits in Power Processing board (+15V). To protect the satellite’s on-board power lines, fuse protection of DC/DC converters is implemented.

g) Control module. It is an FPGA based module that coordinates the work of all modules.

All important elements have hot redundancy. All measured parameters are measured by several ADCs at the same time, which will allow maintaining the system's operability in case of damage to one of the applied ADCs, as well as increasing resistance to radiation effects. The control system is made on a twelve-layer PCB size 205x244 mm. Control board is shown in Figure 5.

Table 2 Power Characteristics

Parameter	Value
Supply voltage	+16Vdc to +40Vdc
Supply current	up to 250 mA
Operation temperature	-55 to +125 ºC
Auxiliary voltage output	15V
Auxiliary source current	up to 4A (Hot redundancy)

Table 3 Control Unit Parameters

Parameter	Number of Channels	Value
Discrete output	27	24V, 700mA
Discrete input	1	24V
Low temperature measurement	16	-40...+125ºC
High temperature measurement	4	-60...+600ºC
High pressure	1	0..200 bar*
Low pressure	4	0..6 bar*
Anode voltage	1	0..350V
Anode current	3	0..6A
Cathode voltage	1	3..30V
Cathode current	1	0..3A
Input bus voltage	3	0..130V
Input bus current	1	0..20A

* Measurement range is determined by the output characteristics of the sensor used.

Figure 5 Control Board

C. Filter Board

Electromagnetic compatibility is a very critical issue for any type of electronic equipment in space applications since almost nothing can be done by ground station rescue operations. Well-designed filters and correct shielding implementation enable reducing parasitic radiation and its possible effects to an acceptable level. Thus, applying a filter on the power input lines is an important step in ensuring electromagnetic compatibility. A good solution is to use a third-party certified power filter. However, this is not always possible due to power and dimension restrictions.

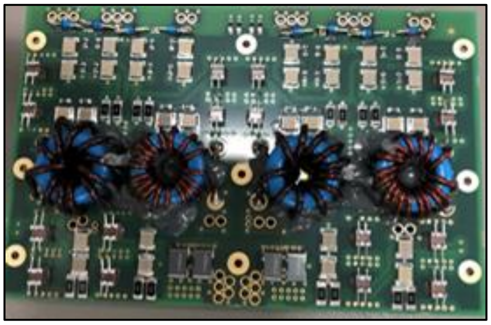

Figure 6 Filter Board

Developing a stable and efficient power filter is a tough and demanding task; however, if there is no suitable filter option from a 3rd party, developing a filter board is the only solution. A small-sized effective filter is developed for the PPCU. The filter is designed for an operating voltage of 100 V and a current of up to 20 A. The calculated filter suppression is 40 dB at the 10 kHz. EMC tests confirm the functionality and performance of the filter which is explained in the EMC tests section in this paper. The Filter board is shown in Figure 6.

D. DC-DC Board

The DC-DC board converts the input voltage 100V to 28V, and is also used to power the control board and the XFU elements. The unit is hot redundant. All components necessary for the operation of two SA50-120-28S-A-H DC/DC converters are installed on the board. In addition, the ON/OFF interface circuit is designed for the termination of the HET operation in case of emergency. This interface has a galvanic optocoupler isolation, which simplifies the connection of the ON/OFF interface with the spacecraft. It is also possible to install redundant fuse protection on the input circuits of the DC/DC board to protect on-board power supplies in the event of a short circuit in the DC/DC converter circuit. The six-layer board has dimensions of 129x89 mm. The electrical parameters of the board are shown in Table 4. The board is shown in the Figure 7.

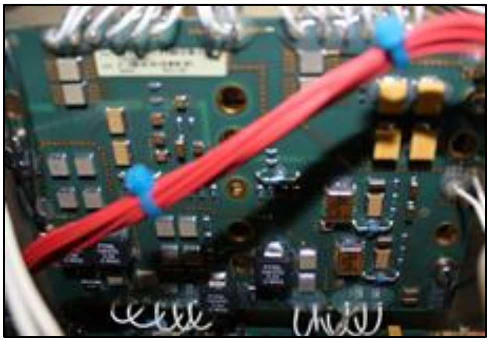

Figure 7 DC-DC Board

Table 4 Electrical Specifications

Parameter	Value
Supply voltage	+86Vdc to +135Vdc
Output voltage	+26V ± 2V
Output power	Up to 100W (Hot redundant)
Efficiency	86%
Supply voltage	+86Vdc to +135Vdc

E. Mechanical Housing

PPCU mechanical body consists of two sections. Bottom section houses the Power Processing, DC-DC and Filter boards while top section holds the Control Board. The mechanical structure also allows upper and bottom placed boards to communicate through inner connectors which are reachable during all assembly process. Mechanical box, shown in Figure 8, is manufactured from monolithic body in order to get rid of the heat that is generated due to the 1.5kW HET operation. All mechanical analyses including quasi-static, modal and random vibration are performed and the results are given in the following paragraphs. All analyses results are planned to be validated by the environmental tests in the last quarter of 2019.

Figure 8 Mechanical Body of PPCU

Spacecraft structures are typically exposed to three major dynamic environments that generate structural loads. High frequency acoustic loads are induced by excitations resulting from the engine generated noise during static firing and lift-off, and from in-flight fluctuating pressures. All those loads will also affect PPCU during launch. PPCU is designed to withstand all those mentioned generated forces.

PPCU structure is designed and analyzed using finite element method to determine its natural frequencies and mode shapes, its stress level during the launch period. Temperature distribution at the space environment and thermal stress distribution of the satellite governing from the temperature distribution. Analyses campaign is done for the PPCU, which consist of quasi static, modal and random vibration analyses.

PPCU mechanical structure is designed from Al6061 T6 material. Properties of the Al6061 T6 is summarized in Table 5. The finite element model of the PPCU geometry consisting of 447868 nodes and 217188 elements is prepared and run in ANSYS 18.2. Mesh structure is shown in Figure 9. Natural frequencies of the PPCU structure is designed considering the excitation frequencies of the T6A. According to the satellite specifications, natural frequencies of the PPCU should not be less than 140 Hz in both axes. Results of the modal analysis for first 6 modes are shown in Table 6.

Table 5 Material Properties of Al6061 T6

Symbol	Definition	Value	Unit
E	Young's Modulus	69	GPa
v	Poisson's Ratio	0.33	-
ρ	Density	2713	kg/m^3
k	Conductivity	154	W/(m.K)
α	Coefficient of Thermal Expansion	24	µm/(m.^{o}C)
c_p	Specific Heat	896	J/(kg. ^{o}C)
σ_{yield_std}	Yield Stress at 24 ^{o}C	255	MPa

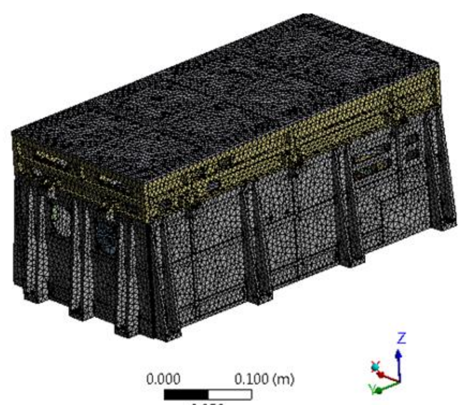

Figure 9 Meshed Finite Element Model

Table 6 PPCU Modal Analysis Results

Mode	Frequency (Hz)
1	391.7
2	427.4
3	446.7
4	454.2
5	471.6
6	489.3

During launch phase, the PPCU has to endure the acceleration loading governing from the launching process. In order to determine the stress level on the PPCU due to these acceleration loads, quasi static launch analyses are performed. Possible launchers handbooks are investigated to determine the quasi static loads that PPCU should withstand. Worst case values chosen for quasi-static launch loads are 60 g in x axis, 67 g in y axis and 57 g in z axis. According to quasi static analysis results, the highest stress occurs on PPCU structure governing from the launching loads is determined as 121MPa. Considering the Al6061 T6 yield stress, margin of safety (MoS) for yield is calculated as 0.2, which is in safe side.

Considering launch environment, the PPCU has to endure also random vibration loads which is caused by acoustic loads. Random vibration profile is obtained by using ECSS-HB-026-03C document as reference. Random vibration profile applied in the analyses is shown Table 7. According to random vibration analysis results, the highest stress occurs on PPCU structure governing from the acoustic loads is determined as 76MPa. Considering the Al6061 T6 yield stress, margin of safety (MoS) for yield is calculated as 0.9, which is in safe side. The results of random vibration analysis are presented in Figure 10.

Table 7 Random vibration analysis profile

Frequency (Hz)	Out of Plane level (g^2/Hz)	Frequency (Hz)	In Plane level (g^2/Hz)
20	6dB/Oct	20	6dB/Oct
100	0.106	100	0.106
400	0.106	200	0.106
2000	-3dB/Oct	2000	-4dB/Oct
	10.18grms		**6.95grms**

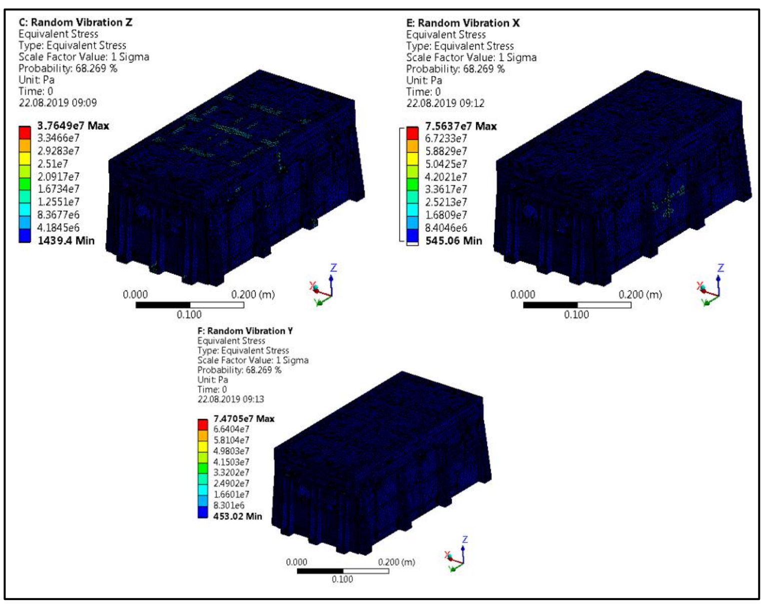

Figure 10 Random Vibration Analysis Results

III. Qualification Tests

After accomplishing a successful prototyping process, a qualification model of the PPCU is completed. The unit is subjected to qualification test campaign including functional-performance, vibration, EMC, thermal-vacuum, and shock tests to be completed in 2019. Functional and EMC tests are successfully performed and the results are presented in the following sections. Coupling tests with the XFU are in progress, which is planned to be followed by the structural and thermal vacuum tests the equipment.

F. Functional Test Results

Functional test of the PPCU is conducted in the 10,000 class clean room environment at TUBITAK UZAY facility in April 2019. Before equipment level functional test, each board inside the PPCU is tested stand alone. Since the power processing board is a high-power unit, its testing and verification is possible only with a heat sink imitating the radiator structure on the satellite panel. For this purpose, a special ground support unit (GSU) is developed specifically for the functional tests. Power Processing Board placed on GSU is shown in Figure 11.

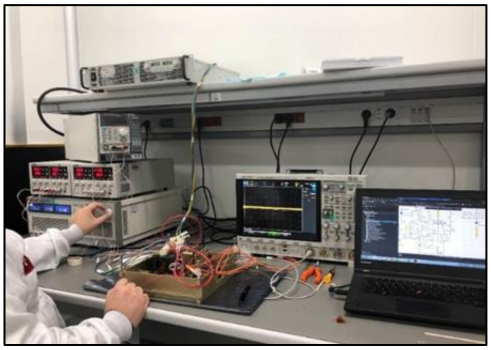

Figure 11 Power Processing Board in GSU

During the equipment level functional tests, all internal and external interfaces are tested. Electronic loads are utilized for the interfaces with the anode and cathodes of the HET. The functional test setup is shown in Figure 12. A special test board is manufactured for representing electronic valves, pressure sensors, heaters and thermistors of the Xenon Feed Unit. Considering the interfaces with the Satellite Management Unit, a MIL-STD-1553 simulator and a test board for the discreet line interface are used. Finally, a commercial power supply is utilized representing Power Subsystem of the satellite with 100 V voltage and 18 A ratings. Considering the maximum operation time of the EPS on the satellite, the unit is operated for one hour during the tests.

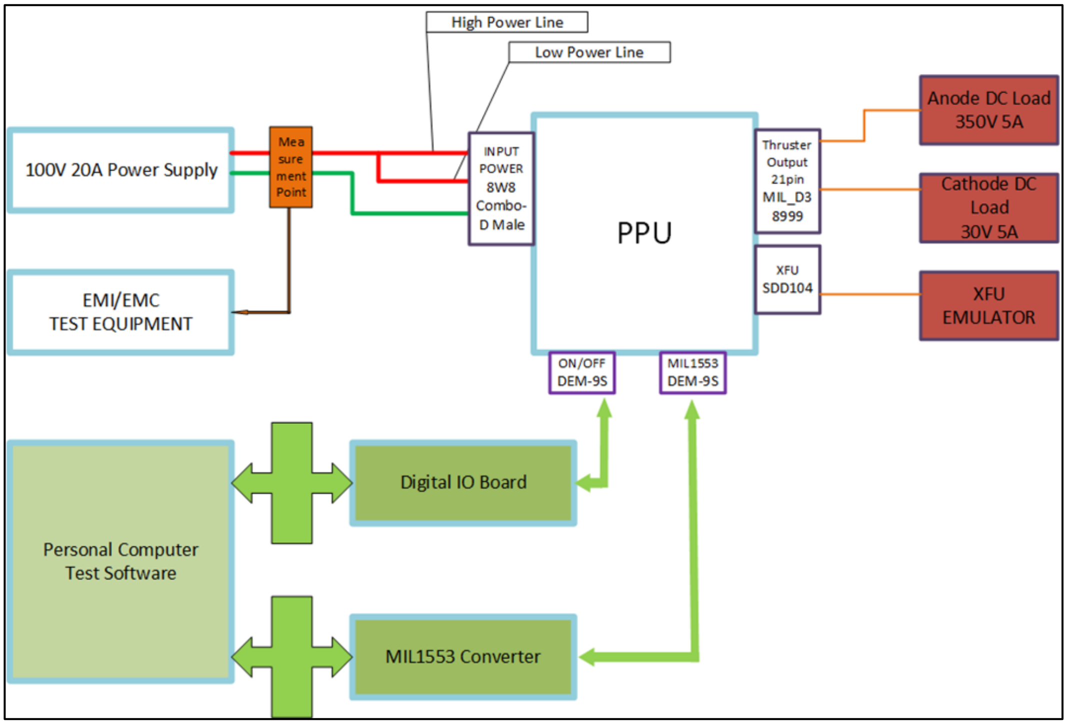

Figure 12 Test Setup for PPCU Functional Test

G. EMC Test Results

The qualification model of the PPCU is tested in terms of EMC to ensure that it can function and perform nominally without any malfunction and deviation beyond the tolerances and does not interfere with the satellite system. The EMC tests are performed according to MIL-STD-461F and tests and limits for space systems are applied. The tests are carried out in clean room environment which is TÜBİTAK UZAY's own facility (Figure 13). Radiated tests are conducted in a EMC test chamber of Turkish Aerospace Space System Integration and Test (USET) facility (Figure 14). The applied EMC tests are listed in Table 8.

In CS101 test, hot power leads are subjected to interference voltage. The level given in standard is tailored to system requirements and increased to $6V_{rms}$ for whole frequency band. The PPCU exhibits malfunction because the fault in the test software which applied voltage level of $10V_{rms}$ to the lead due to the impedance degradation of power lead that is occurred from the high power operation of the PPCU. As a result of this problem the fuses of the PPCU which protect the DC/DC convertors from high currents are destroyed. The test is performed again and the PPCU does not exhibit any degradation of performance and successfully passes.

Figure 13 Conducted Type EMC Test Setup

In MIL-STD-461F, CS114, CS115 and CS116 tests are intended to simulate the environmental effects in space. The interference signal levels for space systems are injected to all interconnected cables including power cables. The PPCU does not exhibit any malfunction, degradation of performance or deviation beyond the tolerance during and after the tests.

Radiated tests are performed in semi anechoic chamber of EMC test facility. RE102 limit is tailored to 70dBμV/m due to neglect the ambient noise of auxiliary equipment. System level analyses show that 20dB RE/RS margin which is defined in ECSS- E- ST- 20- 07C for safety critical equipment is still satisfied with the tailored limit. Emission level of the equipment does not exceed 70dBμV/m. RE102 test results are presented in Figure 15 and Figure 16.

RS103 test is implemented and the equipment is sustaining its operational functions properly during and after the test period. Although the electric field level for equipment which is located inside the main frame is specified as 1V/m in ECSS- E- ST- 20- 07C, PPCU is subjected to 20V/m radiated electric field according to MIL-STD-461F RS103 test. The PPCU withstands with exaggerated electric field level even though it is expected that it is not estimated to be exposed to this radiated field in space environment.

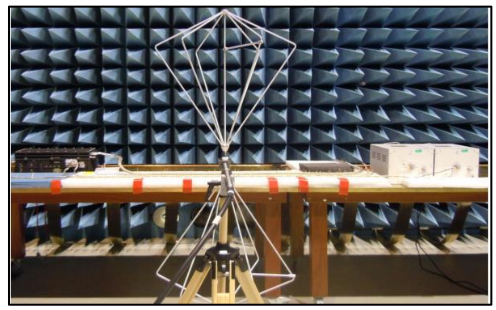

Figure 14 Radiated Type EMC Test Setup

Table 8 Applied EMC Tests

Tests	Frequency	Limit
CS101	30Hz-150kHz	$6V_{rms}$
CS114	10kHz-200MHz	curve 3 (MIL-STD-461F Figure CS114-1)
CS115	30 pulse per minute(impulse excitation)	5A
CS116	10kHz,100kHz,1MHz,10MHz,30MHz,100MHz	MIL-STD-461F Figure CS116-2
RE102	2MHz-1GHz	70dBμV/m
RS103	2MHz-18GHz	20V/m

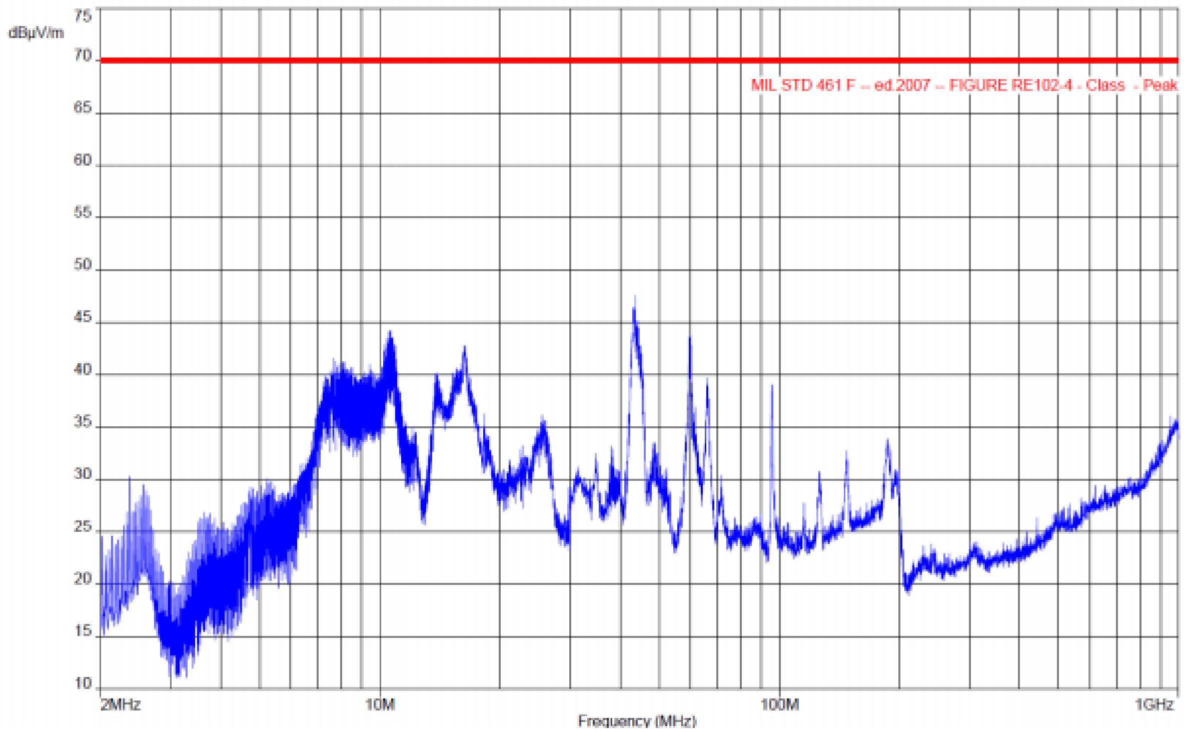

Figure 15 RE102 Test Result, 2 MHz – 1 GHz, Vertical Polarization

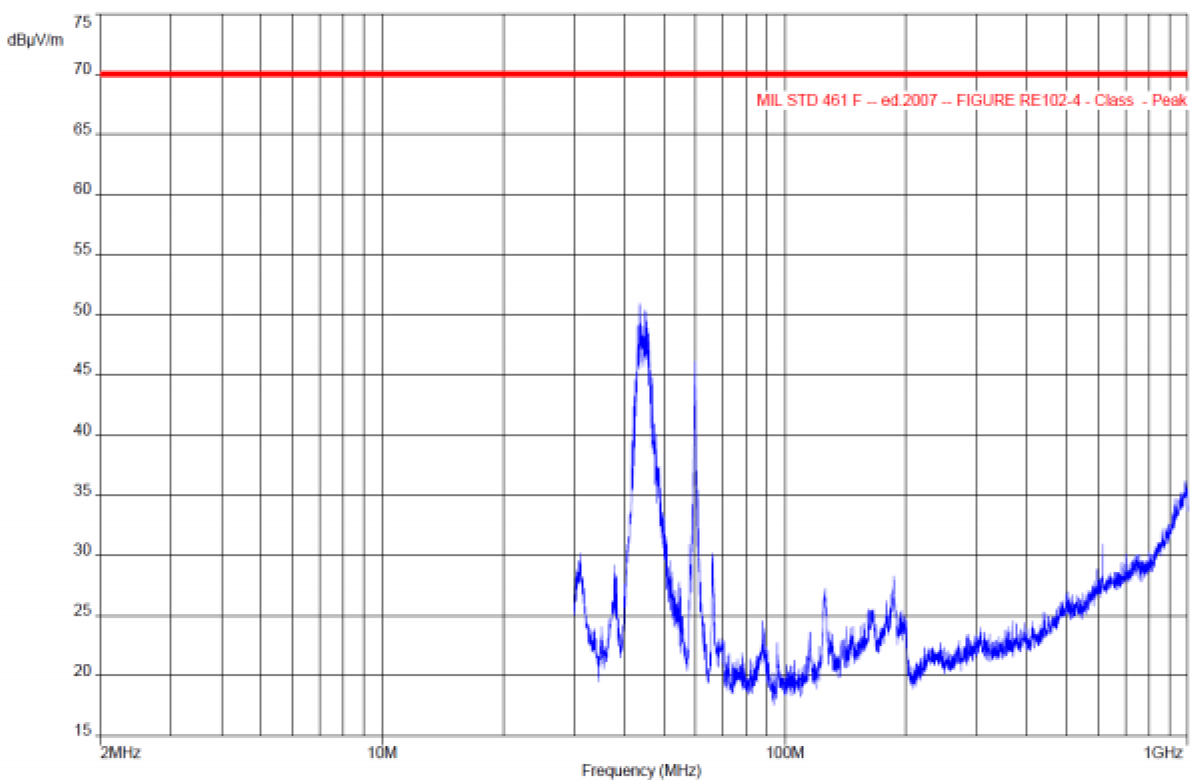

Figure 16 RE102 Test Result, 30 MHz – 1 GHz, Horizontal Polarization

IV. Conclusion and Future Work

In the scope of a Hall thruster development project by TUBİTAK UZAY (HALE Project), a Power Processing and Control Unit for a 1,5 kW Hall thruster system is developed and planned to be used experimentally onboard TURKSAT 6A platform. In this paper, electronic and mechanical design aspects of the unit is extensively explained. A qualification model is manufactured after successful prototyping process. This model has successfully passed functional and EMC tests. To finalize the control algorithm of the equipment, coupling tests with the Xenon Feed Unit are underway. After completing this process, the HET is planned to be included to the test setup for final integration testing. The structural and thermal vacuum tests are planned to be done in November 2019.

Acknowledgements

Authors would like to acknowledge the financial support of Turkish Ministry of Development for HALE Project, and TUBITAK KAMAG, Turkish Ministry of Industry and Infrastructure and TURKSAT Communication Company for TURKSAT6A Project.

References

Proceedings

[1]Uluşen, D., Aydın, B. Ç., Yurttas, Y., Çal, B., Tsybulnyk, A., Neugodnikov, S., Cherkun, O., Güllü, S., "Turkey's First Electric Propulsion System Developed in the Very First Electric Propulsion Laboratory: TUBITAK UZAY's HALE Project Outcome", *9th International Conference on Recent Advances in Space Technologies (RAST), June, 2019*

[2]Uluşen, D., Aydın, B. Ç., Gülle , İ. S., Yurttaş, Y., Cherkun, O., Dağ, B., "Electric Propulsion Activities at TÜBİTAK UZAY: Laboratory Work and Mission Plans" , *International Electric Propulsion Conference, Oct 9, 2017.*

[3]Aydın, B. Ç., Uluşen, D., Yurttaş, Y., Tsybulnyk, A., Neugodnikov, S., Çal, B., Güllü, S., Cherkun., O., "Status Update on the Electric Propulsion Subsystem of Turksat6A Communication Satellite", *International Electric Propulsion Conference, Sep 15-20, 2019.*

[4]Aydın, B. Ç., Uluşen, D., Gülle, İ.S., Yurttaş, Y., Cherkun., O., Tsybulnyk, A., and Neugodnikov, S., "TÜRKSAT6A Communication Satellite Electric Propulsion Subsystem Development Status", *International Electric Propulsion Conference, Oct 9, 2017.*

[5]Tsybulnyk, A., Neugodnikov, S., "Development of High Efficiency Power Processing Unit for Hall Thruster".*International Electric Propulsion Conference, Sep 15-20, 2019.*

[6]Cherkun., O., Uluşen, D., "Cesium Hollow Cathode with Internal Discharge and Gas Feed for Electric Propulsion Applications", *International Electric Propulsion Conference, Oct 9, 2017.*

[7]Neugodnikov, S., Tsybulnyk, A., "Design and Manufacturing of Control Unit for low and medium power Hall Effect Thruster".*International Electric Propulsion Conference, Sep 15-20, 2019.*

[8]Gülle, İ. S., Aydın, B. Ç., Uluşen, D., Yurttaş, Y.," Development Status of Xenon Feed Unit for Electric Propulsion Subsystem of TURKSAT6A Communication Satellite", *Space Propulsion Conference 2018, May 16, 2018.*