Design of Hardware and Software for the Powersupply for AAU Cubesat

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Chapter 1

Introduction

This document is the documentation of power supply of the AAU Cubesat. First and foremost the purpose of this document is to give the reader an idea of how the power supply unit (the PSU from now on) is contructed, ie. insight in the main lines of the design.

This document is created using the two reports ([**?**][1] and [**?**][2]) which were made about the PSU in autumn 2001 - both these reports were however incomplete in their final designs and therefore a revised design and this document have been made.

The revised design of the hardware has been build mainly on the design from [**?**] whereas the software has been created from scratch but with some principles from [**?**].

1.1 Introduction to the PSU of AAU Cubesat

The power supply is a fully autonomous system that receives power from a number of solar arrays with photo-voltaic cells and conditions and distributes this power to a number of users which are the other electronic subsystems on board the satellite. Further, if more power is obtained from the solar cells than consumed by the connected subsystems then this power must be stored in a number of batteries, and when power consumption exceeds power input then the batteries should discharge in order to provide the needed power output. If a subsystem draws a current from the PSU that is large enough to suggest a malfunction of that user then the PSU must cut the current to the users and inform the OBC. Further it must be possible for the OBC to specify which users are allowed to receive power at a given time.

In addition to the above described main functionality the PSU has a set of secondary functions that also must be fulfilled:

1. Collect housekeeping information including satellite temperatures
2. Act as boot-master and external watchdog for the OBC

In figure 1.1 a conceptual diagram of the PSU system is depicted with focus on the main fctionality and interfaces. The following paragraphs will discuss some of the PSU functionality in more detail than already given above.

The power delivered to the users is distributed from a 5 V controlled powerbus.

In order to communicate both housekeeping data and information about e.g. an user shut down due to excessive power consumption the PSU must be able to exchange information with the OBC. This is

[1] http://www.cubesat.auc.dk/dokumenter/psu.pdf
[2] http://www.cubesat.auc.dk/doc.html

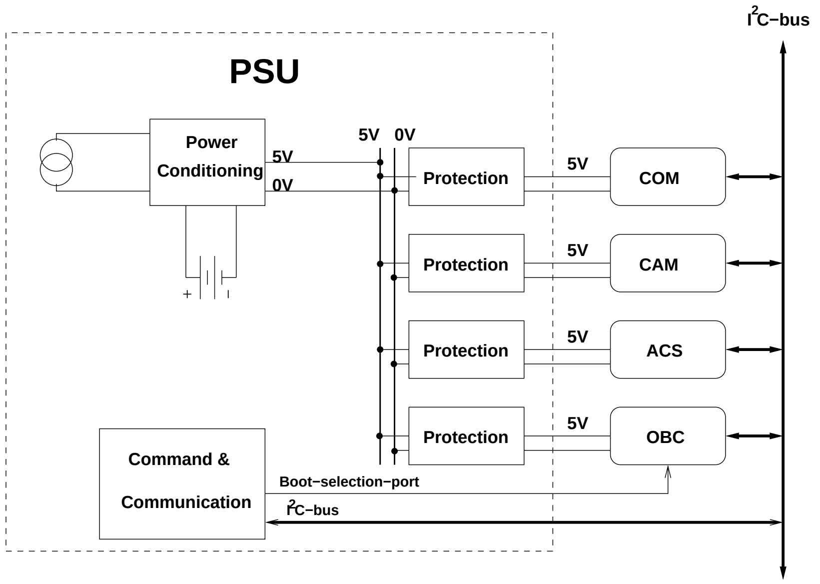

Figure 1.1: Overview of the PSU main interfaces.

performed by means of an I2C-bus, which has been selected as the communication interface between the different systems on board the satellite.

The secondary functions of the PSU regarding boot-master and watchdog functionality is to provide the OBC with a safe method for choosing whether it should boot up using its failsafe software placed in PROM circuitry or boot up using software placed in FLASH-ROM. Furthermore, if the OBC fails to send signals to the PSU through then the I2C-bus the PSU must reboot it because of the assumption that it is not working properly.

When the PSU receives power from the solar cells it is to control the current-flow in such a manner that maximum power is obtained. This control is necessary because there is a complex relationship between power-output, cell voltage, cell current and and received solar radiation.

The batteries chosen for the PSU is to be selected such that they are able to hold such an amount of charge that the satellite is allowed to fully operate throughout its active periods. This of course is under the assumption that the activity level of the satellite is constrained in such a way that the power input/output balance is either positive or zero for a time period corresponding to one period of both satellite activity and inactivity.

1.1.1 User Characteristics

The users of the PSU are the other subsystems of the AAU-Cubesat that requires electrical power in order to operate - identified users are:

OBC handles information from subsystems and controls the satellite

ACS is responsible for controlling the orientation of the satellite such that camera and antennas are pointed in a specified direction

CAM is responsible for the part of the satellite mission which is to take pictures of Denmark.

COM is responsible for transmitting and receiving communication between the satellite and the ground-station. The COM unit consists both of the specific radio as well as a modem

Chapter 2

Hardware

In this chapter the hardware for the Power Supply Unit (PSU) will be designed. This chapter will provide an overview of the hardware configuration by extending the information given in the Introduction with more details regarding the configuration of solar arrays and battery pack. The PSU is depicted in figure 2.1 with all hardware modules. The following sections will state the functionality of the different modules that make up the PSU.

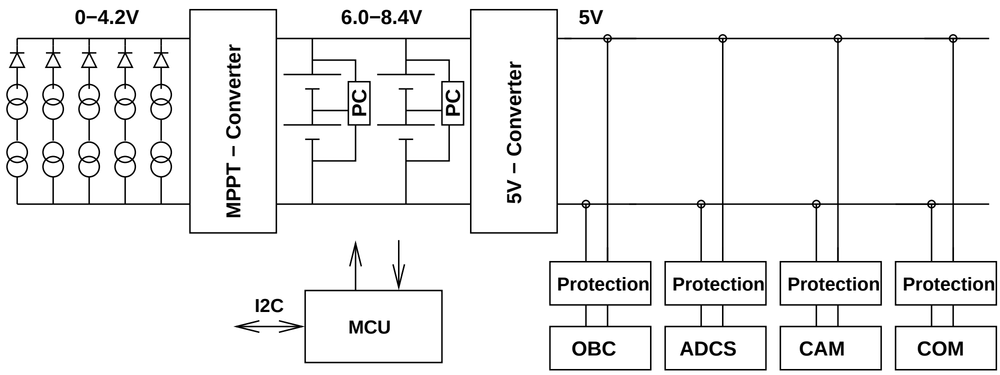

Figure 2.1: An overview of the PSU hardware configuration

2.1 Functionality

In this section a ”walk-through” of figure 2.1 from left to right and a brief discussion on the functionality and configuration of the different modules of the PSU hardware will be done.

Solar Arrays

The solar arrays are configured such that the cells of each side on the satellite are connected in series and the five sides are connected in parallel. This configuration has been chosen, because it was found that it is the best tradeoff between ease of Maximum Power Point Tracking (MPPT) and to improve the converter performance. The analysis of the solar array configuration and MPPT can be found in appendix B on page 33.

The voltage across the parallel connection will in this configuration be approximately 4.0 V depending on illumination input (See appendix B on page 33). The diodes protect the cells from conducting a reverse current.

MPPT Converter

The MPPT-converter performs MPPT on the solar array i.e. it transfers the maximum obtainable power from the solar array to the outputside of the converter. Further, it steps up the voltage to fit the level of the battery pack.

Battery Pack

The battery pack consist of 2 x 2 batteries connected in two parallel strings of two batteries in series. This gives a voltage of between 6.0 V and 8.4 V depending on the state of the batteries. The choice of battery configuration and capacity is documented in appendix A on page 31.

The battery is also responsible for voltage control of the intermediate power bus between the two converters. The batteries keep the average voltage in the range 6.0 - 8.4 V.

Across the batteries are placed protection-circuits (PC) which protects the batteries from over- and under voltage.

5V-Converter

The 5V-converter conditions the voltage for the main 5 V power bus by stepping down the voltage from the intermediate power bus.

Remove before flight pin

Of the other things that are included in the PSU is the "Remove before flight" pin quite important. When this pin that consists of 4 jumpers is inserted the PSU is off. There is a jumper for each battery protection circuit which – when the jumpers are inserted – disconnects the batteries from the rest of the satellite. Also there is a jumper for each converter which – when jumpers are inserted – are off.

User Protection

Each load has an associated protection circuit which will shut down the user i.e. disconnect it from the power bus if the load draws a current that is higher than a specified maximum for that load. This could happen if the load suffered from an internal latch-up due to radiation effects.

The load protection circuit also serves as a controllable on/off switch that lets the PSU MCU switch loads on and off according to the orders that it receives from the OBC which the MCU communicates with through the I^2C-bus.

Digital Hardware

On figure 2.1 the digital hardware or the MCU is shown at the bottom. The MCU is responsible for the measuring of physical values in the system depicted in figure 2.1 and measurement of temperatures at various locations in the satellite. These measurements serve two distinct purposes. The measurements are sent to the OBC for housekeeping information.

2.2 MPPT-Converter

As it can be seen in appendix B on page 33 the maximum power point (MPP) for the chosen solar cells is from 4 to 4.2V depending on temperature etc. The Maximum Power Point Tracker has to fulfill the task of converting the voltage of about 4V from the solar cells up to the battery voltage (6-8.4V). For this reason it is clear that a boost converter is needed for this task, see figure 2.2.

The relationship between input and output voltage for at boost converter is described as follows:

$$\frac{V_o}{V_i} = \frac{1}{1-D} \tag{2.1}$$

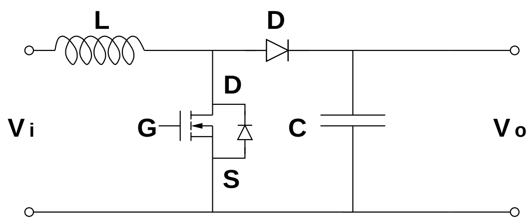

Figure 2.2: The principle of a boost converter

Where:
V_o is the output voltage of the boost converter, i.e. the battery voltage. [V]
V_i is the input voltage of the boost converter, i.e. the solar cell voltage. [V]
D is the controlling duty cycle. []

From this it can be calculated that the duty cycle will be around 50% to achieve the MPP for the solar cells. The switching frequency will be around 80kHz because of the limitations in the digital hardware which will be described later in this chapter.

2.2.1 Choosing components

First of all a switch has to be chosen and as the switch consists of the mosfet and the diode these are the components that has to be chosen. The primary concern when choosing these components is the loss in them, both switching and conducting loss. To minimize the conducting loss it is important to find a diode with a small voltage drop and a mosfet with a small on-resistance (R_{on}). For the mosfet a MTD20N03HDL N-Channel mosfet from ON-Semiconductor has been chosen with a R_{on} of only 0.03Ω and for the diode a SB540 with a forward voltage drop of 0.55 V at 5 A forward current. The switching loss will not be dealt with here but can be read about in [**?**].

Because of the limited space in the satellite and therefor on the PSU-board it is important to find physical small components for the capacitor and especially the coil. Because of this it can be necessary to allow the converter to operate in discontinuous conduction mode (DCM). It has been decided to go with a 22uH coil and a 300uF capacitor. For the converter to go into DCM the following inequality needs to be true:

$$I_L > \Delta I_L \tag{2.2}$$

Where:
I_L is the average continuous current through the coil. [A]
ΔI_L is the ripple current in the coil. [A]

The ripple current in the coil can be calculated in the following way:

$$\begin{aligned}
\Delta I_L &= \frac{V_i}{2L} \cdot D \cdot f_s^{-1} \Rightarrow \\
\Delta I_L &= \frac{4}{2 \cdot 22e-6} \cdot 0.5 \cdot 80e3^{-1} \Rightarrow \\
\Delta I_L &\approx 0.5A
\end{aligned} \tag{2.3}$$

Therefore it can be concluded that the converter will properly operate in continuous conduction mode when the satellite is in the sun and in discontinuous conduction mode when in shadow.

2.2.2 Controlling the converter

To operate the mosfet switch a driver is needed to achieve good switching characteristics and a low-side driver from maxim has been chosen - the MAX 4420. This device can drive one mosfet with current-burst of up to 6A and is therefore capable of switching the mosfet very quickly. See figure 2.3

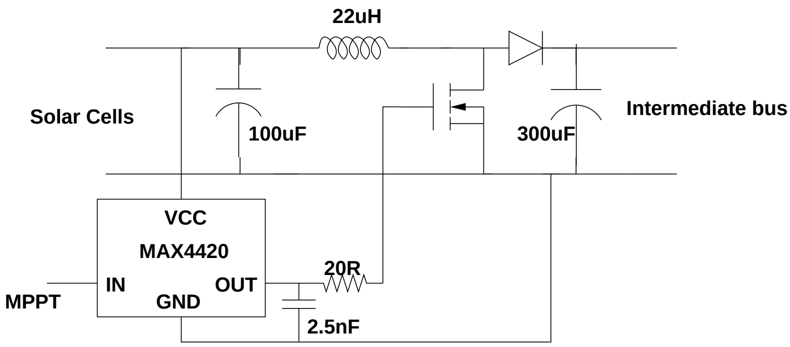

Figure 2.3: The setup of the gate driver and the MPPT converter.

To generate the duty cycle two sources are implemented: a fixed 55% duty cycle and a digital duty cycle from the MCU. The fixed duty cycle is used as a backup if the MCU should fail and therefore would not be capable of delivering the digital duty cycle. To arbitrate between the two sources a multiplexer is used and because of its small size a ADG704 from Analog has been chosen. This has been setup in such a way that should the MCU crash in some way the fixed duty cycle will be chosen (see table 2.1).

A0	A1	Input	MPPT
0	0	S1	Fixed
1	0	S2	Digital
0	1	S3	Fixed
1	1	S4	Fixed

Table 2.1: The truth table for the MPPT

The fixed control signal is provided by a 555 timer circuit setup as an astable multivibrator (see figure 2.4) and is - as said before - a 78 kHz frequency with 55% duty cycle. According to [**?**] the duty cycle and frequency of the astable 555 is described in the following way:

$$f = \frac{1}{0.69 \cdot C(R1 + R2)} \tag{2.4}$$

$$D = \frac{R1 + R2}{R1 + 2 \cdot R2} \tag{2.5}$$

where:
f is the switching frequency [Hz]
D is the duty cycle []

If $R1$ is chosen to 1kΩ the equations can be solved:

$$R2 = \frac{D - 1}{1 - 2D} R1 \Rightarrow R2 = 4.4k\Omega \tag{2.6}$$

$$C = \frac{1}{0.69 \cdot f(R1 + R2)} \Rightarrow C = 3.3nF \tag{2.7}$$

The recommended value for C2 is 0.1uF. The RC - filter on the reset (R) is their to make sure that the MPPT converter does not start before the MCU has booted and take control of the multiplexer. It simply delays the startup for the 555 timer. For R3 and R4 20kΩ is used and for C3 22uF is used. The jumper is part of the remove before flight pin.

2.3 Batteries

To protect the batteries from over and under voltage and over currents. To fulfill this task the UCC3911-1 from Texas Instruments has been chosen. This circuit ensures that if the voltage of the batteries rises above

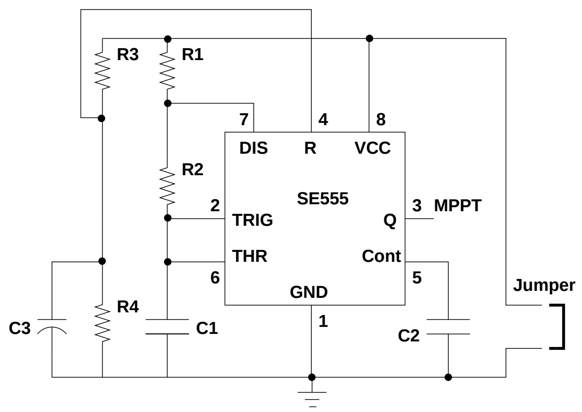

Figure 2.4: The setup of the 555 timer that generates a backup duty cycle for the MPPT.

4.2 V only discharge current are allowed to run though the circuit and vise versa is the voltage drops below 3V. Also the batteries will be disconnected from the intermediate power bus is more than 3.3A are drawn from them. The setup of the UCC3911-1 is shown in figure 2.5 where the jumper from CE to B0 is a part of the remove before flight pin and when in place the circuits will keep the batteries disconnected from the rest of the PSU.

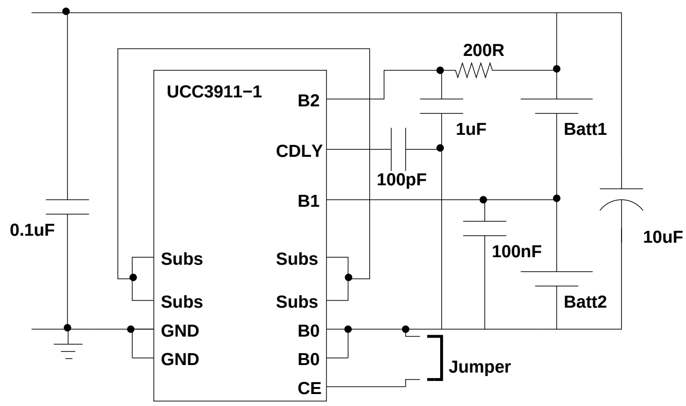

Figure 2.5: The setup of the battery protection circuit UCC3911.

2.4 5V-Converter

For the 5V converter a step down buck converter is used which is quite simple solution since the converter only needs a few external passive components as the mosfet, the inductor and capacitors to deliver the 5V for the main power bus. The choosing of the external components which can be seen in figure 2.6 is described in the datasheet.

2.4.1 Choosing components

For the current sense resistor (R_{CS}) it applies that the maximum allowed peak switching current is equal to R_{CS}/V_{CS} where V_{CS} is minimum 85mV. It is dimensioned by the following equation:

$$R_{CS} = \frac{V_{CS}}{1.3 \cdot I_{out(max)}} = \frac{0.85mV}{1.3 \cdot 3A} \simeq 20m\Omega \tag{2.8}$$

There the R_{CS} is $20m\Omega$ when the maximum continuous output current is 3A.

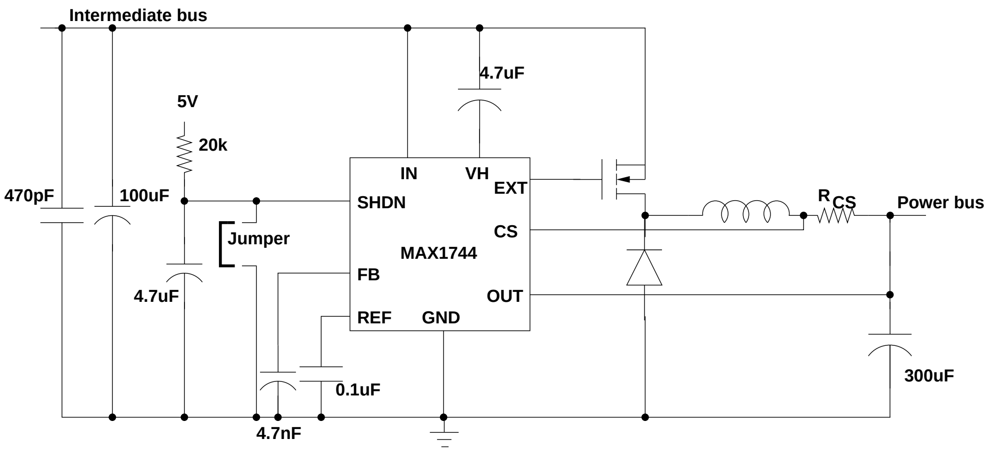

Figure 2.6: The setup of the step down MAX1744 converter.

The inductor is dimensioned according to the following equation:

$$L_{min} = \frac{(V_{in} - v_{out})1us}{V_{CS}/R_{CS}} = \frac{(8.4V - 5V)1us}{85mV/20m\Omega} = 0.8uH \tag{2.9}$$

The actual inductor value should then be chosen between 2 to 10 times L_{min} which leads to the use of a 6.8uH inductor.

The switching transistor should be a P-channel mosfet and a NDT456P is chosen for the task. It has an on-resistance of only $41m\Omega$ and maximum continuous I_D of -7.5A. As diode the same as with the MPPT-converter is used (SB540).

Capacitors are placed both on the input (C_{in}) and output (C_{out}) to minimize ripple voltages both places and these are chosen to 100uF on the input and 300uF on the output.

Also on this converter is a delay after the kill switch is released placed in form of a RC-circuit. This is done to ensure that the batteries and their protection circuits has stabilized before drawing power from them. The time constant for the delay is set to 100ms. In connection with this is also a jumper as a part of the remove before flight pin placed on the reset of the converter.

2.5 User Protection

For each user, i.e. the different subsystems latch-up protection has to be applied. A latch-up can e.g. occurs if a high energy particle short circuits a transistor in a IC. In this case the user has to be shut down for some time before power it up again. For this task the TPS203X series from Texas Instruments has been chosen where devices are available for different maximum currents - see table 2.2.

User	Max. current [A]	Device
OBC	0.3	TPS2030
COM	2.5	TPS2034
CAM	0.6	TPS2031
ACS	0.3	TPS2030

Table 2.2: The choice of protection circuits for the different users.

When a current above the allowed maximum is drawn through on of the protection circuits an overcurrent pin is asserted on it. It is then important to turn of the user by negating the enable pin on the protection circuit which is done through a latch (MAX835). The user will then be shut off at least until the latch is cleared which is done by a 555 timer is astable mode and a time period of 36 seconds. However the enable pin is controlled through an AND-gate by both the latch and from the MCU. That means that it only takes on of them going low to turn of the user but they must both be high to turn the user on. That also means that a user cannot be turned on sooner than 36 seconds after an overcurrent. However is one of the two controlling sources should fail pull-ups are placed on both so that the users will be turned on by default. The setup is shown in figure 2.7 where also a RC-filter is placed on the overcurrent pin to remove the effect of transients.

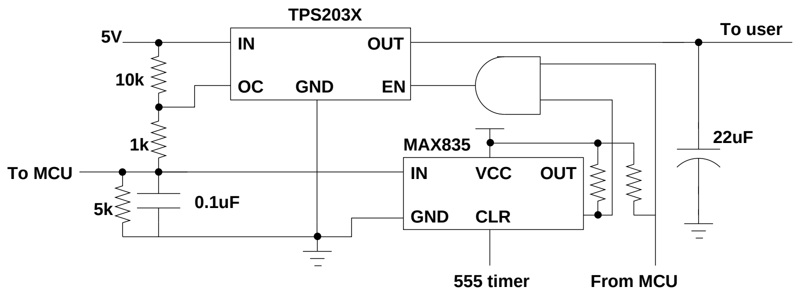

Figure 2.7: The user protection circuits.

2.6 Digital Hardware

The digital hardware consists mainly of a MCU of the type PIC 16c774 from Microchip. This the brain of the PSU and while all very important functions of the PSU like the two converters can operate without the MCU most of them works better with it and also a lot of smaller task needs it. The MCU performs MPPT, gather housekeeping, controls the user protection circuits and a number of other tasks.

PIC 16c774

As a clock source for the MCU a 20MHz crystal thereby enabling the MCU to produce the 78kHz PWM signal needed for the MPPT. It is run from the same supply as the rest of the digital circuits on the PSU – from a 7805 connected to the intermediate bus. As a latch-up protection for the MCU a resister of 20Ω is placed on the supply line – if a latch-up occurs the voltage will drop after resister because of the large current drawn and the MCU will do a brownout reset which will clear the latch-up.

Housekeeping

The PIC 16c774 has 10 analog inputs for a 12 bit ADC but there are more that 10 measurements to be done. Therefore an analog multiplexer (16 to 1) of the type ADG706 is used. These measurements falls into three categories: Currents, voltages and temperatures.

The voltages can be measured either directly or if they are too high then through a voltage divider made of two 100$k\Omega$ resistors which is the case which all of the measured voltages. That is the solar cells voltages and the voltages of both power buses.

The currents are measured by the use of shunt resistors and current measurement circuits (MAX4372). The choice of resistor size and gain of the MAX4372 are shown in table 2.3.

The temperatures are measure with the help of the sensor LM50 from National with a output voltage ranging from 100mV to 1.75V and capable of measuring temperatures from -40^o to 125^o. The following equation describe the relationship between output voltage and temperature:

$$T = \frac{V_{out} - 500mV}{10mV/^oC} \tag{2.10}$$

where:
T is the temperature [^oC]

All measurements are summed up in table 2.4.

Measurement	Physical range	Resistor [Ω]	Gain [V/V]	Device
Solar cell current 1	0-1 A	0.1	50	MAX4372F
Solar cell current 2	0-1 A	0.1	50	MAX4372F
Solar cell current 3	0-1 A	0.1	50	MAX4372F
Solar cell current 4	0-1 A	0.1	50	MAX4372F
Solar cell current 5	0-1 A	0.1	50	MAX4372F
ACS current	0-0.5 A	0.1	100	MAX4372H
OBC current	0-0.5 A	0.1	100	MAX4372H
COM current	0-4 A	0.01	100	MAX4372H
CAM current	0-0.5 A	0.1	100	MAX4372H
Battery charge current	0-1 A	0.1	50	MAX4372F

Table 2.3: Table of the current measurements.

Measurement	Identifier	Physical range	Electrical range [V]
Solar cell current 1	I_Solar_1	0-1 A	0-5
Solar cell current 2	I_Solar_2	0-1 A	0-5
Solar cell current 3	I_Solar_3	0-1 A	0-5
Solar cell current 4	I_Solar_4	0-1 A	0-5
Solar cell current 5	I_Solar_5	0-1 A	0-5
Solar cell voltage	V_Solar	0-4.5 V	0-2.25
ACS current	I_ACS	0-1 A	0-5
OBC current	I_OBC	0-1 A	0-5
COM current	I_COM	0-4 A	0-4
CAM current	I_CAM	0-1 A	0-5
Battery voltage	V_batt	6-8.4 V	3-4.2
Battery charge current	I_batt	0-1 A	5
Bus voltage	V_bus	0-5 V	0-2.5
Battery temperature 1	T_batt_1	-40 to +125 ^{o}C	0-1.75
Battery temperature 2	T_batt_2	-40 to +125 ^{o}C	0-1.75
COM temperature	T_COM	-40 to +125 ^{o}C	0-1.75
PSU temperature	T_psu	-40 to +125 ^{o}C	0-1.75

Table 2.4: Table of the different housekeeping informations to be gathered.

Chapter 3

Software

This chapter deals with the software-design for the PSU where first the required functionality of the PSU is described thereby providing an overview of the PSU and its role in the satellite (see also 1.1 on page 8). Thereafter the actual software is designed and documented.

3.1 The functionality of the PSU

Following the functionality of the PSU will be described. The main purpose of the PSU is of course to provide the rest of the subsystems of the satellite with power which is take from the solar cells. However also other tasks are required by the PSU - e.g. the PSU works as a external Watchdog Timer for the OBC and it must also collect Housekeeping information. The functionality is divided into two categories:

Primary purposes:

1. Transfer power from solar cells to the intermediate power bus and to the batteries (MPPT).
2. Transfer power from the intermediate power bus and the batteries to the primary power bus and thereby to the users (5V Con.).
3. Ensure latch-up protection for the users using the protection-circuits.
4. Protect the batteries from over- and under voltage as well as operation under temperatures outside their range.

Secondary purposes:

1. Function as a external Watchdog Timer for the OBC.
2. Function as a boot-selection for the OBC.
3. Gather Housekeeping information.
4. Communicate with the OBC by I2C.
5. Function as a basic beacon.

Of the 4 primary purposes of the PSU only 3 needs software attention as the 5V converter (2) handles the primary power bus without interventions. The software is divided into functions mainly according to the division shown above. However the main software structure is divided into two parts, a main loop and interrupt routines as shown in the topdown-diagram in figure 3.1.

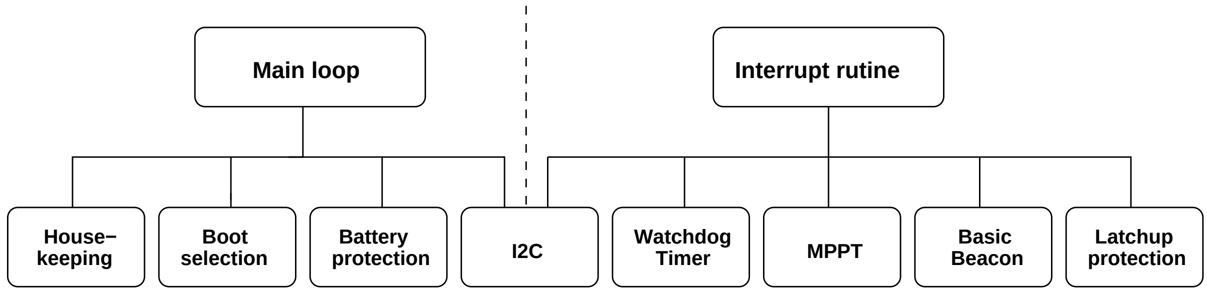

Figure 3.1: The fundamental setup of the software for the PSU.

As it can be seen the main loop contains the gathering of housekeeping, boot selection for the OBC, battery protection and part of the I2C routine. The interrupt part contains the external watchdog timer, maximum power point tracking, user latch-up protection as well as part of the I2C.

3.2 I2C description

The I^2C is a serial communication bus developed by Phillips where masters and slaves are connected through two bidirectional wires, a serial data wire (SDA) and a serial clock wire (SCL). The I^2C features integrated filtering for spikes on the bus, data transfer speeds of up to 3.4 Mbit/s and collision detection and arbitration. The bus is multi-master which means that it is possible to have more than one device controlling the same bus. However this function will not be used in the Cubesat, where only the OBC will function as master and all other devices, including the PSU, are slaves.

The transfer sequence begins with a START condition, which is when SDA goes high while SCL is high. The START condition indicates begin of data transfer and is always generated by the bus-master.

After a data transfer sequence is initiated by a START condition the master sends one byte on the SDA consisting of the address of the slave it wants to communicate with and a $R/\overline{W}$ bit (see figure 3.2). The $R/\overline{W}$ bit determines whether the master writes data to slave or expects to read data from slave. As an extension a to the standard I^2C protocol a header byte and a checksum byte are always sent, the header after the address and the checksum after the data.

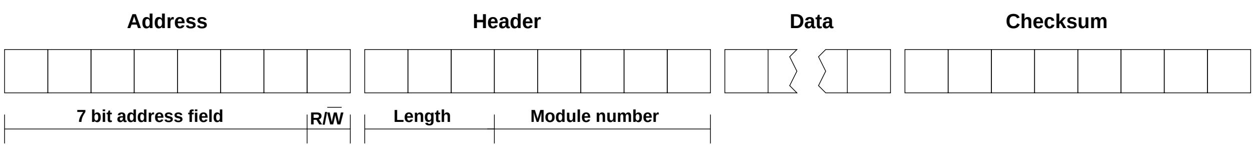

Figure 3.2: To the left is the address byte which is the first in all communication on the I^2C bus, then the header byte which defines the amount of data send and the command as the module-number. After that the actual data and last the checksum.

All bytes transmitted on the bus are followed by a acknowledge signal (A) generated by the receiver to signal that the byte has been read. The transfer sequence are terminated by the master with a STOP condition which is a low to high transition on the SDA while SCL is high.

First in the header byte there are a 3-bit data-length field which defines how many 8 bit data packages the header will be followed by. 000 is equal to one package, 001 to two and so on to 111 which is equal to 8 packages. The rest of the header is a 5 bit module field which is used either to define a module in the slave which the master wish to read or simply to define a command.

The last data package after the actual data is always a checksum which is calculated by adding the header and all data packaged together, the checksum is then the 8 lowest bits of this number. When data is received the checksum is calculated again and is subtracted form the received checksum and if the result is zero the

the data is valid. If the result yields non-zero the data is invalid and a retransmission must be initiated by the OBC.

There are two general communication formats used on the Cubesat between the OBC and the PSU:

Housekeeping request In this format the OBC request housekeeping data, i.e. it begins by sending a header and a checksum, thereby requesting the PSU to make the housekeeping data ready for transmission. The OBC then reads the requested housekeeping. If the PSU received valid data in the request it will send the requested housekeeping, but if the data was invalid an error message in form of the command **INVALID** in the header will be send.

Command request In this format the OBC request a command to be executed, e.g. a subsystem turned off. It begins by writing to issue the command to the PSU, which will test the checksum for errors. The OBC will then read to receive a **VALID** or **INVALID** from the PSU.

It is in connection with this important to remember that only the OBC can initiate communication both back and forth. Therefore the OBC must always ask the slave whether the transmitted data was valid and if not initiate retransmission. If OBC receives invalid data itself it will not inform PSU, but only initiate retransmission.

3.2.1 The protocol between the OBC and the PSU

This description for the communication on the I^2C bus between the PSU and the OBC is also shown in the independent document [**?**]. This includes a description of all commands, and data that can be send both ways.

Requests from OBC

The OBC can issue 24 different requests which each will result in a different response from the PSU, which respectively are shown in the table below:

OBC request	PSU response	Module
Set boot port to PROM	Boot port is set to PROM	31
Set boot port to FLASH-PROM	Boot port is set to FLASH-PROM	30
Reset Watchdog	External Watchdog is reset	29
Turn on specific subsystem	Specific subsystem are turned on	25-28
Turn off specific subsystem	Specific subsystem are turned off	21-24
Basic Beacon ON	Basic beacon is turned on	18
Basic Beacon OFF	Basic beacon is turned off	17
MPPT to Fixed	MPPT is set to fixed source	12
MPPT to Digital	MPPT is set to digital source	11
Send specific housekeeping	Requested housekeeping are send	1-9

Set boot port to PROM When the OBC issues the request “Set boot port to PROM” with module number 31 and data length 0 the PSU sets the boot port low.

Set boot port to FLASH When the OBC issues the request “Set boot port to FLASH-PROM” with module number 30 and data length 0 the PSU sets the boot port high.

Reset Watchdog timer When the OBC issues the request “Reset Watchdog timer” with module number 29 and data length 0 the PSU must reset the watchdog register. Note that the timer is also always reset after any other requests from the OBC.

Turn on subsystem When the OBC issues the request “Turn on specific subsystem” with a module number from 25 to 28 and data length 0 the PSU must turn the specific subsystem on. The subsystem are defined by the module number:

Module number	25	26	27	28
Subsystem	OBC	ACS	CAM	COM

Turn off subsystem When the OBC issues the request "Turn off specific subsystem" with a module number from 21 to 24 and data length 0 the PSU must turn the specific subsystem off. The subsystem are defined by the module number:

Module number	21	22	23	24
Subsystem	OBC	ACS	CAM	COM

Basic Beacon ON When the OBC issues the request "Basic Beacon ON" with the module number 18 and data length 0 the PSU must turn the basic beacon on.

Basic Beacon OFF When the OBC issues the request "Basic Beacon OFF" with the module number 17 and data length 0 the PSU must turn the basic beacon off.

MPPT to Fixed When the OBC issues the request "MPPT to Fixed" with the module number 12 and data length 0 the PSU must set MPPT to the fixed source.

MPPT to Digital When the OBC issues the request "MPPT to Digital" with the module number 11 and data length 0 the PSU must set MPPT to the digital source.

Send Housekeeping Information When the OBC issues the request "Send specific housekeeping" with a module number form 0 - 17 and a data length 0, the PSU must return the requested data. The housekeeping data are defined by the module number:

Housekeeping	Module number	Data length
Battery voltage & Battery current	1	4 bytes
Solar cells current 1 & 2	2	4 bytes
Solar cells current 3 & 4	3	4 bytes
Solar cells current 5 & voltage	4	4 bytes
Bus voltage & PSU resets & User status	5	4 bytes
Battery 1 & Battery 2 & COM & PSU temperature	6	4 bytes
OBC & CAM current	7	4 bytes
COM & ACS current	8	4 bytes
OBC resets & Input power [Wh]	9	4 bytes

The user status uses a 1 for load on and 0 for load off and is depicted at figure 3.3.

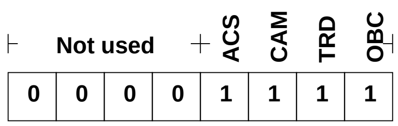

Figure 3.3: The load status byte

The PSU resets is one byte which is 0 at all times except the first time the housekeeping are being requested after a PSU reset where it will be 1. That means that the OBC should add this housekeeping together to keep track of the number of PSU resets.

The OBC resets is two bytes and is the number of timeouts on the external WDT.

The Input power is the incoming power from the solar cells measured in watt-hours.

3.2.2 PSU messages to OBC

The PSU only have two messaged that it can send to the OBC and that is whether the received data was valid or not:

Message	Module number	Reaction from OBC
Data invalid	20	OBC retransmit the data
Data valid	19	OBC does nothing

3.3 Main loop

The main loop is a never ending while-loop which runs as fast as possible and it can be seen in figure 3.4 as a simple flowchart where the different tasks are shown. The first thing in the chart is the Boot-up sequence which has not been mentioned before, then the acquiring of housekeeping, battery protection and last the I2C (hereunder is also the boot selection dealt with). Also a part of the main loop is the clearing of the internal watchdog timer.

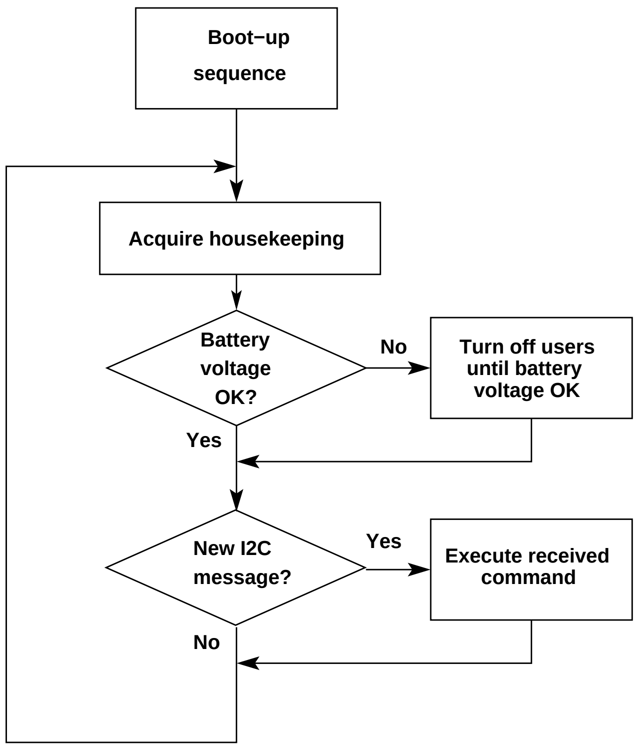

Figure 3.4: Flowchart for the main loop.

3.3.1 Boot-up sequence

The boot-up sequence of the satellite is naturally dealt with by the PSU because of it being the first subsystem to waken. It is defined according to the Bootup Sequence Description [?] which has been made in corporation with the other subsystems.

The defined boot-up sequence:

Step 1: Satellite released from P-POD

- Kill switch released
- 0.3s hardware delay
- PSU is booted

Step 2: 5 min delay

- PSU delays 5min to allow the cubesats from the P-POD to get clear of each other

Step 3: Antenna Deployment

- PSU deploys antennas

Step 4: COM and OBC boot up

- PSU powers COM and basic beacon begins to transmit
- PSU powers OBC with boot-port set for PROM

Step 5: OBC boot sequence

- PSU and OBC goes through the specified (see next section) boot sequence, until a successful boot has occurred

Step 6: PSU enters WDT mode

- PSU begins to work as external Watch-Dog-Timer for the OBC (see next section)

Step 7: PSU awaits beacon off signal

- PSU continues to transmit basic beacon until BASIC_BEACON_OFF signal is received from OBC.

NOTES:

- CAM and ACS is not booted up during initialization - OBC must do this manually

The deployment of the antenna in step 3 is done by asserting the P2T signal for 10 seconds which should be adequate time for the nylon wire to burn through.

3.3.2 Acquiring housekeeping

The acquiring of housekeeping runs in the main loop and samples a new measurement for each run through. There are 17 different devices to measure as shown in table 3.1

```
while(never end)

  sample(device)

  if (device = last device)
     device = first device
  else
     device = next device
```

All measurements except the temperatures are 12 bit which is the maximum resolution of the ADC. Because of the precision of the temperature sensors only 8 bits are required for these measurements.

Measurement	Identifier	Physical range	Bits
Solar cell current 1	I_Solar_1	0-1 A	12
Solar cell current 2	I_Solar_2	0-1 A	12
Solar cell current 3	I_Solar_3	0-1 A	12
Solar cell current 4	I_Solar_4	0-1 A	12
Solar cell current 5	I_Solar_5	0-1 A	12
Solar cell voltage	V_Solar	0-4.5 V	12
ACS current	I_ACS	0-1 A	12
OBC current	I_OBC	0-1 A	12
COM current	I_COM	0-4 A	12
CAM current	I_CAM	0-1 A	12
Battery voltage	V_batt	6-8.4 V	12
Battery charge current	I_batt	0-1 A	12
Bus voltage	V_bus	0-5 V	12
Battery temperature 1	T_batt_1	-40 to +125 ^oC	8
Battery temperature 2	T_batt_2	-40 to +125 ^oC	8
COM temperature	T_COM	-40 to +125 ^oC	8
PSU temperature	T_psu	-40 to +125 ^oC	8

Table 3.1: Table over the different measurements

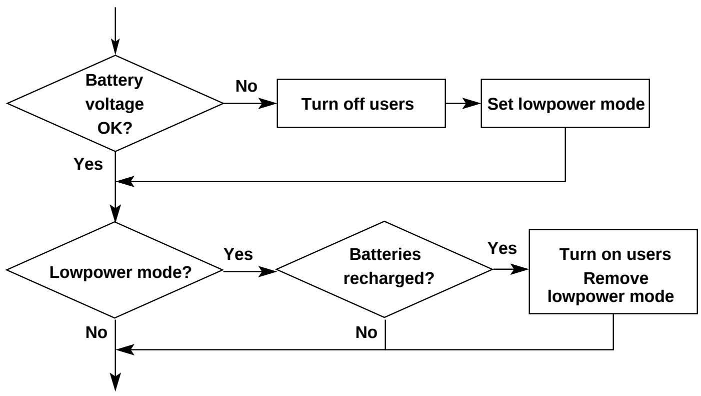

Figure 3.5: Flowchart for the overvoltage protection of the batteries.

3.3.3 Battery Protection

The battery protection consists of three things: Over- and undervoltage protection and protection from operating the batteries in temperatures outside their range. The overvoltage protection is being taken care of in the MPPT routine so only the last two are discussed here. They are based upon the measurements of the battery voltage and temperatures from the housekeeping. In figure 3.5 the overvoltage protection can be seen.

The temperature protection simply ensures that the batteries are not charged when the temperature is outside the range -10 to +55 ^oC - that is it puts the duty cycle for the MPPT-converter to zero.

3.3.4 I2C function

The implementation of the I2C communication are divided into two parts: a interrupt part and a normal function part. The interrupt part takes care of the low level operation of the I2C communication while the function part handles the received data and acts upon it. The interface between the two is two buffers (receive and transmit) and a flag (new message) which indicates whether or not there is new data - see figure 3.6 3.5 the overvoltage protection can be seen.

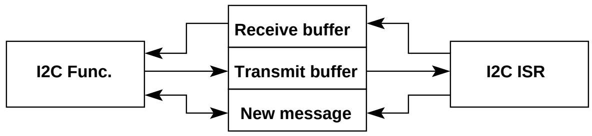

Figure 3.6: The interface between the interrupt and the function part of the I2C implementation.

The I2C function first test if there is a new message from the OBC and if so it calculates the checksum on the received data and if it is valid it will act upon the received command. This can be e.g. to put housekeeping in the transmit buffer or change boot mode or turn basic beacon off. In all case - except with the housekeeping - the transmit buffer is loaded with the command **VALID** so the OBC can be sure that the correct command has been carried out. For the housekeeping the requested module number is returned together with the data. If the received data is not valid, i.e. the the checksum is wrong the command **INVALID** is put in the transmit buffer so that the communication can be reinitiated.

```
if(new message)

  calculate checksum
  if (checksum =VALID)
     act upon received command
     reply VALID
  else
     reply INVALID
```

Boot selection

The boot selection happens when acting upon commands from the OBC. The boot-pin can be placed in two positions: low=PROM or high=FLASH. When the OBC requests a change in boot mode it is also considered as a system reset so that the entire system is booted with the new/old software.

3.4 Interrupt routines

There is three different interrupt-routines in the software: one which runs periodic and two which are aperiodic. The aperiodic ones are the latch-up protection which runs whenever a problem occurs with a user and the I2C. The periodic one is a timed interrupt which runs at 76Hz and is used to basic beacon, external WDT and MPPT.

3.4.1 Basic Beacon

The basic beacon runs when the OBC is off and until the OBC requests it to be turned off. It works by using the P2T signal on the radio to transmit AAU (Aalborg Universitet) in morsecode. The implementation is quite simple and uses a counter to generate the prespecified pattern (AAU=.- .- ...-). When the counter is 1 the P2T asserted, when the counter is 2 it is negated, at 3 it is asserted again and at 6 it is negated (that was .-) and so on. The signal is transmitted once every 10 seconds and lasts for about 340msof which it is on about 180ms so it only uses little power.

3.4.2 External Watchdog Timer

The external WDT functions as a backup for the internal WDT of the OBC - if there has been no I2C communication for 10 seconds a timeout occurs and the OBC is turned off and is not turned on again before after 5 minutes. The function uses a counter that counts up when the OBC is on and down when the OBC is off and this counter is used to time the respectively 10 seconds and 5 minutes. When the 5 minutes has passed the OBC is turned on again on the same boot mode as it had before the timeout - however have 2 timeouts occurred in a row without any I2C-communications at all in between the boot mode is changed. This means that if the OBC never uses the I2C to the PSU it will constantly be power cycled each time in a new boot mode. Note that COM is never turned off since it needs to be on when transmitting basic beacon.

```
if(OBC=ON)
  counter++
else
  counter--

if(OBC=ON and counter=10s)
  turn off OBC, ACS and CAM
  basic beacon on
  counter = 5 minutes

if(OBC=OFF and counter=0)
  if(no i2c communication since last timeout)
    change boot mode
  turn on OBC
```

3.4.3 Maximum Power Point Tracking

The Maximum Power Point Tracking is one of the most tasks of the software as it is one of the primary purposes of the PSU. The role of the MPPT converter in the PSU is to draw the maximum power out of the solar cells using MPPT, and secondly to keep the batteries from over-charging. To maximize the power, it can be measured and used as input in the MPPT-control while the output controls the duty cycle of the MPPT converter. This will result in a change in the voltage level over the solar array, and the current being drawn from it. The measurement of the power would traditionally be done by measuring the voltage over the panels and the current being drawn from them. This configuration can be seen in figure 3.7, as the dotted measuring points.

Because the output of the MPPT converter is directly linked to the batteries, it can be assumed that over a short time period the voltage level will remain constant. Therefore, a variation in the measured output current (measured at the non dotted current measurement point on figure 3.7), will be proportional to the variation in the output power from the MPPT converter. The MPPT can then attempt to get the maximum current out of the MPPT converter, which will also give a maximum output power.

The method of measuring the power through just the output current of the MPPT converter, has several advantages over the double measuring point method, the main one being that only one measuring point is needed for the MPPT. This means that less computation is needed in the MPPT algorithm.

To achieve the secondary task of preventing over-charging of the battery, it is necessary to measure the voltage level of the battery. This measurement point can be seen as the solid line voltage measurement point on figure 3.7.

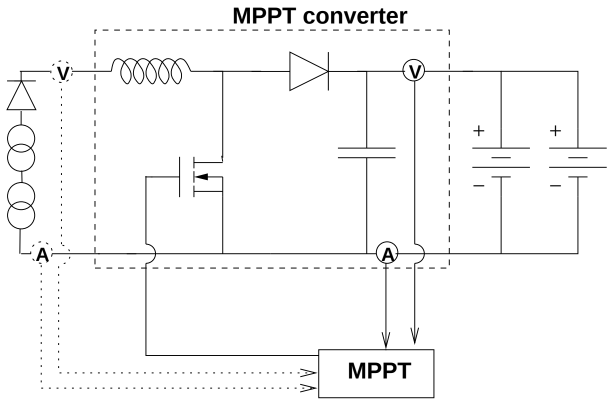

Figure 3.7: The MPPTC with control system with two different measuring point sets

The MPPT algorithm

To carry out the MPPT-regulation a Perturbation and Observation (P&O) algorithm will be used. An illustration of the P&O algorithm functionality is shown in figure 3.8.

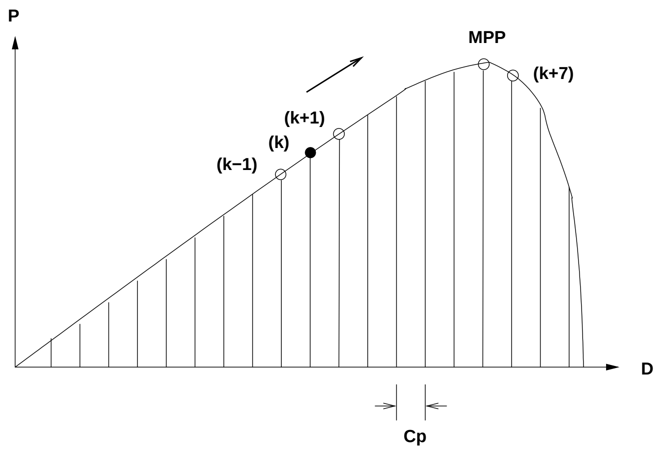

Figure 3.8: The functionality of the MPPT algorithm which moves position point k step by step to the MPP. C_p represents the duty cycle interval between the points

The control will begin by setting the duty cycle at a default value of 0.5, which is around the expected duty cycle , and then measure the current at point (k). It will then change the duty cycle by C_p, and measure the current in the new point $(k+1)$. It then compares it with the current measured in k. A rise in the current will then change the duty cycle in the same direction as the previous change. A decrease in the current will change the duty cycle in the opposite direction of its previous change. The size of these changes is given by C_p. After the duty cycle is changed, a new current measurement is made, and compared to the previous in a similar manner. This repeats itself in a never-ending loop.

Because of the switching frequency of 78kHz (see 2.2 on page 11) the maximum resolution of the PWM-signal is 8 bit or 256 steps ([**?**]) which yields a C_p of 1/256=0.3%. The stepping frequency is chosen to 10Hz which is slow enough for the converter to settle after each step but still fast enough for the MPPT to follow most changes in the MPP.

On figure 3.9 is the MPPT algorithm shown as a flowchart.

First the battery current is sampled and the the difference between the previous and the current value is calculated (ΔI_batt). It is used to examine if the power went up or down and it is then examined which way the last step was. If the step was down and the power stepped up another step down is taken, it the power

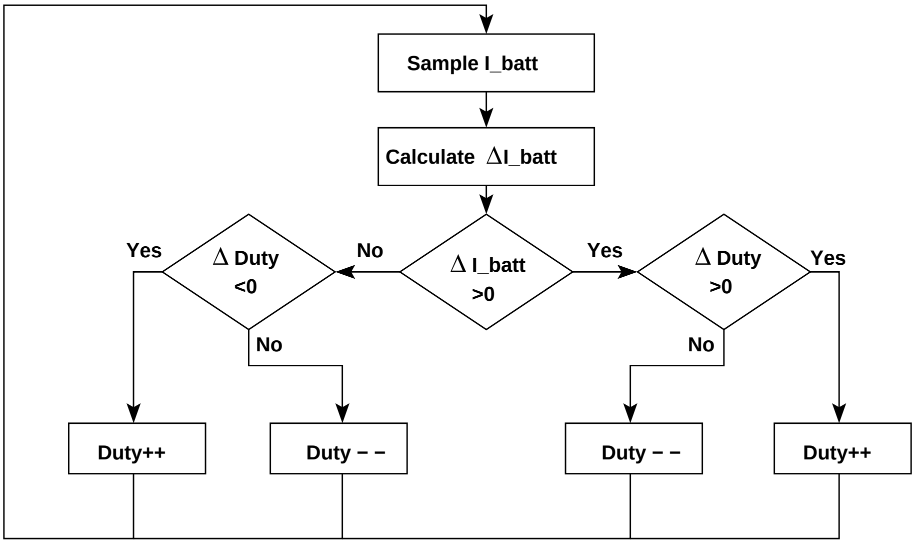

Figure 3.9: Flowchart of the MPPT algorithm.

went down the new step is up and visa versa if the step was up.

Overcharge protection

To ensure that the batteries will not be overcharged an simple algorithm has been designed. If the battery voltage rises above the allowed maximum (8.4V) the possible duty cycle is reduced by a factor of 2 on each run. As soon as the voltage again has dropped below maximum the allowed duty cycle is again released so it again runs from 0-255.

```
if(battery voltage > maximum allowed voltage)
 maximum allowed duty cycle = maximum allowed duty cycle / 2
 if(duty cycle > maximum allowed duty cycle)
    duty cycle = maximum allowed duty cycle
else
 maximum allowed duty = 255
```

In this way the batteries are kept just around their maximum voltage.

3.4.4 Latch-up protection

The latch-up protection ISR runs whenever a user draws too much current, that is when a overcurrent occurs. The interrupt are initiated by the $\overline{OC}$ of the protection circuits and for ACS, CAM and COM the only action taken when a overcurrent occurs are to turn off the specific user - then the OBC must decide to turn the user back on. However for the OBC things are a bit more complicated - when the OBC experiences a overcurrent all users except COM are turn off and the basic beacon are turned on. The situation is then regarded as a external WDT timeout and the same functions are used to deal with it, i.e. the OBC is turn on again after 5 minutes.

```
interrupt

  if(ACS_OC=0)
     turn off ACS
```

```
if(CAM_OC=0)
   turn off CAM
if(COM_OC=0)
   turn off COM
if(OBC_OC=0)
   turn off ACS and CAM
   turn on basic beacon
   start external WDT on count down
```

3.4.5 I2C ISR

The I2C ISR is implemented as a state machine that contains 4 different states which can be seen in figure 3.10.

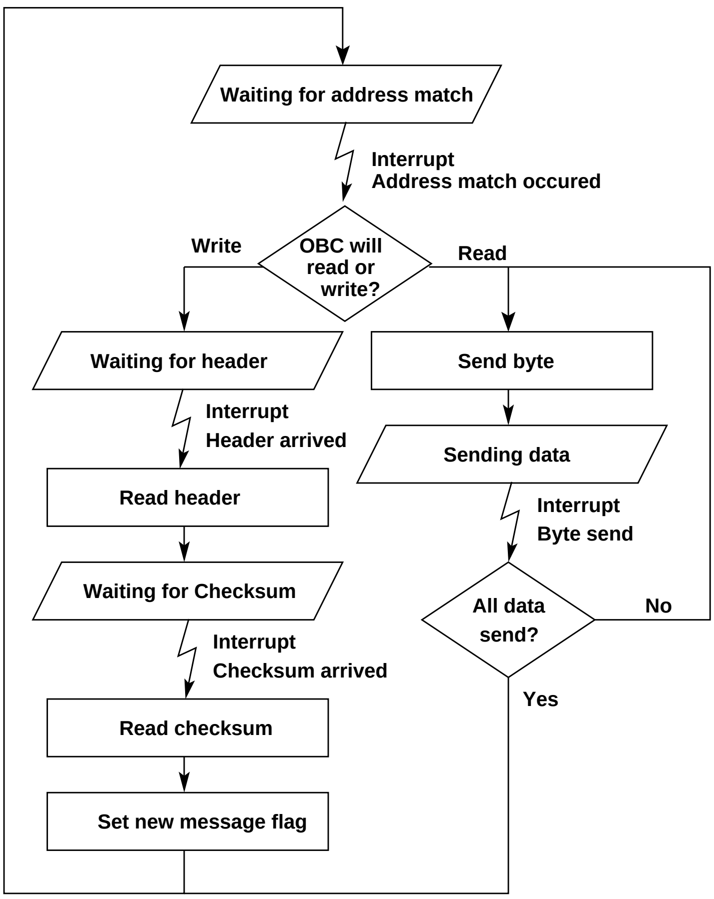

Figure 3.10: The I2C ISR state machine where a rhomb illustrates a state.

The ISR first awaits a address match which is the first part of the I2C communication. After an address match occurs it is determined whether the OBC will read or write. In case of write the ISR waits for the header and next for the checksum, then the new message flag is set for the I2C function and then the ISR returns to wait for an address match. In case of a read the first byte is send and an interrupt occurs when the transmission is completed. It is then examined if there are more data to be send an if so the ISR returns to send another byte - if not the ISR return to wait for an address match.

Appendix A

The battery on AAU Cubesat

The chosen battery for the satellite is a lithium-iodine batter called DLP 443573 from Danionics ([**?**]) with a nominal voltage level of 3.7 V (range from 3 to 4.2 V) and a capacity of 920 mAh (equal to about 3404 mWh). It weighs 26 g and the dimensions are 69 x 39 x 4.9 mm.

The operating temperature range of the battery is from 5 °C to 45 °C, and is best operated close to 23 °C which puts great demands on the thermal design. The battery will after 730 cycles in one year have a capacity of about 80 % equal to 736 mAh.

A quantum of four batteries will be used to fulfill the capacity-need of the satellite giving a capacity of 13616mWh, which should be more than adequate.

A.0.6 Coupling of the Batteries

There are basically two different ways of couple the four batteries together: either in parallel or in series. However a hybrid of the two can also be used (see figure A.1 C).

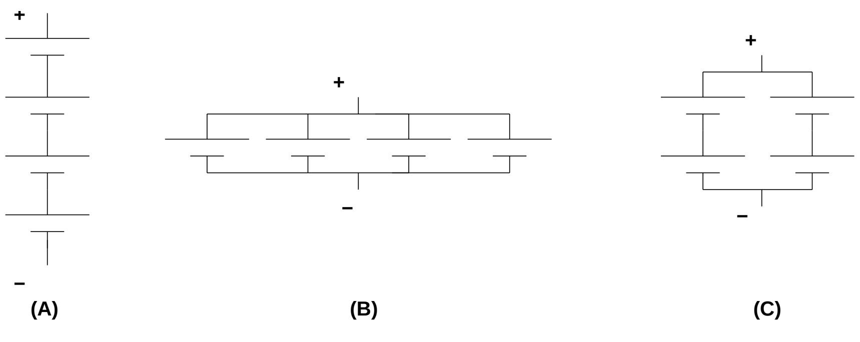

Figure A.1: The coupling of the batteries: (A) is in serial, (B) is in parallel and (C) is a hybrid with the batteries in series two and two

When coupled in series the voltage difference over the batteries is between 12 and 16.8 V and the capacity is 920 mAh. When coupled in parallel the voltage difference over the batteries is between 3 and 4.2 V and the capacity is 3680 mAh. In the hybrid case the voltage is between 6 and 8.4 V and the capacity is 1840 mA. In all cases the power measured in Watt is the same. In the parallel solution the battery voltage is very close to the bus voltage which gives an advantage of small power loss in the converter between them, but a drawback in difficult control of the bus voltage. In the serial solution the battery voltage is much higher than the bus voltage which gives a greater loss of power in the converter but it is easier to regulate the bus voltage. Also the larger voltage can be used as gatevoltage for the switches in the converters. However another problem arises when coupling the batteries in series because the same charge current runs through all of them and if they are not completely balanced they will be fully charged at different times. When the first batteri is fully charged the charging must be stopped, leaving the other batteries not fully charged. This problem is much smaller when choosing a parallel coupling because the batteries will then balance each other, by drawing less current if they are more charged that the rest. The choice falls on the hybrid coupling because it reduces the charging problem while still delivering a high voltage.

A.0.7 Charge/Discharge

The charge method to be used with the battery is constant current between 920 mA and 460 mA, but a lower current can be used. A fully discharged battery will take about one hour to recharge at 920 mA and about two hours at 460 mA (at 23 °C). Danionics informes that the loss in a charge/discharge cycle is around 1% in the beginning of the battery life, but the loss rises slowly as the battery goes through its cycle life. The inner resistance of the battery is normally in the range 30 - 50 mΩ.

When the battery is fully charged the charging must be stopped or otherwise the battery may explode or burst into fire. Therefore the charging must be stopped when the voltage across a single battery reaches 4.2 V which is the upper voltage limit of the battery.

The discharge current must at maximum be 1840 mA continuously, but a larger current (4600 mA) can be drawn momentarily (in 30 seconds). In both charge and discharge the battery must be secured, in order to stay within the described voltage- and current limits.

A.0.8 Vacuum testing the batteries

Because of the soft polymer construction of the batteries it is important to test them i vacuum to determine if they are able to widthstand it. The first tests conducted showed with clearly that the batteries are not able to operate for longer periods of time in vacuum without serious loss of capacity. Therefore the desision was made to incapsule the batteries in epoxy - this was done and the test conducted again. The results are shown in figure **??** and **??**.

TO BE DONE

Appendix B

Solar Cells

In this appendix solar cells are going to be analysed focusing shortly, first on the theory of solar cells in general and afterwards on the actual solar cells that are to be used on the Cubesat.

B.1 Functionality of Solar Cells

The solar cells is the power source in the Cubesat. They deliver the input power to the power supply.

B.1.1 How Solar Cells Work

The solar cells are photo-voltaic cells, which as the name implies convert energy from photons into electric energy. The cells are typically made of doped silicon, and energy from the absorbed sunlight knocks electrons loose creating an electric current. This current can be drawn out through metal contacts to external use for example in a power supply. The silicon is doped like an ordinary semiconductor, and thus there are two plates, one with N-type silicon and one with P-type silicon. Another type of solar cells is the GaAs solar cell. It consists of P-doped and N-doped GaAs on the top and bottom respectively. Each have metal contacts to draw the current. The sunlight is absorbed by the P-doped GaAs and a current can flow. The electric field between the plates generates a voltage and thereby power is obtained.

Should the cells however receive little or no illumination, they change characteristics, and start to act as diodes instead. This also happens if a too high voltage level is forced on the cell. These effects count for both silicium, GaAs and most other known cells.

B.1.2 Voltage-Current Relationship

When drawing power from a solar cell, it is important to note that the power available is dependent on the manner in which it is drawn from the cell. The voltage and current drawn are unlinearly dependent on each other. To obtain the maximum efficiency of the power cells it is therefore important to keep the voltage level at a certain point, depending on the maximum power available. This is called maximum power point tracking (MPPT) and is done by using the I/U characteristics of the particular cell. A typical I/U graph for a solar cell, is shown in figure B.1

As can be seen after a certain point a rise in the current will have a big effect on the voltage level of the cell. Similarly a rise in the voltage level above a certain point will result in a drastic loss of current. For comparison, a power curve is shown with a dotted line. When compared to this curve, the point on the I/U curve that gives the maximum power can be found. This is the maximum power point.

The I, U, and P characteristics, are also dependent on the temperature of the cell. Precisely how, may vary with individual types of cells, but in general, the current increases slightly and the voltage

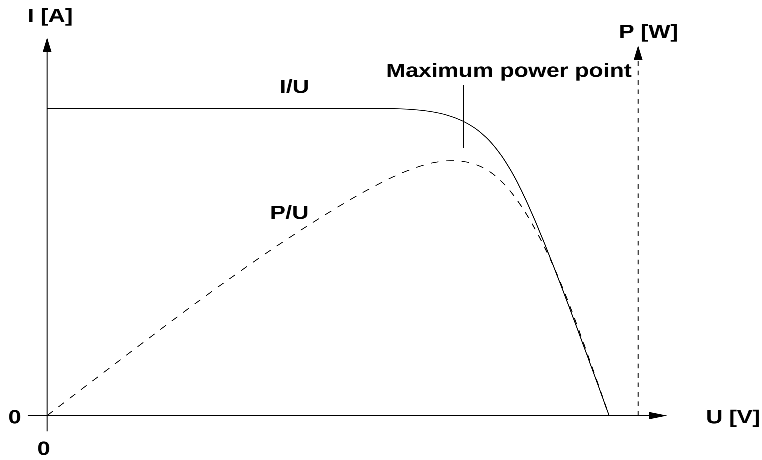

Figure B.1: I/V characteristics of a solar cell

level decreases significantly with increasing temperature. An example of this is shown for a silicon cell in figure B.2 [?].

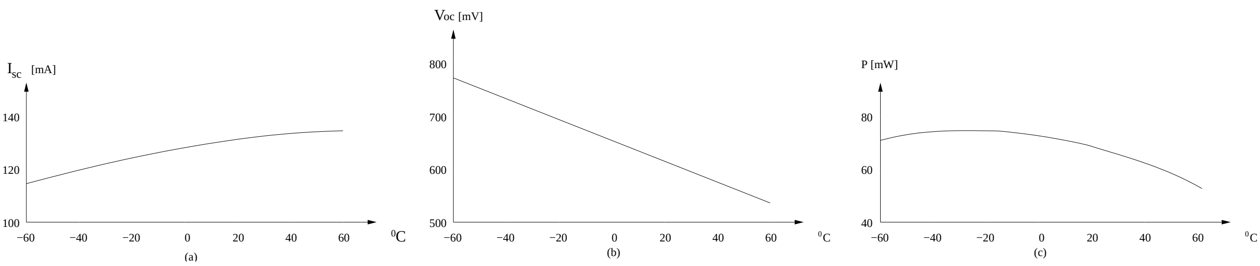

Figure B.2: Temperature effect on I (a), U (b), and P (c) characteristics of a solar cell

Here I_{sc} is the short circuit current V_{oc} is the open circuit voltage, and P is the maximum power. As can be seen, the current increases unlinearly, with a rising temperature (a), while the voltage level decreases linearly with rising temperature (b). These put together give the power curve seen in figure (c), where for ordinary use the effect decreases with a rising temperature. Beyond a certain point (here about -30 °C),the power of the cell will decrease with a fall in temperature. This is caused by the unlinear characteristic of the current/temperature curve. The varying temperature will also cause the point of maximum power to move, which must be taken into consideration if maximum power point tracking is used.

B.1.3 Radiation Dependency

The following describes the dependency of the power on the radiation with regard to two parameters: radiation intensity and the amount of radiation.

Intensity

The maximum flow of electrons caused by the absorption of sunlight is the short circuit current and it is independent of the voltage. This short circuit current depends linearly on the intensity of the light [?]. The open circuit voltage varies a little with light intensity, and the short circuit current varies a lot. Therefore the power is dependent upon the light intensity [?].

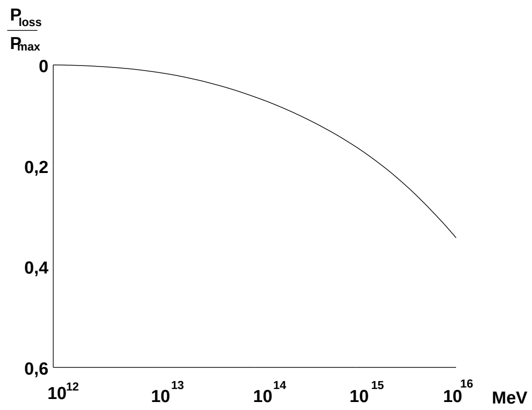

Figure B.3: P_{loss}/P_{max} as a function of total irradiation by 1 MeV electrons

Amount

Figure B.3 shows the power lost in a solar cell relative to the maximum power it can deliver. It is shown as a function of the amount of irradiation by 1 MeV electrons. It shows that the power lost in the solar cell grows as the irradiation grows.

B.2 The Solar Cells on Cubesat

The solar cells on Cubesat will be triple-junction GaAs-solar cells from Emcore. The satellite will be carrying solar cells on five of its six sides, since the last side will be reserved for the payload of the satellite. The cells will be in the form of $76 \cdot 36$ mm panels. There will be two panels on each side. This gives a total of 10 panels, and a total area of $2 \cdot 5 \cdot 7.6\ cm \cdot 3.6\ cm = 273.6cm^2$. The mass of the solar cells is $2.4\ \frac{g}{panel} \cdot 10\ panels = 24\ g$. At beginning of life (BOL) the solar cells have an efficiency of 28 % at 25 °C.

The temperature dependency of the cells is very small, 0.03 % /°C . The temperatures expected are from -40 °C to 80 °C which is approximately $\pm$ 60 °C compared to the defined working temperature of 28 °C. This will give a change in the efficiency of the cells of:

$$\pm 60^0 C \cdot 0.03\%/^0 C \cdot 23\% = \pm 0.41\% \tag{B.1}$$

This means that the temperature variations will cause the cells efficiency to variate from approximately 27.6 % to 28.4 %. To minimise the reflection of sunlight on the surface material of the cells, they are coated with an anti reflective coating. This coating has an absorption of 0.9 or 90%. That means that the maximum amount of sunlight reflected on the surface, at any angle, will be 10%.

Because of lack of data on the solar cells, the maximum power points for different conditions are not known, but a qualified guess is that the maximum power point (MPP) will be at somewhere between 1.8 V and 2.2 V for a single panel.

B.2.1 Connecting the solar panels

As known from [?] the Cubesat will have a total of 10 solar panels. Since it is desired that the panels appear as one unit, they have to be connected in some fashion so that they only have one power output. The cells can either be connected in series or in parallel as shown on figure B.4

Series Connection

When connected in series, the current running through the cells will be the same for all the cells in the connection, whereas the voltage will vary from cell to cell, with the total voltage over the connection being the sum of the individual voltages of each cell. This will, compared to the parallel connection,

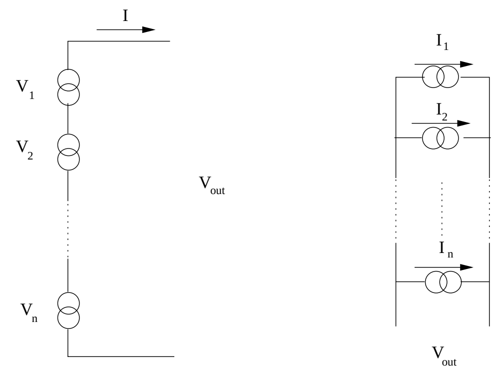

Figure B.4: Series (left) and parallel (right) connection of panels

give an overall greater voltage, and an overall smaller current. Figure B.5 shows the I/U characteristics of two panels in series, each illuminated with a different intensity.

Because of the series connection, the same current will run through both panels, and the voltage over each panel will be determined by this current, and the degree of illumination.

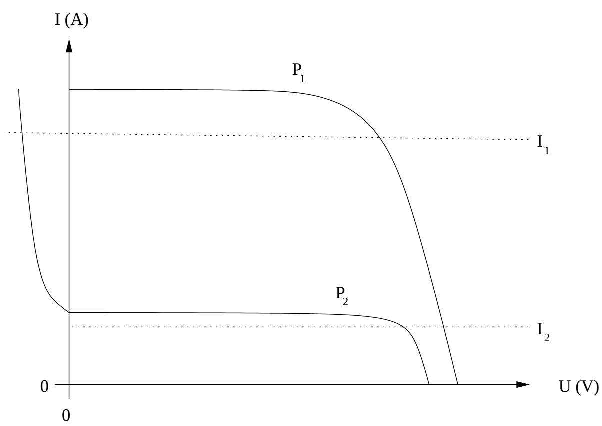

Figure B.5: I/U characteristics of panels with varying degree of illumination connected in series

As can be seen on the figure B.5 [?], if a large current is drawn (I_1), the strongly illuminated panel (P_1) will have a reasonably high voltage and the overall power from that panel will be high. The less illuminated panel (P_2) on the other hand will experience a voltage drop in stead of gain due to the diode effect, which will result in loss of power. If a small current is drawn (I_2), the less illuminated panel (P_2) will give a reasonable high voltage level, but because of the smaller current the overall power from this cell will not be very high, even though it may be close to optimal for this panel. The strongly illuminated panel (P_1) will still have a high voltage, but again the low current will cause the power output of that cell to be far from optimal. The P/U characteristics of the series connection can be seen compared to the P/U characteristics of each panel in figure B.6

It is here obvious that the maximum power of the series connection is less than the maximum power of the single most illuminated panel. This will however only be true, when big differences occur in the intensity of the illumination on the different panels, for example one panel in sun and the other in shadow.

All in all we can conclude, that when the different panels in a series connection are illuminated differently, it is not possible to get the maximum power output from all panels. Moreover, if the difference in illumination is big enough, the total power output will be less than the output would have been from the single best illuminated panel. This though can be averted with the use of diodes.

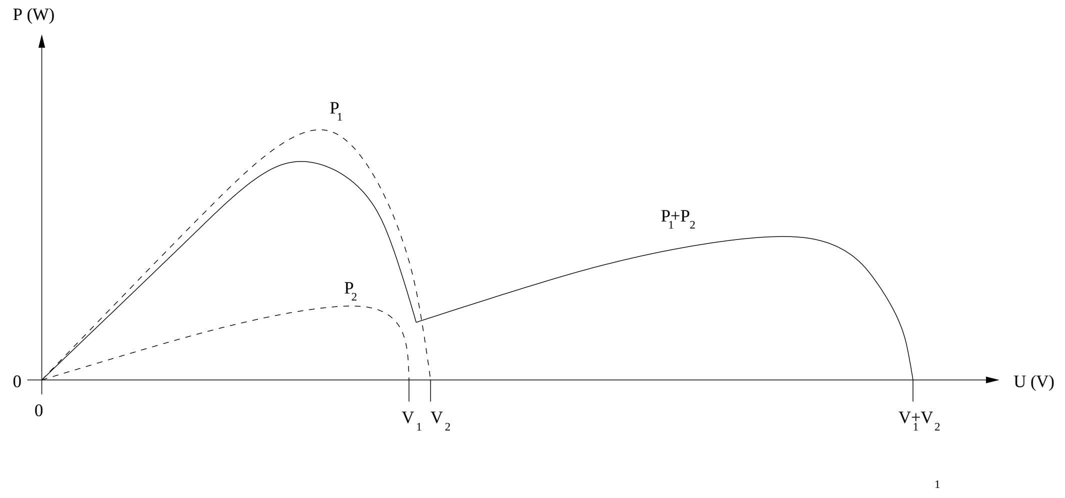

Figure B.6: P/V characteristics of panels, with varying degree of illumination, connected in series

Parallel Connection

When connected in parallel, it is the voltage level that will be the same for all panels in the connection, whereas the current flow will be independently determined for each panel. This gives, compared to the series connection an overall greater current, and an overall smaller voltage. Figure B.7 shows the I/U characteristics of two panels in parallel, each illuminated with a different intensity.

In the parallel connection, the same voltage will occur over both panels, and the current running through each panel will be determined by this voltage, and the degree of illumination.

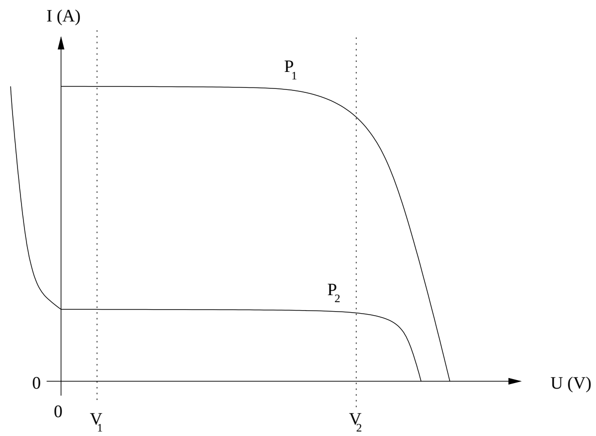

Figure B.7: I/U characteristics of panels, with varying degree of illumination, connected in parallel

As can be seen on the figure B.7[?], the change of voltage level over the panels will effect both panels in a similar manner. A low voltage(U_1) will have both panels working in a low power mode, with little power on the connection output. Operating at a higher voltage(U_2) will cause both panels to operate in a higher power mode, resulting in a higher output on the power bus. Most interesting is that the point of maximum power of the two panels will be close to each other, and therefore the maximum power output on the power bus will be very close to the added maximum power of the two individual cells. This can be seen more directly in figure B.8.

Safety Diodes

Since all the panels on the Cubesat, will never be in the sun at the same time, some of them will be in shadow, and therefore function as diodes.

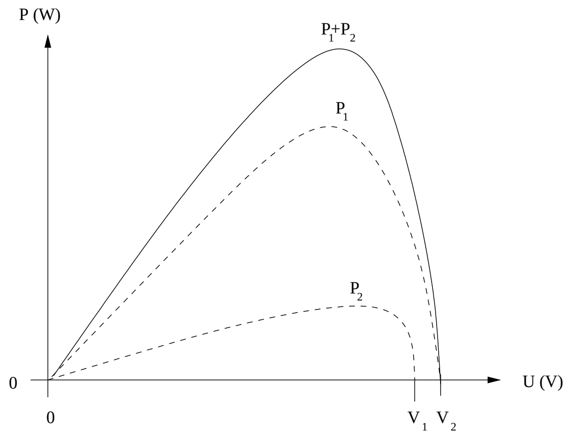

Figure B.8: P/U characteristics of panels, with varying degree of illumination, connected in parallel

If the panels are connected in parallel, this would mean that the power produced by the illuminated cells would be dissipated through the unilluminated cells. To avoid this, diodes can be connected in series with the individual panels, so that no reverse current will run through the shadowed panels. Connected in this way, the diode will also prevent a defect panel shortening to ground from affecting the rest of the panels, and the following circuitry. This could for example happen by a micro meteoroid impact.

If the panels are connected in series, the affect of the shadowed panel would be to effectively shut down the current flow, and thereby the production of power, through the whole connection. The same affect could be seen by a damaged panel. To avoid a shadowed or damaged panel from disrupting the use of the rest of the panels, diodes can be connected in parallel to the individual panels, thereby allowing the current to circumvent the damaged panel in an array.

The disadvantage of using safety diodes, is the dissipation of power in the diode during ordinary running conditions. If the panels are connected in series, the diodes are connected to the individual panels in parallel, and the current through the panel array, will have to go through the diodes connected to the shadowed panels. With the panels connected in parallel, the diodes are connected in series with the individual panels, and the current from any illuminated panel will have to pass through only one diode. There is also a power loss in the reverse biased diodes, caused by the leakage current through these diodes, but this loss is usually negligible.

Panel Connection

The series connection is a bad idea when it comes to connecting panels with widely varying illumination. On the Cubesat there will most of the time be some panels in the sun, though with varying angle, and some in the shadow of the satellite. Therefore the panels on the different sides of the satellite will be connected in parallel. The cells on the same side, will have the same degree of illumination, and therefore do not present the same problem in a series connection. Since the batteries are to be charged at close to 8.4 V to minimise the power loss in the MPPT converter, the voltage level of the final solar array should be as close to that level as possible. Therefore the two panels on the same side are connected in series.

To avoid the problem with shadowed or damaged panels, each set of series connected panels, are to be connected with a series diode. The parallel diodes suggested in B.2.1 are not incorporated, for should one of the panels in the series connection become damaged, the voltage level over the other would be close to twice the optimal operating voltage, and the panel would therefore not be able to be used anyway. So in this connection the parallel diodes would not have any helpful effect. The final panel circuitry can be seen in figure B.9. The power lost in the series diode is proportional to the voltage drop over the diode, and diodes with as low a voltage drop should therefore be used. Since the

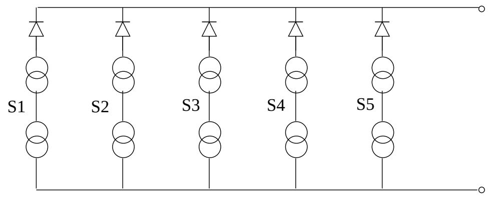

Figure B.9: The circuitry of the solar panels on the Cubesat

effect of a current/voltage ripple on the solar panels is not known, this ripple is attempted minimised by a capacitor, as seen in figure B.9. The size of this capacitor is chosen to be 100 uF as this gives a good dampening of the ripple. The dampening affect was in a crude p-spice simulation shown to be a factor of several hundred, but since the affect of the ripple is not known in the first place, no further resources are allocated to prove or improve this simulation.