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Designing, Implementing and Testing the Solar Power Harvesting System for ESTCube-1

Master’s Thesis in Computer Engineering (30 ECTS)

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Dedicated to my beloved mother.

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1 List of Acronyms

Acronyms and abbreviations that are used in this document:

- ADCS – Attitude Determination and Control System
- AM0 – Air Mass Zero
- BOL – Begin of Life
- CAM – Camera subsystem
- CDHS – Command and Data Handling System
- COM – Communications System
- DC/DC – Direct current to direct current converter
- DRL – Digital rheostat level
- ESAIL – Electric Solar Wind Sail
- EMC – Electromagnetic compatibility
- EMI – Electromagnetic interference
- EOL – End of Life
- EPS – Electrical Power System
- FMI – Finnish Meteorological Institute
- GS – Ground station
- I/O – Input / Output
- I-V – Current versus voltage
- MCU – Microcontroller unit
- MOSFET – Metal oxide semiconductor field-effect transistor
- MPB – Main Power Bus
- MPP – Maximum Power Point
- MPPT – Maximum Power Point Tracker
- OC – Open-circuit
- PC – Personal computer
- PCB – Printed circuit board
- PL – Payload subsystem
- P-V – Power versus voltage
- RF – Radio frequency
- SEL – Single Event Latchup

- SH – Short-circuit
- SMD – Surface-mounted device
- SPI – Serial Peripheral Interface bus
- STR – Structure subsystem
- TBD – To be decided
- TCS – Thermal Control System
- USB – Universal Serial Bus

2 Introduction

Estonian Student Satellite project started in the summer of 2008 at Tartu University with the objective for promoting space and giving students a hands-on experience on developing space technologies. The main outcome of the project was pronounced to be a fully operational picosatellite ESTCube-1 - the first Estonian satellite [1].

The goal of ESTCube-1 satellite is to deploy a single 10 meter long Hoytether in low Earth orbit using a centrifugal force. The success criteria for this objective is the deployment of the tether and the snapshot of the visual confirmation of the deployment. The successful tether deployment is needed to demonstrate technologies for a full-scale Electric Solar Wind Sail (ESAIL) test mission in the future.

The concept of ESAIL has potential to become one of the most efficient space propulsion technologies in the history.

ESAIL is based on the interaction between the positively charged particles in the solar wind with the positively charged tether net deployed from a satellite. Each tether is a fourfold Hoytether structure to be as light as possible, but to maintain the durability needed in the harsh space environment. The concept was proposed by Pekka Janhunen from Finnish Meteorological Institute (FMI) in 2006 [2]. The concept of ESAIL has potential to become one of the most efficient space propulsion technologies ever invented.

ESTCube-1 Electrical Power System (EPS) is responsible for gathering power from solar panels, storing into batteries and distributing it to the whole system.

The main goals of the current work were to:

- Analyze solar panels characteristics and solar power harvesting concept.
- Analyze the concept of Maximum Power Point Tracking (MPPT).
- Analyze requirements for solar panel controller.
- Propose a solar panel controller design for ESTCube-1.
- Develop a solar panel controller prototype.
- Test the algorithm of MPPT.
- Test the efficiency of solar power harvesting.

The work consists of eight Chapters. The Chapter 3 gives a more detailed overview of ESTCube-1 satellite with focus on EPS subsystem.

Chapter 4 analyzes the concept of solar power harvesting and the need of MPPT. Also the general characteristics of solar cells are analyzed and the simple model of solar cell work is pointed out.

Chapter 5 proposes the design layout of solar panel controller, the implementation of MPPT algorithm and the implementation of solar panel controller software. Based on the design layout, the solar panel controller prototype development with measurement analyzes are described in Chapter 6. Chapter 5 and 6 form the main body of the work.

In Chapter 7 the future activities are proposed and in Chapter 8 most important results are concluded and the completion of goals is assessed.

3 Overview of ESTCube-1 satellite and Electrical Power System

ESTCube-1 is designed according to the CubeSat standard [3]. It is a single unit CubeSat with dimensions of 100 x 100 x 113.5 mm and mass up to 1.33 kg.

The satellite body consists of main frame and side panels that are attached to the main frame. The satellite body is made of aluminum 6061-T [4]. All 6 side panels have solar cells and one side panel includes an antenna deployment system. PCB's (Printed circuit boards) for different subsystems are fixed inside the main frame, see Figure 1.

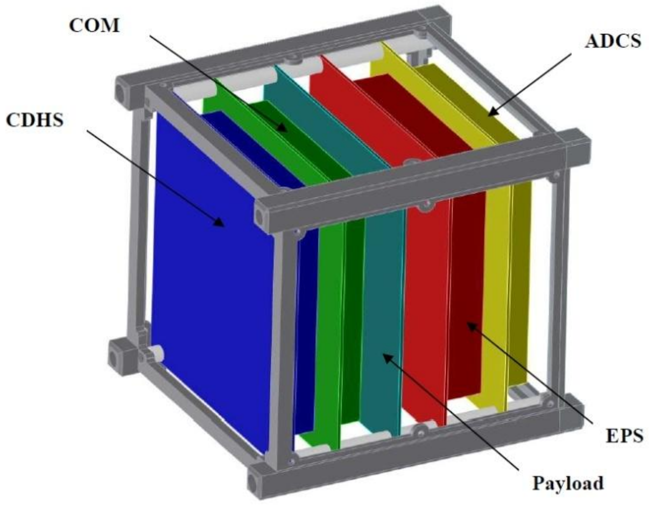

Figure 1: Proposed positions of different subsystem PCB's inside the satellite.

Satellite is divided into the following onboard subsystems (in alphabetical order):

- Attitude Determination and Control System (ADCS) stabilizes the satellite in orbit and maintains the required orientation. During the tether experiment, ADCS starts satellite to rotate and maintains the needed rotation for tether experiment.
- CAM (Camera) is responsible for the Earth surface imaging for educational and public outreach purposes and tether deployment verification as a part of the primary payload mission.
- Command and data Handling System (CDHS) is the data and telecommand administration system of ESTCube-1. CDHS is responsible for taking autonomous decisions to control the satellite.

- Communications System (COM) is responsible for communication between ground station (GS) and the satellite. The satellite is going to operate in two amateur radio bands:
    - Uplink in 2 m band (145 – 146 MHz)
    - Downlink in 70 cm band (435 – 438 MHz)
- Electrical Power System (EPS) generates power using solar panels, stores it in the batteries and distributes power according to different subsystems needs and mission phases.
- Payload (PL) subsystem includes the needed hardware and instruments for the tether experiment, including the tether itself.
- Structure (STR) subsystem provides mechanical structure for the satellite. All other subsystems are attached to it.
- Thermal Control System (TCS) is responsible for tolerable thermal conditions inside the ESTCube-1 satellite. Different paints and coating are used to provide fixed temperature range on-board the satellite.

3.1 Electrical Power System

Electrical Power System is responsible for the following tasks:

- Initial switch-on of the satellite subsystems and antenna deployment.
- Power generation.
- Power storage.
- Power distribution.
- Single Event LatchUp (SEL) [5] protection provision for the whole spacecraft electronics (also full EPS operation has to be ensured even if a subsystem is compromised).
- Beacon control.

The main task of the EPS is to collect power from solar panels, store it in batteries and distribute power for other subsystems.

Main parts of the EPS are shown in Figure 2.

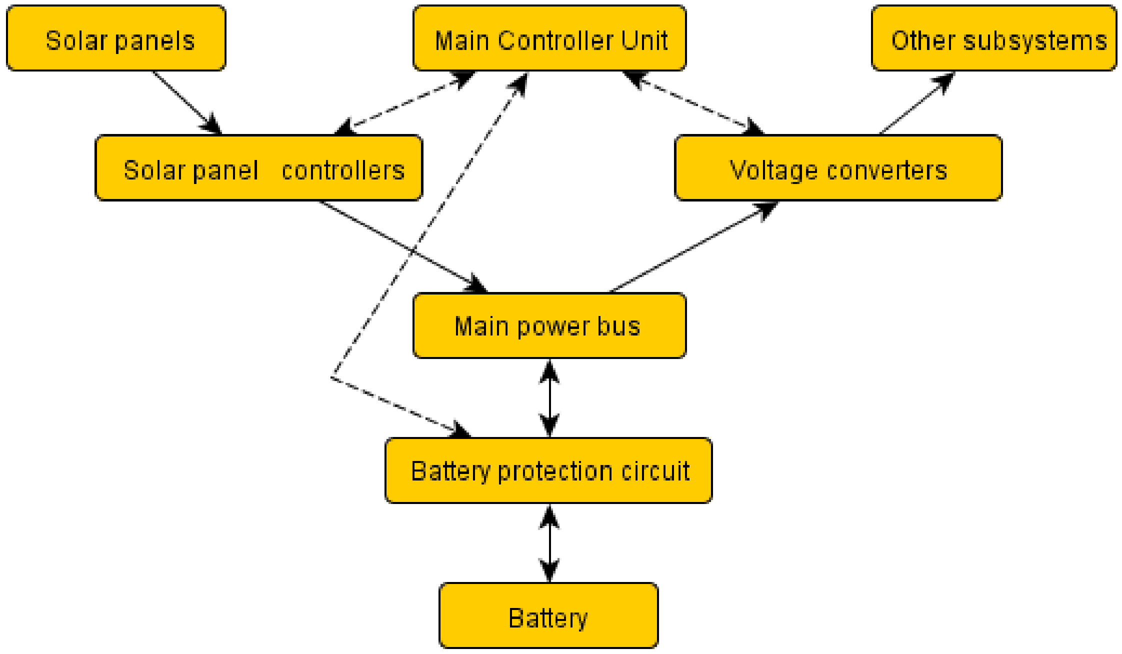

Figure 2: Main parts of Electrical Power System. Solid arrows represent power flow and dashed lines data flow.

Main power bus (MPB) is the electrical backbone of the EPS which interfaces together power producing and consuming components.

Main Controller Unit (MCU) controls the whole EPS functionality. Detailed overview of preliminary design of MCU and MPB can be seen in EPS Phase B report [6].

Solar panels harvest energy from the sunlight, manage it with the solar panel controller and forward it to the MPB.

Battery protection circuit is responsible for battery charging [7].

Voltage converters interface the MPB to other subsystems and perform voltage conversion and power distribution [8].

4 Solar power harvesting system

As mentioned earlier solar panels will be attached to each of the six sides of ESTCube-1. Each panel consists of two solar cells in series while the panels on the opposite sides of the satellite will be connected in parallel to the solar panel controller. The general layout of solar power harvesting is shown in Figure 3.

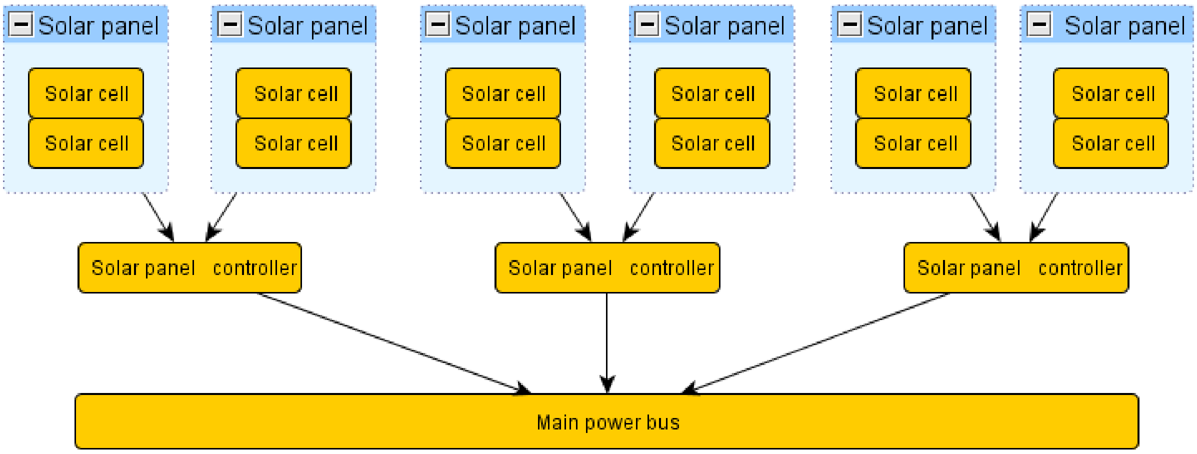

Figure 3: Solar power harvesting.

The main purpose of solar panel controller is to extract power from the solar panel by the means of Maximum Power Point Tracking (MPPT) to maximize energy production. The concept and exact implementation is described in following sections.

Secondary task of the solar panel controller is to provide telemetry data that shows the health of the solar panels. This data can be used as a parameter in the overall satellite health report or as an approximate way to determine the satellite attitude.

4.1 General characteristics of solar arrays

A solar array is an assembly of many thousand individual solar cells [9]. A solar cell is a solid state electrical device that converts sunlight into electric energy by the photovoltaic effect.

Each solar cell has a semiconductor p-n junction as shown schematically in Figure 4.

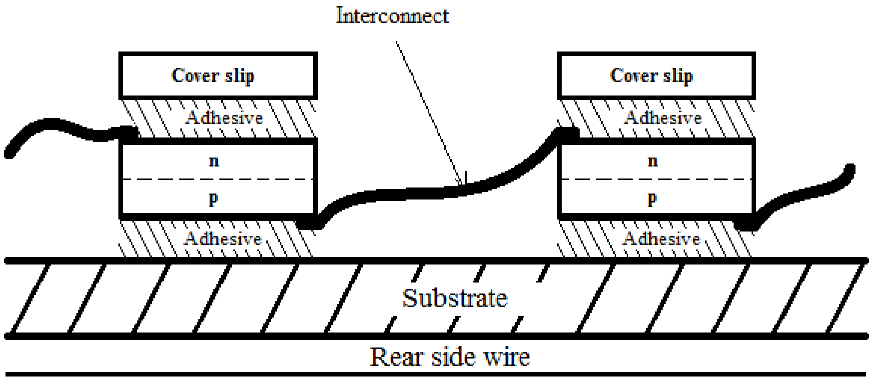

Figure 4: Assembly schematic of a typical solar cell.

With no light the junction achieves an equilibrium state in which no current flows, but with light, photons with sufficient energy will create electron-hole pairs, and the radiation is converted to a potential across the cell with usable electrical power. The Incident photon energy needed for this must exceed a band gap that depends upon the material, as can be seen in Table 1.

Table 1: Band gap of semiconductor materials.

Material	**Band gap (eV)**
Si	1.12
CdS	1.2
GaAs	1.35
GaP	2.24

All solar cells are characterized by their current versus voltage curve, called the I-V curve. In the dark the I-V curve of a solar cell is the same of as of a reverse-biased diode. When photons with enough energy penetrate the solar cell and hit the semiconductor material, the density of mobile electron-hole pairs are increasing. The I-V curve is then moved upwards, see Figure 5.

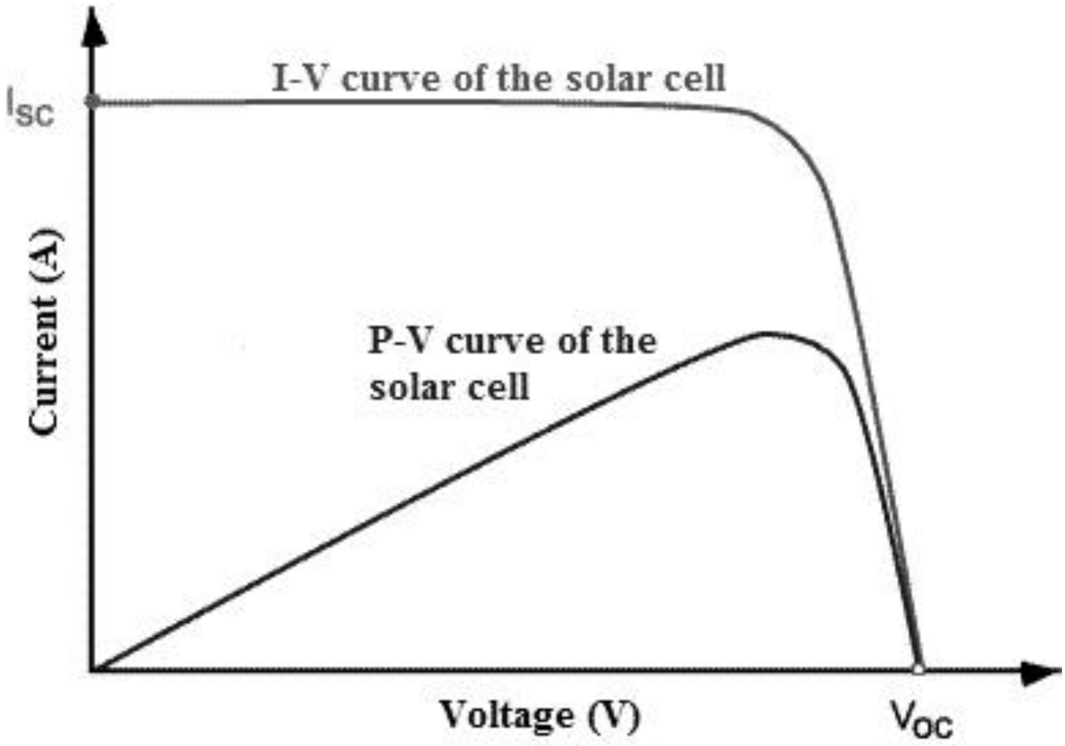

Figure 5: I-V and P-V curve of the solar cell in the light.

A power versus voltage curve, called the P-V curve, can be derived from the I-V curve. The P-V curve has a maximum, called the Maximum Power Point (MPP) (3.) in Figure 6. Manufacturers do not always provide the I-V curve of a solar cells. More likely they provide:

- The open-circuit voltage (**V_{oc}**) is the maximum voltage from a solar cell and occurs when the net current through the device is zero.
- The short-circuit current (**I_{sc}**) is the maximum current from a solar cell and occurs when the voltage across the device is zero (short circuited).
- Current on maximum power point (**I_{Pmax}**) (1.) on Figure 6.
- Voltage on maximum power point (**V_{Pmax}**) (2.) on Figure 6.

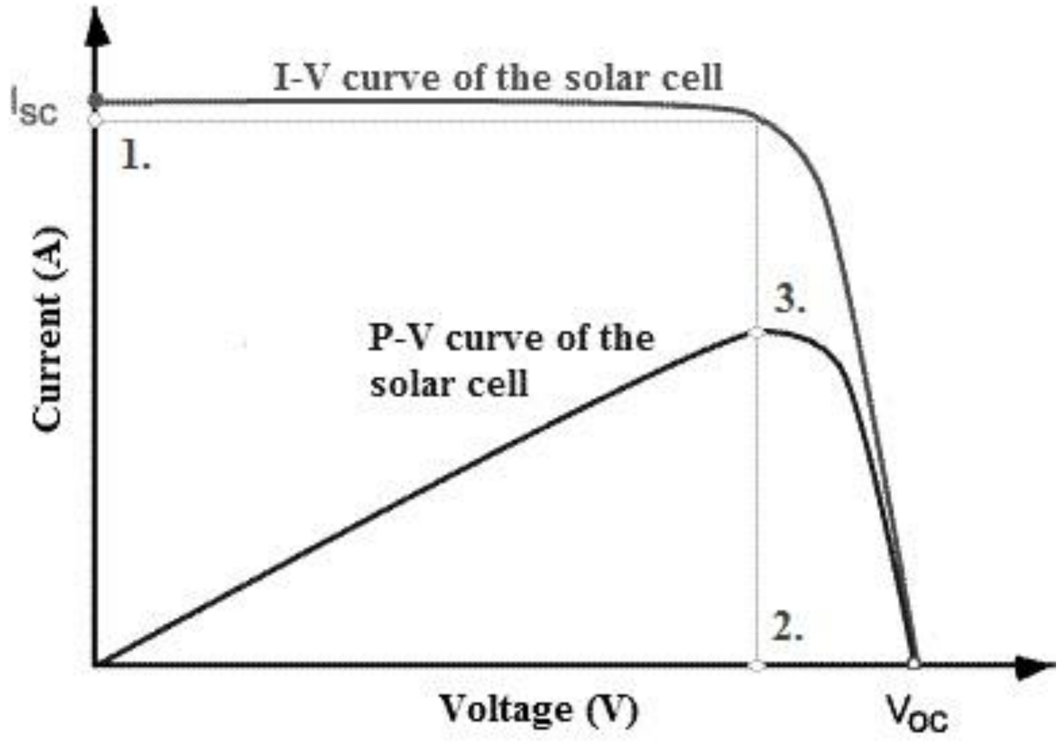

Figure 6: P-V curve of the solar cell and Maximum Power Point.

The most important environmental parameters which the I-V curve depends on are [10]:

- The light exposure – the current increases with the light intensity. I-V curves are generally given for a particular spectrum. "Air Mass Zero (AM0)" is the spectrum of the sunlight in space, at the sun-earth distance.
- The temperature – in usual temperature ranges , the efficiency of solar cells decreases with temperature. The short-circuit current slightly increases with temperature, while the open-circuit voltage decreases.
- The age – radiation in space tends to decrease the efficiency of a solar cell over time. Commonly used terms to define the age of a solar cell are Begin of Life (BOL) and End of Life (EOL). Begin of life is a term when solar cell characteristics have not been reduced by environmental conditions.

4.2 Solar panel selection

In ESTCube-1 preliminary system requirements and design phase there has been a consideration between bare solar cells and PCB mounted solar panels (Clyde space solar panels with magnetorquers) [11]. EPS team has decided to use bare solar cells. Decision is based on a fact that bare solar cells are cheaper and some of our partners have experience and facilities for the solar cells PCB mounting [12]. Solar cells PCB mounting gives a good knowledge and hand-on experience for the students.

Three space qualified high efficiency solar cells were considered in ESTCube-1 preliminary system requirements and design phase:

1. Bare solar cells from Azur Space Solar Power (Azur Space, 2011).
2. Bare solar cells from Centro Elettrotecnico Sperimentale Italiano (CESI, 2011).
3. Bare solar cells from Spectrolab (Spectrolab, 2011).

These manufactures provide space qualified solar cells and panels with very similar electrical characteristics (efficiency of 28 - 30% with total power generation around 2 W per side, in sun phase).

Considered solar cells with main electrical characteristics can be seen in Table 2.

Table 2: Main electrical characteristics of considered solar cells.

Solar cell type	**Area (cm^2)**	**I_{sc} (A)**	**V_{oc} (V)**	**P_{max} (W)**	**Eff (%)**
Azur Space TJ Solar cell 3G28C [13]	30.18	0.525	2.669	1.202	28
CESI CTJ - 28% [14]	30.15	0.522	2.6	1.2	28
Spectrolab UTJ - 28,3% [15]	30.15	0.515	2.655	1.15	28,3

It has been decided that ESTCube-1 will use Azur Space solar cells. According to the Table 2, they provide highest power and research has been shown that there are least problems (shipping etc.) to get them. Azur Space solar cells are triple junction GaAs solar cells with an efficiency of more than 28%.

A mechanical drawing of a single cell is given in Figure 7.

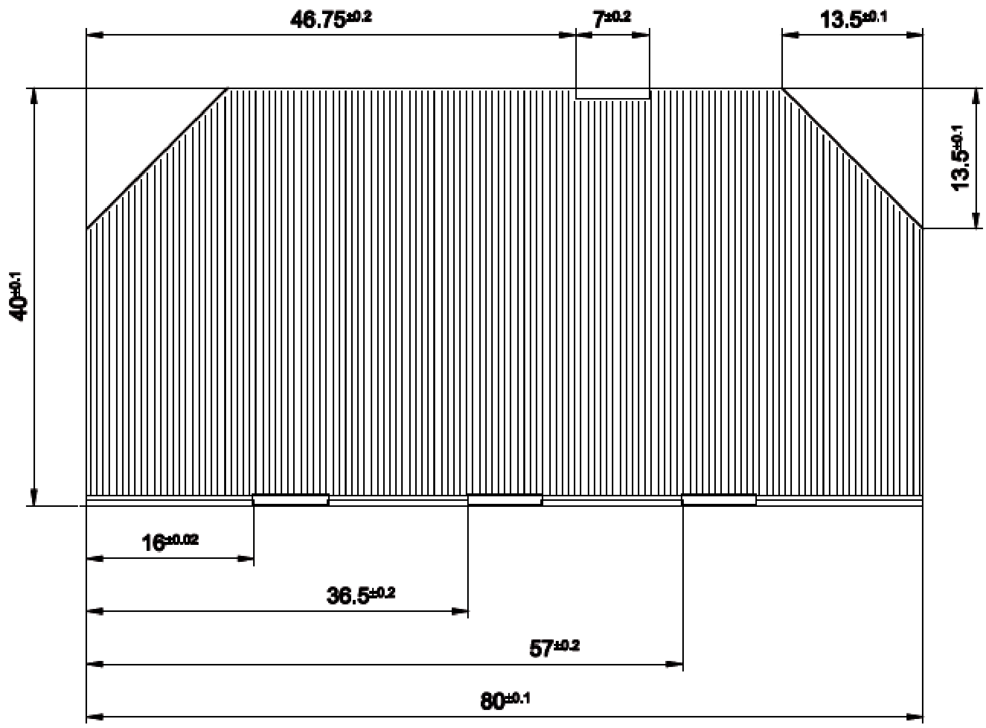

Figure 7: Azur Space solar cell dimensions in mm.

The dimensions of the solar cells are 80 mm x 40 mm with cropped corners, resulting in a total surface of 30.18 cm^2. The base material consists of different structures of GaInP/GaAs/Ge on Ge substrate and for the anti-reflecting coating TiO_x/Al_2O_3 is used. Average surface density is 86 mg/cm^2, which is 26 g per cell. The thickness of one cell is 150 ± 20 µm and the thickness of contact metallization is 4 – 10 µm.

Azur Space solar cells are equipped with an integrated bypass diode to protect adjacent cell in the string. Main electrical characteristics of Azur Space solar cells are shown in Table 3.

Table 3: The electrical data of Azur space solar cell.

Spectrum: AM0 (1367 W/m^2); T = 28°C	**Value (in BOL)**
Average open circuit $\mathbf{V_{oc}}$	2669 mV
Average short circuit $\mathbf{I_{sc}}$	525 mA
Voltage @ max. Power $\mathbf{V_{pmax}}$	2379 mV
Current @ max. Power $\mathbf{I_{pmax}}$	505 mA
Average maximum power $\mathbf{P_{max}}$	1.201 W
Average efficiency $\boldsymbol{\eta_{bare}}$	30.1 %

4.3 Simple model

An ideal solar cell can be modeled by a reverse-biased diode in parallel with a current source and when a shunt resistor (**R_{sh}**) and a series resistor (**R_s**) are included an even more practical model is formed. The equivalent circuit is shown on Figure 8.

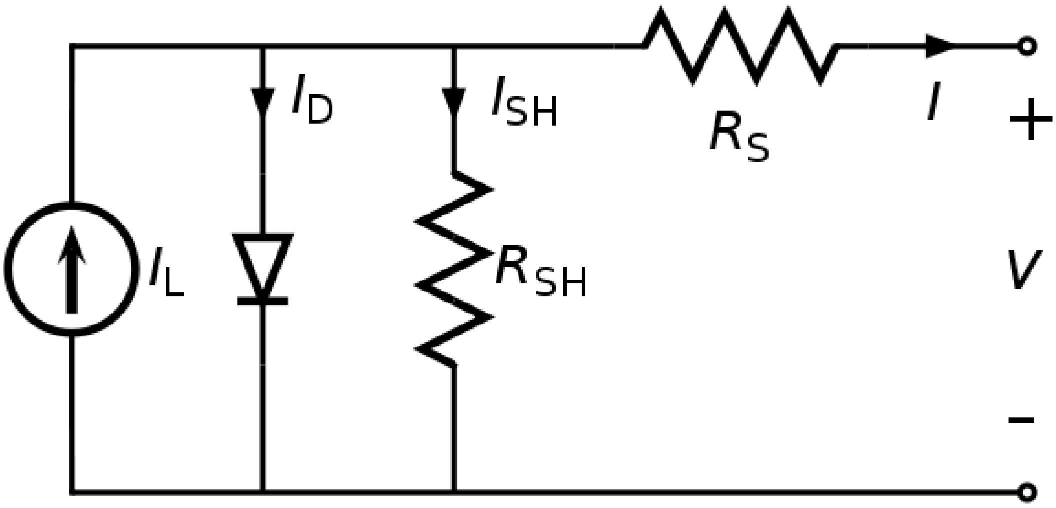

Figure 8: The equivalent circuit of a solar cell

The mathematical equation for this circuit is (1):

$$I = I_{ph} - I_s\left[e^{\frac{q(V+IR_s)}{nkT}} - 1\right] - \frac{V+IR_s}{R_{sh}} \qquad \textbf{(1)}$$

Where,

- I – Solar panel output current (A)
- V – Solar panel output voltage (V)
- I_{ph} – Photogenerated current (A)
- I_s – Diode current (A)
- R_s – Series resistance (Ω)
- R_{sh} – Shunt resistance (Ω)
- n – Solar panel ideality factor
- q – Electric charge = $1.60e^{-19}$ C
- k – Boltzmann constant = $1.38e^{-23}$ J/K
- T – Temperature (K)

The solar panel datasheet does not provide values for $\mathbf{R_{sh}}$ and $\mathbf{R_s}$, so for the model simplification, $\mathbf{R_s}$ will be zero. The resistance $\mathbf{R_{sh}}$ has generally a value of several hundred Ohms (Ω). The current in $\mathbf{R_{sh}}$ is very small compared to the other currents, and the effect of $\mathbf{R_{sh}}$ can thus be neglected [16]. Solar cell models without $\mathbf{R_{sh}}$ give satisfactory results. Solar panel ideality factor **n** has been taken 3.34 and diode current $\mathbf{I_s}$ 2.26 x 10^{-14} A.

According to the values ($\mathbf{I_{sc}}$, $\mathbf{V_{oc}}$) that are taken from the solar panel datasheet and using the equation above, an I-V curve of Azur Space solar panel can be simulated. Simulations have been done using MathCAD. In Figure 9, the I-V curve and in Figure 10, the P-V curve is simulated for the case described in datasheet (the full insolation of 1367 W/m^2 and with the temperature of 28°C). The short circuit current $\mathbf{I_{sc}}$ is 525 mA and the open-circuit voltage $\mathbf{V_{oc}}$ is 2669 mV. According to the datasheet, in the maximum power point, the maximum current $\mathbf{I_{Pmax}}$ is 505 mA and maximum voltage $\mathbf{I_{Pmax}}$ is 2379 mV.

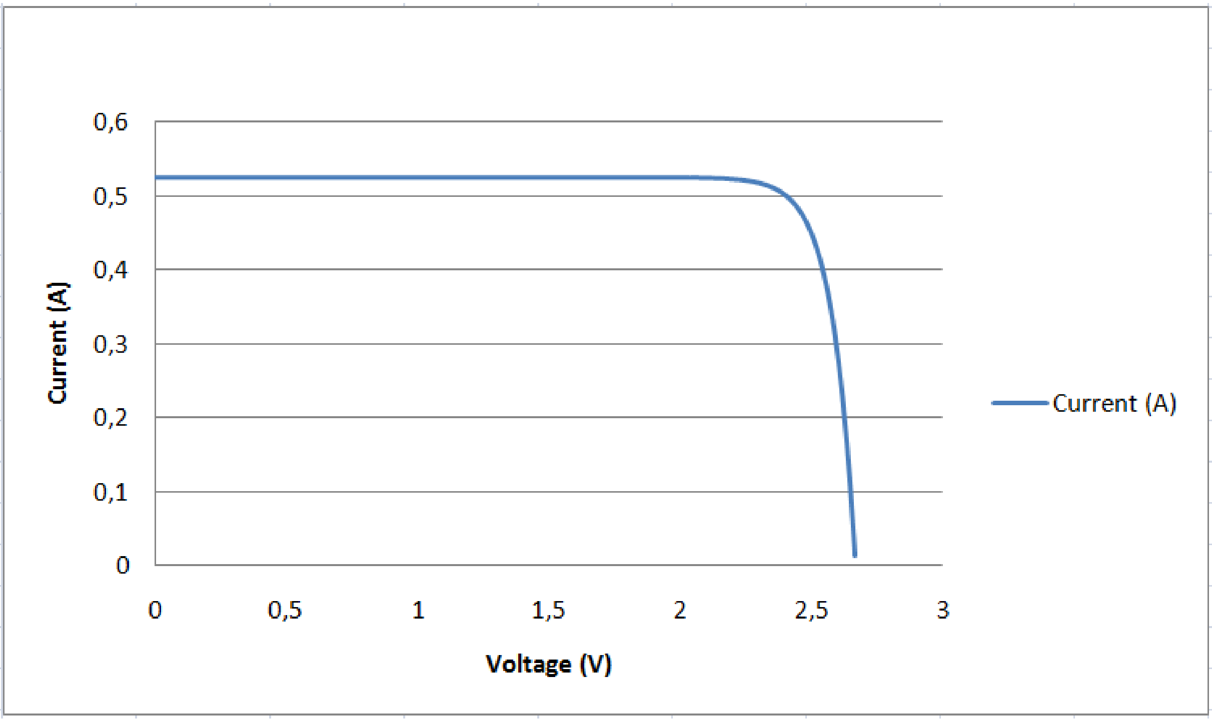

Figure 9: Modeled I-V curve of the Azur Space solar cell.

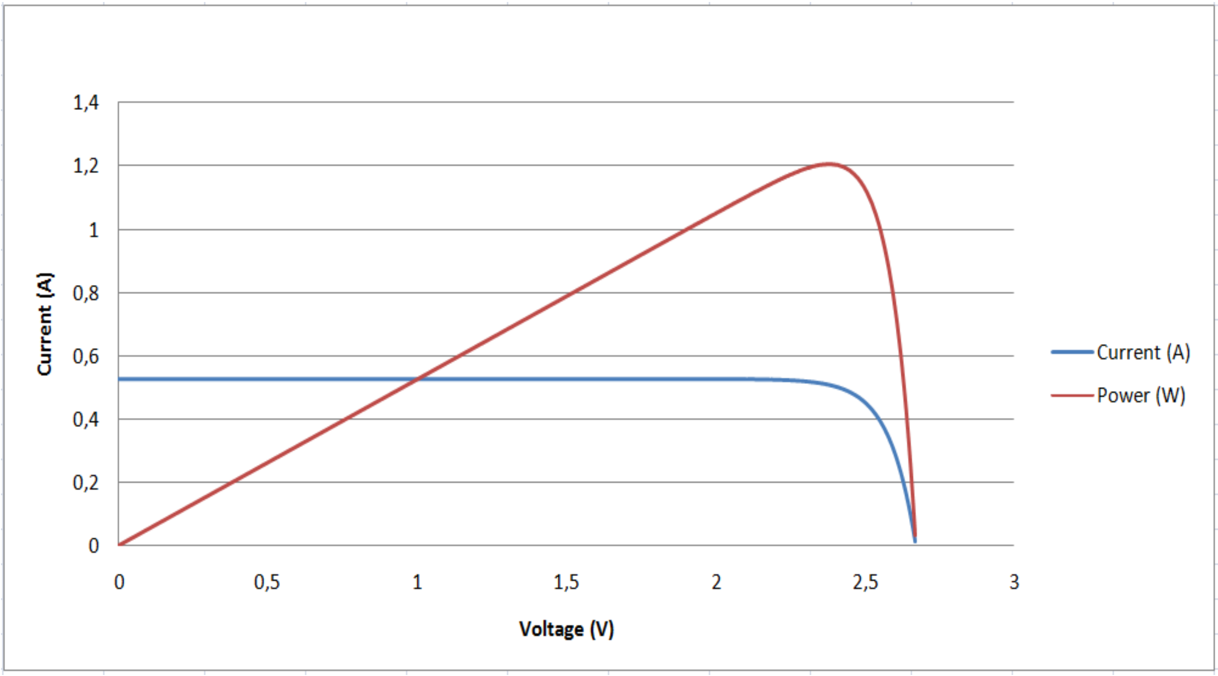

Figure 10: Modeled P-V curve of the Azur Space solar cell.

4.4 Maximum Power Point Tracker

According to the P-V curve in Figure 10, there always exists a current value which must be maintained to get the maximum power. Since the maximum power point depends on many parameters (for example illumination of solar panels and their temperature), it changes dynamically through the progress of the satellite operation. This change has to be tracked to get the maximum power.

This process is called maximum power point tracking or MPPT. The main idea is to create a virtual consumer with an adjustable internal resistance and to change that virtual resistance to a value that results in maximal power production. The power dependence on resistance can be seen in Figure 11.

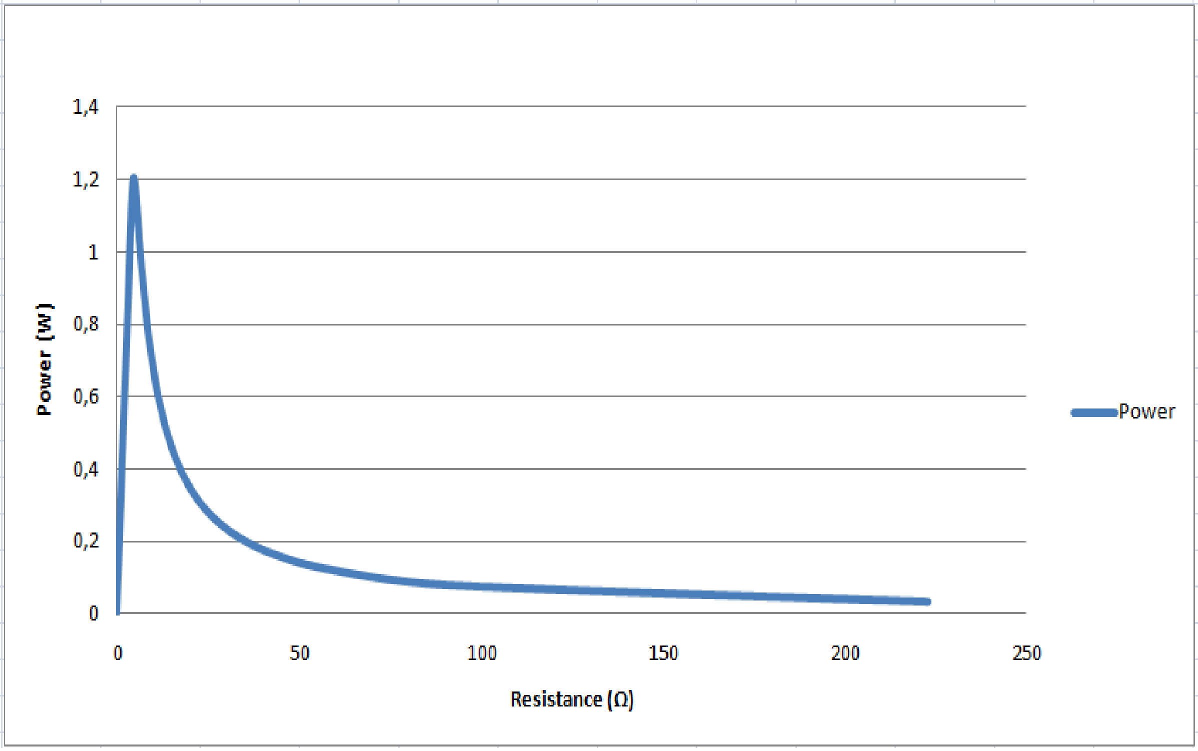

Figure 11: The relation between the resistance of the virtual consumer and power production.

A sharp peak is visible and it corresponds to the virtual consumer resistance - the maximum power peak resistance.

In case of ESTCube-1 the resistance is composed of all the components that consume power. The resistance is dynamic and changes constantly due to different power conditions. Considering short timescale and small current and voltage changes with the use of adequate filtering capacitors the system can be viewed as a classic constant value resistance. By default this resistance is not controllable.

Because of the uncontrollable resistance the MPPT effect can be achieved by converting the voltage level of solar panels to a variable voltage on the resistance. In this case, the resulting virtual resistance $\mathbf{R_{virtual}}$ depends on the voltage of the resistance. The virtual resistance can be trivially derived from the conversation of energy is determined by the ratio between input and output voltages ($\mathbf{V_{solar}}$ and $\mathbf{V_{consumer}}$), the original consumer resistance $\mathbf{R_{consumer}}$ and the conversion efficiency $\boldsymbol{\eta}$ (2).

$$R_{virtual} = \left(\frac{V_{solar}}{V_{consumer}}\right)^2 \times R_{consumer} \times \eta \qquad \textbf{(2)}$$

Therefore changing the output voltage is enough to change the virtual resistance in order to achieve the effect of adjustable virtual consumer resistance required for MPPT. From this equation (3) the optimal output voltage at maximum power (**P_{max}**) can be found:

$$V_{consumer} = \sqrt{P_{max} \times R_{consumer} \times \eta} \qquad \textbf{(3)}$$

This maximum is unfortunately not stable because any fluctuations will cause the power point to shift to a lower value. Therefore this maximum must be constantly dynamically tracked.

The equation (2) illustrates the effect of the voltage conversion, but does not simplify the understanding of system work. In realistic system the resistances are not constant. The main power bus is designed so that the resistance increases with the increasing voltage and decreases with decreasing voltage by the control of battery protection circuit. Also the efficiency of conversion is strongly dependent on input and output voltages and the current passing through the system.

Low output voltage causes less power drainage than can be produced by the panels, but too high output voltage makes the converter output oscillate that lower output power. This operation can be understood considering that it takes several switching pulses to drain the input capacitor:

1. The power drain is momentarily higher than the power production of solar panels. This causes emptying of input capacitors and lowering of input voltage.
2. This increases the current drained from solar panels and therefore power production decreases (the voltage drop causes also the efficiency of converter to decrease).
3. At certain point the voltage on input capacitors is too low to allow the converter to work and the converter shut down.
4. Then the solar panels start charging the input capacitors until the voltage is high enough for converter to operate and the converter turns on.
5. And the cycle starts over again.

The MPPT algorithm can still be implemented without knowing the analytical solution. The idea is to use a classical non-linear dynamic optimization. A value of converter output voltage has to be found in case of the power transferred to the main power bus is maximal. There are a lot of algorithms or methods to do that. A good overview about different algorithms with simplified explanation can be found in reference [17].

According to the earlier research by the ESTCube-1 EPS team [18], a Hill-climbing method is used. The idea is to change the output voltage to direction that causes the output power to increase by using constant step size. Implementing the MPPT as dynamic optimization also automatically integrates adjustment to solar panel current and voltage characteristics and to the consumption characteristics.

4.5 Requirements analysis for solar panel controller

When designing a controller module, certain requirements (minimum/maximum/typical current and voltage) have to be taken into account, because these values depend strongly on environmental conditions (temperature, radiation etc). Table 4 below gives a small overview of them. Particular values have been taken from Clyde Space solar panel datasheet, because other manufacturers do not reflect these in their datasheet [11]. It can be presumed that the Azur Space solar panels have approximately same values.

Table 4: Description of electrical requirements of the MPPT modules.

Name	**Value**
Minimal input voltage	0.0 V
Minimal typical input voltage (normal operation)	4.0 V
Maximal typical input voltage (normal operation)	5.5 V
Maximal input voltage	6 V
Minimal output voltage ($\mathbf{V_{MPPT\_min}}$)	3.3 V
Maximal output voltage ($\mathbf{V_{MPPT\_max}}$)	4.2 V
Maximal input current	600 mA
Maximal converted power	2.52 W
Output voltage ripple requirement	TBD

5 Solar panel controller design layout

The basic proposed structure of the solar panel controller circuit is shown in Figure 12. It has been divided into 5 sub-modules: input block, current limiter, converter module, MCU interface and output block. Electromagnetic Interference (EMI) is applied to all critical spots.

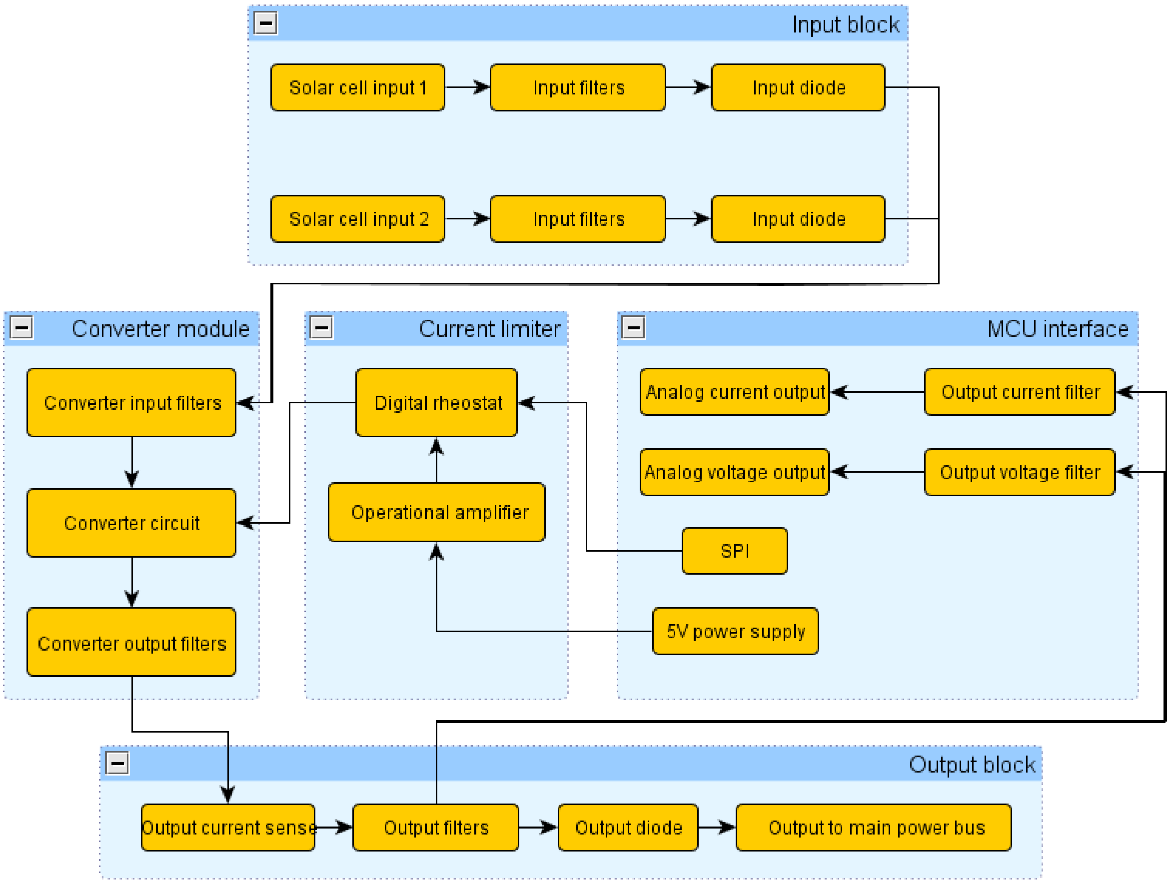

Figure 12: The solar panel controller prototype layout.

Input block

Input block filters prevent the travel of high frequency noise from solar panels and to solar panels. Solar panel acts like antenna, it transmits and receives interference. The primary input filters are just bypass capacitors. Input filters are followed by diodes that protect solar panels against reversed voltage (the solar panels act like consumers if they are reverse biased with higher voltage). Input diodes converge to a single power line that proceeds to converter module.

Converter module

The main part of the converter module is to handle the up- and down conversion of voltage received from inputs in order to provide optimal current drain from solar panels that would maximize the energy production. This is regulated by the voltage applied to the Main Power Bus. A buck-boost DC/DC converter has been chosen to implement the converter circuit. The converter switching regulator is considerable noise source and therefore large decoupling capacitors and ferrite beads for filtering are applied to the converter inputs and outputs.

Current limiter

Current limiter circuit has been chosen according to the typical application in voltage converter datasheet. A digital rheostat has been added to the circuit to make the current limiter adjustable. The concept is needed for MPPT implementation that is explained in following paragraphs.

MCU interface

MCU interface consist of all the connections to the EPS MCU pins to control the solar panel controller. There is a SPI interface to control the current limiter. For feedback purposes an analog current and analog voltage output pins have been added. Also decoupling capacitors have been added to provide filtering.

Output block

Output block contains output current sense that measures the output current of the solar panel controller module. It functions as the main parameter for maximum power point tracking. The module provides output filtering to avoid interference travelling to and from the main power bus. Output diode prevents the module to become a voltage consumer.

5.1 MPPT algorithm implementation

The MPPT algorithm for a single solar panel controller:

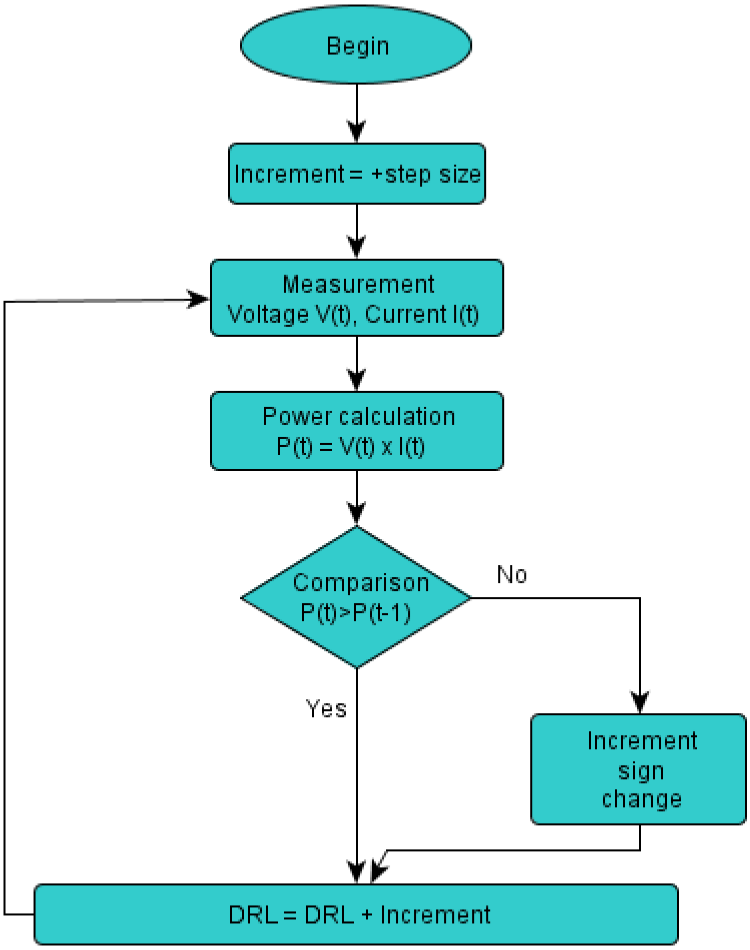

Figure 13: Hill-climbing MPPT algorithm block diagram

As can be seen in Figure 13, the algorithm begins by setting the increment sign to "+step size". Increment sign shows in which direction the output voltage will be turned. With the output voltage and output current measurements the output power is calculated. Next step is to compare the previous output power with the new one. If the new output power is higher, then the DRL (digital rheostat level) will be increased by a constant step size. If the new output power is lower, then the sign of the increment will be changed and DRL will be decreased. DRL changes the current limiter and new output voltage and current values are measured again.

5.2 Solar panel controller software implementation

The implementation of solar panel controller software is shown in Figure 14. Software itself is written in C language and it can be found in Appendix section.

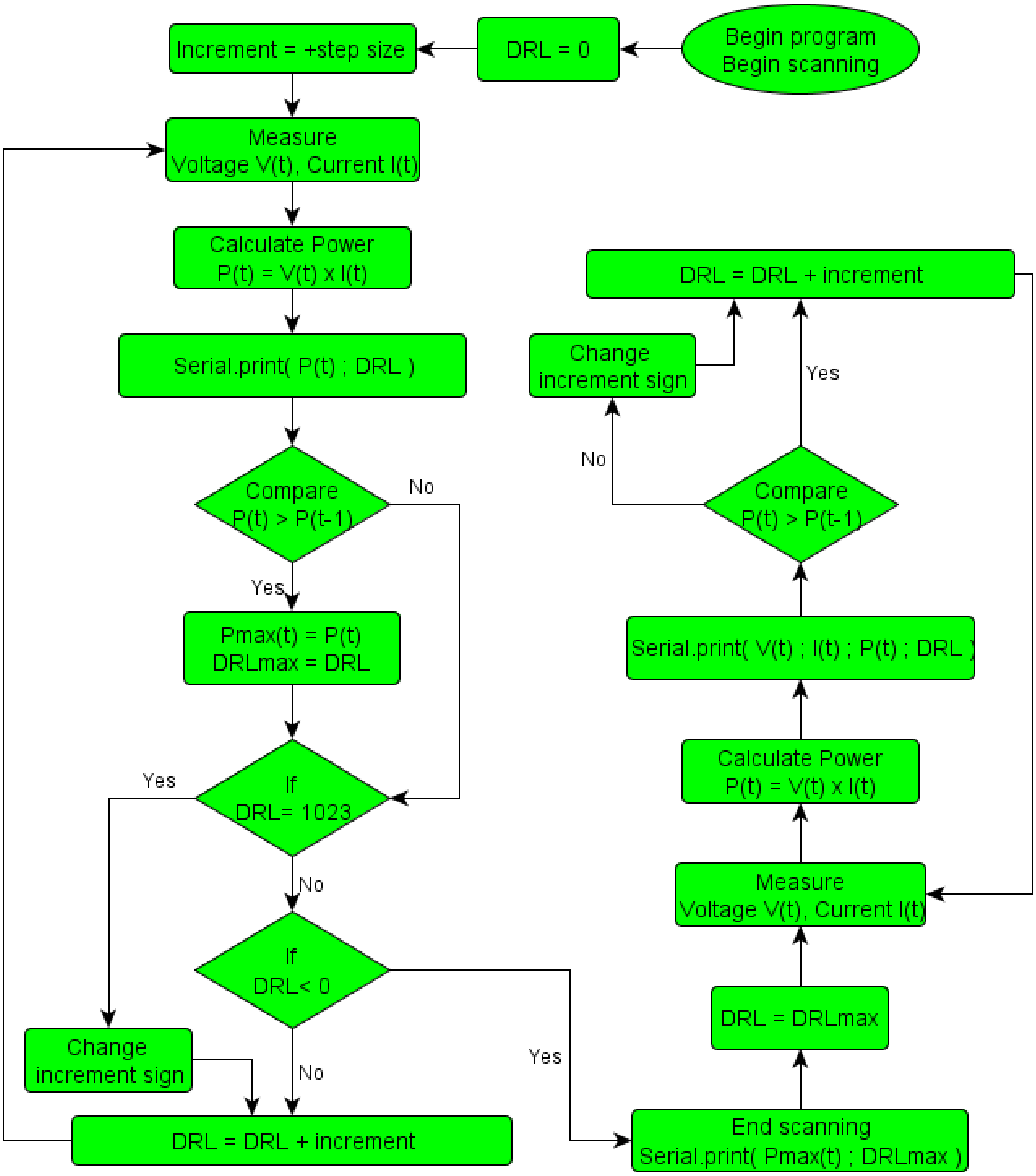

Figure 14: Solar panel controller software block diagram.

The software begins with the maximum power point scanning part. Digital rheostat level is changed from maximum value to 0 and the increment sign is changed positive. Then the output current and output voltage are measured and output power is calculated.

Digital rheostat level and output power is sent to Serial port which readings can be seen for example with a Serial monitor. After that the level of digital rheostat is changed by step size and new values for output current and voltage are measured. Digital rheostat level increases to level 1023 and then the sign of the increment is changed. Now the level decreases to zero again. During this scanning operation maximum output power and the digital rheostat level at that point are stored and sent to Serial port after the scanning.

With the help of stored digital rheostat level at maximum output power, the maximum power point tracking begins. Digital rheostat level is changed to the value where the output power was maximal. In this case the tracker is near the maximum power point and tracking begins. During the tracking, output voltage, output current, output power, level of the digital rheostat and the adequate resistance are sent to Serial port. Maximum power point tracking acts according to the MPPT algorithm.

6 Solar panel controller prototyping and testing

Solar panel controller prototype was developed as one of the primary goals to test the solar harvesting system.

The developed prototype supports testing of:

- Solar power harvesting
- Solar panel controller efficiency
- MPPT algorithm and its behavior
- Solar power telemetry data collection

Prototype includes input interfaces

- External power supply connector for operational amplifier in the current limiter
- 2 solar panel connectors
- SPI interface to the digital rheostat in the current limiter

Prototype includes output interfaces

- Power output
- 3 analog pins for output voltage and current measurements

The goal of this work is to develop and test circuits for:

- Voltage conversion
- Output current sense monitoring
- Adjustable current limiting

The test layout of solar panel controller prototype is shown in Figure 15. It has been divided into 4 different groups: solar power unit, solar panel controller board, control and measurement unit and consumer part.

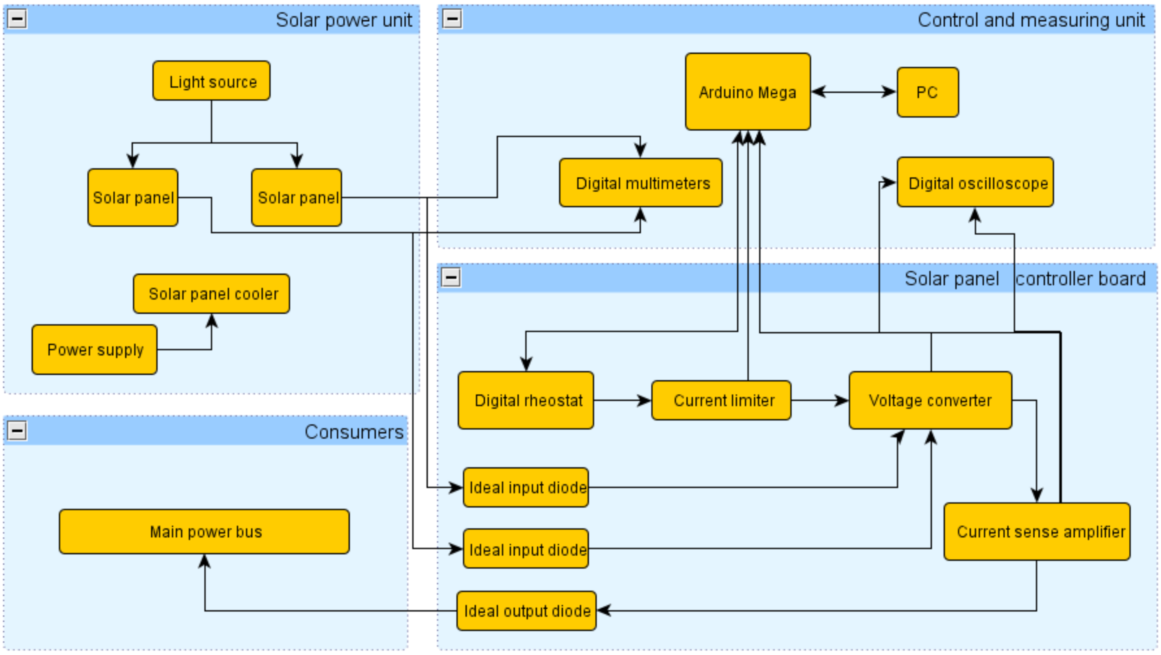

Figure 15: Prototype testing layout for solar panel controller.

Solar power unit

The two main parts of the solar power unit are solar panels and light source. Due to the fact that the space qualified solar panels have not been purchased yet, the regular ground solar panels were used for testing. Those solar panels are larger in dimensions than the Azur Space cells but their efficiency is much lower. It is known that power production of solar panels depend on the light density, solar panel efficiency and the area of solar cells. Therefore ground solar panels with larger area showed almost the same output values as can be seen in Azur Space solar cells datasheet. Also the price of ground solar panel was very low and that is why aforementioned concept was the perfect choice for testing.

For the light source a 300 W halogen floodlight was used. To get the needed power from the panel, the floodlight was placed as close as possible to the solar panel. The temperature of the solar panel increased and a cooling system was needed. Two PC fans and an external power supply for the fans were used to cool down the panel.

Solar panel controller board

Solar panel controller board is used to extract power from the solar panels by the means of Maximum Power Point Tracking to maximize energy production. It delegates the power to the consumer (main power bus) and collects measurements for the control and measuring unit.

Control and measuring unit

The Arduino Mega microcontroller board, controlled by the PC over USB port, was used to control the solar panel controller [19]. The Arduino Mega microcontroller board was chosen because it has:

- The same microcontroller (ATmega1280) that EPS is planning to use.
- SPI interface to control the current limiter.
- 16 analog input pins to collect measurements.
- 54 digital I/O pins
- Regulated 3.3 V and 5 V outputs to supply the operational amplifier of the current limiter.
- Very useful Arduino software to program the microcontroller board and with serial monitor, simple textual data can be sent to and from the Arduino board. Serial monitor was used to see the current, voltage, power and resistance measurements on PC screen.

Also a digital oscilloscope and digital multimeters were used for efficiency measurements.

Consumers

To test the solar panel controller board and to test the output current and voltage a consumer has to be on the solar panel controller output. Different resistors and rheostats were used for testing. Also a battery protection circuit with a battery was used as the output (consumer) during the battery charging test.

6.1 Prototype board implementation proposal

Design rules for the prototype board were:

- 2 layer PCB board
- Copper coated PCB
- LPKF Protomat milling
- SMD components are used, except for pinheaders

Rules for PCB layout design:

- Isolation – 0.3 mm
- Spacing – 0.254 mm
- Width – 0.4 mm
- Hole diameters – 3.2 mm
- Via drill holes – 0.6 mm

General recommendations to follow:

- As much ground area should be designed around the filter as possible
- All RF components should be placed as close together as possible
- For every chip, a capacitor should be used for de-coupling the supply voltage
- Screw holes do not need to be isolated from the ground plane
- A ground via should be near every conductor to ground connection
- A ground via should be near every transistor to ground connection
- Ground vias with regular steps should be used on board edges to prevent board edge RF radiation

Component selection for the prototype (the whole list is in Appendix section):

- Resistors (R12, R17, R18, R19) – 0805
- Resistors (all others) – 0603
- Capacitors (1 uF, 10 uF, 22 uF) – 0805
- Capacitors (all others) – 0603

- Inductors (EPCOS B82442T110) – 1210
- Ferrite Beads - 1210
- Transistors (FDN306P) – SOT23
- Transistors (BC858W) – SOT323
- DC/DC Converter (LTC3440) – MSOP-10
- Digital rheostat (AD5174) – MSOP-10
- Current sense amplifier (LT6105) – MSOP-8
- Dual operational amplifier (MAX9916EKA) – SOT23-8
- Ideal diode (LTC4412) – TSOT-23
- High voltage diode (BAS21) – SOT-23
- Schottky diode (PMEG2010EA) – SOD-323W
- Schottky diode (MBRM120LT1G) – POWERMITE
- External connectors – Pinheader

Solar panel controller prototype schematic is shown in Figure 16. Different important parts of the schematic are pointed out for simplifications.

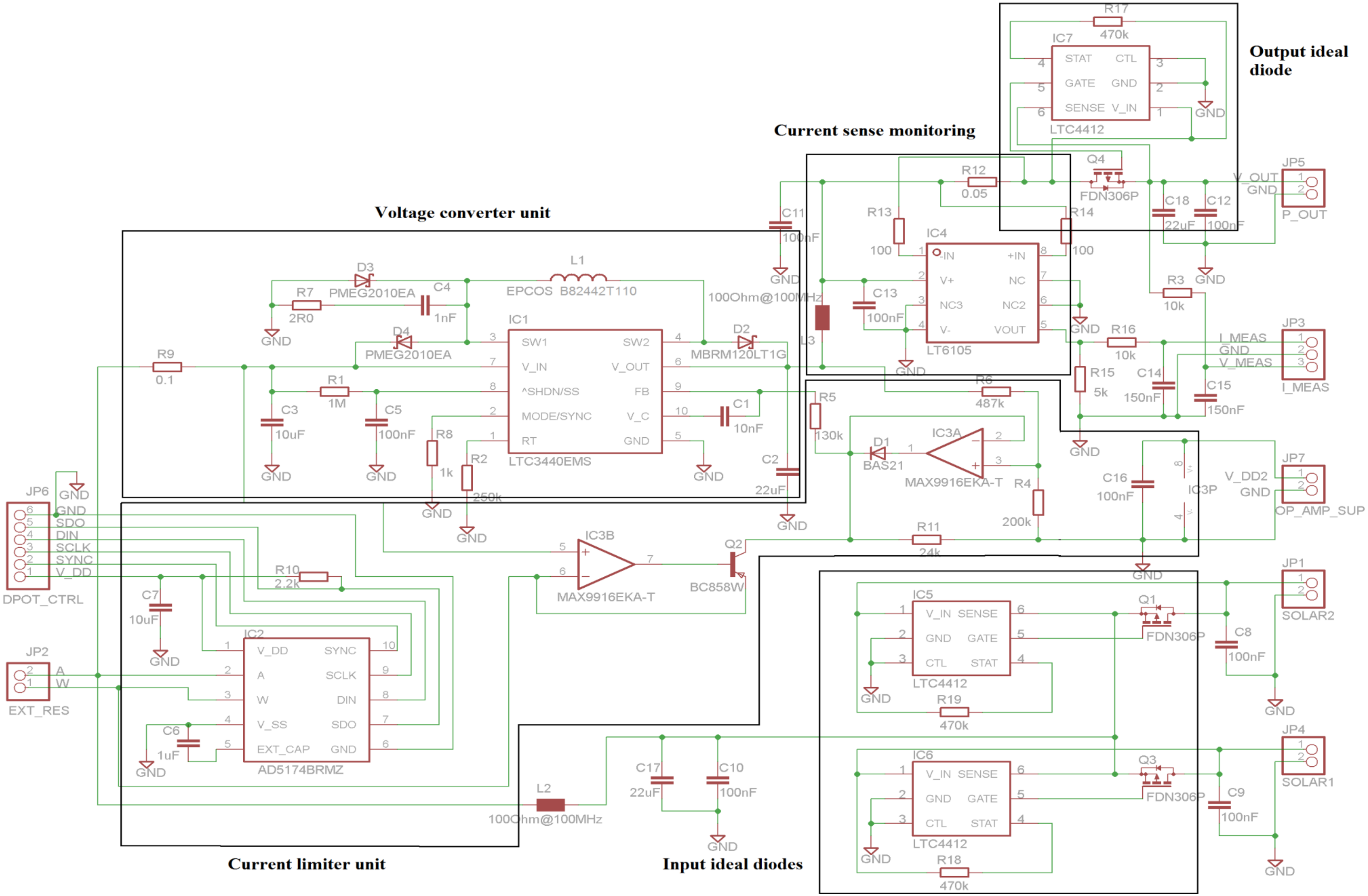

Figure 16: Solar panel controller schematic

Two different versions of input and output diodes have been tested to improve the controller efficiency. The older version had Schottky diodes for protection; the newest concept has ideal diodes to improve the efficiency, see Figure 16. Ideal diode LTC4412 by Linear Technology [20] has very wide operational supply voltage, such as 2.5 – 28 V and the quiescent current is very low, only 11 μA. Other components near it, such as P-channel MOSFET, FDN306P by Fairchild Semiconductors [21] was chosen according to the ideal diode datasheet.

Voltage converter unit is implemented using a buck-boost DC/DC converter LTC3440 by Linear Technology [22]. It features suitable input and output ranges, micro power operation and high efficiency. All the resistors and capacitors near the voltage converter LTC3440 have been taken according to the datasheet. The same goes for the selection and positioning of the Schottky diodes. Both Schottky diodes (PMEG2010EA and MBRMLT1G) across synchronous switches are recommended by the datasheet. The main efficiency affecting component of the converter circuit is the inductor that was carefully selected in order to provide optimal performance. Different inductors in different packages were tested during the Phase B of ESTCube-1 and B82442T110 by EPCOS [23] was considered to be a good choice.

The main component of current limiter is the operational amplifier MAX9916EKA by MAXIM [24]. It offers the same functionality as the one (LT1490A) which was recommended in voltage converter LTC3440 datasheet. To adjust the current limiter for controlling the MPPT, a digital rheostat AD5174 by Analog Device [25] was added. It is a single-channel, 1024-position digital rheostat with a SPI interface. Its maximal resistance is 10 kΩ. Other current limiter components have been taken from the voltage converter datasheet.

An extended input range current sense amplifier LT6105 by Linear Technology [26] was used to monitor output current. Output current monitoring is needed for maximum power point tracking.

The solar panel controller schematic and board has been created with the Eagle Layout Editor by CadSoft Computers. Solar panel controller prototype PCB layout is shown in Figure 17 (top side) and Figure 18 (bottom side). Most of the components are placed according to the datasheet recommendations and according to the EMC good practice rules.

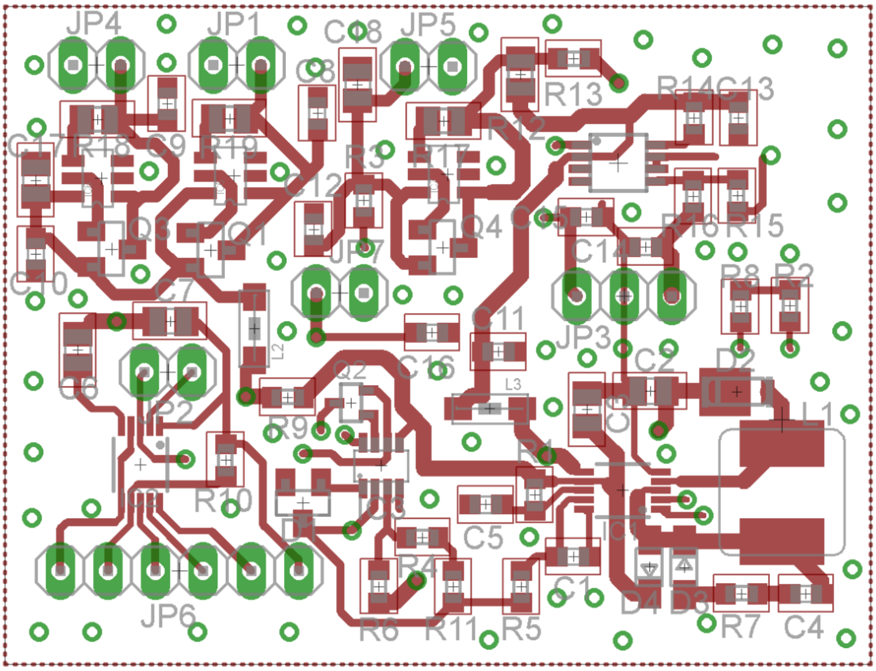

Figure 17: Top side of the solar panel controller prototype PCB layout.

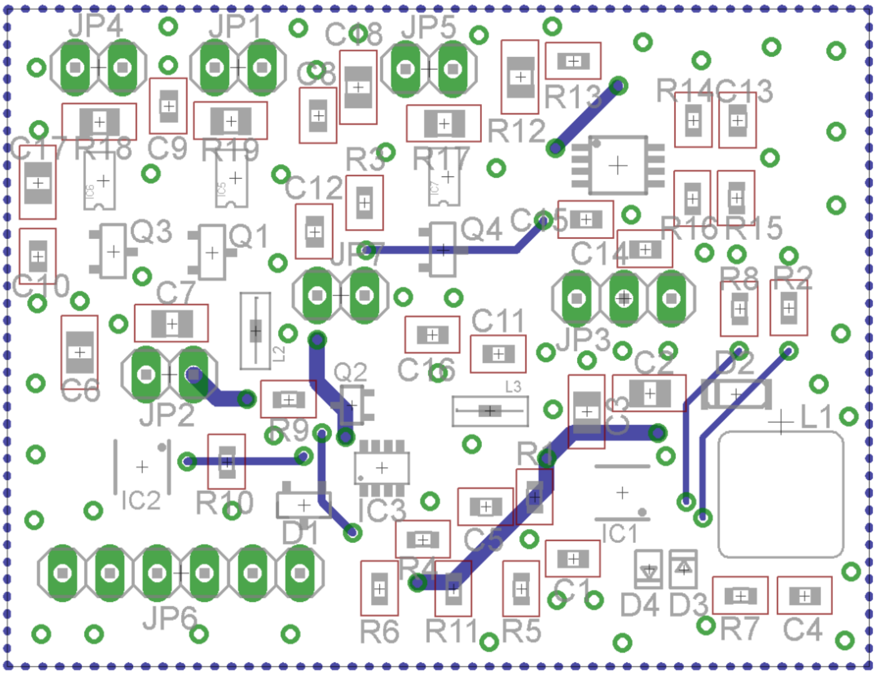

Figure 18: Bottom side of the solar panel controller prototype PCB layout.

6.2 Tests and measurements

6.2.1 Solar panel controller efficiency measurements

In order to verify the compliance of the solar panel controllers to the aforementioned requirements, several tests were conducted. The overall efficiency of the first prototype of the solar panel controller is given in Table 5. Unmodified circuit had both input and output OR'ing Schottky diodes. As can be seen in the table the efficiency depends on the value of the effective consumer resistance. The worst case scenario is tested with 4.3 Ω resistance. Table 5 shows what would happen to the efficiency of the board, if either the input or output diode was removed. This was the main reason why the controller board was redesigned.

Table 5: Efficiency measurements of first prototype

Effective consumer resistance 8.10 Ω	**V_{in} (V)**	**I_{in} (A)**	**P_{in} (W)**	**P_{out} (W)**	**Efficiency (%)**
Unmodified	4.28	0.384	1.644	1.3	**79.1**
Without input diode	4.25	0.387	1.645	1.38	**83.9**
Without output diode	4.28	0.385	1.648	1.36	**82.5**
Effective consumer resistance 4.3 Ω					
Normal case	4.14	0.39	1.615	1.13	**70**
Without input diode	4.21	0.392	1.65	1.21	**73.3**
Without output diode	4.17	0.389	1.622	1.23	**75.8**

The efficiencies of the redesigned board are given in Table 6. The effects of the replacement of the Schottky diodes with the ideal diodes are clearly visible.

Table 6: Efficiency measurements of improved prototype

Effective consumer resistance (Ω)	**V_{in} (V)**	**I_{in} (A)**	**P_{in} (W)**	**P_{out} (W)**	**Efficiency (%)**
2.7	4.34	0.277	1.202	0.11	**9.15**
4.4	4.09	0.308	1.26	0.93	**73.8**
7.10	4.34	0.277	1.202	1.08	**89.85**
15.1	4.5	0.275	1.237	1.208	**97.6**

6.2.2 Maximum Power Point behavior

The power point of solar panel can be changed by modifying the resistance of the digital rheostat. In case of a certain resistance of digital rheostat the power is maximal.

The whole range of digital rheostat level was scanned and output power was logged at a certain lighting condition and at fixed consumer resistance.

The results of scanning in both directions can be seen on Figure 19. A distinctive peak can be seen which correspond for the maximum power point of the current conditions. On both sides the efficiencies are considerable lower and this exemplifies the need for Maximum Power Point tracking. The good overlap between the two graphs means that the system always has a single maximum, which is independent of the direction of approach, simplifying algorithm development.

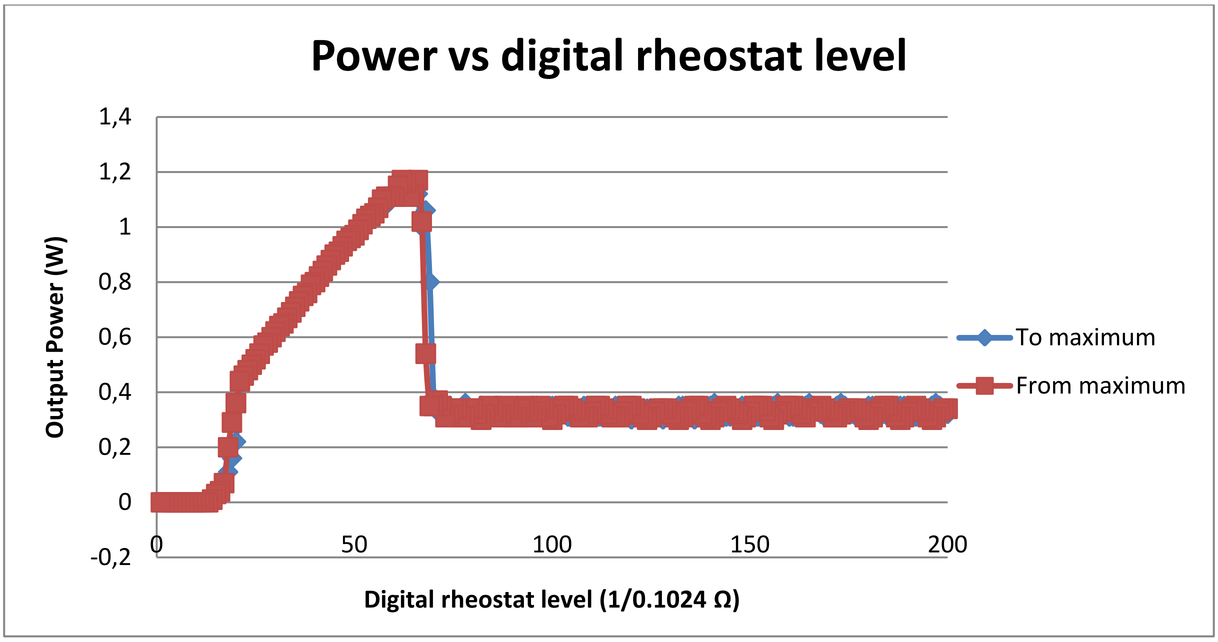

Figure 19: Output power dependence on digital rheostat level. Maximum Power Point can be seen at level 65

6.2.3 Maximum Power Point Tracking

To confirm the correct operation of power point tracking system a following test was conducted.

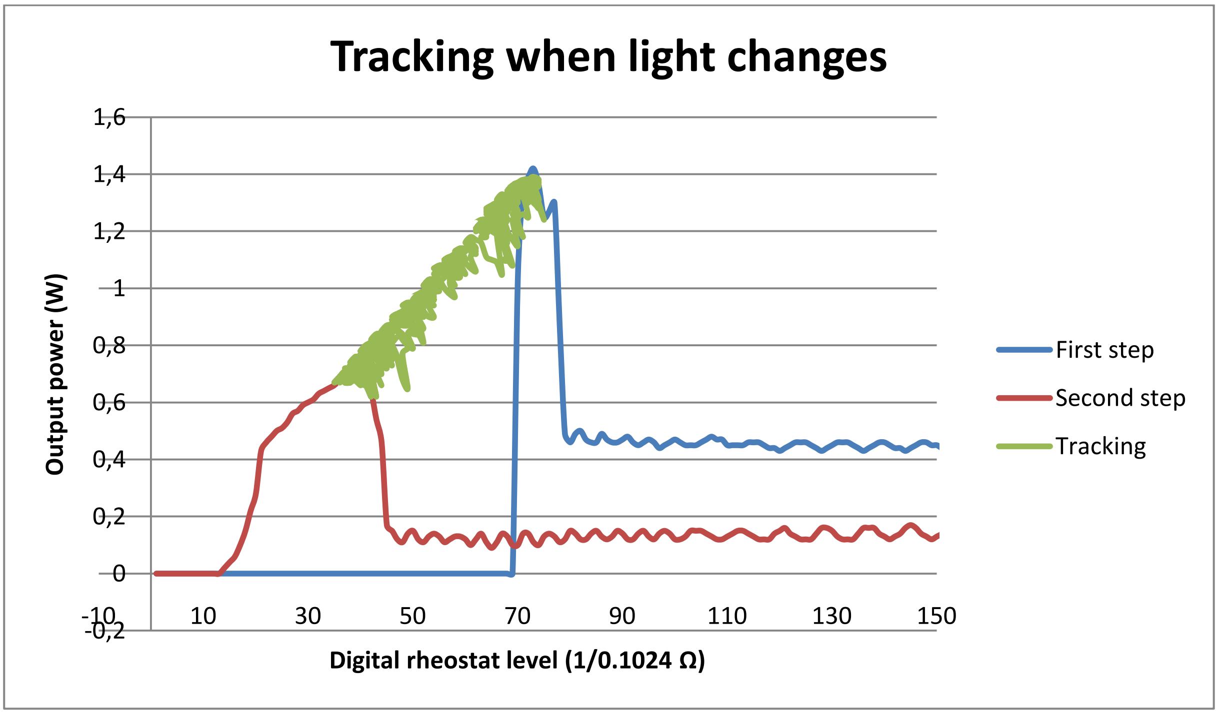

Figure 20: Demonstration of Maximum Power Point Tracking

During the test at first the Maximum Power Point was found by scanning the whole range of digital rheostat values. Then the tracking process was started and at the same time the distance between a solar panel and light source was changed. It is clearly visible that the Maximum Power Point is tracked. From the new position of light source the scanning process was started again to find the new Maximum Power Point. The algorithm manages to track the maximum power point as a transition from high light to low light state. In Figure 20, the high light condition is the blue graph and low light condition is the red graph.

6.2.4 Battery charging using the MPPT system

To test the MPPT system in real life situation we conducted a battery charging test in cooperation with Martynas Pelakauskas, an ESTCube-1 EPS team member, who is designing the battery protection circuit for ESTCube-1, a battery charge test with solar panel was implemented [7]. As can be seen in Figure 21, the output power of the solar panel controller is decreasing with the increase of battery voltage, because of the voltage drop on the output diode. The new prototype board is designed with ideal diodes that make the output voltage drop negligible.

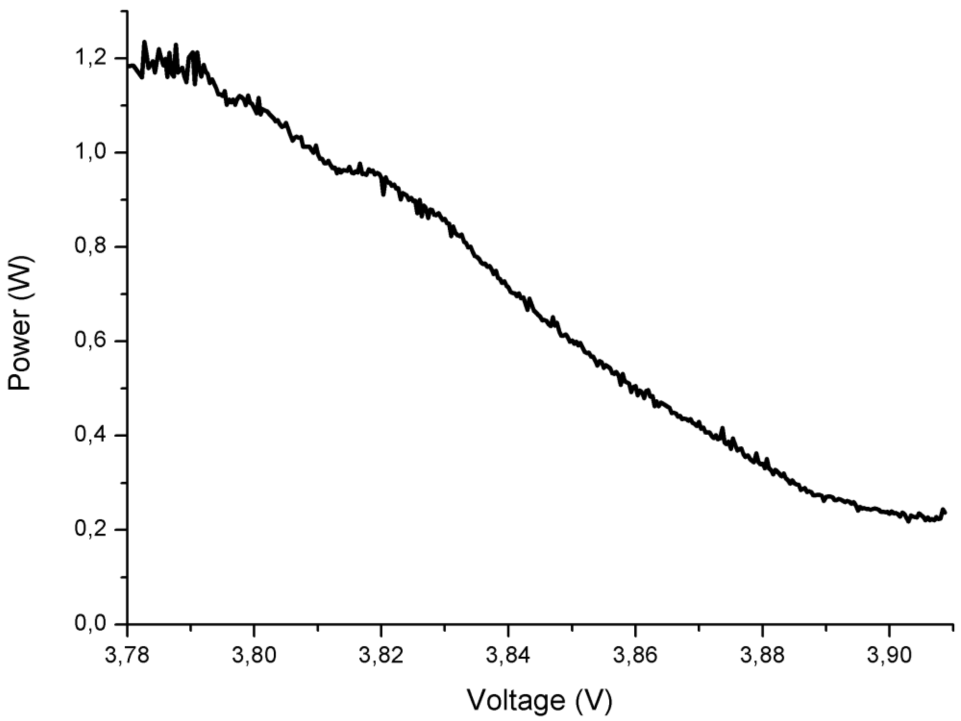

Figure 21: The output voltage versus output power during battery charge.

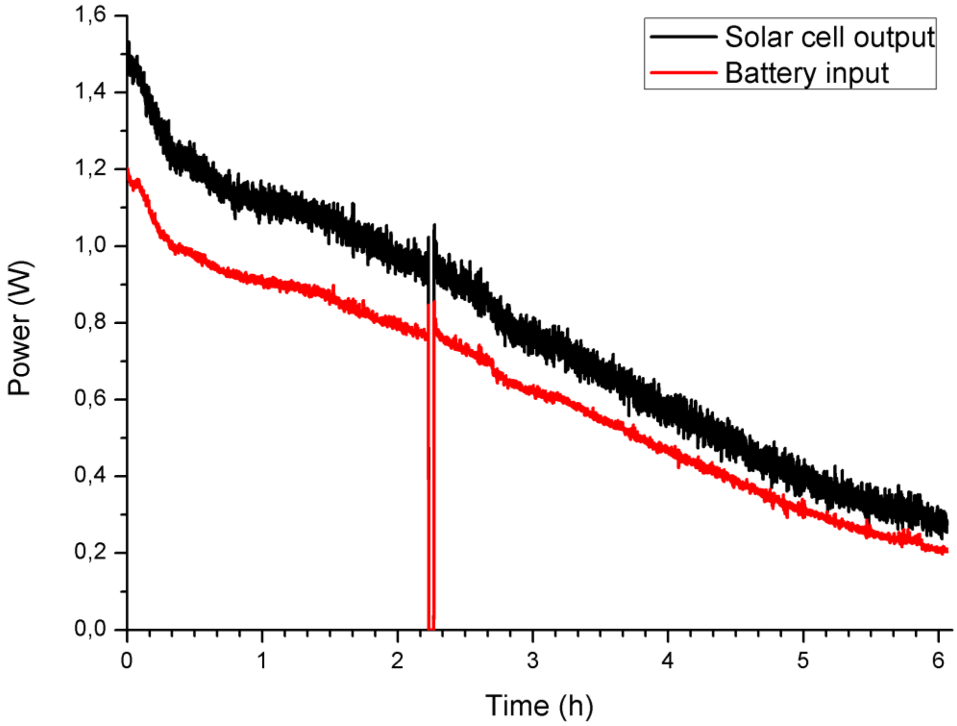

Figure 22: The power losses inside the solar panel controller.

As can be seen in Figure 22, the output power of the solar panel controller (battery input in Figure 22) is less than the output power of solar panel (solar cell output in Figure 22) due to converter losses.

7 Conclusion

The main goals of this thesis were to analyze solar panels characteristics and solar panel harvesting and to understand the concept and need for Maximum Power Point Tracking. Based on the analysis a solar panel controller design for ESTCube-1 was proposed and the prototype of the solar panel controller was developed. Primary tests for MPPT algorithm verification were completed.

The most important results of this work are:

- Solar panel controller is fully operating according to expectations.
- New assembled board, with ideal diodes to increase overall efficiency, is ready and operating. Efficiency tests have been collected.
- The primary testing of proposed MPPT algorithm was successful.
- Software that was written to demonstrate MPPT is fully working and ready for modifications.
- A good and quickly installable test setup has been worked out.
- A battery test was acceptable with minor allowances.

Recommended future steps based on the work are:

- New solar panel controller boards needs more testing and efficiency measurements should be analyzed. If needed, even new improvements shall be contrived.
- Tests with more than one solar panel should be implemented.
- Solar panel controller tests have to be accepted according to test plan (vacuum test, temperature test etc).
- If all the test results are acceptable a new board layout for 4 layers PCB should be implemented.
- Space qualified solar panels shall be tested.
- Fully operational EPS model shall be assembled.

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9 ESTCube-1 päikeseenergia kogumise süsteemi kavandamine, teostamine ja katsetamine.

Ramon Rantsus

Kokkuvõte

Eesti Tudengisatelliidi projekt sai alguse 2008 aasta suvel Tartu Ülikoolis. Eesmärgiks oli edendada kosmesetehnoloogia alaseid teadmisi. Projekti peamiseks väljundiks sai satelliit nimega ESTCube-1 – Eesti esimene satelliit.

Satelliidi kõik kuus külge on varustatud päikesepaneelidega, et satellidi erinevad alamsüsteemid saaksid piisavalt energiat. Käesoleva magistritöö peamiseks eesmärgiks saigi päikeseenergia kogumise süsteemi väljatöötamine.

Kõik käesolevale magistritööle seatud eesmärgid täideti. Põhiline eesmärk oli analüüsida üleüldist päikesepaneelide tööpõhimõtet ja maksimaalse võimsuspunkti vajalikkust. Päikesepaneelide nõuetele tuginedes pakuti välja päikeseenergia kogumise süsteemi põhimõtteline riistvaraline ja tarkvaraline lahendus ja arendati välja töötav prototüüp.

Töö olulisemad tulemused:

- Loodi täielikult töötav päikeseenergia kogumise süsteem.
- Loodi tarkvara päikeseenergia kogumise süsteemi juhtimiseks.
- Maksimaalse võimsuspunkti jälgimise algoritm töötab.
- Ideaaldioodidega päikeseenergia kogumise prototüüp sai kokku pandud ja testitud.

Tuginedes käesoleva töö tulemustele on järgmise sammuna sobilik teha:

- Täiustatud päikeseenergia kogumise prototüüp tuleb täielikult testida ja antud tulemused põhjalikult analüüsida.
- Nende analüüside põhjal tuleb päikeseenergia kogumise süsteem teha neljakihilisele plaadile, et sellega vähendada kogu alamsüsteemile mõeldud pinna kasutust.
- Prototüüp tuleb testida vastavalt testplaanile (vaakumtest, temperatuuritest jne).
- Peagi saabuvaid kosmosesse mõeldud päikesepaneele saab hakata testima.
- Täielikult töötav elektri alamsüsteem on vaja kokku panna.

Appendix A: Software code

```
/**
 *Maximum Power Point Tracker sketch
 *For Arduino 0022
 *
 *By Ramon Rantsus
 *EstCube-1 Electrical Power Subsystem, 2011
 *
 *Uses scanning for initial power point estimation and hill-climbing for further tracking.
 *
 *Requirements:
 *Current sense voltage connected to A0
 *Voltage measurement connected to A1
 *SPI connection to digital potentiometer, pin 10 as slave select
**/

// inslude the SPI library:
#include <SPI.h>

//Define pins for connecting external devices

// set pin 10 as the slave select for the digital pot:
const int slaveSelectPin = 10;

//Analog input for current measurement
const int analogInPin = A0; //I_meas

//Analog input for voltage measurement
const int analogInPin2 = A2;//V_meas

//Initialize variables
//ADC reads
int sensorValue = 0;
int sensorValue2 = 0;
//Potentiometer level and resistance
int level = 0;
double resistance = 0;

//Hill-climbing direction
```

```
int dir = 1;

//Voltage and current variables
double voltage = 0;
double currentV = 0;
double current = 0;

//Power variables and potentiometer levels
double power = 0;
double power_old = 0;
double power_peak = 0;
double power_peak2 = 0;
int level_peak=0;
int level_peak2=0;

//State: >0: scanning, 0: hill-climbing
int state = 0;

//Coefficients for calculating voltage and current (see corresponding methods)
double voltageCoef = 0.00475;
double currentCoef = 0.33333;

/**
 *Setup method-initializes connections
 **/
void setup() {
	// set the slaveSelectPin as an output:
	pinMode (slaveSelectPin, OUTPUT);

	// initialize SPI:
	SPI.begin();

	// initialize serial communication at 9600 bps
	Serial.begin(9600);
	Serial.println();

	// Send command to digital potentiometer to allow changing its resistance
	digitalPotWrite(7,2);
}
```

```
/**
 *Reads MPPT module output current and returns it as mA
 **/
double readCurrent()
{
	//Read value from current measurement using ADC
	sensorValue = analogRead(analogInPin);
	//Convert ADC signal to voltage using a predefined constant
	currentV = sensorValue * voltageCoef;

	 //Calculates the current from the voltage (mA)
	return currentV * currentCoef * 1000;
}

/**
 *Reads MPPT module output voltage and returns it as V
 **/

double readVoltage()
{
	//Reads the output voltage level (V)
	sensorValue2 = analogRead(analogInPin2);
	return sensorValue2 * voltageCoef ;
}

/**
 *Main loop of the sketch
 *Scans and tracks the Maximum Power point
 **/
void loop() {
	//While state is greater than zero enter scanning section
	while (state >= 0){
		 level=1;
		//Scan the power to potentiometer level dependence in both directions
		while (level > 0) {
			//Read output current
			current = readCurrent();
```

```
        //Read output voltage
        voltage = readVoltage();

        //Calculates the output power (W)
        power = (current/1000)*voltage ;

        if (power > power_peak) {
                power_peak = power;
                level_peak = level;
        }
        Serial.print(power);
        Serial.print(" ");
        Serial.println(level);

        //Increase the potentiometer level
        level += dir;

        //If potentiometer level reaches maximum, change direction
        if(level>=1023)
        {
                //Save the maximum of this run
                power_peak2=power_peak;
                level_peak2=level_peak;

                //Initialize varibles for next run
                power_peak=0;
                dir=-dir;
        }
        //Write new digital potentiometer level
        digitalPotWrite(1, level); //Write level
        delay(10); //Wait for the system to stabilize
}

//Output the results to serial port
Serial.println();
Serial.print("First max ");
Serial.print(power_peak);
Serial.print(" and level ");
Serial.println(level_peak);
```

```
        Serial.print("Second max ");
        Serial.print(power_peak2);
        Serial.print(" and level ");
        Serial.println(level_peak2);
        Serial.println();

        state -= 1;
        level = (level_peak+level_peak2)/2; //The starting point of tracking
        power_old = power_peak;//Reference power
        digitalPotWrite(1, level);//Write the point to potentiometer
}
//Read output current
current = readCurrent();
//Read output voltage
voltage = readVoltage();
//Calculates the output power (W)
power = (current/1000)*voltage ;
resistance = (10.0 * level)/1.024; //Calculate approximate digital potentiometer
//resistance

//Output current, voltage, power, digital potentiometer resistance and its level //for
//logging

Serial.print(current);
Serial.print(" ");
Serial.print(voltage);
Serial.print(" ");
Serial.print(power);
Serial.print(" ");
Serial.print(resistance);
Serial.print(" ");
Serial.print(level);
Serial.print(" ");
Serial.println();

//Hill-climbing: if the power decreased from last step, change step direction
if (power < power_old) {
        dir = -dir; //Inverse direction
}
```

```
	//Change the level
	 level += dir;

	//Limit the possible range of the potentiometer values
	if (level>1023) level=1023;
	if (level < 0)  level = 0;

	//Write the level to potentiometer
	digitalPotWrite(1, level);

	//Store current power for reference
	power_old = power;
	delay(10);
}
/**
*Method for sendinga a command (address) and its parameter (value) to the digital
potentiometer
 *Data packet format (2 bytes):
 * Byte 1: aaaa aavv
 * Byte 2: vvvv vvvv
 * a- address bit
 * v- value bit
 **/
void digitalPotWrite(int address, int value) {
	// take the SS pin low to select the chip:
	int First, Second; //Define two variables for the upper and lower byte of the command
	First = (address << 2); //Shift address left by two
		First |= ((value >> 8)&7); //Take bits 9 and 8 from value and add them after the
	address
	Second= value&255;  //The bits 0-7 form the second byte of the packet

	//Activate digital potentiometer connection by setting slave select low
	digitalWrite(slaveSelectPin,LOW);

	//  send in the address and value via SPI:
	 SPI.transfer(First);
	 SPI.transfer(Second);
	// take the SS pin high to de-select the chip:
	digitalWrite(slaveSelectPin,HIGH);
}
```

Appendix B: Solar panel controller schematics part list

Exported from EC1_EPS_MPPT_prototype_final_ver_2.sch at 21.05.2011 1:13:27

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Part	Value	Device	Package	Library	Sheet
C1	10nF	C-EUC0603	C0603	resistor	1
C2	22uF	C-EUC0805	C0805	resistor	1
C3	10uF	C-EUC0805	C0805	resistor	1
C4	1nF	C-EUC0603	C0603	resistor	1
C5	100nF	C-EUC0603	C0603	resistor	1
C6	1uF	C-EUC0805	C0805	resistor	1
C7	10uF	C-EUC0805	C0805	resistor	1
C8	100nF	C-EUC0603	C0603	rcl	1
C9	100nF	C-EUC0603	C0603	resistor	1
C10	100nF	C-EUC0603	C0603	rcl	1
C11	100nF	C-EUC0603	C0603	resistor	1
C12	100nF	C-EUC0603	C0603	resistor	1
C13	100nF	C-EUC0603	C0603	resistor	1
C14	150nF	C-EUC0603	C0603	resistor	1
C15	150nF	C-EUC0603	C0603	resistor	1
C16	100nF	C-EUC0603	C0603	resistor	1
C17	22uF	C-EUC0805	C0805	resistor	1
C18	22uF	C-EUC0805	C0805	resistor	1
D1	BAS21	BAS21	SOT23	diode	1
D2	MBRM120LT1G	MBRM120LT1G	POWERMITE	EC1_B_EPS_PARTS	1
D3	PMEG2010EA	PMEG2010EA	SOD-323W	EC1_B_EPS_PARTS	1
D4	PMEG2010EA	PMEG2010EA	SOD-323W	EC1_B_EPS_PARTS	1
IC1	LTC3440EMS	LTC3440EMS	MSOP-10	EC1_B_EPS_PARTS	1
IC2	AD5174BRMZ	AD5174BRMZ	MSOP-10	EC1_B_EPS_PARTS	1
IC3	MAX9916EKA-T	MAX9916EKA-T	SOT23-8L	maxim	1

IC4	LT6105	LT6105	MSOP8	LT6105	1
IC5	LTC4412	LTC4412	TSOT-23	LTC4412	1
IC6	LTC4412	LTC4412	TSOT-23	LTC4412	1
IC7	LTC4412	LTC4412	TSOT-23	LTC4412	1
JP1	SOLAR2	PINHD-1X2	1X02	pinhead	1
JP2	EXT_RES	PINHD-1X2	1X02	pinhead	1
JP3	I_MEAS	PINHD-1X3	1X03	pinhead	1
JP4	SOLAR1	PINHD-1X2	1X02	pinhead	1
JP5	P_OUT	PINHD-1X2	1X02	pinhead	1
JP6	DPOT_CTRL	PINHD-1X6	1X06	pinhead	1
JP7	OP_AMP_SUP	PINHD-1X2	1X02	pinhead	1
L1	EPCOS B82442T110	FP3-150-R	FP	EC1_B_EPS_PARTS	1
L2	100Ohm@100MHz	WE-CBF_1210	1210	wuerth-elektronik	1
L3	100Ohm@100MHz	WE-CBF_1210	1210	wuerth-elektronik	1
Q1	FDN306P	FDN306P	SOT23	FDN306P	1
Q2	BC858W	PNPSOT323	SOT323	zetex	1
Q3	FDN306P	FDN306P	SOT23	FDN306P	1
Q4	FDN306P	FDN306P	SOT23	FDN306P	1
R1	1M	R-EU_R0603	R0603	resistor	1
R2	250k	R-EU_R0603	R0603	resistor	1
R3	10k	R-EU_R0603	R0603	resistor	1
R4	200k	R-EU_R0603	R0603	resistor	1
R5	130k	R-EU_R0603	R0603	resistor	1
R6	487k	R-EU_R0603	R0603	resistor	1
R7	2R0	R-EU_R0603	R0603	resistor	1
R8	1k	R-EU_R0603	R0603	resistor	1
R9	0.1	R-EU_R0603	R0603	resistor	1
R10	2.2k	R-EU_R0603	R0603	resistor	1
R11	24k	R-EU_R0603	R0603	resistor	1
R12	0.05	R-EU_R0805	R0805	resistor	1

R13	100	R-EU_R0603	R0603	resistor	1
R14	100	R-EU_R0603	R0603	resistor	1
R15	5k	R-EU_R0603	R0603	resistor	1
R16	10k	R-EU_R0603	R0603	resistor	1
R17	470k	R-EU_R0805	R0805	resistor	1
R18	470k	R-EU_R0805	R0805	resistor	1
R19	470k	R-EU_R0805	R0805	resistor	1

Appendix C: Picture of the prototype board and test solar panel

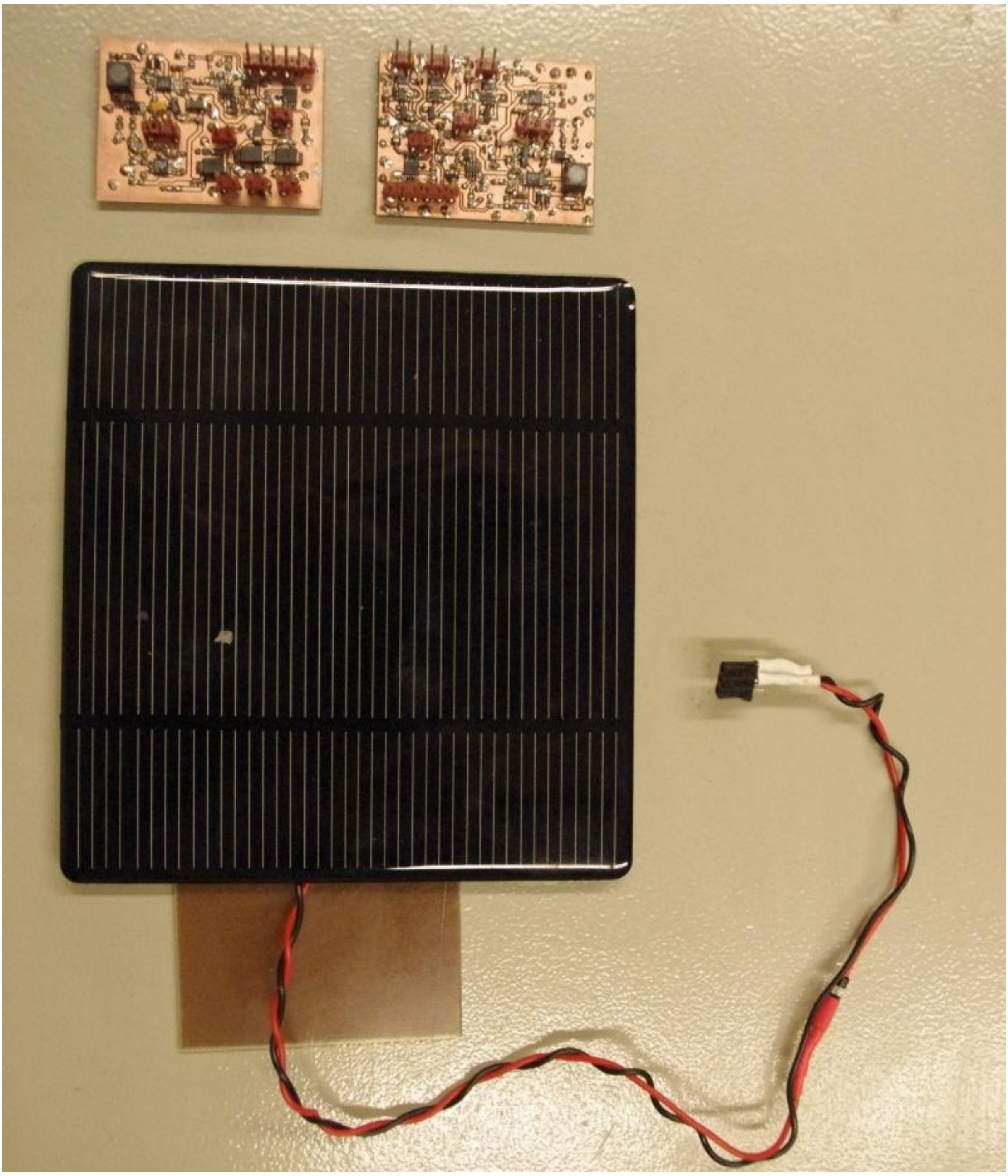

Figure 23: Picture of prototype boards and test solar panel.

Appendix D: Picture of the test setup

As can be seen in Figure 24, the Arduino software is used and the built-in the Serial monitor is collecting output currents and output voltages. Solar panels with the light source are on the right.

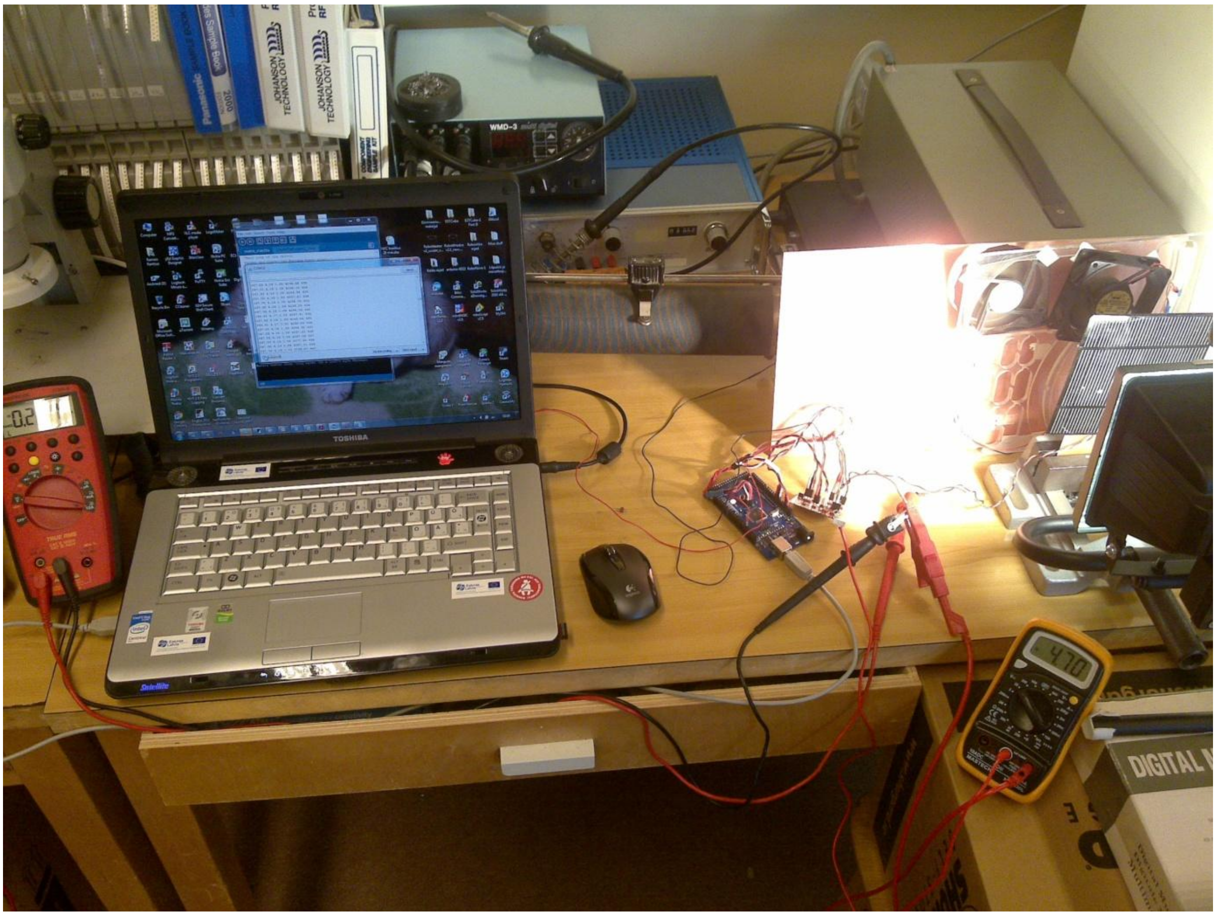

Figure 24: Picture is taken during the second efficiency test.