UNIVERSITY OF TARTU

Faculty of Science and Technology

Institute of Technology

Karl-Indrek Raudheiding

TESTING OF VOLTAGE CONVERTERS FOR THE ELECTRICAL POWER SYSTEM OF ESTCUBE-2

Bachelor’s Thesis (12 ECTS)

Supervisors: Mihkel Pajusalu PhD

BSc Erik Ilbis

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Abstract

The focus of this thesis is to design a testing platform which helps to thoroughly test voltage converters for the electrical power system of ESTCube-2. The first part will focus on developing this platform, the second part will focus on designing voltage converter testing modules and the third part will focus on measuring the efficiency of these modules. The modules were also tested in current balancing mode. The best overall performance was seen by the LTC3603 voltage converter.

Table of Contents

List of figures

Acronyms and abbreviations

ADC – analog-to-digital converter

CAD – computer-aided design

COM – Communication port

CSV – Coma-separated values

EPS – electrical power system

HTSSOP – Heat-sink Thin-Shrink Small Outline Package

LED – Light-emitting diode

Li-I battery – Lithium-Ion battery

LUFA – Lightweight USB Framework for AVRs

MOSFET – metal-oxide-semiconductor field-effect transistor

MCU – microcontroller unit

QFN – Quad Flat No-leads package

USB – Universal Serial Bus

1. Introduction

The preparations for Estonia's first satellite ESTCube-1 started in the summer of 2008. The project was a collaboration between students from the University of Tartu, Estonian Aviation Academy, Tallinn University of Technology and University of Life Sciences. After hard work it was finally finished and launched to the low Earth orbit on May 7-Th, 2013 [1]. The main mission of ESTCube-1 was to test the electric solar wind sail [2]. [3]

ESTCube-2 and ESTCube-3 are the successors to the ESTCube-1 project. ESTCube-2 will be launched to Earth's orbit and has the main goal to test the electric solar sail technology further. Compared to ESTCube-1, the new satellite will be larger and with increased electrical energy production capabilities. As there are more subsystems on-board, the demand for electricity is also higher.

The EPS is a subsystem that provides electrical power to all the other subsystems on-board the satellite. It is responsible for harvesting, storing and distributing electrical power. Electrical power has to be regulated very efficiently as the resources are limited. Previously developed ESTCube-1 electrical power system (EPS) is not sufficient for this task. Therefore an improved EPS has to be designed. Due to harsh operating environment thorough testing and evaluating for all the components of the EPS is indispensable. This thesis will focus on the testing of the voltage converters for the EPS.

The main goals of this work are to:

- design a device to test the voltage converters;
- choose best voltage converter candidates for the satellite;
- design and manufacture voltage converter test modules compatible with the testing platform;
- demonstrate that the device is capable of testing these converters.

2. Overview

2.1 Overview of the ESTCube project

ESTCube-1 is a one unit CubeSat measuring roughly 10 x 10 x 10 cm and weighing 1.05 kg [4]. The aim of developing the CubeSat standard was to lower the cost and deployment time of the picosatellites by standardization the design. [5]

At the time of writing this thesis, ESTCube-1 has been in Earth's orbit over two years [3]. It has proven to survive the hostile environment of space and given valuable experiences for future missions. Most of the systems on-board the satellite have proven their reliability. The EPS has fulfilled the expectations subjected to it. The attitude determination and control system was successful in spinning the satellite up to the desired speed needed for the experiment of deploying the solar wind tether. The electron gun needed to charge the tether was proven to work. Unfortunately, due to a mechanical failure in the deployment system of the electrical solar wind sail, the tether could not be unreeled and the experiment of testing the sail could not be performed.

The successful launch of ESTCube-1 laid the foundation for planning ESTCube-2 and ESTCube-3 missions. ESTCube-2 will test the sail in Earth's orbit providing information needed to prepare for the ESTCube-3 mission. ESTCube-3 will test the electrical solar wind sail in outer space away from Earth's magnetic field. The preparations for ESTCube-2 have started and the aim is to build a three unit CubeSat. The expanded size will also set higher requirements on EPS.

2.2 Overview of the ESTCube-1 EPS

ESTCube-1 EPS consists of energy harvesting, storage and distribution systems, various release switches and magnetic actuator drivers. They are connected together through the main power bus, which is a battery-stabilized unregulated power rail. The energy storage system uses two one-cell Lithium-Ion (Li-I) batteries. The power distribution unit is responsible for providing the other subsystems with regulated electrical power. There are different voltage lines for 3.3 V, 5 V and 12 V supply voltage. The 3.3 V and 5 V lines use LTC3440 high efficiency buck-boost switching converters from Linear Technology for maximum output current of 0.6 A for the 3.3 V line and 0.9 A for the 5 V line. The 12 V line uses LM2700 boost switching converter from National Semiconductor for maximum output current of 1.3 A. [4]

The EPS of ESTCube-1 uses voltage converters in hot-redundant mode to improve the reliability of the system which means that each regulated voltage line has two converters working in parallel. The outputs are connected together via low voltage drop diodes. The feedback for the voltage converters is taken from the diode output to compensate the voltage drop over the diode. The double-redundant system achieved average efficiency of 85% but it was proposed that specialized power summing chip could improve it further. [6]

Compared to ESTCube-1, the new, larger satellite demands more power. Therefore more powerful voltage converters are required. While ESTCube-1 used single-cell Lithium-Ion batteries for energy storage, ESTCube-2 will use two cells in series and therefore operate on higher main power bus voltage (6 V to 8.4 V). Since the required output voltages remain the same (3.3 V and 5 V), only buck converters can be used. Due to their mission-critical application, the converters need to be thoroughly tested in order to validate their suitability for the application in question. To aid this process a voltage converter testing platform should be designed.

3. Voltage converter testing platform

There are many critical aspects that need to be considered when choosing voltage converters for the EPS of a satellite. In space environment, dealing with excess heat is complicated and therefore high efficiency of voltage converters is very important. The reliability is another critical aspect as there is no means to fix an electrical malfunction after the launch of the satellite. To thoroughly conduct all the tests required to improve the probability of a successful mission an aiding platform is needed.

3.1 System requirements

During planning of the testing platform following requirements were set:

- Capability to monitor both 3.3 V and 5 V converters
- Real-time efficiency monitoring
- Operating with input voltage of 6 V to 8.4 V
- Socket for quickly swapping converter test modules
- Terminal blocks to connect input power source and output load
- Flexible setup (jumpers to bypass or disable components)
- Closely emulate the real planned system on-board the satellite (redundant design and load balancing)
- Operating two converters in parallel while measuring the efficiency of load sharing circuit
- Capability to measure maximum output current of 2 A for a single converter
- Capability to measure maximum output current of 4 A for two converters in parallel

3.2 Hardware

The voltage converter testing board was designed with EAGLE CAD software. It uses 4-layer construction and the physical size is 95x75 mm. The general overview of the board can be seen on the fFigure 1.

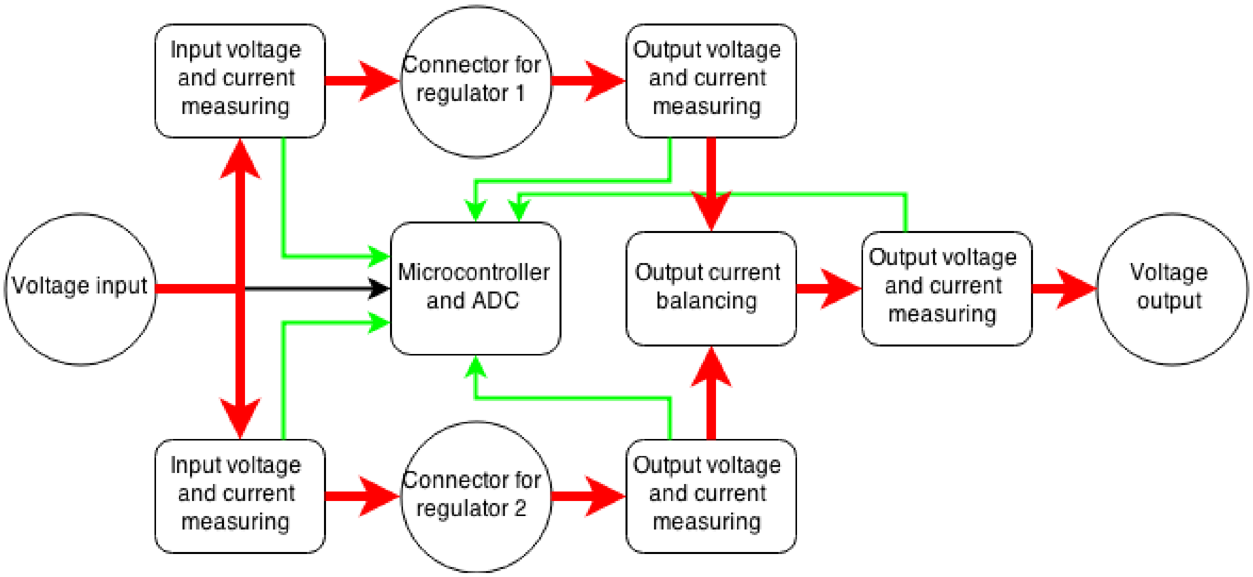

Figure 1. The general overview of the converter testing board (red arrow mark the route of testing current, green arrows mark the analog measurements).

The system is controlled by an Atmel ATmega32u4 [7] microcontroller (MCU). Mostly because it was previously familiar to the author of this work and it supports the Universal Serial Bus (USB) connection. The MCU and other devices along with the analog-to-digital converter (ADC) are powered by a general purpose 5V low dropout voltage converter AP1117E50G-13 from Diodes Inc. For analog measurements there is MAX1230 [8] ADC form Maxim Integrated. It is a 16-channel 12-bit ADC capable up to 300ksps sampling rate. The ADC uses MAX6145 [9] 4.5 V voltage reference from the same company.

For measuring efficiency of a converter, both input and output power has to be known. To calculate the power running through the circuit the voltage and current has to be measured. A voltage divider circuit was used, as voltages beyond the voltage reference of the ADC have to be measured. To measure the current in the circuit, a high precision current sense amplifier LT6105 from Linear Technology was used.

To protect the device and converters form excessive load condition (short circuit at the output terminal for example), an FPF2700 adjustable over-current protection load switch from Fairchild Semiconductor was added before converters. The maximum load of 2.5 A was set by resistor. The switch also enables to manually cut power form the converters. It is possible to cut power while changing the converter connected to the testing platform and it also gives possibility to simulate a converter failure while testing load sharing mode. This load switch could also be used on the satellite as it has good total ionizing dose tolerance which means it should show resilience to higher radiation in space [10].

The testing platform also includes LTC4370 current balancing controller [11] from Linear Technology. The device lowers the load subjected to a single voltage converter by balancing it between both converters while still preserving the advantage of hot-redundancy. The ideal diodes are connected in parallel with traditional low voltage-drop Schottky diodes (DB2430700L from Panasonic). The setup is flexible and can be altered. With jumpers, the balancing circuit can be manually enabled or disabled, the Schottky diodes can be connected or the whole system can be bypassed. By default, the Schottky diodes are disconnected and the current balancing system is controlled by the MCU.

The final design of the testing platform can be seen on Figure 2. The schematics are added in appendix 1.

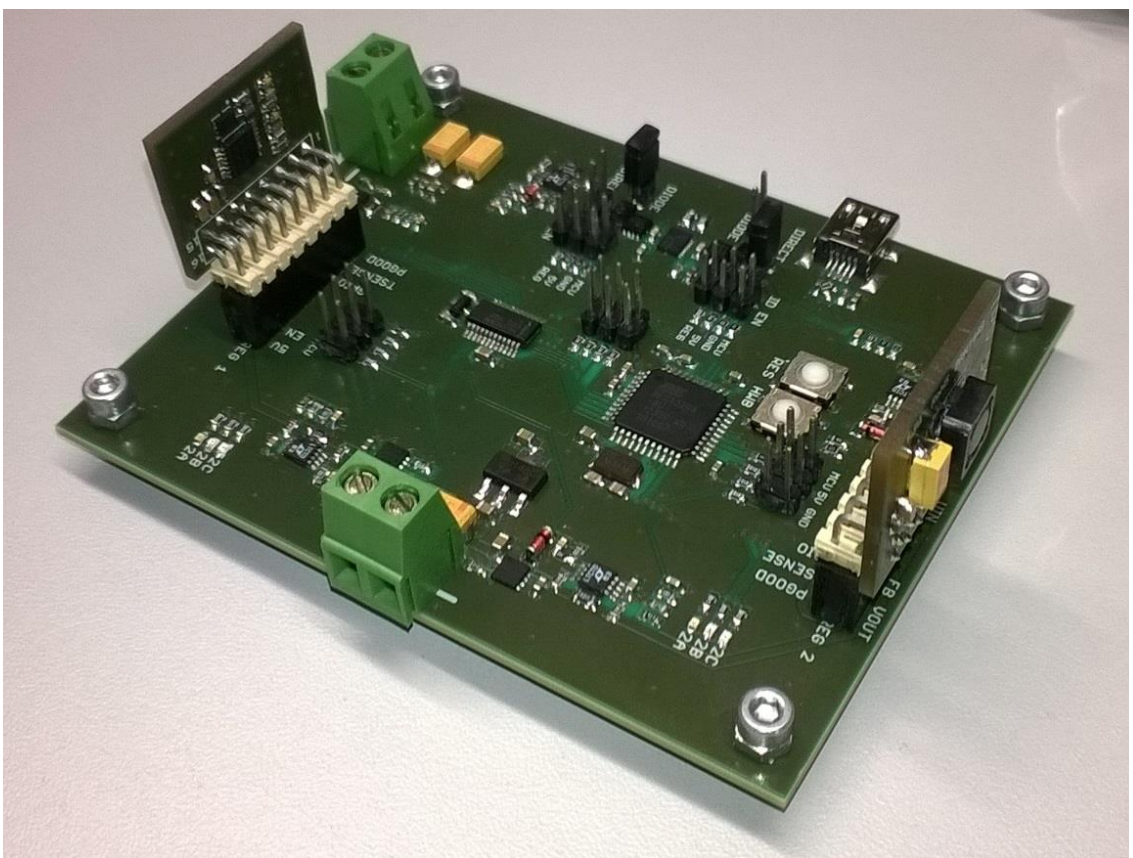

Figure 2. The testing platform and two converter testing modules connected to the device.

3.3 Software

The software consists of two components: low level logic on the device and PC based control and monitoring interface. The device is connected to the computer via a USB cable. The device uses Lightweight USB Framework for AVRs (LUFA) drivers which emulate a Communication port (COM) on the microcontroller. The data is exchanged between the testing platform and the PC interface by the determined packet structure shown on the Figure 3. The packet starts with a synchronization byte which is followed by command byte. The command byte determines how much data is expected. If there are two synchronization bytes after expected amount of data bytes the packet is considered valid. Otherwise the packet is discarded and a new packet starting bytes are searched.

Synchronization byte	Command byte	Data byte	. . .	Synchronization byte	Synchronization byte

Figure 3. The packet structure.

3.3.1. The low level logic

The low level logic on the device was programmed in C. The software on the device is passive and only reacts to commands received from the controlling interface. As the device performs basic tasks, such as measurement data collection, data transmission and switching various devices, two basic commands are to “toggle state” and to “get data”.

The “toggle state” command has one parameter and depending on the parameter one of the following state is changed:

- Light-emitting diode (LED) 1 - 6
- Enable pin of either voltage switch 1 or 2
- Enable pin of either converter 1 or 2
- Enable pin of either cannel 1 or 2 on the two ideal diode chip

The “get data” command returns a packet of current states set and raw data form ADC. The data in the packet is structured as follows:

- One byte of states of the LED-s.
- One byte of states of the switches, converter and ideal diode chip enable pins.
- 8 bytes of converter 1 voltages and current readings from ADC
- 8 bytes of converter 2 voltages and current readings from ADC
- 4 bytes of output voltage and current readings from ADC
- 4 bytes of converter 1 and 2 temperature sense pin voltage readings from ADC

When any other command is received an error message is returned.

3.3.2. PC based control and monitoring interface

The controlling and monitoring interface was written in Java and is based on the backend used in the EPS control and monitoring interface of ESTCube-1 [6]. The programm runs 3 threads which is illustrated on Figure 4.

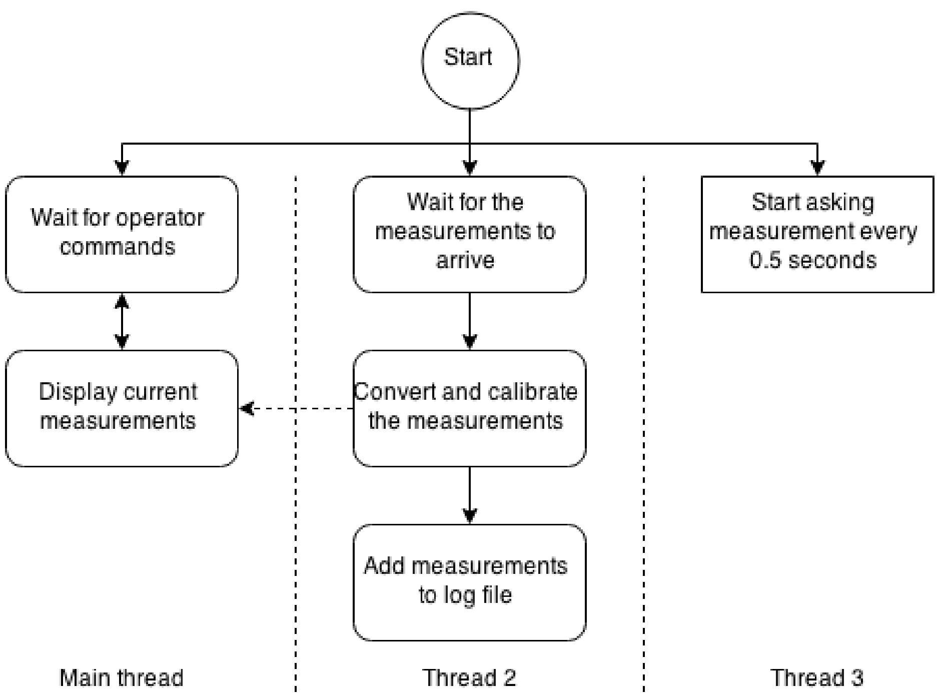

Figure 4. Flow chart of the PC based control and monitoring interface.

The main thread shows current values on the screen and processes the operator commands. The interface is shown on the Figure 5. All the buttons on the screen also act as indicators being colored when they are set and gray when they are not set. The LED statuses are irrelevant at this stage but in course of further development can easily be tied to indicate certain events like fault signals from load switches (electrically connected to MCU) if needed. In the upper left corner there is an indicator text "device" which is green when the USB connection to the device is activated and red when it is not.

Second thread manages the incoming data. When a packet is received it is first validated by checking the length of the packet and synchronization bits. Next the raw data from ADC is converted to human readable values by functions described in the calibration section. These values are saved for the main thread to display them on the screen. If the logging function is activated the measurements are also saved to the log file. The log file is a Coma-separated values (CSV) file which can be easily analyzed in different data analyzing environments.

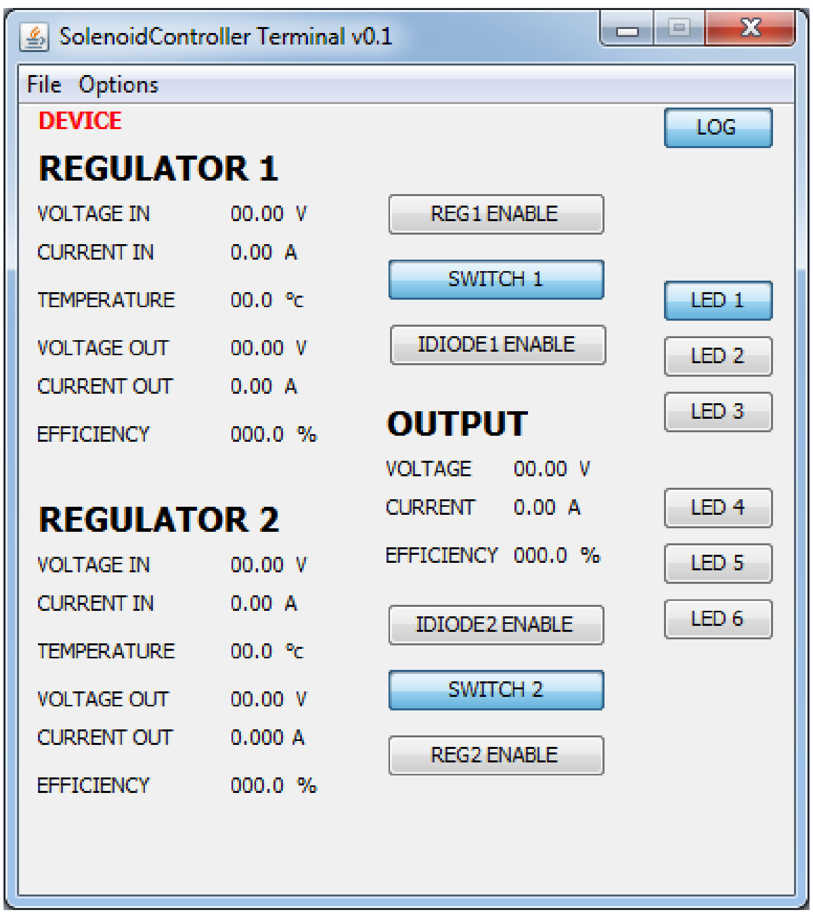

Figure 5. PC based monitoring and controlling interface.

The third thread is a relatively simple thread which only asks new data from the device by sending the “get data” packet. The data is asked periodically after set time which can be easily changed. In this case it was set to ask new data every 0.5 seconds.

3.4 Calibration

All the measurement circuits had to be calibrated to ensure correct results. For the calibration Tektronix DMM4050 6.5-digit precision multimeter and TTi QL355TP two channel power supply were used.

To calibrate the voltage readings a wire was soldered to every voltage measurement point, both voltmeter and ADC readings were recorded on specific voltage levels throughout the range. Voltage was determined from the ADC readings using a linear function.

The readings of current sense amplifiers were calibrated as shown on the Figure 6. Wires were soldered to each side of the shunt resistor. The circuit consisted of a power supply, a load resistor, an ammeter and a shunt resistor. Power supply was operated by setting the current limit and increasing it step by step. Load resistor was needed to increase the voltage subjected to current sensing circuit. ADC readings from the current sense amplifier and ammeter were recorded up to saturation point of the current sensing amplifier. The saturation point, which determines the maximum current measurement, was reached at 4 A at the load balancing circuit output and at 2.2 A in other current measurement points. This proves that the testing platform meets the requirements in current measuring. Current was then determined from the ADC readings using linear function.

A special attention must be paid designing the current sensing amplifier circuit. When using very low value shunt resistor (in this case 15 mΩ and 7.5 mΩ), the copper resistance of the traces is considerable and adds to the shunt resistor value. In the future designs special calibration test points should be added.

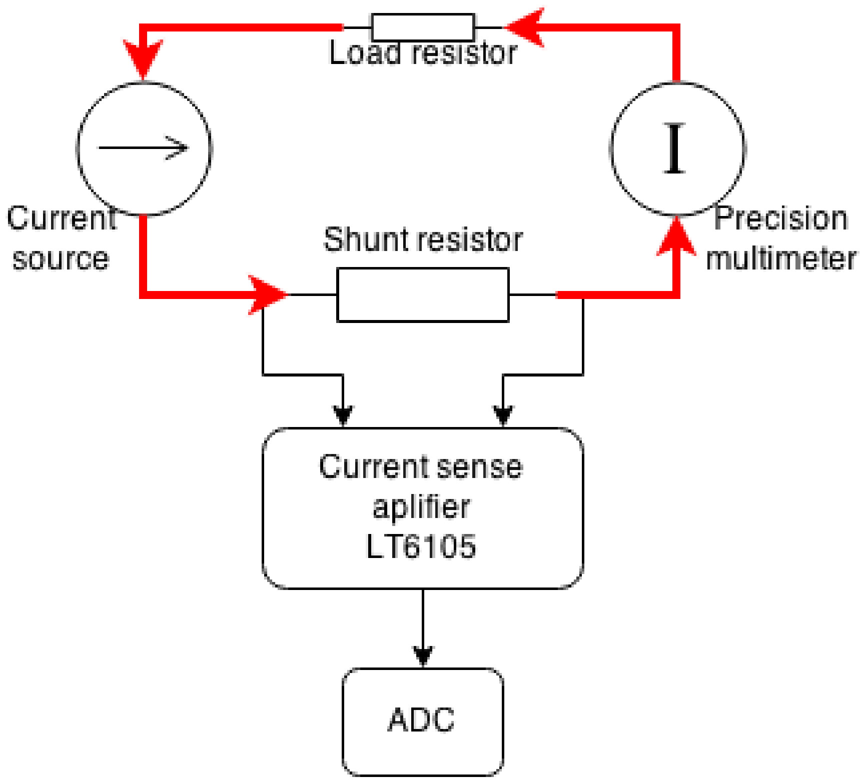

Figure 6. Current sense amplifier calibration circuit.

4. Voltage converters

During the first stages of planning the EPS following requirements to voltage converters was set:

- Are configurable to both 5 V and 3.3 V output voltages
- Manage the maximum output current of 2 A
- Work with input voltage of 6 V to 8.4 V
- Have high efficiency over the whole output current range
- Maximum efficiency should be achieved as fast as possible
- Should be available in a package with good thermal performance (Quad Flat No-leads (QFN), Heat-sink Thin-Shrink Small Outline Package (HTSSOP), etc.)
- Small packages are preferable
- Have as low electromagnetic noise emitting as possible

For efficiency reasons only switching converters were considered as in the design of ESTCube-1 [6]. More specifically, synchronous switching converters were considered. While asynchronous converters use diode between the inductor and ground, synchronous converters use metal-oxide-semiconductor field-effect transistor (MOSFET) switches eliminating the forward voltage drop of the diode. Therefore they are more efficient [12]. This difference is illustrated on Figure 7.

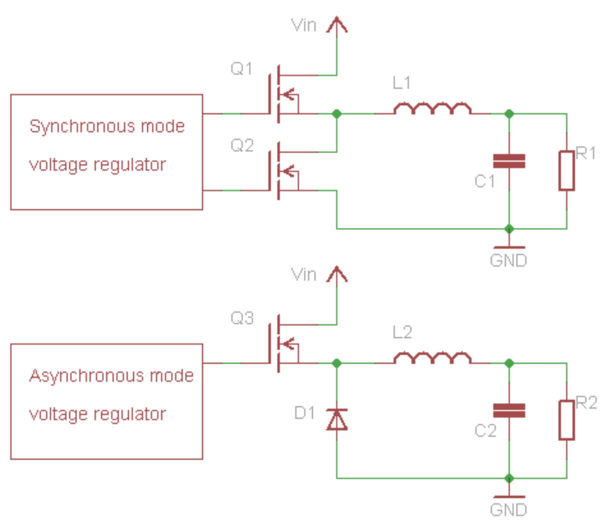

Figure 7. Synchronous and asynchronous mode converters.

To further improve the efficiency over the whole regulation range different manufactures have used various technologies. Linear Technology converters may include Burst Mode operation which lowers the switching frequency of the converter at lighter load condition [13]. Some converters even turn off parts of the circuitry between the bursts to reduce the power consumption of the device [14]. Texas Instrument's converters use a similar method which is called Auto-Skip mode and improves the efficiency at lighter loads [15]. Converters utilizing these technologies were preferred.

For testing, two different types of converters were selected: converters with internal power switch and converters with external power switch. There are advantages to both converter types. Converters with integrated power switching have smaller footprint as they need less external components. Converters with external power switching have the advantage of being able to use desired switching transistors. As external MOSFETs are used, higher currents can be switched and the converter chip generates less heat as most of the heat is dissipated on the MOSFETs. Transistors in packages with good thermal performance should be used.

To make sure that voltage converters would not interfere the communications with electromagnetic noise, it was decided to use switching frequency up to 500KHz. Lower switching frequencies mean a larger value inductors must be used. To reduce the radiated noise shielded inductors were used. Inductors were placed as close to the converter chip as possible as it reduces the EMI [16].

Among many candidates a selection of four converters was made. One converter with external switching: TPS51117 [15] from Texas Instruments; and three converters with internal switches: TPS54228 [17] from Texas Instrument, LT8614 [14] and LTC3603 [18] from Linear Technology.

All of the selected converters showed great efficiency at datasheet and all of them had features to reach high efficiency at light load. TPS54228 and TPS51117 had the feature of auto-skip mode [15] [17]. LT8614 and LTC3603 both benefited from the Burst Mode operation. With the TPS51117 the Vichey SQA410EJ MOSFETs could be tested.

Based on the above-mentioned chips and design considerations testing PCB-s were designed and manufactured. The PCB-s were designed with Altium Designer software as all the other satellite electronics which provides opportunity to re-use all the previous work. Two sets of four separate testing modules were manufactured and tested. The schematics has been added to appendix 2. Two converter testing modules can be seen connected to the testing platform on the Figure 2.

5. Testing

Testing of the voltage converters using the testing device was relatively simple task, testing 4 different converters in 3 different voltages and 2 different setups (24 tests) took only about 40 minutes. As speeding up the testing process, the system fulfilled one of the main goals of the testing platform. The voltage converter tests were conducted with constant input voltage, 5 V output voltage and the efficiency graphs were created by changing the load subjected to the converter. TTi QL355TP power supply with desired voltage was connected to the input of the testing device. TTi LD300 DC electric load was connected to the output of the testing device. Changing the converters and the load subjected to the converters were only manual operations the operator was required to do. If needed, load changing could also be automated in the future, further improving the convenience of the testing process.

In the first setup one converter was inserted into the testing board. After changing the load through the desired range, the software had collected all the data in a CSV file and it was ready to be analyzed. The tests were repeated on different input voltage levels to simulate different charge levels of the battery on the satellite (8.4 V – full charge, 7.4 V – nominal charge, 6.6 V – low charge). In the second setup the converters were subjected to the same conditions but two identical converters were working in parallel implementing the load sharing.

5.1 Single converter test

In the first setup the converters were tested in the range of up to 2.1 A load. Based on the data XY-plots (Figure 8, Figure 9 and Figure 10) were generated comparing the efficiency at different load levels.

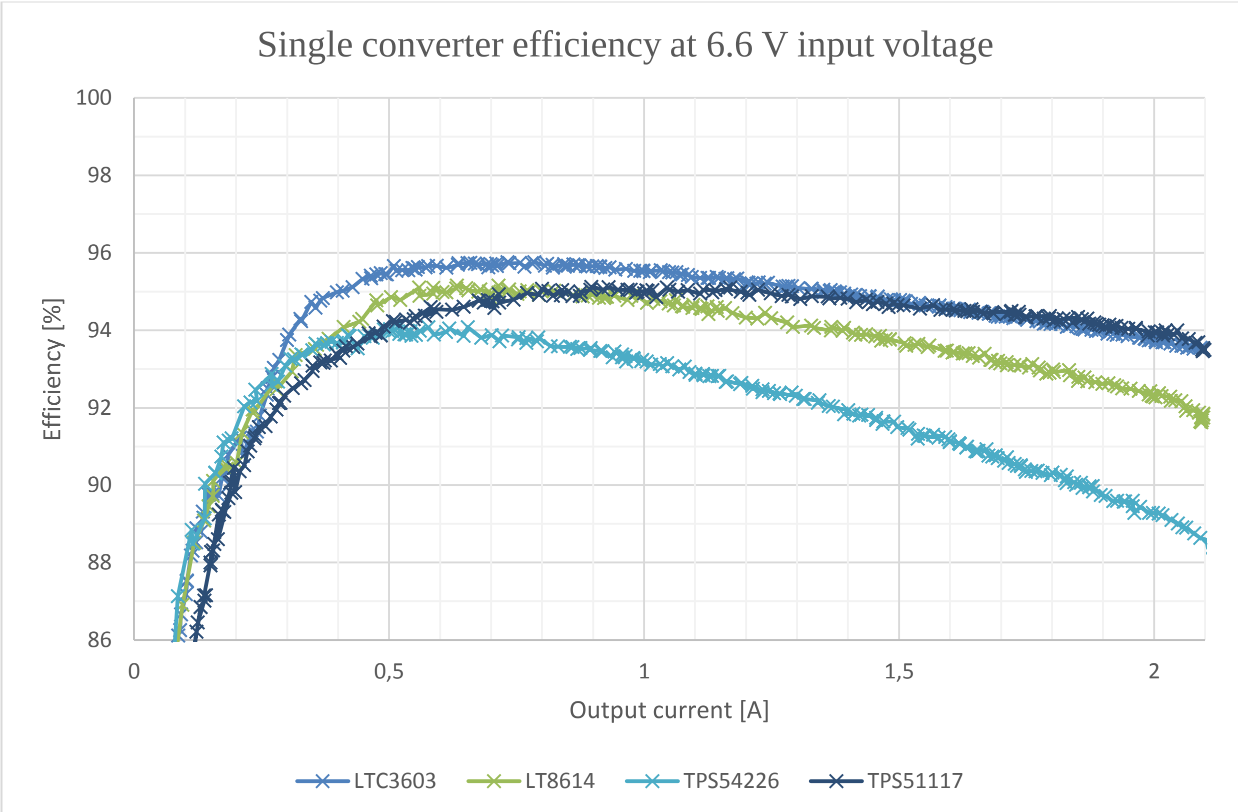

Figure 8. Single converter efficiency at 6.6 V input voltage (5 V output voltage).

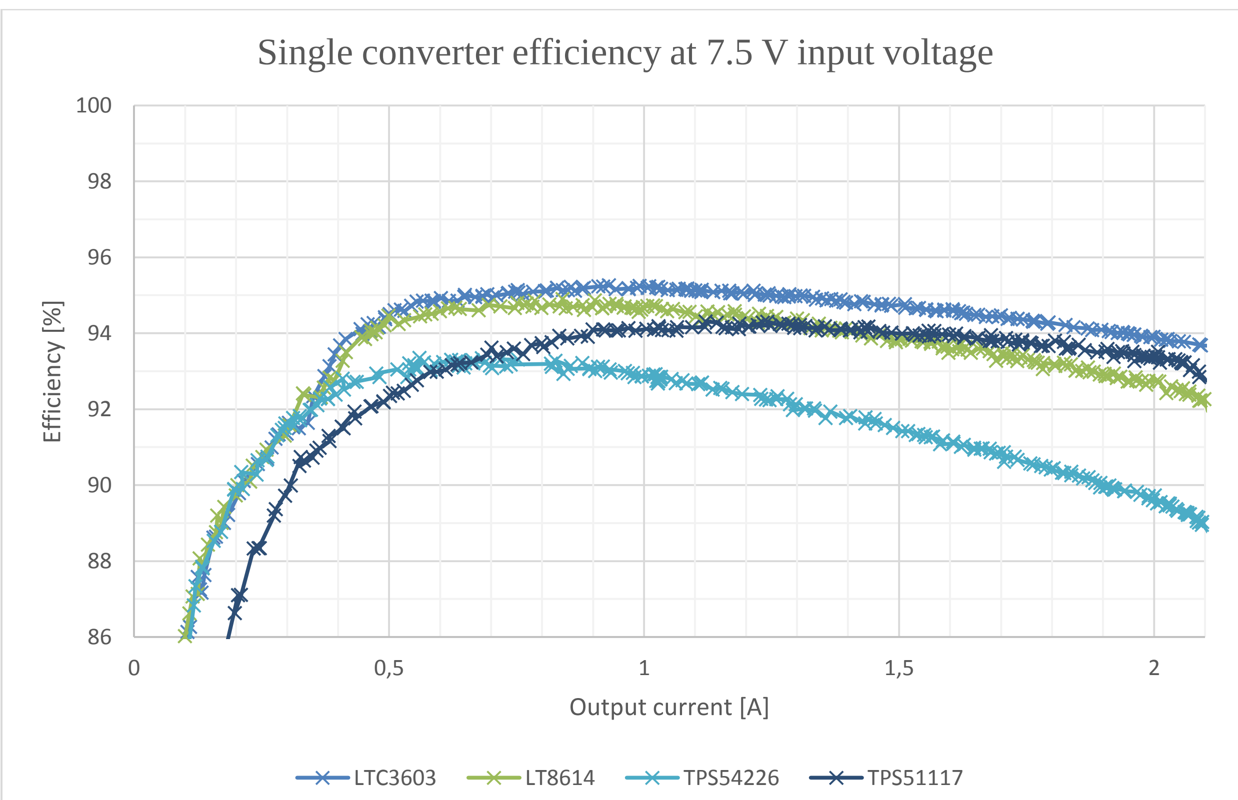

Figure 9. Single converter efficiency at 7.4 V input voltage (5 V output voltage).

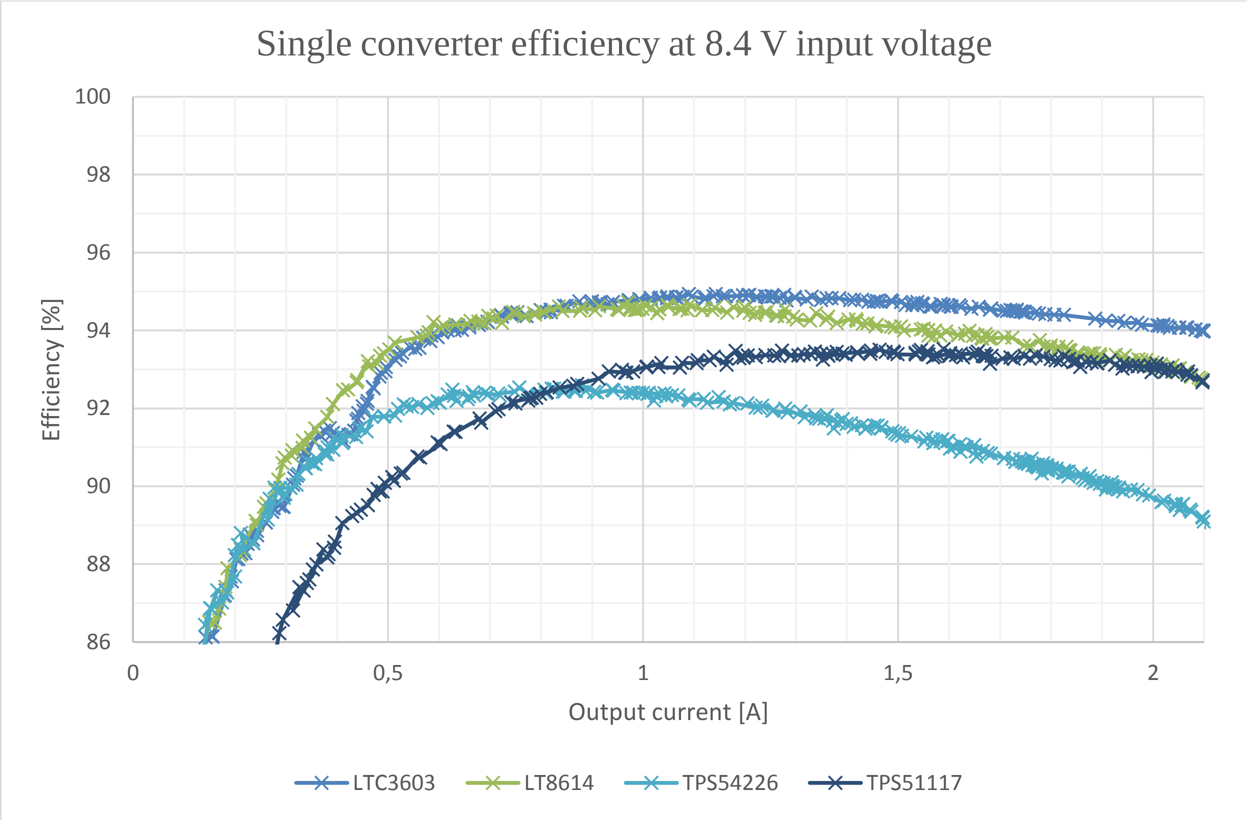

Figure 10. Single converter efficiency at 8.4 V input voltage (5 V output voltage).

Based on the plots following conclusions can be made:

- LTC3603 showed best peak efficiency at every input voltage level;
- At input voltage of 6.6 V and 7.4 V all the converters with internal MOSFETs reached 90% of efficiency near the load of 0.2 A and at 8.4 V input level near the load of 0.3 A;
- TPS51117 with external MOSFETs is slowest to gain efficiency over 90%.

5.2. Converters in load balancing mode

In current balancing mode total load, up to 3.5 A, was divided by two converters working in parallel. For every input voltage range a XY-plot was generated showing the system efficiency at different loads. System efficiency is calculated by dividing output power of the balancing circuit by the sum of input power of both converters. The results can be seen on Figure 11, Figure 12 and Figure 13.

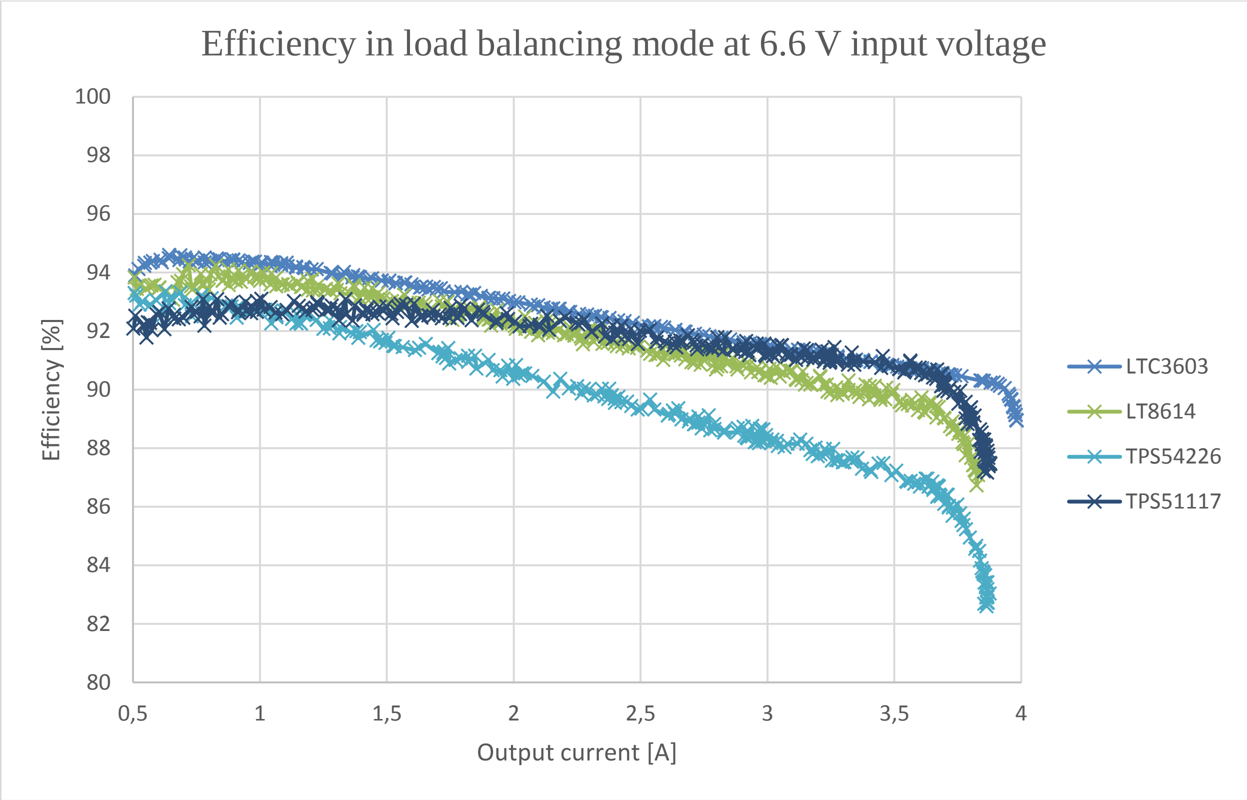

Figure 11. Efficiency in load balancing mode at 6.6 V input voltage (5 V output voltage).

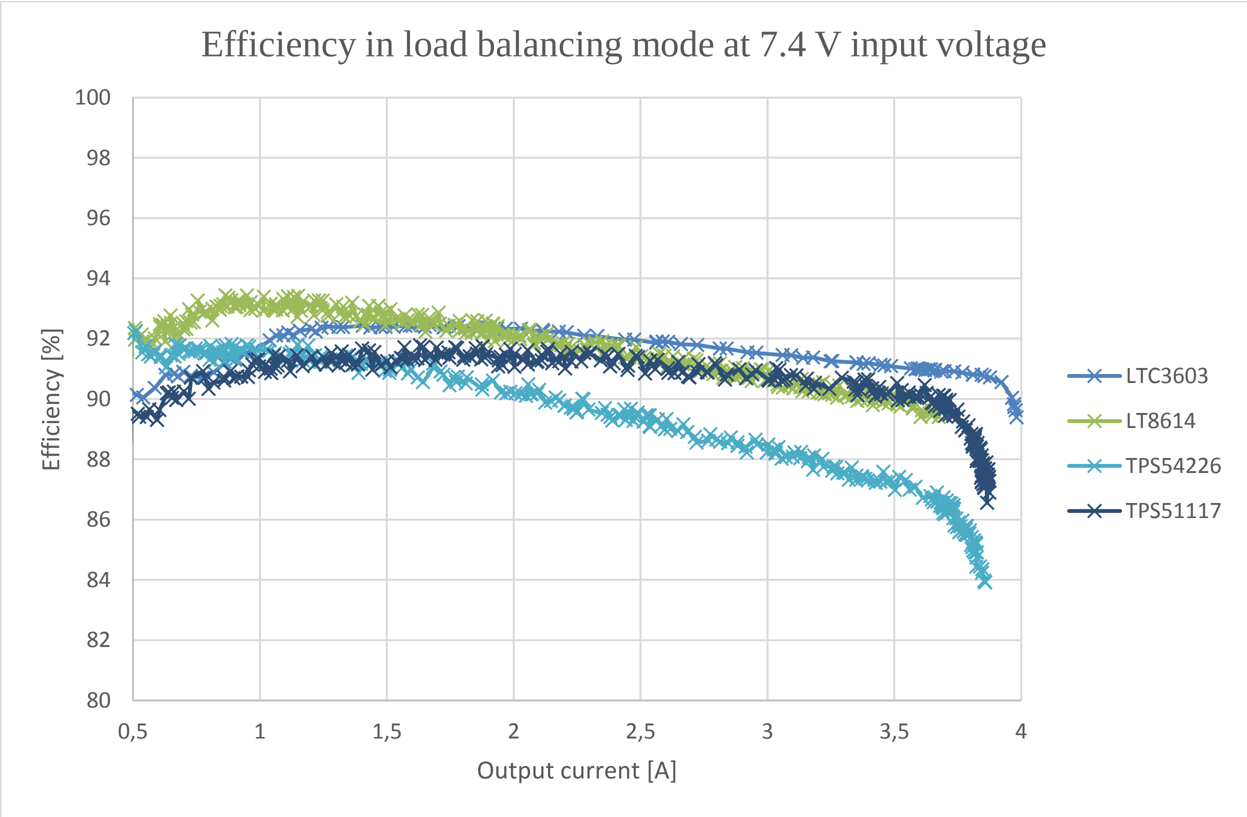

Figure 12. Efficiency in load balancing mode at 7.4 V input voltage (5 V output voltage).

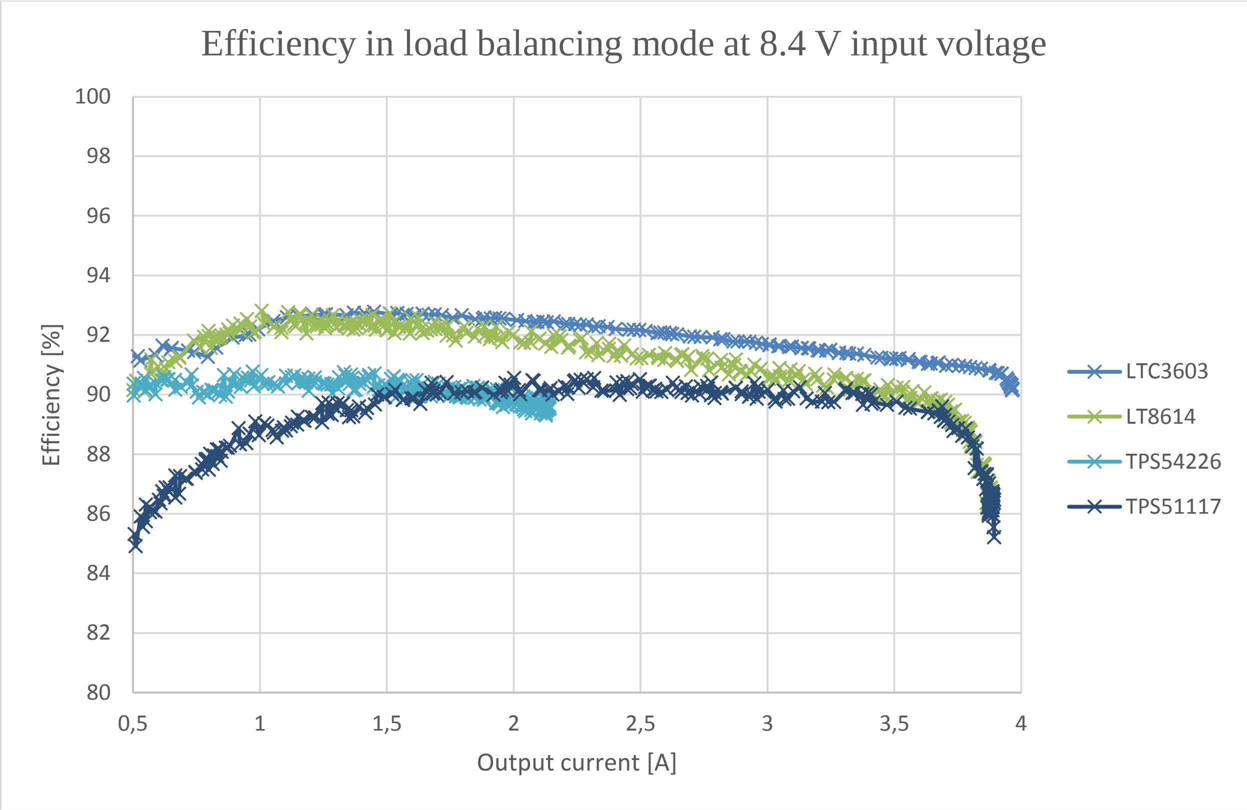

Figure 13. Efficiency in load balancing mode at 8.4 V input voltage (5 V output voltage).

Based on these tests following conclusions can be made:

- There is more noticeable efficiency drop in heavier loads when operating with input voltage level near the output voltage level;
- The LTC3603 shows the smoothest performance with the balancing controller from the same company.

6. Conclusion

The goal for this work was to aid the process of designing EPS for ESTCube-2. The larger satellite needs more power and therefor the EPS of ESTCube-2 in not sufficient. During the process of this work following goals were achieved:

- Easy to use testing platform to speed the testing of voltage converters was designed and manufactured;
- Software to control and record data from this platform was designed;
- The measurement range of the testing platform was validated and calibrated;
- Four voltage converter testing modules were designed and manufactured;
- Efficiency of these converters was measured;
- Efficiency of these converters in load balancing mode was measured providing data of the efficiency of balancing circuit;

The data collected from both tests provides valuable information for future tests. Based on current data, the best overall performance was seen with the LTC3603 voltage converter. The same chip also showed the smoothest performance with the load balancing circuit. The testing will continue after defending this thesis. Further testing must be concluded to determine parameters like converter output ripple, emission of EMI and behavior in temperature chamber.

7. Kokkuvõte

ESTCube-2 elektrienergia alamsüsteemi pingeregulaatorite testimine

Selle töö eesmärgiks oli aidata kaasa ESTCube-2 nanosatelliidi elektrienergia alamsüsteemi disainimisele luues testimisplatvorm erinevate pingeregulaatorite testimiseks. Kuna loodav uus satelliit on oma eelkäijast, ESTCube-1'st, oluliselt suurem ja vajab rohkem energiat, siis eelmine elektrienergia alamsüsteem pole selleks piisav. Selle töö käigus saavutati järgnevad eesmärgid:

- valmis lihtsasti kasutatava testplatvormi disain ning see sai ka valmis toodetud;
- testplatvormile sai valmistatud tarkvara, mis võimaldab platvormi juhtida ning testi tulemusi talletada;
- testplatvormi mõõtepiirkonnad said kontrollitud ning kalibreeritud;
- valmis nelja pingeregulaatori testmoodulid;
- nende regulaatorite efektiivsused said mõõdetud;
- mõõdetud sai ka nende regulaatorite efektiivsused, kui kaks identset regulaatorit töötasid koormuse jagamise režiimis.

Nende testide tulemused on suureks abiks edasiste testimiste sooritamisel. Praeguste andmete põhjal näitas parimat üleüldist tulemust LTC3603 pingeregulaator, samuti tundus see regulaator hästi toimivat praeguse koormuse jagamis ahelaga näidates kõige stabiilsemat tulemust. Testimine jätkub ka peale selle bakalaureuse töö kaitsmist ning edasistes testides tuleb määrata ka muud parameetrid nagu regulaatorite väljundpinge stabiilsus, elektromagnetlaineliste häirete tekitamine ning käitumine erinevatel töötemperatuuridel.

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Appendices

Appendix 1 – Schematics of the voltage converter testing platform

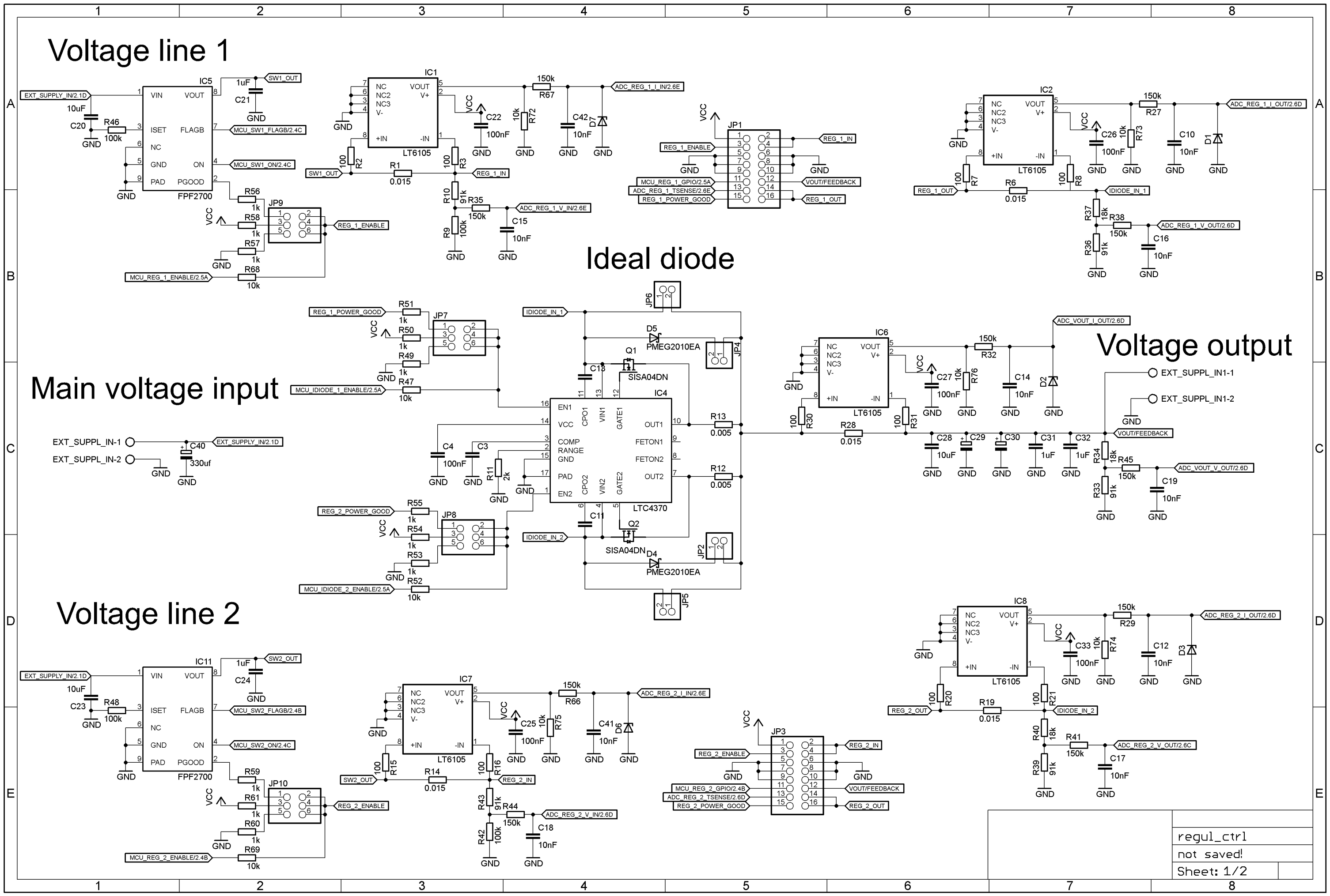

Figure 14. Schematics of the voltage converter testing platform (measuring and balancing circuit).

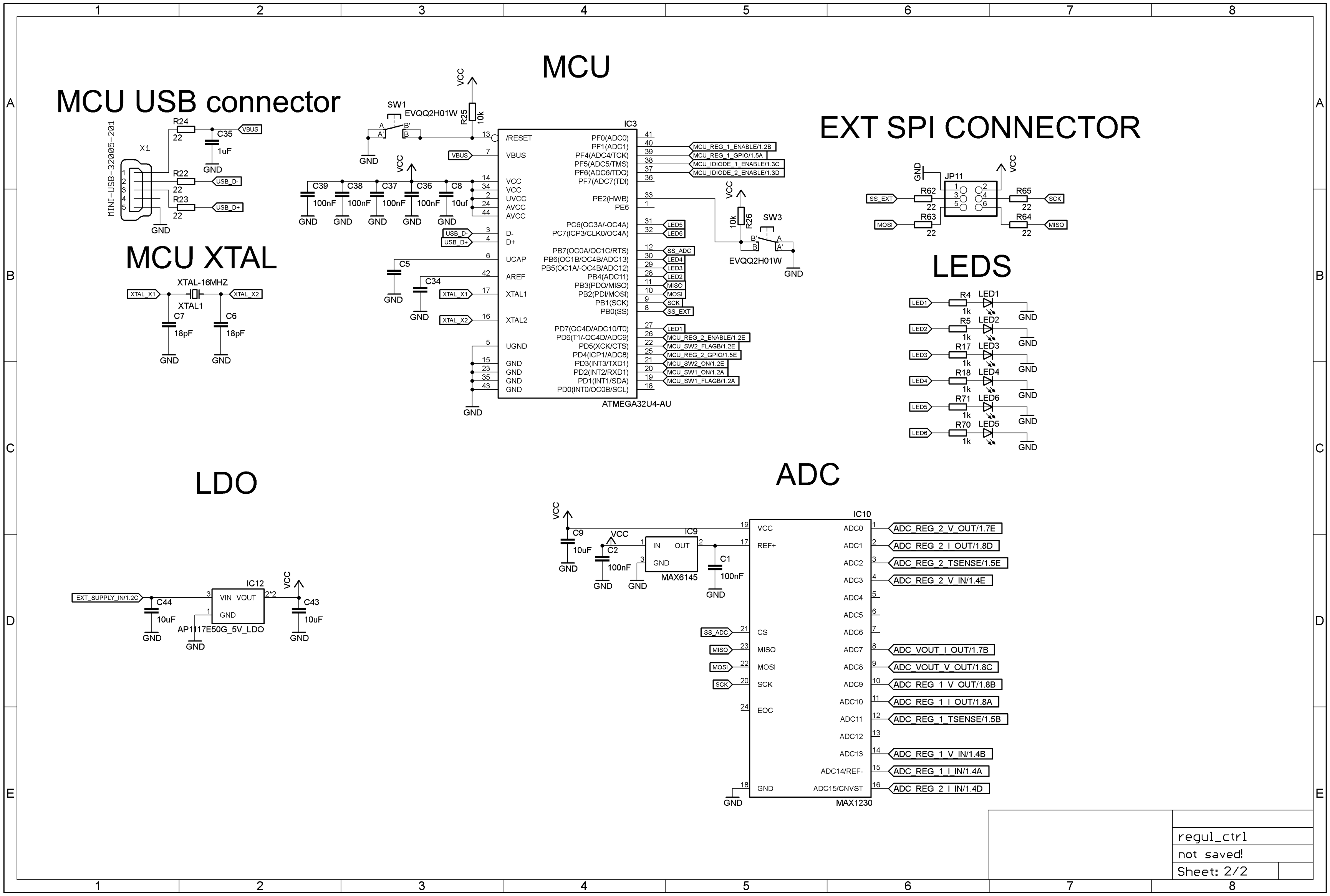

Figure 15. Schematics of the voltage converter testing platform (MCU and ADC).

Appendix 2 – Schematics of voltage converter testing modules

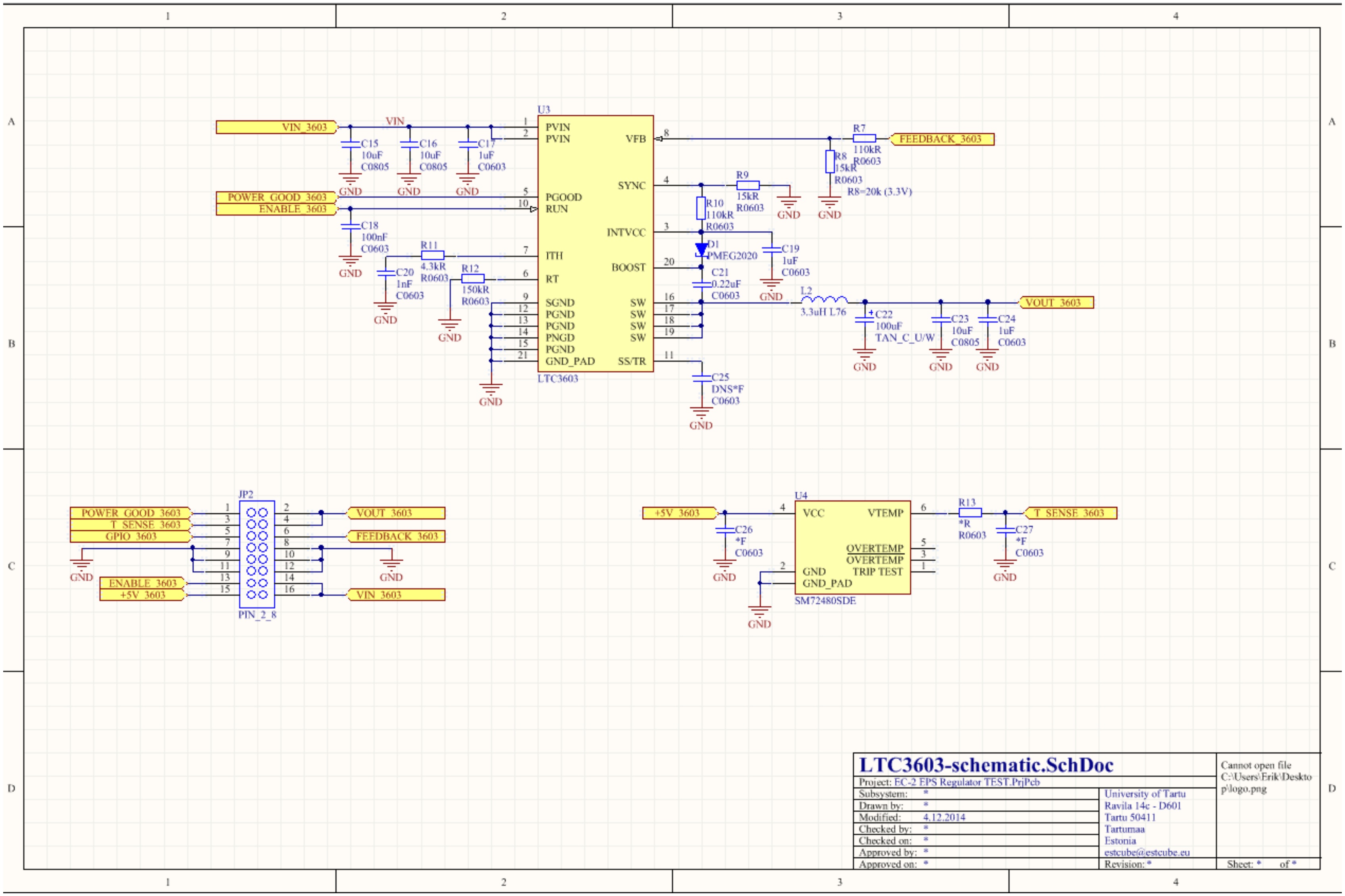

Figure 16. Schematics of the LTC3603 voltage converter testing module.

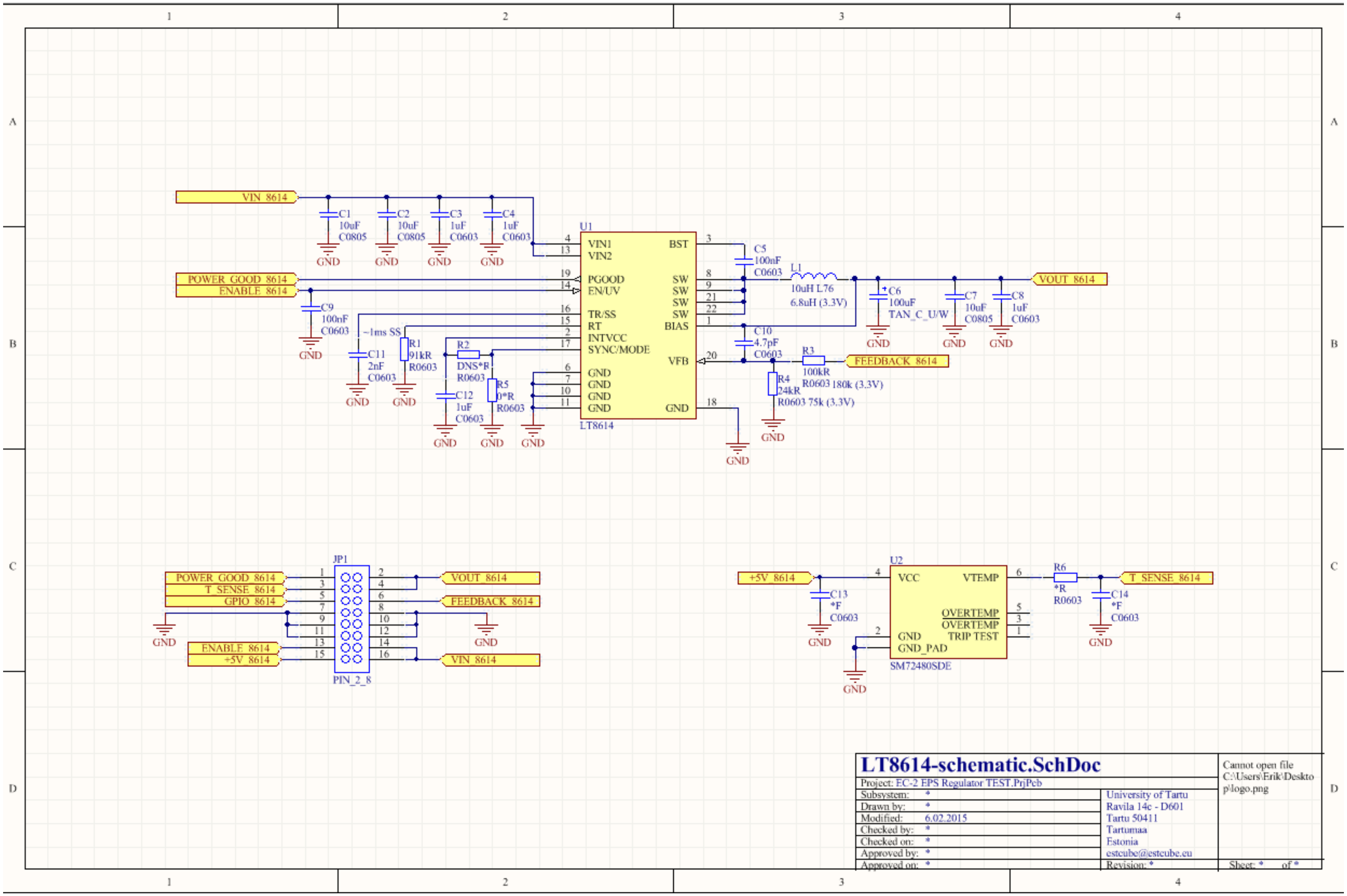

Figure 17. Schematics of the LT8614 voltage converter testing module.

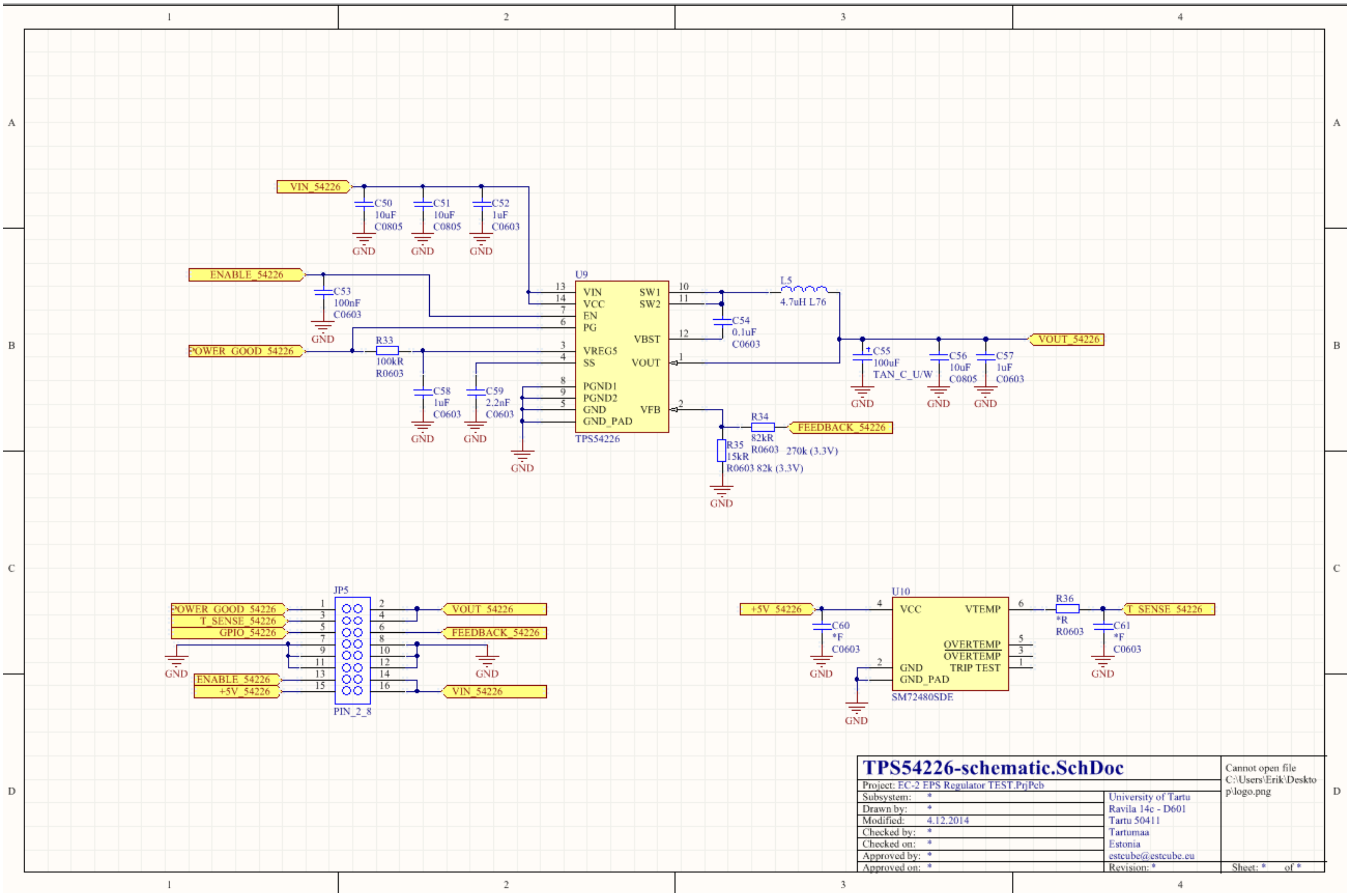

Figure 18. Schematics of the TPS54226 voltage converter testing module.

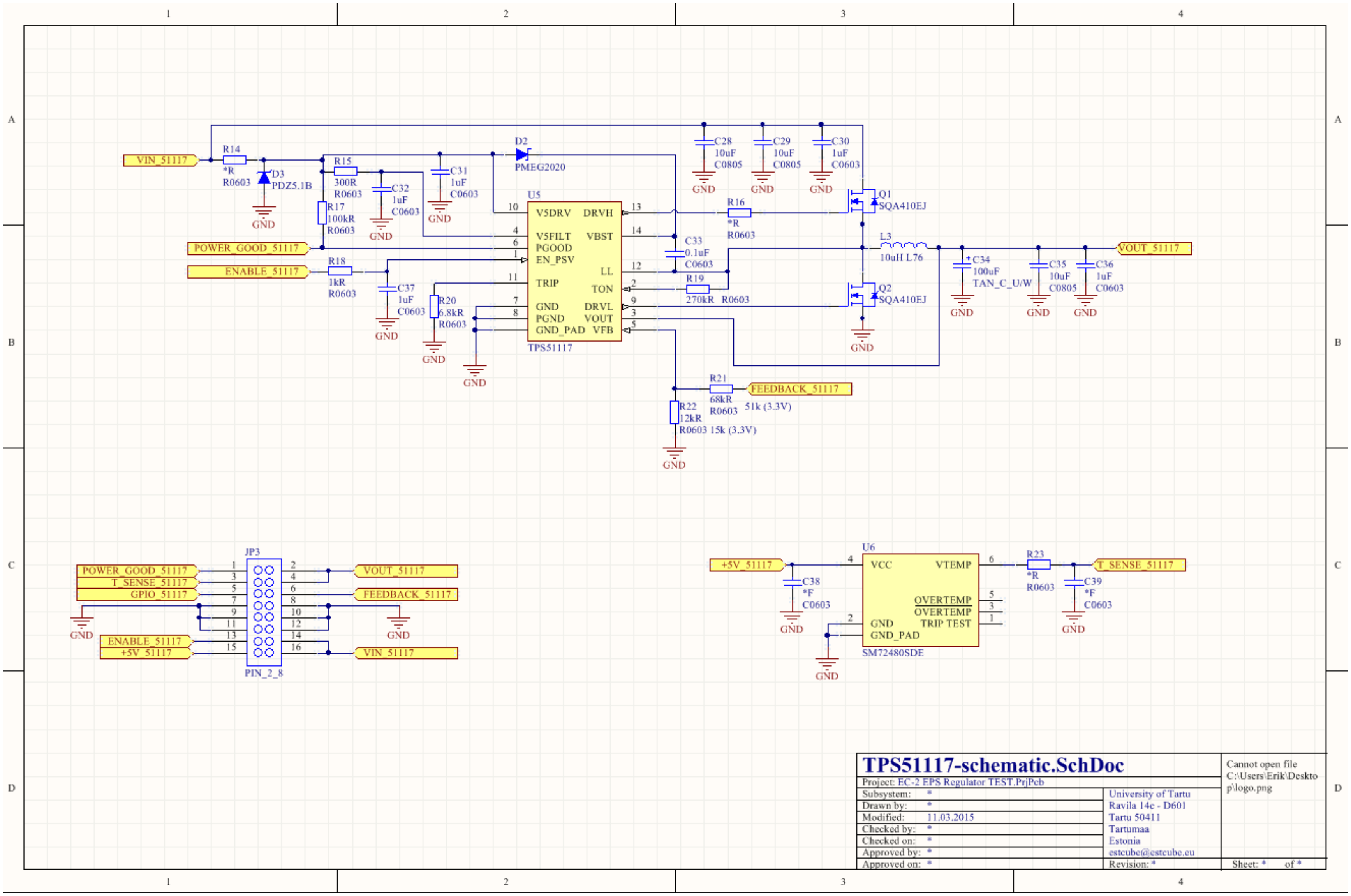

Figure 19. Schematics of the LTC51117 voltage converter testing module.

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