NTNU – Trondheim
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Electrical Power System of the NTNU Test Satellite

Design of the EPS

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Problem Description

NTNU is currently designing a student satellite, NUTS, with a planned launch in 2014. It is designed according to the CubeSat specifications. The Electrical Power System (EPS) is an essential part of the satellite. During previous master- and project-assignments, including that of Lars Erik Jacobsen autumn 2011, work has been done on the EPS. The goal of this master thesis assignment is to finalize the development, design and test of the EPS.

The thesis work shall start with a literature research phase that shall include general circuit board system power distribution, special considerations related to satellites, and the relationship between solar panels and battery charging. This shall be followed by a study of the previously suggested solutions in the NUTS project, as well as in other related projects. Based on the theory and previous project work, the EPS design should be finalized, implemented, and tested.

Assignment given: January 16, 2012
Supervisior: Per Gunnar Kjeldsberg

Abstract

The NTNU Test Satellite (NUTS) project is aiming to launch a $10 \times 10 \times 20$ cm nanosatellite by the year 2014. The goal is to design and develop a low cost satellite by exploring the use of commercially available components. This work will focus on the power system of the NUTS satellite, which consists of a power distribution system, the backplane, and a power condition system, the Electrical Power System (EPS).

This thesis describes the design and evaluation of the EPS module, which is a critical part of the satellite, because without power the satellite will not be able to operate. The electrical power system of the satellite consists of the solar cells, batteries, and voltage converters. With limited power available, the main focus of the design has been to implement an efficient system with minimum losses in power conversions.

The Electrical Power System (EPS) module has been designed with simplicity, reliability, and redundancy in mind. The designed is based on the requirements of a reliable power source, with the main goals of charging the batteries with power from the solar cells and regulates the battery voltage down to the requested voltages of the backplane. A charger is chosen for its abilities to provide efficient and safe charging by using proper strategies for efficient energy harvesting and charging. To accommodate the voltage request of the backplane, four fixed value regulators is chosen for the design. For power monitoring of the provided power from the solar cells and batteries, current monitor sensors are implemented after each charger circuit and the batteries. Based on the specification of the solar cells and the batteries a final design of the main functionalities has been provided and a prototype of the EPS module has been produced.

The proposed solution offers a reliable and redundant system, where a loss of one charger or converter will not mean the end of the mission. The EPS module has been tested and evaluated, and displays good performance results in terms of charging the batteries and voltage regulation. The efficiency of the EPS chargers is found to be 95 %.

Sammendrag

NTNU Test Satellitt (NUTS) er et prosjekt for master studenter ved NTNU og tar sikte på å sende opp en $10 \times 10 \times 20$ cm nanosatellitt i løpet av år 2014. Hovedmålet med prosjektet er å designe og utvikle en satellitt med lave kostnader. Dette gjøres ved og utforske bruken av kommersielle komponenter som vanligvis ikke blir brukt i større satellitter. Arbeidet i denne rapporten vil ha fokus på satellitten effekt system, som består at et system for distribuering av effekt, bakplanet, og et system for tilføring av effekt, Elektriske Effekt Systemet (EPS).

Denne oppgaven beskriver designet og evalueringen av EPS modulen som er en kritisk del av satellitten, for foruten effekt vil ikke satellitten kunne fungere. Det elektriske effekt systemet består av solceller, batterier og spenningsregulatorer for konvertering av spenninger fra solcellene til batteriene, og fra batteriene til bakplanet. Med begrenset effekt tilgjengelig har hovedfokuset vært å designe et effektivt system med minimale tap ved spenningskonverteringer.

EPS modulen er designet med fokus på enkelhet, pålitelighet og redundans. Designet er basert på kravene om en pålitelig effekt kilde, som har som hovedfunksjoner å lade batteriene med energi fra solcellene og konvertere batteri spenningen ned til den ønskede spenningen på bakplanet. En effektiv lader er valgt for sine egenskaper til å lade batteriene effektivt og sikkert ved bruk av gode strategier for effektiv anskaffelse av energi og ladning. For å oppfylle kravet om fire ulike spenningslinjer til bakplanet er fire spenningskonvertere med bestemt utgangsspenning valgt. For å måle tilført effekt og batteri status har hver ladekrets og batteriene blitt implementert med en strøm sensor.

Designet av EPS modulens hovedfunksjoner er utviklet og en prototype er produsert. Design løsningen er et enkelt, pålitelig og redundant system, hvor et tap av en lader eller konverter ikke vil bety slutten på satellittens operasjon. Prototypen av EPS modulen er tested og evaluert med gode resultater for ladning av batteriene og spenningskonvertering. Effektiviteten til laderne er målt til 95 %.

Preface

This report is a result of the final thesis work, to complete my Master's Degree in Electronics, and was accompliched during the spring of 2012 at the Institute for Electronics and Telecommunications at NTNU.

The NTNU Test Satellite project consists of a group of students from several NTNU departments, which shall explore the opportunities for designing and developing a small satellite. The project was brought to my attention during the course Experts in Team, where I attended the student village, The Student Satellite. The main focus of this thesis is to design and develop an Electrical Power System module for the NUTS satellite, which consists of energy harvesting, battery charging, and voltage conversion.

The thesis is a continued work of the specialization project from last semester [1]. The project was intended to be preliminary work for this thesis and was used to get an understanding of the power system in general. As a result, there are some references throughout this thesis to my specialization project for further derivations of different solutions found in the project.

I would like to thank the other students in the project group and project leader Roger Birkeland, for many good moments, advice, and discussions. Many thanks to Andreas Østensen, for guidance in Altium and with the soldering of the EPS prototype. A special thanks to Torgeir Wiik, for guidance in how to comprehend with the task and the report.

Finally, I would like to thank my supervisor, Professor Per Gunnar Kjeldsberg for good advice and guidance in the making of this report.

Trondheim, 11.06.2012

Lars Erik Jacobsen

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ADC	Analog to Digital Converter	p. 31
ADCS	Attitude Determination and Control System	p. 10
ANSAT	The Norwegian Satellite Program	p. 2
BCR	Battery Charge Regulator	p. 44
BOM	Bill of Material	p. 71
CAD	Computer Aided Design	p. 25
CCCV	Constant Current, Constant Voltage	p. 12
COTS	Commecial off the Shelf	p. 1
DOD	Depth of Discharge	p. 7
EMC	Electromagnetic Compability	p. 18
EPS	Electrical Power System	p. 2
FF	Fill Factor	p. 15
GEO	Geostationary Earth Orbit	p. 8
HiN	Narvik University College	p. 2
IC	Integrated Circuit	p. 13
I^2C	Inter-Integrated Circuit	p. 29
LEO	Low Earth Orbit	p. 2
MPP	Maximum Power Point	p. 14
MPPT	Maximum Power Point Tracking	p. 3
NAROM	Norwegian Centre for Space-related Education	p. 2
NTNU	Norwegian University of Science and Technology	p. 2

NUTS	NTNU Test Satellite	p. 2
OBC	On-Board Computer	p. 9
PCB	Printed Circuit Board	p. 4
PGA	Programmable Gain Amplifier	p. 29
P-POD	Poly-Picosatellite Orbital Deployer	p. 1
PV	Photovoltaic	p. 13
PWM	Pulse Width Modulation	p. 32
RBF	Remove Before Flight	p. 6
SCL	Serial Clock	p. 31
SDA	Serial Data Line	p. 31
SOC	State of Charge	p. 7
TT&C	Telemtry, Tracking and Command	p. 9
UiO	University of Oslo	p. 2

Chapter 1

Introduction

In the recent years there has been a general growth of interest in space missions from several universities all over the world. Universities have traditionally been limited by cost and time aspects associated with a space mission. However, new technology developments in nano- and picosatellites have opened up opportunities for universities and other small organizations with low budgets and short time frames to design and develop their own satellites.

A nanosatellite, which this project is based on, is defined as an artificial satellite with a mass between 1 and 10 kg. Satellites of this size are considered in the "small satellite" category, which means that they are usually passengers on larger satellite missions or independent rockets [5]. The nanosatellites are normally designed according to a known standard, such that a common deployment mechanism can be used. This project will follow the CubeSat Standard [2]. In the case of the CubeSat Standard, which will be discussed more in detail later, the common deployment mechanism consists of a Poly-Picosatellite Orbital Deployer (P-POD). This deployer includes a spring that pushes the satellite out of the deployer when the rocket has reached the wanted orbit height area.

The new technology can drastically reduce the development cost and development time of small satellites by scaling down the design and make use of *commercial of the shelf* (COTS) components. In addition, the lifespan of a small satellite is considered very short compared too a larger satellite mission. For this reason, the use of new and innovative components that are not purpose built for space missions can be taken into account in the design of a small satellite, and hence achieve a lower development cost.

A challenge related to developing a small satellite is defining a scaled down design which is as energy- and power-efficient as possible, since they are driven by batteries primarily. Furthermore, there are many requirements and constraints that have to be considered, for instance related to the power supply from the batteries and/or solar panels, volume and weight. For a larger satellite mission the requirements of reliability and redundancy, because of the long lifespan of 5-10 years, can result in a very complex system with a small degree of flexibility. However, since the lifespan of small satellites is considered very short, 3-12 months, the flexibility is much greater. As a result, factors like simplicity and power-efficiency can be favored against the requirements of reliability and redundancy.

1.1 NUTS – NTNU Test Satellite Project

The Norwegian University of Science and Technology (NTNU) Test Satellite (NUTS) project is aiming to launch a nanosatellite into Low Earth Orbit (LEO) by 2014. The satellite is a double cubesat, measuring $10 \times 10 \times 20$ cm and weighing less than 2.66 kg, which conforms to the CubeSat Standard [2]. The satellite will carry an IR-camera for atmospheric observations as its main payload.

The NUTS project was started in September 2010, and is a part The Norwegian Satellite Program, ANSAT, run by NAROM (Norwegian Centre for Space-related Education). This program involves three educational establishments, namely the University of Oslo (UiO), Narvik University College (HiN) and NTNU. The program is developed with the intention to stimulate cooperation between different educational institutions in Norway and with the industry. The students will experience team work and hands-on training [6].

The main goal of this master thesis is to continue the work with the Electrical Power System (EPS) module that was started in my project work of last semester [1]. The thesis will focus on the design, component choices, manufacturing and testing of the EPS module with regards to the theory presented in Chapter 3. The EPS module is responsible for harvesting energy from the solar cells to charge the onboard batteries, and to regulate the battery voltage down to the required power lines of the backplane of the satellite.

1.2 Previous Student Satellite Work at NTNU

NTNU has previously been involved in the NCUBE student satellite project with other Norwegian universities. This project resulted in the construction of two satellites, NCUBE-1 and NCUBE-2. The satellites were single Cube-

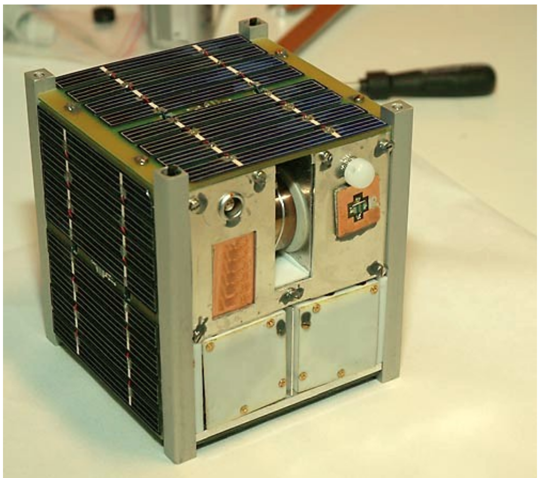


Figure 1.1: The Norwegian satellite NCUBE-2.

Sats with the dimensions $10 \times 10 \times 10$ cm and had a weight around 1 kg. Unfortunately, both the NCUBE satellites had problems. The NCUBE-2, launched on October 27, 2005, suffered from no radio contact. The NCUBE-1, launched on July 26, 2006, had problems with the second stage of the rocket. As a result, the release of the satellite from the rocket was aborted.

In the autumn of 2006, three master students started from scratch with defining new specifications for the design of a small student satellite. In their report they provide a general system specification with the requirements and constraints concerning of a small student satellite [7]. In the following years there have been several students involved in the design and specification of the different sub-systems for the NUTS project. In this thesis, power management strategies and discussion from previous students will be considered regarding the design of the EPS module. A power management strategy that will be discussed in greater detail is the use of MPPT (Maximum Power Pointing Tracking). The use of this strategy in the NUTS satellite was first presented in the Master's thesis of Lars O. Opkvitne [8].

The most recent contribution to the power management of the satellite is given in the Master's thesis of Dewald De Bruyn [9]. Together with Marius Volstad [10], De Bruyn provides a functional prototype for the backplane of the satellite. The backplane is the power and communication distributer inside the satellite, and is thus a crucial part of the satellite. The thesis also outlines the necessary requirements and constraints for the Backplane and the EPS. Based on these requirements and constraints an analysis of the backplane's power solutions and a design proposal of the EPS was presented in my project work of last semester [1]. The design proposal was outlined by the requirements of simplicity, redundancy, and reliability. The report also presents a battery charger with good applications for the EPS module.

1.3 Scope and Outline

As mentioned in Section 1.1, the main scope of this thesis is to design, manufacture, and test an Electrical Power System for the NUTS satellite. The final solution will be implemented in Altium designer tool and the Printed Circuit Board (PCB) will be produced by an external company.

The disposition of this thesis is as follows: Chapter 2 presents some general information on the satellite. This includes the information about the CubeSat standard, and the Power Systems that includes the Power Supply and Energy Storage of the satellite. This is important information to understand the requirements for the EPS.

Chapter 3 is dedicated to the theory of the solar cells, batteries, and electronics in space. This forms the requirements and strategies needed to design an EPS.

In Chapter 4, an overview of the EPS is presented. This includes the implementation of the design and testing results of the finished module.

Chapter 5, presents a short discussion of the design and results of the EPS module.

In Chapter 6, a conclusion and suggestions for further work on the EPS module is presented.

Chapter 2

Background

This chapter gives a brief overview of the satellite and the requirements related to power management. Some previous solutions of the power management are presented. In [1], a solution for the EPS architecture and the removal of two slave slots on the backplane, to increase the battery bank are presented.

2.1 The CubeSat Standard

The CubeSat Standard [2] was developed by the Polytechnic University of California and Stanford University to ease the development and deployment of nanosatellites. The standard includes the mechanical and electrical requirements. Some mechanical requirements from [2] are:

- The width of the CubeSat shall be 100.0 ± 0.1 mm
- A single CubeSat shall have a height of 113.5 ± 0.1 mm, while a triple CubeSat shall have a height of 340.5 ± 0.3 mm.
- The minimum width of the rails is 8.5 mm. The rails are a part of the framework of the satellite, as shown in Figure 2.1.
- The satellites weight shall not exceed 1.33 kg for a single CubeSat, or 4 kg for a triple CubeSat.

The NUTS project intends to build a double CubeSat satellite. Although the CubeSat Standard presents the requirements for a single and a triple CubeSat, a double CubeSat dimensions can be calculated to a height of 227.0 ± 0.2 mm and a mass of 2.66 kg.

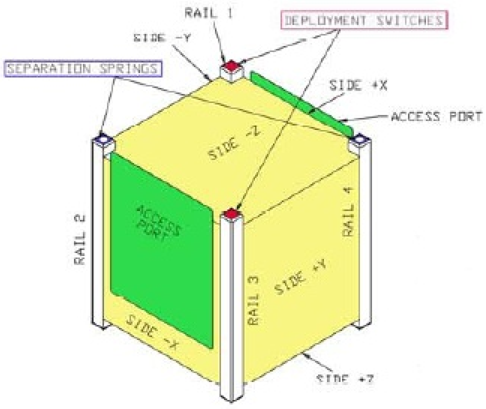


Figure 2.1: CubeSat specification [2].

The electrical requirements are provided to prevent interference with the launch vehicle, payloads or other CubeSats. Some important electrical requirements from [2] are:

- No electronics shall be active during launch
- The satellite shall have a deployment switch, to completely turn off the power in the satellite when depressed.
- The satellite has to include a Remove Before Flight (RBF) pin.

The RBF pin is used to disconnect all power to the satellite and is removed when the satellite is placed in the P-POD. When the satellite is deployed from the P-POD the deployment switch is released. Although the satellite now has power, some operational requirements have to be fulfilled. These requirements state that the satellite has to wait at least 30 minutes, after ejection from the P-POD, to begin transmitting with the RF transmitters with power greater than 1 mW. The deployment of antennas and other structures on the satellite must also wait at least 30 minutes after ejection from the P-POD.

The electrical and some of the operational requirements are important to consider when designing the EPS module, as this regulates and controls the power supply to the satellite.

2.2 Satellite Power Systems

For a satellite to be operative, it is important to have a stable and reliable power system. Without electrical power the satellite will not be able to do anything else than drift around in orbit.

When designing a satellite's power system, the batteries and the solar panels become a major factor for the dimensions of the satellite. The required size of the solar panels and batteries depends on the requirements for the payload(s) and the lifetime of the mission. Since efficiency of both the batteries and solar panels decrease with time, it is important to have good estimates on how much energy the solar panels can harvest and how much power the batteries can provide. These estimates will give an idea of how large area of solar panels is needed, and how large batteries the satellite mission requires. Some calculations on power- and orbit-estimates can be found in [9]. In [1], some calculations on the charging time and the state-of-charge (SOC) of the batteries are presented.

2.2.1 Power Supply

The power supply of the NUTS satellite consists of solar panels[1] and batteries. The efficiency of the solar panels depends on the irradiation and temperature of the cells, as discussed in more detail in Section 3.2. Hence, it is desirable to find the optimal operating conditions of the solar cells. For this reason the maximum power pointing tracking (MPPT) strategy, which will be discussed in Chapter 3, is considered for the EPS module to maximize the effect from the solar panels.

The batteries that has been evaluated and chosen for the NUTS satellite are the A123 APR18650M1A cells [11]. These cells are lithium-ferrite-phosphate cells ($LiFePO_4$). The reason for choosing lithium batteries over the traditionally nickel-cadmium (NiCd) batteries is that these batteries possess a so-called "memory" effect. The "memory" effect causes the capacity to deteriorate over time. As a consequence, the batteries requires periodical reconditioning by forcing a 100% *Depth of Discharge*[2] (DOD) cycle. The main reason for choosing these $LiFePO_4$ battery cells over conventional Li-Ion battery cells is the number of possible charge cycles [9].

The $LiFePO_4$ cells also provide a more stable environment in form of more stable chemistry for safety, number of charge-discharge cycles and temperature stability. However, the $LiFePO_4$ has a slight disadvantage to the Li-Ion

[1] An array of solar cells.
[2] 100% DOD equals to the status empty in state-of-charge (SOC) of the battery.

when comparing the energy yield of the two. As a result, the battery pack of the $LiFePO_4$ is heavier than the Li-Ion for the same amount of energy. Nevertheless, the weight of the battery pack will not be crucial for the total weight requirement of the satellite.

2.2.2 Energy Storage

Rechargeable batteries are used on-board to provide power to the satellite when in eclipse. The required stored energy varies with the different orbits. For instance, a satellite travelling in a Geostationary Earth Orbit (GEO) has a maximum eclipse transit of 72 minutes during a 45-day period around the spring and autumn equinox[3]. The batteries shall supply power during these occasional eclipses. However, in a Low Earth Orbit (LEO) a satellite is seduced to an eclipse period of up to 40 % of the total orbit. As a result, the batteries are exposed to many more charge-discharge cycles.

The capacity of the batteries will gradually decrease with the number of charge-discharge cycles it is exposed to. The capacity loss depends on the *depth-of-discharge* (DOD) of the cycles. The result is that a battery pack of a LEO satellite has to have a larger capacity then a battery pack of a satellite in the GEO with the same power requirements. In [9], De Bruyn calculate a worst-case DOD of the battery pack for an average power usage of 3.43 W. The result shows a DOD of 13.9 % of the batteries during one eclipse.

For the NUTS satellite a battery pack of 4 $\times$ 1.1 Ah battery cells are proposed, where two and two cells are connected in series and the two series are connected in parallel. As a result, the battery pack has a capacity of 2.2 Ah at 6.6 V. However, the result of the discussion on number of modules in [1], led to the removal of two slave module slots on the backplane in favour of an increase of the battery bank. As a result, the NUTS satellite will carry two battery packs connected in parallel, resulting in a nominal value of 6.6 V and a capacity of 4.4 Ah. The configuration is presented in Figure 2.2. This results in a total power of 29 Wh.

By increasing the battery bank, the calculations done by De Bruyn must be recalculated. Assuming a worst-case average power usage of 3.43 W during eclipse, the battery capacity usage becomes:

$$\frac{3.43W}{6.6V} \cdot 35min = 0.52A \cdot 35min \approx 0.3Ah \tag{2.1}$$

[3] An equinox is when the tilt of the Earth's axis is inclined neither towards nor away from the sun. As a result, the center of the sun is aligned with the Earth's equator.

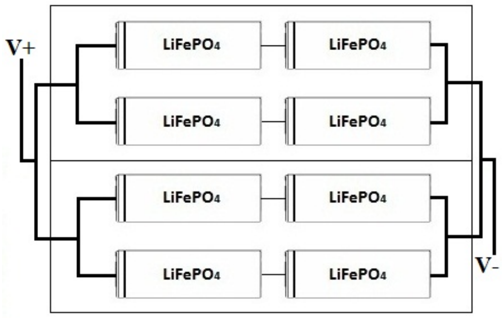


Figure 2.2: The battery configuration of the NUTS satellite, parallel connection of two battery packs.

Compared to the new total capacity of 4.4 Ah, the maximum DOD is:

$$\frac{0.3Ah}{4.4Ah} = 6.82\% \tag{2.2}$$

2.3 NUTS Overview

The NUTS system is designed as a distributed architecture around the backplane, as shown in Figure 2.3. The backplane provides power and communication interfaces to the system, and connects all submodules together. The EPS module is responsible for providing a regulated power supply, and the backplane then distributes it to the modules. As a result, the EPS module connections with the backplane differs some from the connections between the backplane and the other modules. This is mainly because the EPS supplies power, while the other modules receive power.

The system consists of two master modules and three slave modules. One of the master modules is the on-board computer (OBC), which is the main mission computer. The module contains a microprocessor and memories for software and data storage. The OBC shall monitor the system health, perform logging of flight data, and issue control commands to the rest of the system. A prototype of the OBC was implemented by Marius Volstad in his Master's thesis work [10]. The other master module is the Telemetry, Tracking & Command (TT&C) module, which provides the communication unit for the satellite. The module contains two radio transceivers, one with a frequency of 145 MHz and one with a frequency of 437 MHz. The module shall be able to receive commands from the ground station and transmit data packages back to the ground station. This module is considered critical, because a loss in communication will mean an end to the mission. A prototype of the TT&C module was provided and presented by Asbjørn Dahl in [12].

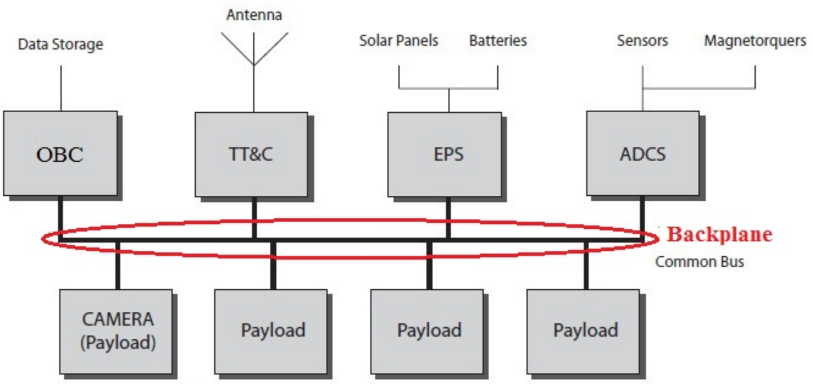


Figure 2.3: NUTS Sub System Modules.

The slave modules of the satellite are the Attitude Determination & Control System (ADCS), EPS, and the payload. The ADCS module shall obtain estimates about the orientation of the satellite and provide de-tumbling and stabilization to the satellite. Good estimates are calculated by using different sensors and algorithms. These estimates are then passed to the attitude controller which uses magnetorques as actuators to stabilize the satellite. Several students are currently working with the ADCS system.

The payload evaluated for the NUTS satellite is an infrared camera to photograph different gravity waves and wavepatterns around the earth. A current study of possible cameras and conditions they will work in, and how to handle the image data is performed by Marianne Bakken [13] and Snorre Rønning [14].

The EPS which is the main topic of this thesis, shall supply 2×3.3 V and 2×5.0 V power rails to the backplane. It is responsible for charging the batteries with power from the solar cells, and to protect the batteries from over-charging and over-discharging. Finally, it shall provide telemetric data about battery state-of-charge and available power from the solar panels to the OBC. The OBC use the telemetric data to issue the shut-down functions of the subsystems in the satellite when the batteries suffer of low voltage or failure. The EPS module will be considered in Chapter 4 of this thesis.

During this last year, several master students have worked with the NUTS satellite. In the Master's thesis of Kai Inge Rokstad [15], an analysis of using carbon fiber as material for the frame structure and a frame prototype of the satellite is provided. He also presents different solutions for the final assembling of the satellite. In the Master's thesis of Sigvald Marholm [16], an evaluation of the antennas and prototypes is provided.

Chapter 3

Theory

This chapter presents theory about the batteries, the solar cells, and the strategies considered when implementing the EPS module.

3.1 Battery Theory

A battery converts chemical energy to electric energy through the use of an electrolyte, which is a substance that consists of free ions and as thus electrically conductive. The battery consists of two or more voltaic cells. These voltaic cells consist of two electrodes of different metals or metallic compounds, which are connected in series by the conductive electrolyte. One electrode contains an overflow of anions[1] while the other electrode contains an overflow of cations[2], and represents the anode and cathode respectively of the electrolyte connection [17]. A redox reaction creates an electric potential difference between the electrodes.

During discharge, a chemical process occurs which generates energy that can be utilized from the battery in form of an electric current at a certain voltage. This chemical process starts when the electrodes are immersed in an electrolyte substance. An oxidation occurs at the anode which leads to the release of electrons. Consequently, a reduction occurs at the cathode which leads to a reduction of electrons. As a result, the cathode is now acceptable for new electrons. These electrons travel through the lead connection, forcing a current in form of electron movement from anode to cathode. This current is used to power the load over the battery.

During charging, this chemical process has to be reversed. By introducing a higher voltage over the batteries, the electrons are forced in the

[1] Negative charged ions.
[2] Positive charged ions.

opposite direction. As a result, the potential at the anode and cathode is reversed. When charging a battery, there are some issues to consider when using lithium-ion batteries. Over-charging and over-current are crucial issues when operating with lithium-ion batteries. When lithium batteries are charged beyond their nominal voltage, plating of metallic lithium will start to form at the anode and the cathode material will become an oxidizing agent. As a result, the batteries lose stability and produces carbon dioxide, which increases the pressure inside the cells [18]. This can lead to an explosion of the batteries if the over-charging continues for longer periods of time. If an over-charging incident occurs and is handled immediately, by cancelling the charging, the result of the over-charging will only have an effect on the capacity of the batteries. The capacity suffers a reduction due to the plating that forms on the anode, and therefore changes the electrical potential between the anode and cathode of the battery. However, the batteries are still functional compared to if they explode.

The electrodes are chosen accordingly by their chemical abilities. The materials of the electrode define the open-circuit voltage which is the difference in chemical potential between the cathode and anode, as shown by:

$$V_{oc} = \frac{\mu_{Li(c)} - \mu_{Li(a)}}{F}, \tag{3.1}$$

where $\mu_{Li(c/a)}$ is the chemical potential of the cathode and anode respectively, and F is Faraday's constant [19].

As mentioned in Section 2.2.1, the $LiFePO_4$, lithium-ferrite-phosphate, battery cells A123 APR18650M1A [11] are chosen for this project. To achieve safe charging of these cells, the manufacture recommend a charge voltage of 3.6 V per cell. This results in a charge voltage of 7.2 V for the battery configuration chosen for the satellite. Nevertheless, it is important to implement a charging strategy to protect the batteries from over-charging. Without a proper charging strategy the battery cells may be charged too rapidly or over-charged, which can cause damage to the batteries, as mentioned above.

By using a proper charging strategy, the batteries lifetime can be increased in contrast to not using a charging strategy.

CCCV - Constant Current Constant Voltage

The CCCV charging strategy is a common charging strategy for low voltage lithium-ion batteries. The strategy uses constant current to charge the batteries until they approach their nominal battery voltage, as shown in Figure 3.1. When the charge voltage approaches the nominal battery voltage, the charge current will begin to drop. This is a result of the reduced required

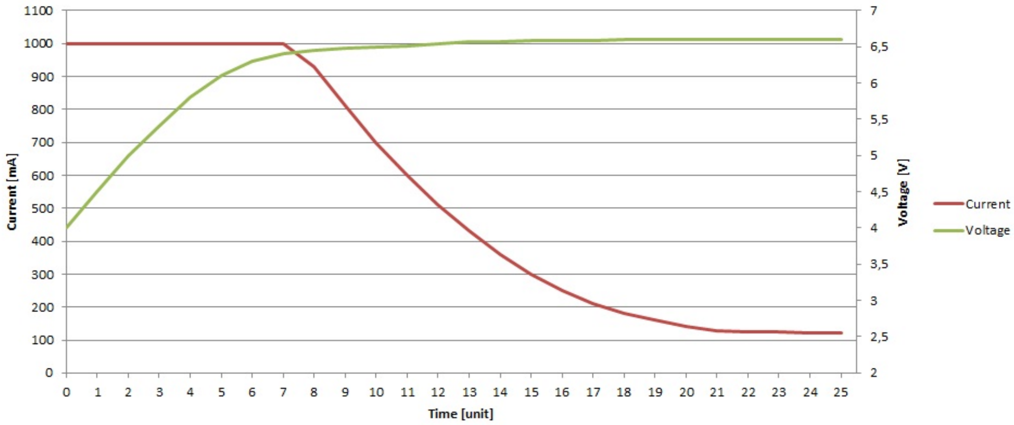


Figure 3.1: IV characteristics of the CCCV charging strategy.

current to maintain the voltage level, hence constant voltage. By using this strategy, the slow top charging of the batteries will reduce the chances of over-charging the batteries. When the charge voltage equals the nominal battery voltage, the charge current will become insignificant. As a result, this strategy offers a safe and reliable charge for the batteries, and reduces the likelihood for over-charging the batteries.

The regulation of the charge current requires that the charger is implemented with circuitry for sensing the current drawn from the batteries and the voltage provided to the batteries. Some chargers has this sense circuitry implemented in the components IC (Integrated Circuit), while other chargers uses external components for sensing the voltage and current provided to the batteries.

3.2 Solar Cell Theory

The solar cells intended for use on the NUTS satellite contains photovoltaic (PV) cells, which denotes the use of photodiodes in unbiased operating mode. Photovoltaic is a method which generates electrical power by converting radiation from the sun to an electrical current. To convert the radiation energy to electrical current, the photovoltaic cells use semiconductors that exhibit the photovoltaic effect. The photovoltaic effect occurs when photons of light exit electrons into a higher state of energy. This allows the electrons to act as charge carriers for an electric current [20].

The efficiency of solar cells is determined by the doping characteristics of the semiconductors. When doping the semiconductors it is important to either have an excess of positive charged carriers (p-type) or a surplus

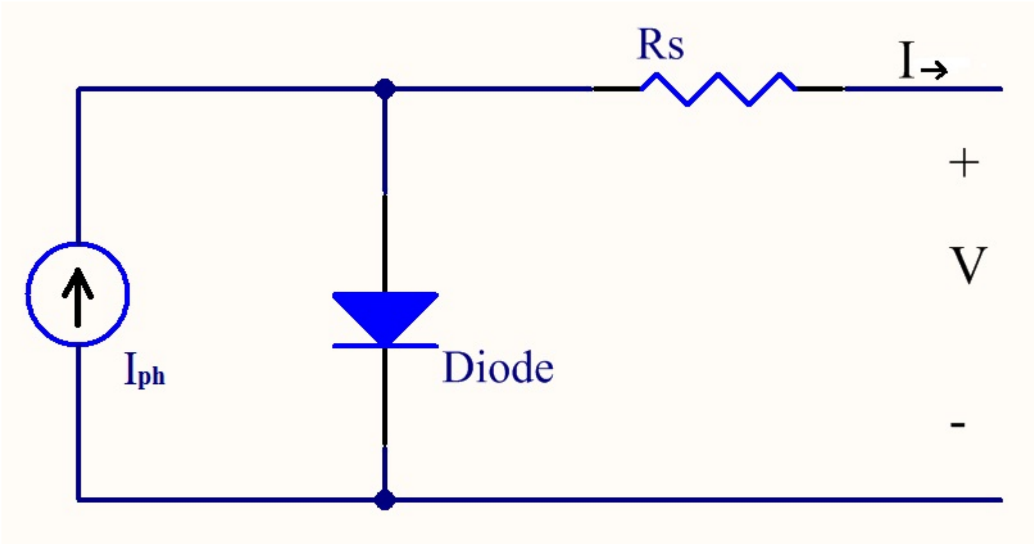


Figure 3.2: PV cell equivalent circuit.

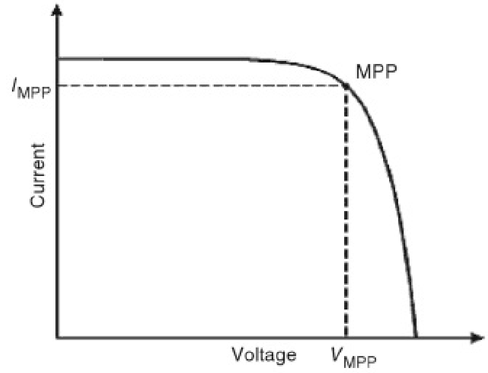
of negative charged carriers (n-type). When contact occurs between the two layers of the semiconductor a p-n junction is formed. As a result, an electrical field arises, causing the separation of charge carriers released by light. This leads to free electrons in proximity of the electric field, which then forces the electrons from the p-side to the n-side, creating a current [3].

The diode current of a solar cell is given by the Shockley equation:

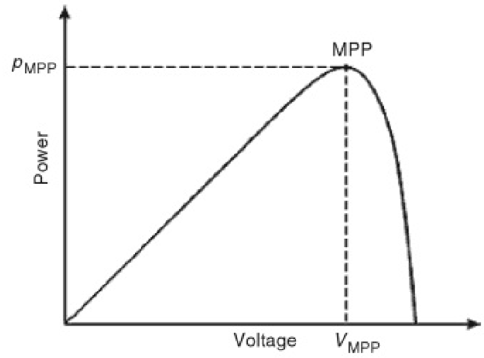
$$I_D = I_0[\exp{(\frac{qV}{nkT})} - 1], \tag{3.2}$$

where I_0 is the reverse saturation current, q is the charge carrier, k is Boltzmann constant, T is the cell temperature, V is the generated voltage, and n is the ideality factor of the cell. A simple equivalent of a PV cell is presented in Figure 3.2.

The irradiation and the temperature of the cell are two important factors that influence the amount of solar energy the cell can harvest. This leads to an optimal operating point or a Maximum Power Point (MPP) for maximum utilization of the solar cell, as shown in Figure 3.3. It is therefore highly desirable to maintain the MPP, to harvest the maximum amount of energy available from the cell at any time. The PV solar cell has two limiting factors, the open-circuit voltage V_{OC} and the short-circuit current I_{SC}. The I_{SC} increases with the irradiation on the cell, while the V_{OC} decreases when the temperature of the cell increases [21]. The V_{OC} can be found by the



(a) I-V characteristic of a PV solar cell.



(b) P-V characteristic of a PV solar cell.

Figure 3.3: The characteristic of a PV solar cell with MPP [3].

following equation.

$$V_{OC} = \frac{nkT}{q} ln[\frac{I}{I_0}] \tag{3.3}$$

The I_{SC} is equal to I_{ph}, which is the current generated by the cells irradiation, when $V = 0$. As a result the I_{SC} are proportional with the cell irradiation.

The maximum power points are related to these factors in form of a "Fill Factor" (FF):

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}}, \tag{3.4}$$

where the FF is a measure of the quality and series resistance in the junction of the semiconductor in the cell [22]. The quality of the PV cell increase when the FF is close to unity. This result also affects the efficiency (η) of the solar cell, as expressed by:

$$\eta = \frac{V_{OC} \cdot I_{SC} \cdot FF}{P_{in}} \tag{3.5}$$

The equation presents the ratio of the output electrical power versus the input solar radiation power P_{in}. The efficiency of the solar cells on the NUTS satellite is approximately 30% [23].

Since the solar cell has a nonlinear I-V curve, shown in Figure 3.3, it is difficult to utilize the solar cells efficiently without a proper tracking strategy. It is therefore desirable to use a battery charger that has the Maximum Power Point Tracking (MPPT), since the MPP moves when the temperature and radiation changes.

MPPT - Maximum Power Point Tracking

Maximum Power Point Tracking is a method for tracking the maximum operating point of the solar cell for maximum utilization. The MPPT use different strategies to simulate the behavior of the solar cell under the different conditions. As mentioned above, the I-V characteristic of the solar cell is nonlinear, which is a result of the change of cell radiation and temperature.

A MPPT controller usually uses one of three strategies: Perturb and observe, Incremental conductance, or Constant voltage.

Perturb and observe: This strategy is the most common approach for MPPT. The algorithm perturbs the operating voltage by small increments and observes the change in power. When the change in power is positive, it means that the operating voltage moves towards the MPP. The algorithm will then make a new voltage perturbation in the same direction as the observed power. If the algorithm observes a negative power change, it will move its perturbation back to the previous operating voltage, hence keeping it at the MPP. However, the MPP may change over time due to a reduction in the resistance of the solar cell. To keep the solar cell at its maximum, the algorithm alters the internal load resistor of the MPPT controller to match the resistance of the solar cell at the MPP [24].

Incremental conductance: This strategy measures incremental changes in the solar cell array current and voltage to predict the effect of a change in voltage. The strategy utilizes the incremental conductance to compute the changes in power when the voltage is changed. As a result, the MPP is calculated by comparison of the incremental conductance to the solar cell array conductance. When the incremental conductance is zero, the operating voltage is at the MPP. The controller maintains the voltage value until the irradiation changes, where then it repeats the process of measuring and calculating new values [3].

Constant voltage: This strategy uses an estimated value for the MPP, based on the open-circuit voltage (V_{OC}). The process produce an interrupt to measure the V_{OC}, and based on this value it resumes operation with the operating voltage at a fixed ratio, for instance 80% of the V_{OC}. To maintain the operating point at MPP, it regulates the array voltage and compares it to the fixed reference voltage. This reference voltage is the result of the estimation value calculated from a PV module characteristics [25].

3.3 General Electrical Theory

This section describes some of the general constraints around electronics in space, and functionalities regarding the electrical power system of the satellite.

3.3.1 Electronics in Space

The electronics in space must operate in a different environment than on the earth. There are three major factors of difference than has to be considered. Firstly, there is the space radiation like electromagnetic radiation and high energy particle radiation. Secondly, there is the vacuum environment of space, which can cause problem with cooling of components because of the lack of air. Another issue is the lack of pressure that can harm parts containing liquids or other expanding materials. The vacuum also restrains the use of some types of plastic that evaporates in vacuum. As a result, careful consideration of component materials is important. Finally, it is important to consider component or system reliability. A component or system that fails in space is not as easy to fix as if the component or system was down on earth. Below are some considerations on these matters.

Radiation

The easiest way to stop the radiation from penetrating the satellite is to use thick lead plates as the shell of the satellite. However, this solution is not a desirable solution because of the weight requirement of the satellite. Another solution is to shield the components to limit the radiation. Therefore, it is important to choose components that have been designed with radiation in mind.

Vacuum

As mentioned, the lack of atmospheric pressure and air causes problems for components. Firstly, there is convection. The lack of air results in a poor heat dissipation of the components. The heat transportation in space is done by radiation. As a result, the satellite will encounter a great difference in temperature when it is exposed to the sun and when in eclipse. These temperature changes cause mechanical strains on the components, since the materials expand and contracts with the changes in temperature. As a result, it is important to choose components that have the appropriate thermal coefficient. In this project a thermal area of the components of -40 ^{o}C to

+80 ^{o}C is considered a minimum, and should if possible be in the area of −40 ^{o}C to +125 ^{o}C. Another issue of convection is that the temperature changes alter the electric properties of semiconductors. When a semiconductor reaches temperatures above absolute zero, electrons will be released to become charge carries. The amount of released electrons is doubled for each 11 deg Kelvin increase in temperature. As a result, the intrinsic currents will rise exponentially, and will become significant with higher temperatures [26].

Secondly, there is the problem with the lack of pressure. This leads to concerns when operating with liquid components, since the rate of evaporation depends on pressure. With less pressure the quicker the liquids evaporate, and in vacuum all liquids evaporate. A solution would be to incorporate all electronic components containing liquids into a pressure chamber. However, this would cause an increase in the weight of the satellite and result in a higher cost. As a result, components containing liquids such as electrolyte capacitors and batteries, which are not pressure shielded, are not suitable for space.

However, the satellite needs a power source for operating in the eclipse. Therefore, some modifications have to be made to make the batteries suited for space. A solution is to place the batteries in a housing that has a pressure seal, heating and insulation. This solution offers the batteries an isolated environment where a controlled housing temperature can optimize the battery's performance.

Reliability

The reliability of the electronics in space is very important, since a change of a faulty component is not possible. When using the commercial components it is important to design a system where failure of a component does not mean the end of the mission. The system has to be designed with a backup solution if a component should fail. Hence, increase the reliability of the satellite, the system must be designed with some level of redundancy. Testing and retesting of the system is a vital part of the design process for validating a component or system for space. Important tests are:

- Part stress test.
- Thermal test.
- Mechanical test.
- Electromagnetic compability (EMC) test.

These tests will find the maximum rating for which the component or system can withstand in the different environmental parts [27].

3.3.2 Voltage Regulation

This section is dedicated to the voltage regulation needed to accommodate the charging voltage and the voltages of the satellite's subsystems. In most systems, the need for a specific voltage requires a regulation of either a step-up or a step-down of the supplied voltage. For instance, a microcontroller which operates on a voltage of 3.3 V, cannot be supplied directly from a battery with a voltage of 6 V. The solution is to use a step-down converter to bring the voltage level of the battery down to 3.3 V before supplying the microcontroller.

Buck Converter

A buck converter, or a "step-down" converter, is a regulator that converts the input voltage down to a requested voltage. A simple schematic of the buck converter is presented in Figure 3.4a. The basic operation of a buck converter is to regulate the energy provided to the load. By using a switch, the buck converter stores energy in the inductor when the power supply is connected. When the power supply is disconnected, the inductor with stored energy is discharged into the load. The energy stored in the inductor is given by:

$$E = \frac{1}{2} L \cdot I_L^2, \tag{3.6}$$

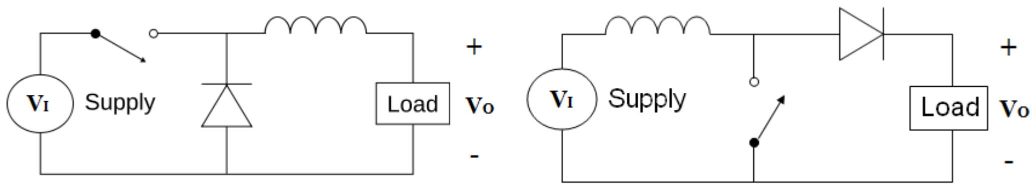
where L is the inductance of the inductor and I_L is the current through the inductor. When the switch is ON, the voltage over the inductor is $V_L = V_I - V_O$. When the switch is OFF, the voltage over the inductor becomes $V_L = -V_O$. As shown in Appendix A.1, the energy stored in the inductor is determined by the current and the periods of the ON and OFF states.

The output voltage over the load is then determined by the ratio of the ON/OFF state of the converter, also referred to as the *duty cycle*. To convert 6 V down to 3 V, which is a half of the original voltage, a duty cycle of 50% is required under ideal conditions. The duty cycle of the converter is given by equation 3.7;

$$D = \frac{V_I}{V_O}, \tag{3.7}$$

where V_I is the input voltage, or power supply, and the V_O is the regulated output voltage.

A buck converter is used to regulate the voltage of the batteries down to the requested voltages of the subsystems of the satellite. In the NUTS satellite, this means that the battery voltage of 6.6 V is regulated down to 3.3 V and 5.0 V with fixed value regulators.



(a) Buck converter.

(b) Boost converter.

Figure 3.4: Voltage regulation.

Boost Converter

A boost converter, or a "step-up" converter, does the opposite of the buck converter. This converter produces a larger output voltage than the input voltage. A simple schematic of a boost converter is present in Figure 3.4b. In difference from the buck converter the inductor is placed on the same side as the power supply of the switch. As a result, the power supply stores energy in the inductor when the switch is ON. However, the boost converter does not supply any energy to the load in the ON state, which results in a voltage over the inductor of $V_L = V_I$. When the switch alters, the energy in the inductor tends to collapse and the polarity changes. This results in that the energy in the inductor is added to the supplied energy, giving it a boost and hence produces a larger output than the input. The energy of the inductor is given by equation 3.6.

The output voltage is determined by the changes in the inductor current, which depends on the time periods in ON or OFF states. The change in inductor current is shown in Appendix A.2 and from these equations the duty cycle of the converter can be determined. The duty cycle of a boost converter is given by:

$$D = 1 - \frac{V_I}{V_O} \tag{3.8}$$

A boost converter is used in the battery charger to "boost" the voltage produced by the solar cells to the proper battery voltage. When operating with voltage converters it is important to consider the Ohm's law of power, $P = VI$. Since, the power is equal on both sides of the converter, Ohm's law presents that the current changes when the voltage changes to maintain the power. It is therefore important not to make large conversions when the current is a factor in the system. Hence, a major increase in the voltage will result in a major decrease of the current.

Chapter 4

Electrical Power System - EPS

This chapter presents the design requirements, layout, and implementation of the Electrical Power System (EPS), which together with the Backplane forms the power system solution of the satellite. A test analysis of the EPS module alone and together with the solar cells and batteries is presented.

4.1 Overview

The EPS may be referred to as the heart of the satellite, since it is controlling the main power sources of the satellite. Without power the satellite will not be able to operate, and as a result the main requirement for the EPS is reliability. The purpose of the EPS module is:

- To supply the backplane with 2×3.3 V and 2×5.0 V power rails.
- To charge the batteries with energy from the solar cells.
- To provide telemetric data about battery status and power produced by the solar cells.

4.2 Requirements

The main task of the EPS module is to provide power to the satellite. As a result, some basic requirements with regard to the design are needed. They are:

- Efficient and reliable harvesting of solar cell energy.
- Efficient and reliable charging of the batteries.

- Safe charging of the batteries.
- Power monitoring of the chargers and batteries.
- Protection of the batteries.
- Efficient regulation of output voltage to the backplane.
- Maximum printed circuit board (PCB) size of 86×83 mm.

These requirements to the design implemtation are based on the theory presented in Chapter 3, and will be the main points of consideration in the design of the EPS.

4.2.1 Battery Charging and Energy Harvesting

The energy harvesting from the solar cells can be done efficient by implementing a MPPT strategy, as discussed in Section 3.2. In this section, the I-V curve of the solar cells efficiency is presented and the maximum power point (MPP) shows the most efficient operating point of the cell. It is therefore desirable to find this point of operation as fast as possible and use a algorithm to maintain the maximum operating point.

To charge the batteries safe and efficiently, a low power and highly efficient battery charger with the CCCV charging strategy should be used, as discussed in Section 3.1. The CCCV strategy charges the batteries by using constant current until the battery voltage appoaches its nominal voltage, then the current is reduced gradually to maintain the voltage, hence constant voltage. By using a charger with this strategy implemented the chances of over-charging the batteries is reduced, since the current will drop to an insignificant level for the charge.

The operational lifetime of the mission is directly linked to the lifetime of the batteries. As a result, improper battery management can cause damage to the batteries and reduce their capacity. This is a major point of failure for the entire satellite and should be one of the main consideration when designing the EPS module. Charging or discharging Li-Ion batteries beyond their safe limits can cause irrevesible damage to the batteries, and as a result protection circuitry is required. The battery pack includes an external protection circuit, which will be discussed later in this section.

4.2.2 Power Monitoring

Power monitoring of the battery status and delivered power from the solar cells is important to protect the satellite from failure. With the telemetric data from the sensor, the master modules (OBC and TT&C) can issue shutdown commands to protect the batteries from discharging below its threshold or overcharging. The data can also be utilized for estimation of chargetime or remaining power of the batteries with regards to the power consumption of the operating modules of the satellite. These estimates is useful to schedule different operating task and to prevent over-discharging of the batteries.

4.2.3 Battery Protection

The battery pack chosen for the NUTS satellite is implemented with an external protection circuit developed by AA Portable Power Corp. [28]. This external circuit provides protection against over-charging, over-discharging, over-current, and short circuit protection. During charging the circuit also provides equilibrium charging between the two battery cells of a serial connection. As a result, the electrical potential over each battery cell will be equal and reduce the chances of damaging the battery cells.

However, the EPS module IC components should include basic protection circuitry as over-voltage and over-current protection to prevent further damage to other parts of the satellite. If such protection circuitry is not implemented in the ICs, it should be implemented with external components.

4.2.4 Voltage Regulation

To be able to supply the backplane with power from the batteries and solar cells, efficient voltage regulation with minimum loss is required. The backplane is implemented with four power rails, 2×3.3 V and 2×5.0 V. As mentioned in Section 2.2.2, the chosen battery configuration provides a nominal voltage of 6.6 V. To convert the battery voltage down to the required voltage of the power rails, the EPS should contain four step-down DC/DC converters.

The converters should include over-voltage protection for safety, and when choosing an IC component, fixed value of the output voltage is desirable.

4.2.5 Printed Circuit Board

The mechanical requirement of maximum PCB size of the EPS is provided by Kai Inge Rokstad [15]. He is currently working on the mechanical structure

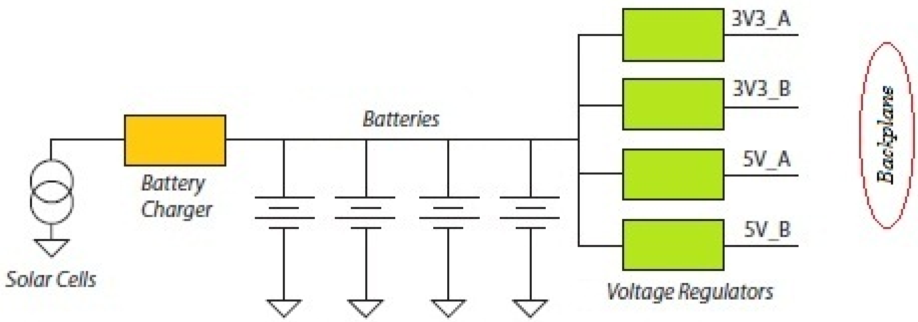


Figure 4.1: Simple architecture of the Electrical Power System.

of the satellite, and a solution for easy assembly and access of the different subsystems of the satellite. The final size depends on the solution found by Rokstad. As a result, the PCB prototype will be produced with the minimum requirements of 80 mm × 80 mm. The maximum size of the PCB may have a length of 83 mm and a width of 86 mm.

4.3 EPS Architecture

The architecture of the EPS module should be based on the design philosophies of simplicity, redundancy, and reliability. A more complex system may impose more reliability in the case of failure handling, however the number on components and power consumption will increase, hence the overall efficiency of the system will decrease as a result. It is important to design a system which is reduntant, in case of system or component failure. If a system is designed with redundancy in mind, the complexity and reliability will automatically increase. The solution is to find the architecture that impose a simple system with good redundancy and reliability.

In Figure 4.1, the overall main architecture chosen for the EPS is presented. The NUTS satellite will carry 18 solar cells distributed over the four long sides and the top side. To fulfill the requirements for charging the batteries with these solar cells, an efficient solar battery charger was found in [1]. However, the specification of this battery charger resulted in a consideration to the design regarding the amount of voltage and current produced by the solar cells and the requirements of the batteries. Since the batteries have a nominal voltage of 6.6 V and the solar cell produce at maximum 2.3 V, the configuration of the solar cells is an important factor in the design of the EPS. As a result, several configurations of the solar cells and the number of

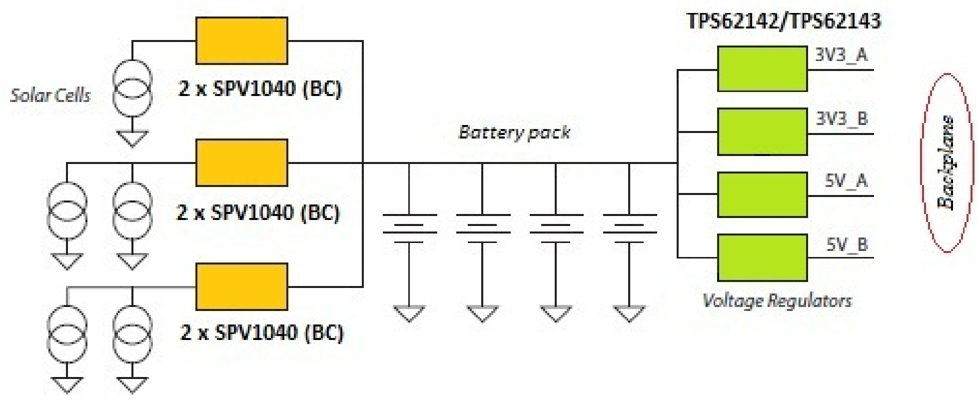


Figure 4.2: Final architecture for the Electrical Power System.

battery chargers were considered.

A more detailed solution of the EPS architecture, which comprehends with the requirements for the charging of the batteries from the solar cells is presented in Figure 4.2. This architecture requires a battery charger with step-up abilities to boost the voltage from the solar cells to the required voltage of the batteries. The voltage regulators provide the correct voltage to the four power rails connected to the backplane. The voltage regulators are step-down converters, which regulates the battery voltage down to the required voltage level of the four power rails.

This architecture offers a reliable and redundant system where a failure in a single charger, regulator, or damage to a solar cells, does not result in a total loss of power.

4.4 Implementation

In this section the implementation of the Electrical Power System is presented. The design process and layout of the EPS module is provided with the chosen design solution and components.

4.4.1 Altium Designer

Altium Designer is a *computer aided design* (CAD) tool for designing electronic systems. A decision was made in 2011 to use a common design tool for the NUTS systems. The reason for this decision was that the earlier designed subsystems of the NUTS satellite was designed in different CAD tools, often chosen by the designer of the specific subsystem. As a result, furture alter-

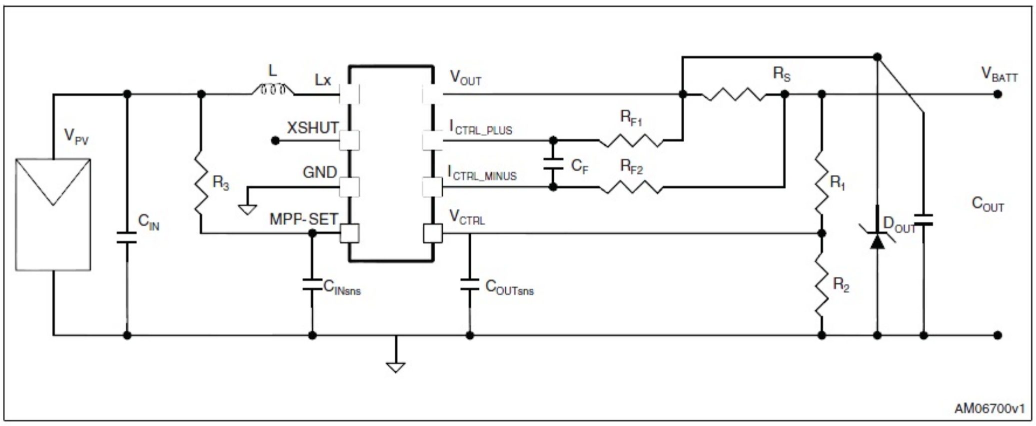


Figure 4.3: SPV1040 application circuit [4].

ation or reuse of the design may require expensive licenses for other CAD tools that was used. By using a common CAD tool, the designer has only one tool to relate to, and the different systems are gathered together in one designer tool.

One major task of designing the EPS was to learn the Altium Designer program. To create schematics of the different circuits in the system and the layout of the PCB.

4.4.2 Battery Charging and Energy Harvesting

The SPV1040 is a high efficiency solar battery charger from ST Microelectronics [29], and will be considered for the battery charging of the NUTS. The charger was a result of the specialization project of last semester [1], and will be compared to alternatives in Chapter 5. The charger includes both the MPPT feature, for maximum utilization of the solar cells, and the CCCV charging strategy for safe charging. It operates on an input voltage of 0.3 V to 5.5 V, and includes output voltage regulation, overcurrent and overtemperature protection. The output voltage regulation is controlled by a sensory circuit, I_{CTRL_PLUS} and I_{CTRL_MINUS}, and a voltage divider, as shown in Figure 4.3. The overcurrent and overtemperature disconnects the charger from its output terminal until it reaches an acceptable level, where the charger is reconnected at the output terminal.

The SPV1040 uses a step-up (boost) converter to increase the input voltage to the required charge voltage of the batteries. As a result, the current from the solar cells will decrease according to $P = V \cdot I$, where P is the power delivered from the cells, V is the delivered voltage, and I is the delivered current. Since the charger is a step-up converter with a maximum output voltage of 5.2 V, the configuration of the solar cells must be considered with this in mind. This restricted output voltage of the charger also impose an important design choice with regards to the battery configuration. The nominal voltage of the battery configuration is 6.6 V, which is higher than the maximum output of the charger. To accommondate the proper charge voltage for the battery configuration of the NUTS, two chargers has to be connected in series. The charge termination voltage[1] of the batteries in the chosen configuration is 7.2 V. As a result, the charge voltage of one charger should be set to 3.6 V, such that two chargers in series will result in a total charge voltage of 7.2 V.

According to [11], the maximum voltage and current produced by a solar cell is 2.3 V and 505 mA. With an output voltage of 3.6 V of the charger, the solar cell configuration is restricted to only parallel connections between the cells, since a serial connection of two cells will produce a higher input voltage than the output voltage of the charger. However, a parallel connection between the solar cells require a blocking diode or switch between each parallel connection. This blocking diode or switch must have a low forward voltage, since a voltage drop over the diode means a reduction of the output voltage of the cells. For simplicity, a Schottky diode from Vishay [30], that is also used in the charger circuit, is recommended as a blocking diode. This diode offers a very low forward voltage of only 320 mV. However, the bypass switch SPV1001 from ST Microelectronics [31] offers a forward voltage drop of only 120 mV. The drawback of the bypass switch is the package size of 10 mm × 15 mm, which will impose an issue of area available when placed on the solar panel PCB. The Schottky diode has a more sustainable package size of 2.3 mm × 1.4 mm.

The first design proposal of the solar cells to the batteries configuration is presented in Figure 4.4. This configuration proposes a solution with one charger per solar cell, which will result in a very redundant system. The result of this configuration is the use of 18 chargers. To use 18 chargers in the design of the NUTS EPS is both unnecessary and unefficient. However, the solution can be optimized by connecting the opposite solar cells into the same charger. This can be justified as the irradiation will be high on the cells facing the sun, while it will be very low on the opposite side. This solution will reduce the number of chargers to 10; 4 chargers for the front and back cells, 4 for the left and right cells, and one for each cell on the top to achieve the proper charging voltage.

The second design proposal of the solar cells to the batteries configuration is presented in Figure 4.5. In this solution the charger is responsible for

[1]End-of-charge voltage specified for the batteries is 3.6 V per battery cell.

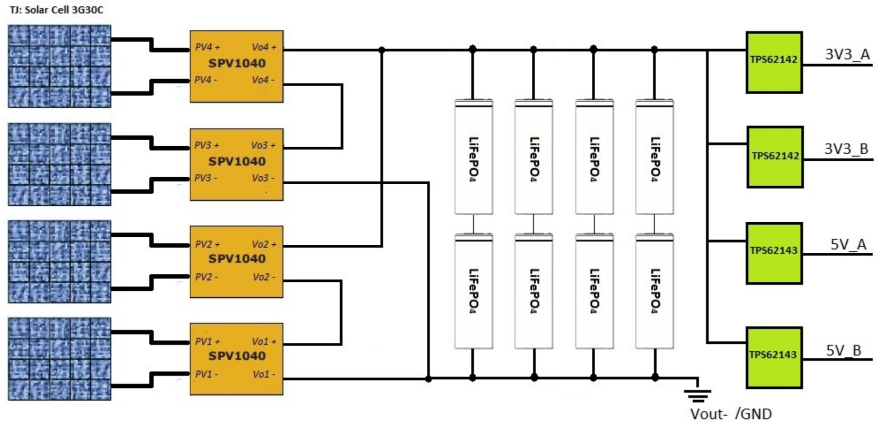


Figure 4.4: First solution of the solar cell and battery charger configuration side panel.

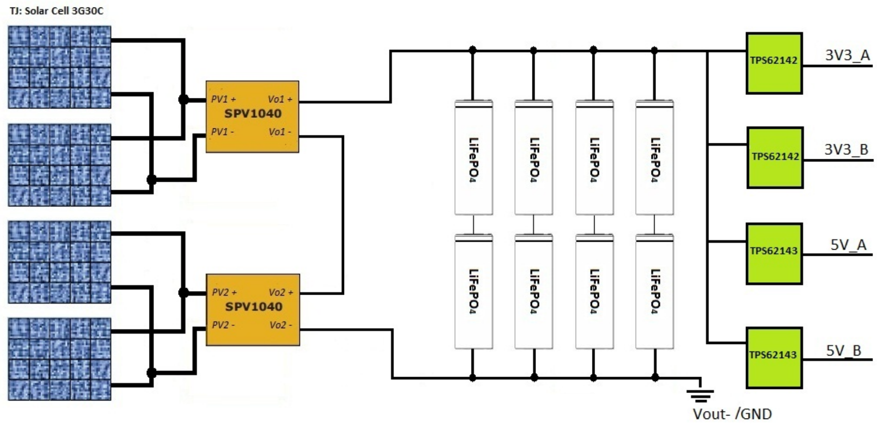


Figure 4.5: Second solution of the solar cell and battery charger configuration side panel.

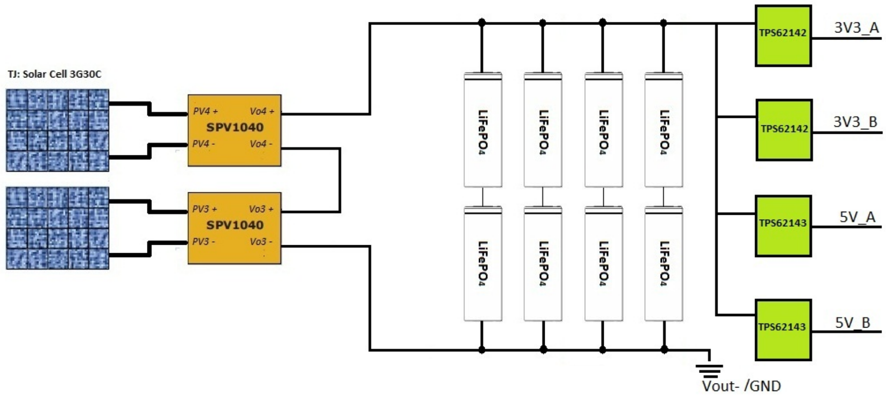


Figure 4.6: Solar cell and battery charger configuration top panel.

4 cells instead of 2 in the first solution. The 4 cells are pairs of parallel connected solar cells on opposite sides. This configuration offers smaller design layout with only 6 chargers and less power consumption. The worst case power dissipation of the charger is 295 mW [29], this result in a reduction of 3540 mW when the number of chargers is reduced from 18 to 6. The power dissipation refers only to the power consumed in the device (or heat) and not the total power consumption, which includes the consumed power of operation. As a result, a reduction in number of chargers will decrease the power consumption by at least 3540 mW in worst case. It also reduces the amount of single point of failures by reducing the number of chargers. The system becomes less redundant, however the redundancy of this configuration is still considered good.

To accommodate the mechanical requirement to the PCB size[2], the design layout is considered as an important factor in the choice of solution for the EPS charger configuration. With regards to the size of the PCB, complexity, and the power consumption, the second design proposal was chosen in favour of the first design proposal.

As mentioned above, the solar cells on the top panel are required to have one charger each to accommodate the charging voltage of the batteries. As a result, the configurations of the solar cells on the top panel differs from side panels. The two solar cells on the top panel are connected to one charger each to acceive the appropriate voltage level for charging the batteries, as shown in Figure 4.6. The side panels consists of four individual cells that are parallel connected in pairs, as shown in Figure 4.5. These pairs of solar cells are connected into a battery charger together with a pair from the opposite side of the satellite. This configuration offers redundant and reliable system where a failure in a single battery charger, voltage regulator or damage to a solar cell, does not result in a total loss of power.

4.4.3 Power Monitoring

The power monitoring is implemented by measuring the voltage drop across a shunt resistor. The INA219 from Texas Instruments is a high-side current shunt and power monitor, which includes the I^2C interface [32]. High-side current measuring is preferred to low-side current, as it does not introduce problems with shifted ground potential [1]. The INA219 contains a programmable gain amplifier (PGA), which can be used to set the full-scale operating range of the current monitor. It includes an analog to digital con-

[2]Kai Inge Rokstad is currently working with the frame and the structural inside the frame. The maximum size of the PCB is set to 86 mm $\times$ 83 mm.

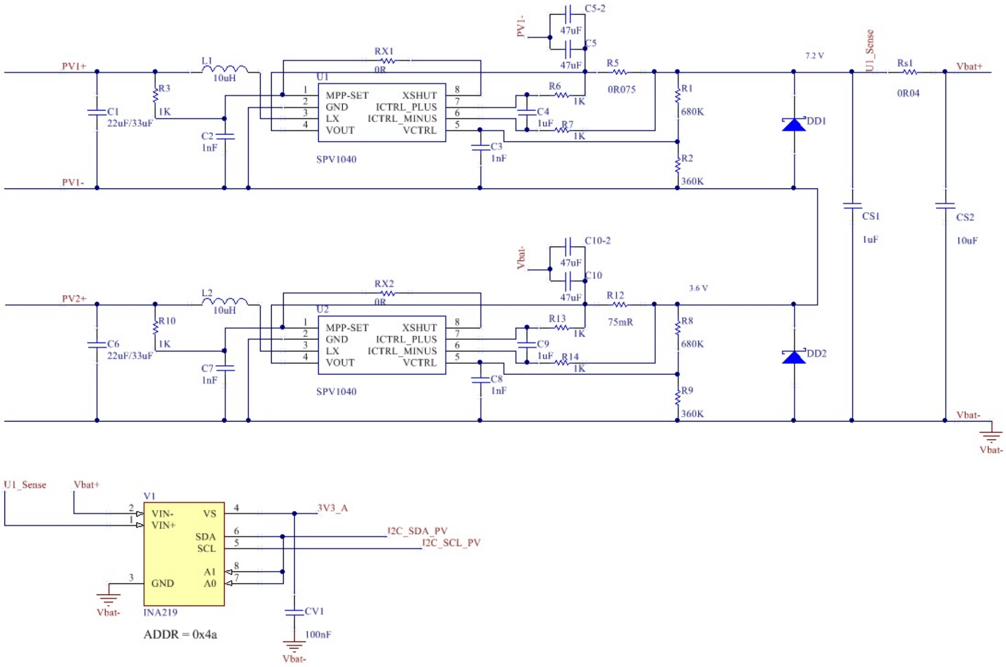


Figure 4.7: Charger circuit.

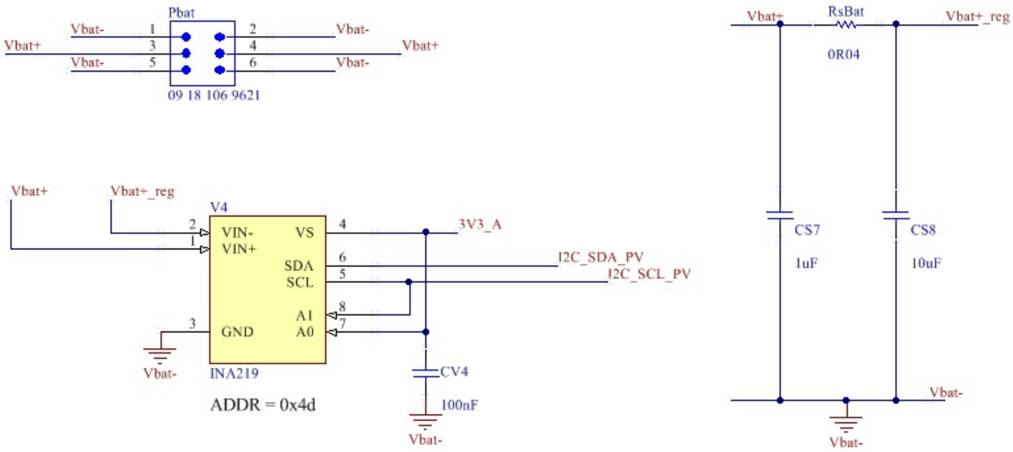


Figure 4.8: Battery connector.

verter(ADC), which result in the opportunity of reading the measured current directly in amperes by multiply the measured value with a calibration value. With an additional multiplier register, the calculated power value, which is a product of the measured shunt current and voltage, can be stored for a read-out.

The INA219 is highly desirable for the EPS module, since it is already used on the backplane. However, the INA219 supports only 16 different I^2C addresses and the backplane is currently using all of them. As discussed in [1], the removal of two slave slots of the backplane was recommended as only one payload is intended at the moment and to allow a larger battery pack. This results in the release of four addresses which can be utilized on the EPS, hence four INA219 is implemented in the EPS module.

The four current monitors are implemented with one in each charger circuit and one for the battery connector, as shown in Figures 4.7 and 4.8. The monitors are addressed by pulling the address pins $A0$ and $A1$ to either low (GND), high (V_{s+}), or to the I^2C lines (SCL, SDA). In Table 4.3, the different address configurations is presented.

A1	**A0**	**Address**	**A1**	**A0**	**Address**
GND	GND	1000000	SDA	GND	1001000
GND	V_{s+}	1000001	SDA	V_{s+}	1001001
GND	SDA	1000010	SDA	SDA	1001010
GND	SCL	1000011	SDA	SCL	1001011
V_{s+}	GND	1000100	SCL	GND	1001100
V_{s+}	V_{s+}	1000101	SCL	V_{s+}	1001101
V_{s+}	SDA	1000110	SCL	SDA	1001110
V_{s+}	SCL	1000111	SCL	SCL	1001111

Table 4.3: INA219 Address configurations.

4.4.4 Voltage Regulation

The voltage regulation of the four power rails is implemented with four fixed value step-down converters from Texas Instruments, 2 × TPS62142 (3.3 V) and 2 × TPS62143 (5.0 V) [33]. The step-down converters is part of the same production family, which result in many common features with only difference in the regulated output voltage. The schematic of the voltage regulation circuit is presented in Figure 4.9.

The TPS6214x is a synchronous switched-mode power converter based on the DCS-Control (Direct Control with Seamless Transition into Power-

Save Mode) regulation topology. This topology combines the advantages of hysteretic, voltage-mode and current-mode control including an AC loop directly associated with the output voltage. The control loop receive information about the output voltage changes and feeds it to a comparator stage, where the switching frequency is set and as a result, it provides immediate response to the dynamic load changes. It uses a voltage feedback loop to perform accurate DC load regulation. The converter uses pulse-width mod-

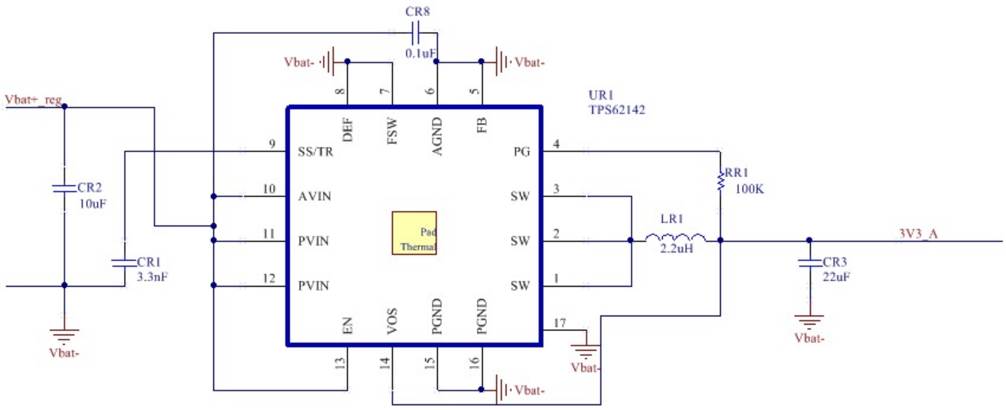


Figure 4.9: The voltage regulation circuit with TPS6214x.

ulation (PWM) for medium to heavy load conditions and a power-save mode at light loads. The switching frequency during this mode can be set to 2.5 MHz (typical) or 1.25 MHz. A higher frequency results in a lower switching time, however more power is needed to operate at this high frequency. Since the converter has a fixed value output and the power conditions of the satellite will be pretty consistent, the lower frequency is chosen for the EPS module. The converter maintain high efficiency and low power consumption by enter a power-save mode when it detects light loads. In this mode, the switching frequency decreases linearly with the load current. Other features the TPS6214x converter includes are:

- Soft-Start and Tracking.
- Current Limit and Short Circuit protection.
- Undervoltage Lockout.
- Thermal Shutdown.

The soft-start and tracking helps preventing unwanted voltage drops from high-impedance power supply or batteries by include a delay of 50 μs before start switching. This feature is implemented by connection a external capacitor between the SS/TR pin and ground (Vbat-).

The current limit of the device is 2 A and when the load current reaches this limit, the high-side field-effect transistor (FET) is turned OFF. To avoid a shoot-through[3] current, the low-side FET is switched ON to sink the inductor current. If a short circuit is detected, the current limit is reduced to 1.6 A.

During an undervoltage lockout or a thermal shutdown the power FETs are both switched OFF. An undervoltage lockout occurs when the input voltage drops below 2.7 V, however this condition will not occur unless the batteriy protection circuitry fails and the batteries discharge below their threshold. The temperature of the device is monitored by a temperature sensor at the junction. The device will enter thermal shutdown if the junction temperature T_J exceed 160^oC.

The TPS6214x converters was chosen for their features, and their small package size of 3 mm $\times$ 3 mm and the low number of external components needed. Since the converters are a part of the same family, the design layout will be the same for the 3.3 V and the 5.0 V converter. As a result, this impose simplicity in the design. Other converters that were considered for the voltage regulation was the LM2592HV from National Semiconductors and the LTC1624. The LM2592HV is a simple switch power regulation with a fixed frequency of 150 kHz, however the switch has a higher quicient current and it lacks many of the safety features of the TPS6214x. The LTC1624 is switching regulation controller with a fixed frequency of 200 kHz, however the component size of 5 mm $\times$ 4 mm and external components circuitry infavoured this for the TPS6214x. The optional converters have a lower frequency which requires less power, however the lack of extra features to save power and the need of more external components. The higher frequency of the TPS6214x results in a faster regulation. The efficiency of all three is around $85 - 90$ %. As a result, the optional converters is infavoured in lack of better efficiency than the TPS6214x.

4.4.5 Schematic Design & PCB Layout

The schematic design and the PCB layout was implemented in Altium Designer. The EPS schematics spans 10 B5 sheets, see Appendix B. The EPS schematic is divided into seperate schematics for the different circuits and connectors of the EPS module.

The PCB design was implemented on a 4-layer printed circuit board, with

[3]The current that occurs while both devices/transistors are ON.

two layers (TOP and BOTTOM) for signal routing, one internal layer for a ground plane (Vbat-), and one internal layer for a power plane (Vbat+_reg). All components have been placed on the top layer and routed together on the top layer. Alternativ signal routing is done by using the bottom layer and via's. A via is a connection point which runs through the board and connect the top layer to another layer in the board.

Althought the design of the charger circuits and regulator circuits are similar to each other respetively, some considerable amount of time has been spendt on the layout and routing of the components on the PCB. The uncertainty around the specification of the PCB size led to a re-design of the board layout during the process, hence more time spendt. However, since the time was spendt on making the layout nice and identical, and placed on a minimum specified PCB size of 80 mm × 80 mm. This resulted in a minimal layout, which leaves more space for later add-ons to the EPS.

The prototype PCB was produced by an external company located in Bergen, Elprint Norge ASA. The component acquisition and soldering of the prototype was done inhouse at one of NTNU's labs. The soldered PCB of the EPS is presented in Figure 4.12. A summary of the main components, chosen for the EPS module is presented in Table 4.4. A complete list of components is presented in Appendix C.2.

Manufacture	**Component**	**Purpose**	**Quantity**
ST Microelectronics	SPV1040	Battery Charger	6
Texas Instruments	INA219	Power Monitoring	4
Texas Instruments	TPS62142	3.3 V Voltage Regulator	2
Texas Instruments	TPS62143	5.0 V Voltage Regulator	2

Table 4.4: The chosen components for the EPS prototype.

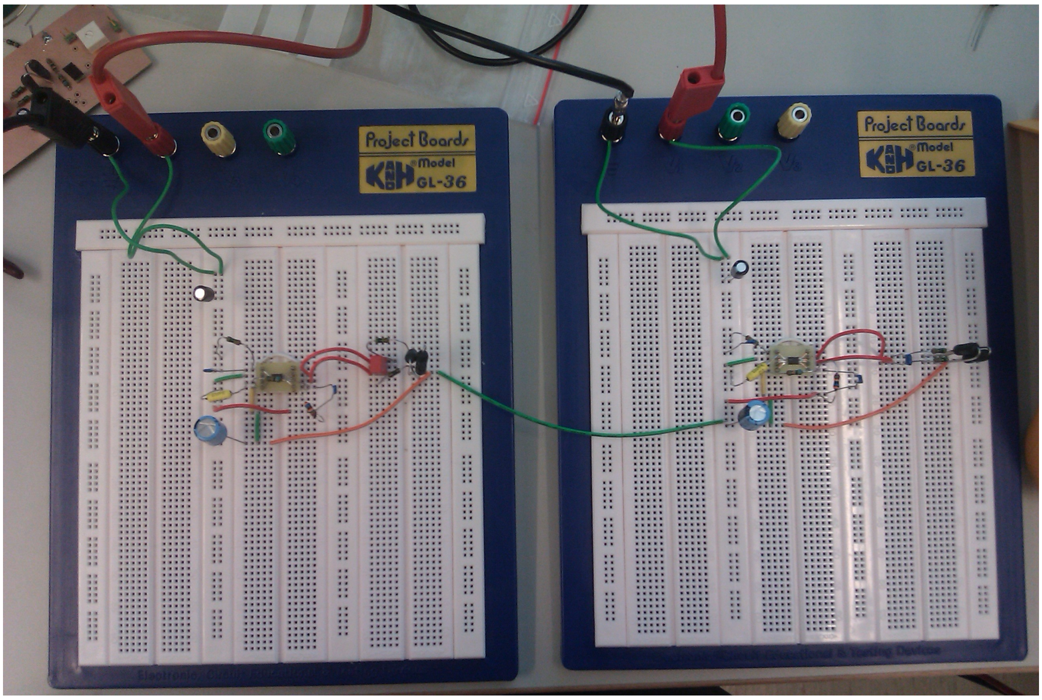


Figure 4.10: Battery Charger test on breadboard, serial connection.

4.5 Testing and Results

A prototype of the EPS module has been produced to test the feasibility of the solution. Before the prototype were produced a simple test of the battery chargers was performed. This test was performed to confirm the charger application circuit and serial connection of the chargers.

4.5.1 Battery Charger - Test Module

This test module was implemented to test the battery charger, and a series connection of two battery chargers to achieve the proper battery charge voltage. The test layout was created using a breadboard and electrolyte thru-hole components.

The testboard was implemented by using the application circuit present in Figure 4.3. The component values where calculated from equations found in the chargers application note [4]. The test was conducted under "ideal" conditions with the maximum power point voltage delivered from the solar cells as the input voltage of the chargers. The maximum input voltage is 2.3 V.

The test started with testing one charger seperatly. At initial start-up the charger did not produce any regulation of the input. The lack of regulation was a result of too small capacitor on the output which works as a ripple restricter on the output voltage. This capacitor is placed in parallel with the load on the output to reduce the ripple and is calculated by the following equation

$$C_{OUT} \geq \frac{I_{SC}}{F_{SW} \cdot V_{OUT\_rp\_max}}, \tag{4.1}$$

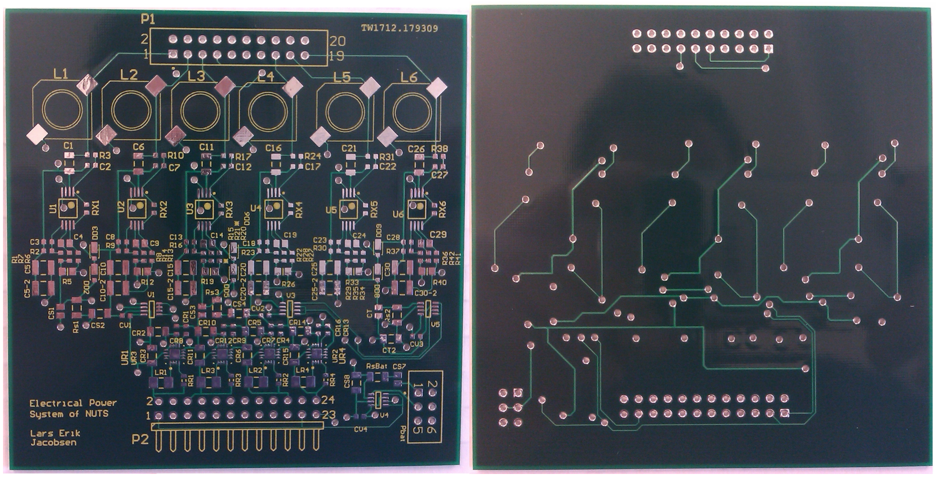
where I_{SC} is the short circuit current of the solar cell, the F_{SW} is the switching frequency of the charger, and the $V_{OUT\_rp\_max}$ is the maximum output ripple voltage specified by the designer. The equation shows that the ripple is directly influenced by the capacitor size since the frequency and the I_{SC} is predefined by the charger and the solar cells. When the capacitor is too small the ripple becomes excessive and will result in an open capacitor condition of the capacitor, hence no charging of the capacitor. See Section 4.4.2, for more details on the output capacitor.

The solution was to change the output capacitor of the charger for a larger capacitor. The new capacitor has a capacitance of $100\mu F$. This resulted in a regulated voltage on the output with a voltage of 3.634 V on a single charger.

The layout was copied onto another breadboard and then connected in series with the first charger. This resulted in an output voltage of 7.289 V, which is a sufficient result to the recommended charge voltage of the batteries of 7.2 V [11]. The results of this test led to an alteration of the capacitors on the input and output of the charger. The changes were implemented in the schematics and layout of the EPS module.

4.5.2 Prototype Module

The EPS prototype is a four layer PCB card with two signal layers and two power layers. In Figure 4.11a and 4.11b, the unsoldered version of the EPS module is presented. The PCB prototype was produced by an external company, Elprint Norge AS. After some visual inspections to verify that the PCB complied with the design layout, the components where soldered on the PCB. A new visual inspection was conducted of the finished soldered PCB, to verify that the right components were used and complied with the silkscreens on the board. Figure 4.12, presents the soldered version of the EPS module, ready for testing.



(a) Unsoldered frontside. (b) Unsoldered backside.

Figure 4.11: The Electrical Power System PCB module.

Initial Start-up Test

The initial start-up of the EPS prototype was performed without batteries or load connected, and with external power supply. The result was a high current, which indicates that a short circuit is presented in the system. The module did not produce any regulation on the output and the input voltage over the chargers in series was not equalized. The causes of these errors were found to be:

1. All negative input lines on the chargers were connected to the *Vbat-* (GND) net, which resulted in a wrong electrical potential of one of the chargers in the series. This also influence the other charger in the series to have the wrong potential.

2. The Schottky diode on the output of the chargers was connected in the wrong direction, which was a result of not mapping the pins correctly when designing the footprint of the diode in Altium. As a result, the diode of the first charger blocked the output and the diode of the second charger led to a short between positive and negativ nodes of the second charger.

The following actions were performed to solve the issues. Firstly, the negative input wire of charger 1, 3, and 5 was disconnected from the solar cell input connector, and soldered directly in the via[4] to the left of the capacitors

[4] A via is a connection point between different layers of the board.

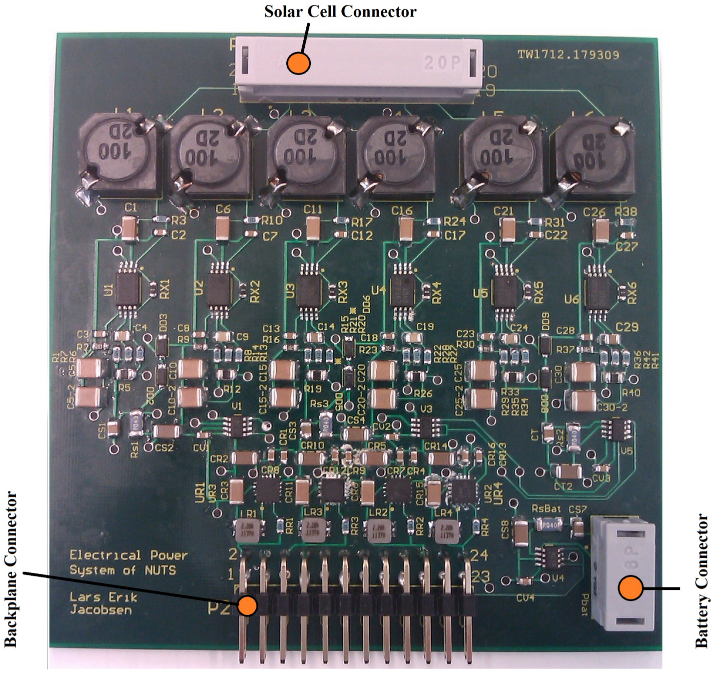


Figure 4.12: The soldered PCB of the EPS.

$C1$, $C11$, and $C21$ respectively. Secondly, the Schottky diodes was removed from the PCB prototype. Unfortunatly, the component could not be turned and soldered on again because of lack in space and the different solder pads on the PCB. The Schottky diodes are placed in parallel with the output of the chargers and the removal of the diodes will not have an effect on the charger or rest of the system. The

The result of these actions was an output voltage of a single charger of 3.772 V and 7.568 V from the serial connection of two chargers. However, the regulators did not provide any voltage on the output. The error was a result of a missing connection at the sensory circuit of the batteries, shown in Figure 4.13. As a result, the output of the chargers (battery terminals) was not connected to the input power net (*Vbat+_reg*) of the voltage regulators. The cause of the missing connection was found in the schematic of the battery sensor circuit, see Appendix B. The *Vbat+* net was not connected to the wire of the resistor *RsBat*, hence no connection with the *Vbat+_reg* net. This final alteration resulted in a regulated output voltage of the backplane connector.

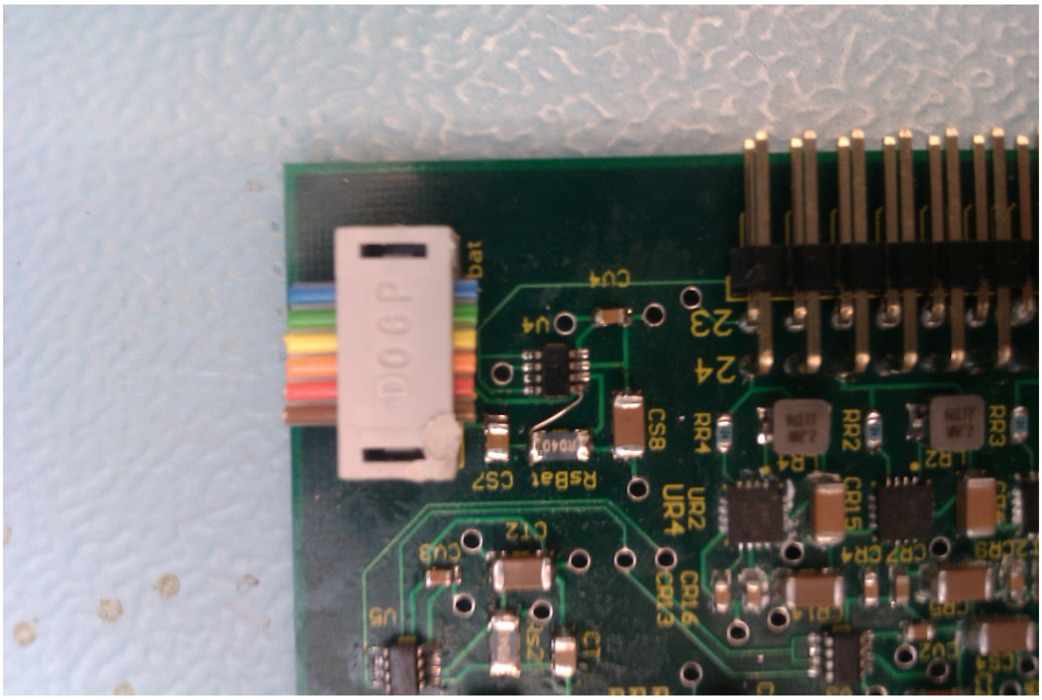


Figure 4.13: The missing connection.

Verification Tests

The verification tests of the EPS module is divided into:

- A test of the battery chargers.
- A test of the output of the voltage regulators.
- A charging test of the batteries with external power supply.
- A charging test of the batteries with solar cells as power supply.
- A load test with batteries as power supply.
- A test with the backplane, provide power to the OBC and read the values from the EPS sensors.

The battery chargers were tested with a result of 7.568 V output voltage over the battery terminals. This result is without the Schottky diodes on the output terminals on the chargers, see Appendix B for schematics. A change of the 360 kΩ resistor to a 390 kΩ resistor resulted in a output voltage of 7.220 V without the diodes. The voltage regulation test resulted in an output

Test of:	Result	Expected Result	Deviation
Testboard Chargers	7.289 V	7.2 V	1.22 %
Prototype Chargers (without diode)	7.568 V	7.2 V	4.86 %
Prototype Chargers (adjusted output)	7.220 V	7.2 V	0.28 %
Regulator 1 (3V3_A)	3.298 V	3.3 V	0.06 %
Regulator 2 (5V_A)	5.002 V	5.0 V	0.04 %
Regulator 3 (3V3_B)	3.288 V	3.3 V	0.36 %
Regulator 4 (5V_B)	4.998 V	5.0 V	0.04 %

Table 4.5: The results of the prototype testing.

voltages of the different regulators of 3.298 V, 5.002 V, 3.288 V, and 4.998 V. A summary of these results is given in Table 4.5.

The charging tests of the batteries were performed on one battery pack and the use of an external power supply, forcing an input voltage of 2.3 V of the chargers. The first test was performed to verify that the chargers charged the batteries. The result of this test was an increase of the battery voltage from 6.1 V to 6.55 V in 25 minutes.

A second test of charging the batteries from an empty state to a fully charged state was performed. The test was based on the assumption of two sides fully irradiated, which provides a maximum voltage of 2.3 V and a maximum current of 1 A into each of the four chargers in use. The empty state of the batteries showed a voltage of 4.6 V. The result of the second test was a fully charged battery pack in 55 minutes.

The final test of charging the batteries was performed to verify if the batteries can be charged up after an eclipse period. As mentioned in Section 2.2.2, the assumed average power consumed during eclipse is 3.43 W. The test is conducted by connecting a constant power load of 3.43 W to the batteries and discharge the batteries for a period of 35 minutes. After a discharging period, the chargers are connected to the batteries and the load removed, and the charging period is set to 60 minutes. The result of this test after 2 cycles are presented in Figure 4.14. The cycle test was repeated with the worst case scenario of only irradiation in the top side, resulting in a maximum input voltage of 2.3 V and a maximum current of 500 mA into each charger. The result is presented in Figure 4.15.

A final test with the backplane was conducted with good results. The backplane was provided with the right voltages and the OBC was working properly. A readout of the sensor resulted in good measurements of the

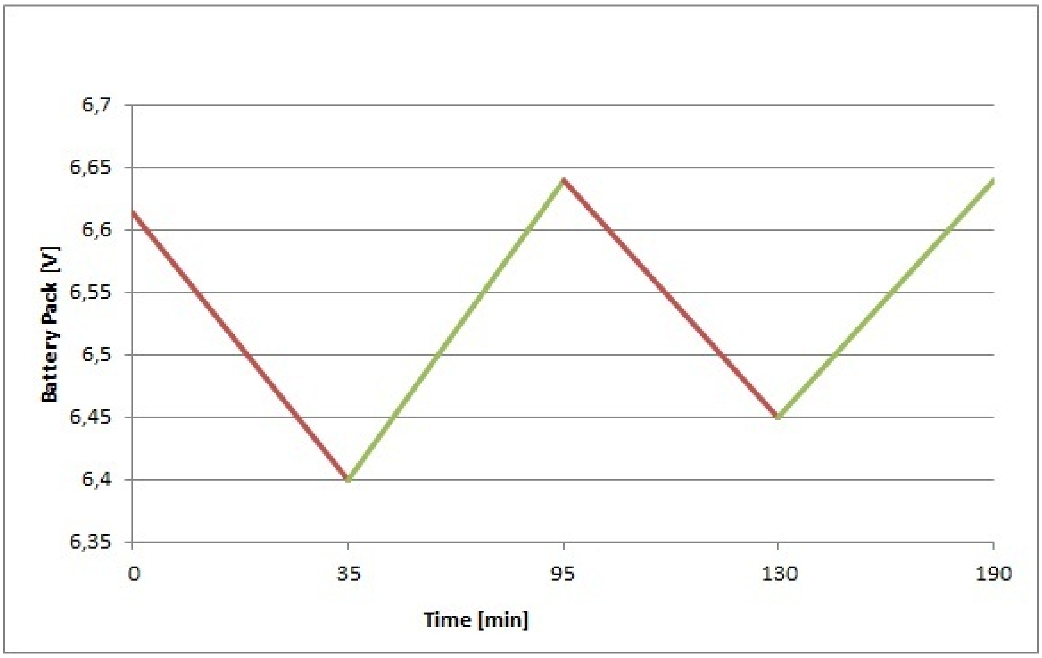


Figure 4.14: Discharge - charge cycle for two orbits.

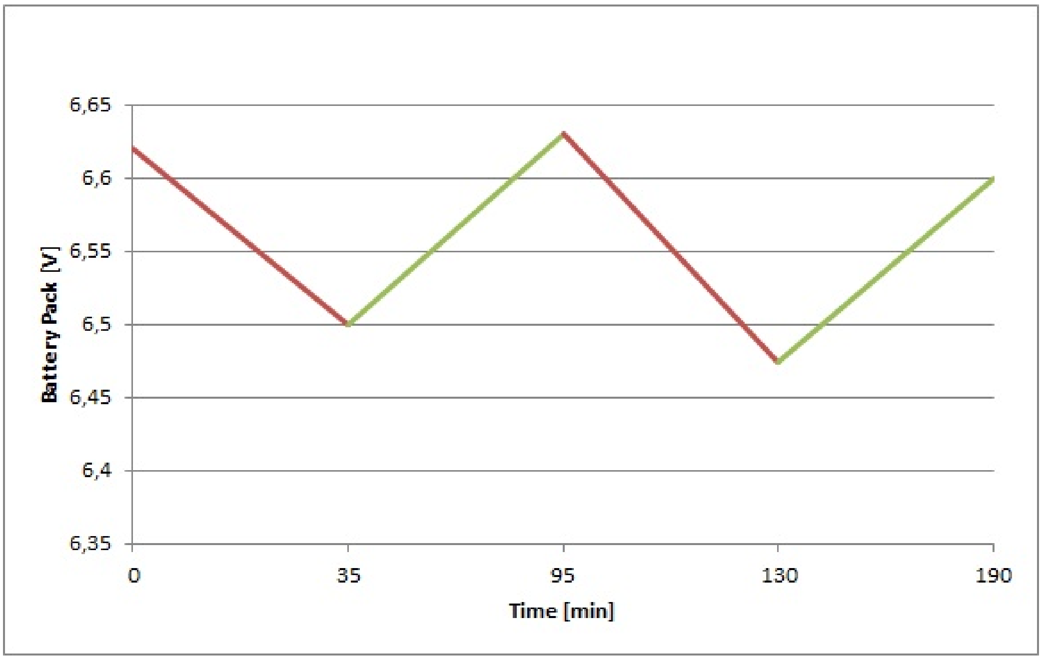


Figure 4.15: Discharge - charge cycle for two orbits worst case.

currents drawn by the different active modules. This test was performed with different power sources. Firstly, the chargers with power supply as the power source. Secondly, the batteries as standalone power supply, resulting in a test of the batteries with a load. Finally, the chargers with power supply and batteries were used as providers, conducting a charge of the batteries as well as providing power to the backplane.

4.5.3 Engineering Module

As the prototype only required minor alterations for operating as requested, the engineering model was not produced at this stage. The decision to not produce a new prototype or engineering module was a result of the little remaining time of the master thesis period and the implementation of other functionalities. As a result, the prototype of the battery charging and voltage regulation is verified and will form the base of the engineering module. The engineering model will also be implemented with the required kill switches and remove before flight (RBF) pin from the CubeSat standard [2].

The switches should be placed between the battery connector and the regulation circuitry to prevent power to the backplane during launch. The switches use a spring mechanism, placed in the frame structure to break the connection between the batteries and the EPS. When the spring is compressed, the switch will be open and the batteries are disconnected. The switch will close when the satellite leaves the P-POD, and the batteries will provide the power.

The RBF pin should be placed in parallel with the switches, since the pin implements an override of the kill switches. The RBF pin is needed to be able to provide power to the satellite during its stationary position in the P-POD before launch. When the pin is inserted, the batteries are connected and provide power to the satellite by overriding the kill switches. The pin is removed before flight, and the kill switches stops the batteries from providing power to the satellite.

Chapter 5

Discussion

5.1 Design Evaluation

The design for the NUTS Electrical Power System implemented in this thesis provides a good platform for the power supply of the NUTS satellite. The EPS is designed to be redundant, reliable, and simple with the proper strategies to provide an efficient power harvesting and supply for the satellite.

The final engineering module will include the kill switches and the remove before flight (RBF) pin, which is required in the CubeSat standard [2]. The kill switches and RBF pin was not implemented in the prototype design because of the availability of the suitable switches. A final decision of kill switches and RBF pin must be made before they can be implemented in the design.

5.1.1 Battery Charger and Voltage Regulation

In compliance with the design philosophy of simplicity, use of the SPV1040 will lead to a simpler design of the EPS module. The advantages of the SPV1040 are the many attributes it includes, that the module requires for a safe and reliable charging of the batteries. It also solves the issue of achieving high enough voltage from the two top solar cells, since the voltage of the two solar cells would not be sufficient to charge the batteries.

The drawback of the SPV1040 is its utilization, the requirement of one charger per solar cell results in the use of 18 SPV1040 battery chargers, which increases the cost and complexity of the project. However, the number of battery chargers can be lowered by parallel connection of two solar cells and connecting the solar cell pairs on opposite sides to the same SPV1040 battery charger. This configuration offers the same input voltage on the charger, but a higher current is achievable. The configuration reduces the required number of battery chargers to 6; 4 to accommodate the side panels and 2 to accommodate the two solar cells on the top panel. As shown in Section 4.4.2, the reduced power consumption of 3540 mW is achieved by reducing the number of chargers to 6. Although, this is a rough estimate of the power reduction, it indicates the power savings of a reduction in the number of chargers.

The advantages of using the SPV1040 include the embedded MPPT feature and the voltage- and current protection features which is already implemented in the chip. An alternative solution of the battery charge regulator (BCR), provided by De Bruyn [9], features seperate protection circuitry, a battery charger from Diode Inc., and a microcontroller for the MPPT algorithm implementation. Compared to the design proposal by [9], a simpler design that doesn't require a separate microcontroller for the implementation of the MPPT feature and that includes important protection circuitry is provided with the SPV1040. The efficiency of the SPV1040 is up to 95%, which is 4% higher than the efficiency of the solution suggested in [9], and 2-5 % higher than the commercial solution from Gomspace [34] and Clyde-Space [35].

The SPV1040 is a very new and innovative component, which offers many good options for harvesting energy from solar cells. As a result, the charger is not widely used just yet. The CubeStar satellite from the University of Oslo (UiO) and the Fox-1 satellite from The Radio Amateur Satellite Corporation (AMSAT) are those of knowledge, apart from the NUTS satellite that will use the SPV1040 battery charger in their satellite. Where the NUTS EPS design differs from the CubeStar and the Fox-1 is that the NUTS will carry a larger battery pack with higher nominal voltage, which requires a higher charging voltage and therefore a serial connection of two chargers.

5.1.2 Solar cells and Batteries

The solar cells and batteries were already chosen before this thesis and the configuration of the solar cells is an important factor in charging of the batteries. The configuration of the solar cell must provide together with the charger a proper charging voltage and current for the batteries. The solar cell configuration of parallel connection between two solar cells, which are connected with a solar cell pair on the opposite side will result in a sufficient voltage and current for the charger to boost up to the charging voltage of the batteries. One important factor of this configuration is the use of a blocking diode between the cells to protect the cells from reversal currents.

By including the blocking diode on the solar cell the voltage will drop over the diode. Two possible solutions were provided, one diode and one switch. The switch has a lower forward voltage, which is desirable, however the package size of the switch and the number of switches needed for the configuration imposes an issue of area available. As a result, a Schottky diode was recommended for use on the solar cells. This diode offers a low voltage drop and protects the cells from reversal currents.

5.1.3 EPS Architecture

The final architecture was designed around the investigated charger and the power specification of the solar cells and batteries. The request for four power lines to the backplane, designed by De Bruyn [9] resulted in the use of four fixed value voltage regulators as output of the EPS module.

The goal of this thesis was to design a simple, reliable, and redundant system. By using the SPV1040 battery charger, a solution with a microcontroller may be avoided. Although, a microcontroller could be utilized for more than the implementation of the MPPT algorithm, the complexity and power consumption of the system would increase. As a result, the simplicity and efficiency of the SPV1040 is favored for a conventional battery charger with a microcontroller to control the charging of the batteries. The architecture imposes a great deal of redundancy for the philosophy of simplicity. The charging of the batteries are divided between several chargers and solar cells. As a result, the loss of one charger or solar cell will not result in a total loss of the capability of charging the batteries. The four regulators offers an redundant solution of providing two sets of each voltage level to the backplane, and in the case of the loss of one voltage regulator another power line is available for use.

The overall reliability of the system is increase by the redundant solutions of the EPS architecture. Although, the system is fairly simple, the reliability of the system is considered sufficient enough for the NUTS satellite. The reliability may have been improved by implementing a more complex system, however this would increase the cost and time of the project. It may also result in a less efficient system.

The consequence of failures in the system can be categorized as minor, major, or critical. For the system to reach a critical level of failure, all the chargers, solar cells, or voltage regulators have to fail. If all chargers or solar cells fail, there will be no power to charge the batteries. The system will then slowly drain the batteries and the mission will come to an end when the batteries are discharged. If all the voltage regulators fail, the backplane will not be provided with power and the satellite be not be able to operate. The system will however be able to provide power on the irradiated side of the orbit without the batteries. The loss of the batteries will only have an effect on the operation in eclipse, but since the camera shall operate in eclipse the need of the batteries is considered important, and a loss will be a major failure. As a result, the minimum requirements for a functional electrical power system are two chargers of the same series, a minimum of one solar cell per charger, and one of the voltage regulators of 3.3 V of the irradiated side of the orbit, and batteries if operation in eclipse is required.

The loss of one voltage regulator is considered a major failure, since the redundancy of the provided power to the satellite is lost. A loss of one charger is considered a major failure, since this means a loss of another charger and a total of 8 solar cells. As a result, the amount of energy lost will have a major impact on the charging of the batteries. However a loss of one or more solar cells is considered as minor failures of the total system failure.

5.2 Result Evaluation

In Table 4.5, the results from the testing of the EPS module are presented. These results are evaluated individually in the following sections.

5.2.1 Battery Charger Testboard

The results of the charger testboard confirmed the assumption of how to connect the chargers in series. The result of 7.289 V on the output of the charger is within 1.22 % from the requested voltage of 7.2 V, which is considered as a very satisfying result.

5.2.2 EPS prototype

The overall result of the EPS prototype is a system that provides charging of the batteries with energy from solar cells (power source), and regulates the battery voltage down to the required voltage of the power rails to the backplane.

The battery chargers produced an output voltage of 7.568 V, which is a little higher than expected. However, the test result is without the Schottky diode on the charger circuits, see Appendix B for schematics. As a result, the voltage drop over the top diode is not withdrawn from the overall result. The voltage drop over this diode is 320 mV, which withdraw from the measured output will result in an output voltage of 7.248 V. This result is similar to the result of the charger testboard and is considered as a satisfying result. The final PCB with the diodes included should also be fine tuned by altering the output resistors of the chargers to ensure the right voltage, see Appendix B.

The requirement, provided by the backplane solution, for four voltage regulators resulted in the use of four fixed value regulators. The results of the regulator test spans from 0.04 % to 0.36 %. Although, the result of regulator 3 differs from the other regulators, the final results of the regulators are sufficient. The reason for the difference in the results can be found in the load and line regulation of the regulator. The load and line regulation depends on the external components of the device [33], and therefore the result may be affected by an inaccurate external component.

The results of the charging test showed that the total time of charging the batteries from an empty state to a fully charged state was approximately 55 minutes. This result would be doubled for a double battery pack, however it indicates that the chargers are efficient enough to charge the batteries from empty state to fully charged state within 2 hours. This is assumed for charging with no load and a scenario of two fully irradiated side panels. In the charge cycle test, the first results show that the solar cells provide enough power for the chargers to charge the batteries to a fully state after a discharging period in eclipse. In the second result, it is showed that the solar cells almost provide enough power to replace the lost power of the eclipse period. However, it is fair to assume that the worst case scenario does not occur every orbit and therefore the solar cells provides enough power to charge the batteries to a fully state after an eclipse. The efficiency of the chargers was measured to be around 95 %.

A more thorough test with the solar cells as power supply was not performed, since a proper light source was not found in the time of testing. As a result, the solar cells did not provide enough energy to produce an operating voltage and current for the chargers. However, a short test of the solar cell outside showed that with more irradiation from the sun, the voltage and current produced by the cell was higher than an external light source of a lamp. As a result, it will be assumed that the solar cells are able to provide the proper voltages and currents in space.

The results of the final test with the backplane showed that the EPS module was able to provide sufficient power to the backplane. The sensor readout was verified and the backplane operated as expected. The overall performance of the EPS prototype is considered very good and is a good foundation for the engineering module of the EPS.

Chapter 6

Conclusion

The Electrical Power System (EPS) is an important part of the NUTS satellite in that it provides power to the rest of the systems of the satellite. The primary tasks of the EPS module are to charge the batteries with energy from the solar cells efficiently and safely, and to provide two regulated 3.3 V and two regulated 5.0 V power rails to the backplane connector. The secondary task is to provide telemetric data about provided power from the solar cells and the state-of-charge of the batteries.

In this thesis, the design of the EPS module was produced and a prototype has been developed and tested. The EPS module provides an efficient charging of the batteries through the SPV1040, which integrates the strategies of maximum power point tracking (MPPT) and constant current - constant voltage (CCCV). The MPPT strategy tracks the solar cell's most efficient operating point, as the temperature and irradiation of the cell changes, utilizing the maximum potential of the solar cells. The CCCV strategy allows efficient and safe charging of the $LiFePO_4$ batteries. The power to the backplane is provided with fixed output voltage step-down converters.

The design of the EPS module provides a simple, reliable, and redundant solution for the electrical power system of the NUTS satellite. The prototype includes the main functionalities for charging the batteries, voltage conversion, and power monitoring. The requirements of an efficient and simple power conversion, both from the solar cells to the batteries and from the batteries to the backplane connector, have been realized with good results. All verification tests have been evaluated and the efficiency of the chargers has been found to be 95 %, which is higher than the previous suggested solutions. The simplicity and efficiency of the EPS module makes it a very good candidate for the NUTS satellite.

Although, a lot of work was done on the EPS module, some features remains to be implemented on the engineering module. The features include the kill switches and the remove before flight pin, which is required by the CubeSat standard. The work done here presents some good results of the main functionalities of the EPS module and it provided a good foundation for the EPS engineering module.

Chapter 7

Further Work

A prototype of the EPS module with the main functionalities was provided in this thesis, however a final engineering module is yet to be produced. As mentioned in Section 4.5.3, an engineering module of the EPS was not produced. The engineering module of the EPS shall include the required kill switches and the remove before flight (RBF) pin.

The errors found in the prototype are revised and alterations in the schematics and in the PCB layout have been made. Although these alterations have been implemented in the design files, more testing of the EPS prototype will be required to verify the proper operation. The functionalities provided in the prototype module are comprehensive enough to do further testing of the system.

When the engineering module is produced with the Schottky diodes, which were removed from the prototype, a final adjustment of the output of the chargers should be made. The adjustment of the output is simply done be replacing the 360 kΩ resistor on the output of the chargers, as mentioned in Section 4.5.2.

The final configuration of the solar cells is yet to be decided, however a solution was provided in this thesis. To realize this solution, blocking diodes or switches must be implemented between each parallel connection of the solar cells. These diodes or switches should have a low forward voltage as possible to achieve maximum voltage of the solar cells.

A final power budget of the satellite must be conducted when all subsystems of the satellite are produced and operational.

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Appendix A

Voltage Regulation

A.1 Buck converter calculations

The change of the current through the inductor is determined by:

$$V_L = L\frac{dI_L}{dt} \tag{A.1}$$

The increase in current through the inductor when the converter is operating in ON state is given by:

$$\Delta I_{L_{on}} = \int_0^{t_{on}} \frac{V_L}{L}dt = \frac{(V_I - V_O)}{L}t_{on} = \frac{(V_I - V_O)}{L}DT \tag{A.2}$$

The change in the OFF state is then given by:

$$\Delta I_{L_{off}} = \int_{t_{on}}^{t_{on}-t_{off}} \frac{V_L}{L}dt = -\frac{V_O}{L}t_{off} = -\frac{V_O}{L}(1-D)T \tag{A.3}$$

Since the overall change in current through the inductor is zero, the duty cycle can be determined from;

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = \frac{(V_I - V_O)}{L}DT - \frac{V_O}{L}(1-D)T = 0, \tag{A.4}$$

where D is the duty cycle.

A.2 Boost converter calculations

The change of the current through the inductor is determined by:

$$V_L = V_I = L\frac{dI_L}{dt} \tag{A.5}$$

The increase in current through the inductor when the converter is operating in ON state is given by:

$$\Delta I_{L_{on}} = \frac{1}{L}\int_0^{t_{on}} V_I dt = \frac{V_I}{L}t_{on} = \frac{V_I}{L}DT \tag{A.6}$$

The change in the OFF state is then given by:

$$\Delta I_{L_{off}} = \int_{t_{on}}^{t_{on}-t_{off}} \frac{(V_I - V_O)}{L}dt = \frac{(V_I - V_O)}{L}t_{off} = \frac{(V_I - V_O)(1-D)T}{L} \tag{A.7}$$

Since the overall change in current through the inductor is zero, the duty cycle can be determined from;

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = \frac{V_I}{L}DT + \frac{(V_I - V_O)(1-D)T}{L} = 0, \tag{A.8}$$

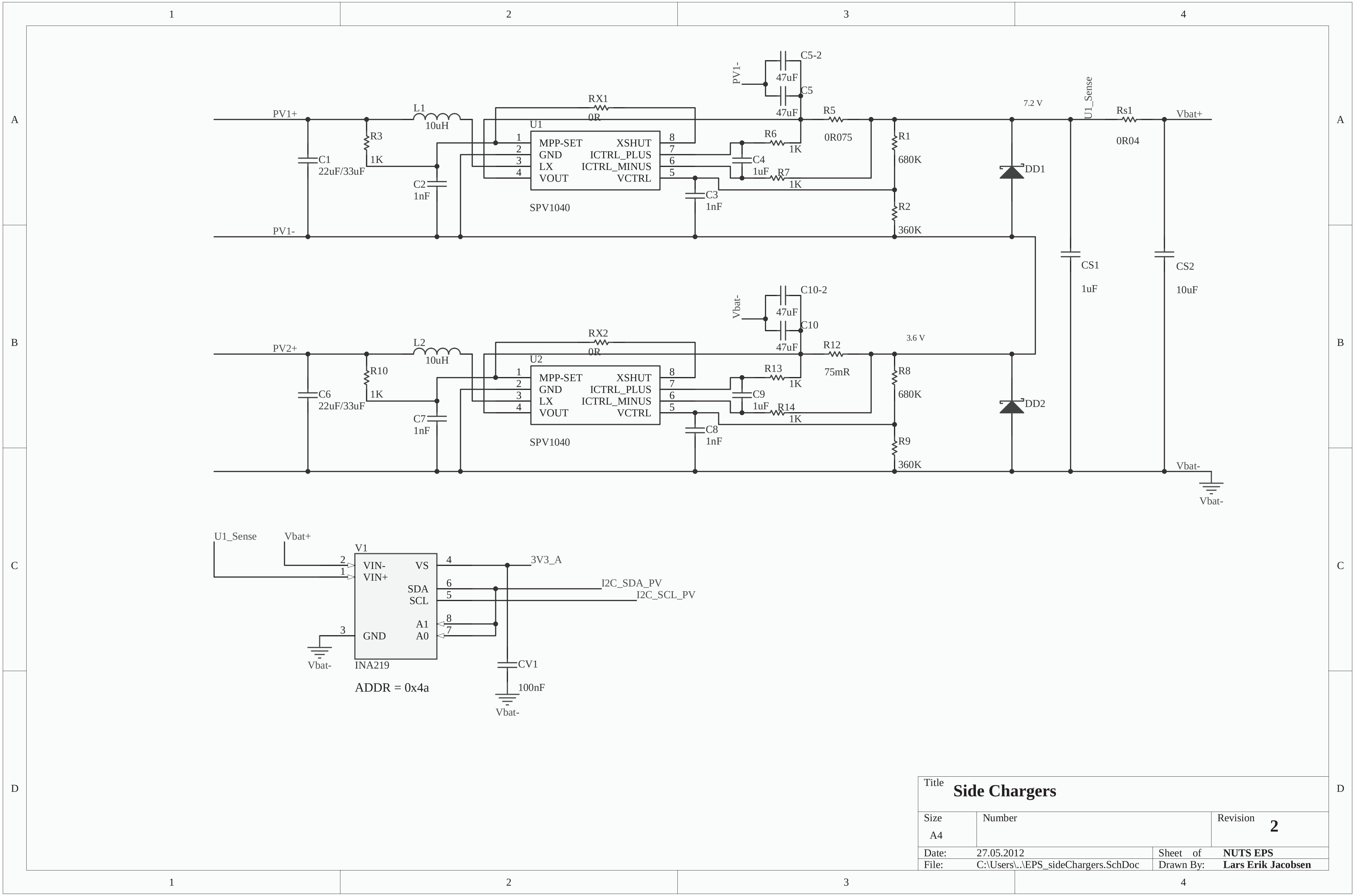
where D is the duty cycle.

Appendix B

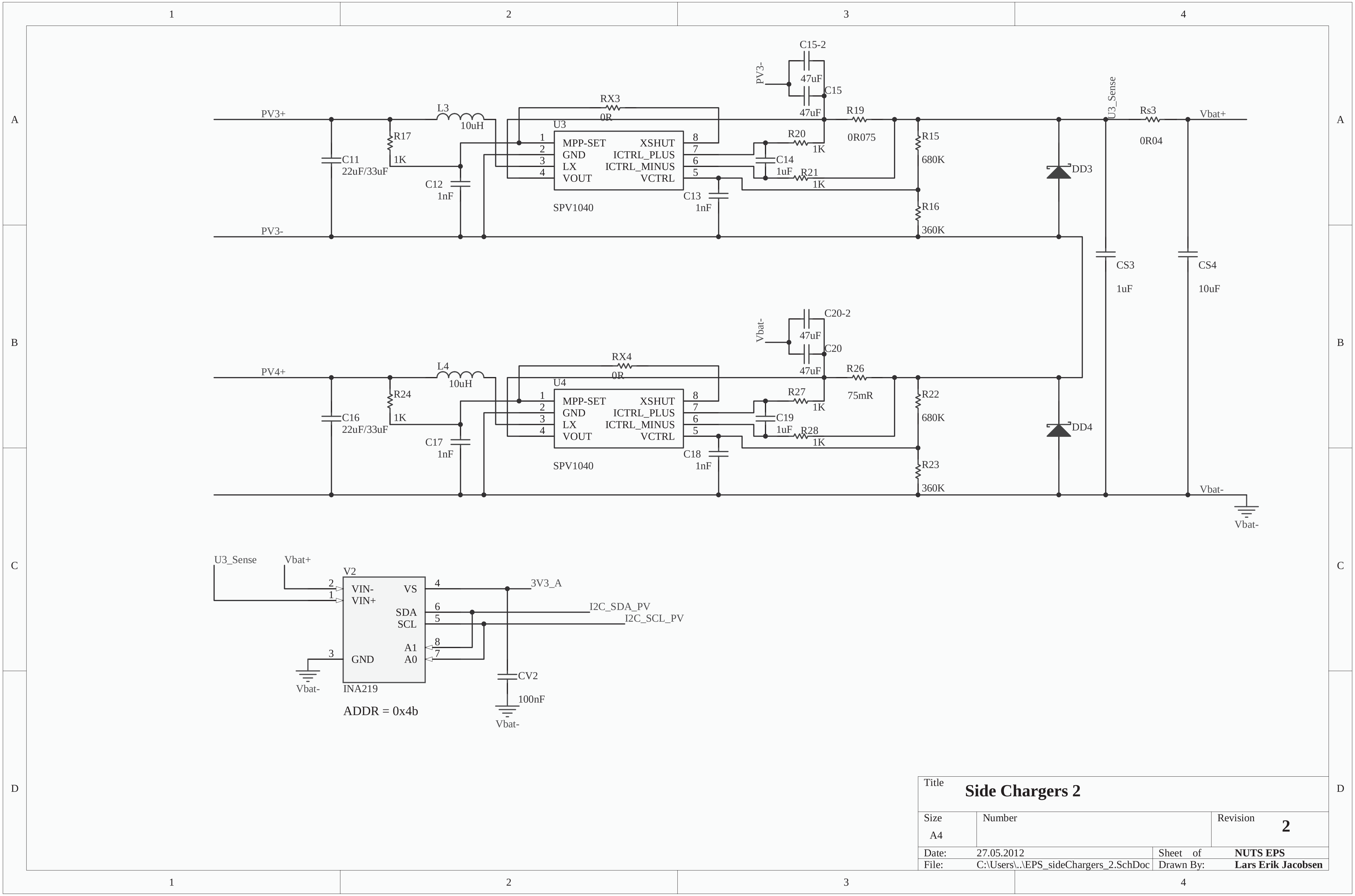
EPS Schematics

B.1 EPS Schematics

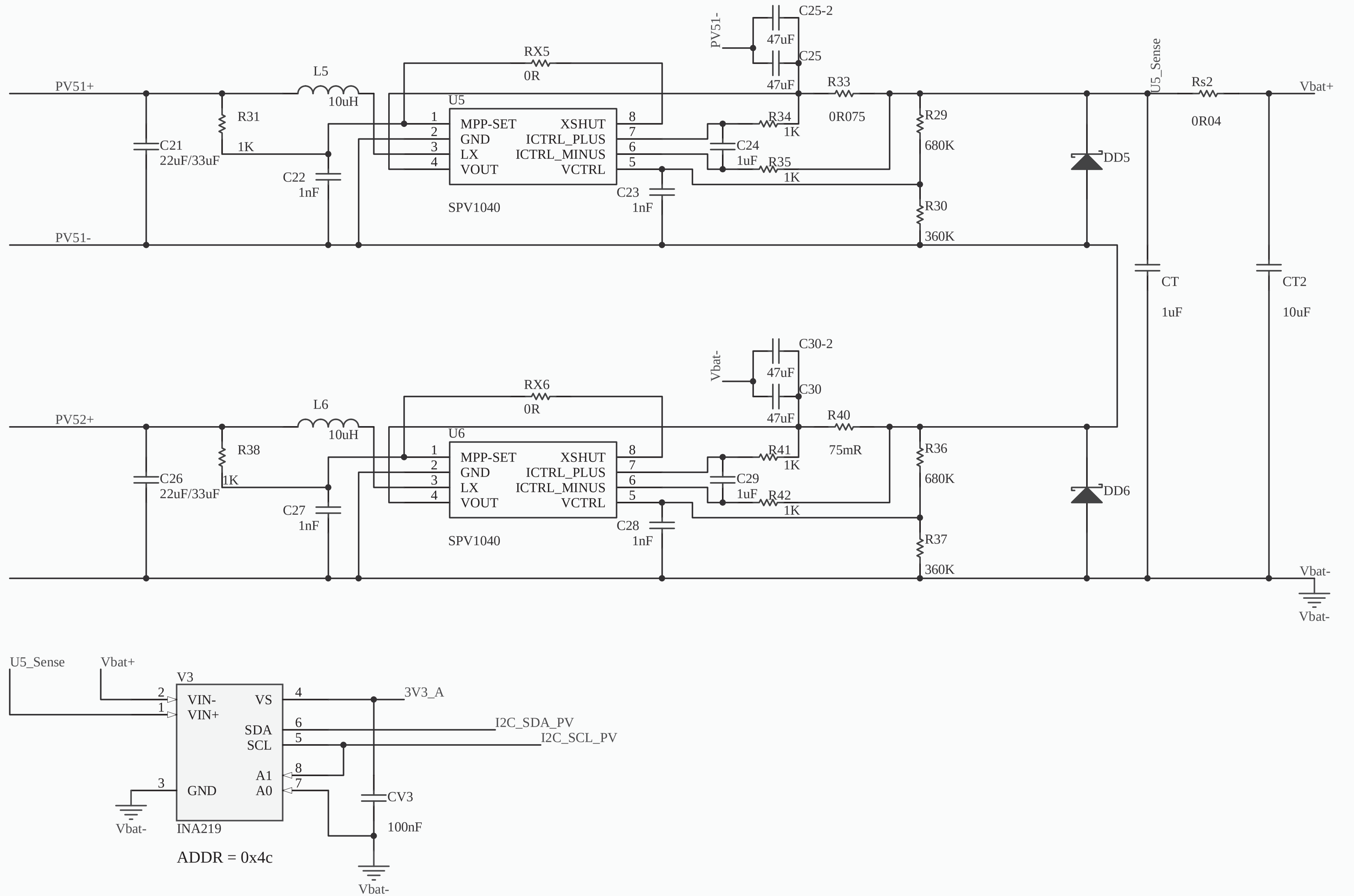
The NUTS EPS schematics are divided into segments of a larger design. The design consists of 10 schematics. The version of the schematics presented here are the schematics used to produce the EPS prototype with the alterations required and found in Chapter 4.



PV1+
PV1-
C1
22uF/33uF
R3
1K
L1
10uH
C2
1nF
RX1
0R
U1
MPP-SET
GND
LX
VOUT
XSHUT
ICTRL_PLUS
ICTRL_MINUS
VCTRL
SPV1040
C3
1nF
C4
1uF
R6
1K
R7
1K
C5-2
47uF
C5
47uF
R5
0R075
R1
680K
R2
360K
7.2 V
DD1
U1_Sense
Rs1
0R04
Vbat+
CS1
1uF
CS2
10uF
PV2+
C6
22uF/33uF
R10
1K
L2
10uH
C7
1nF
RX2
0R
U2
MPP-SET
GND
LX
VOUT
XSHUT
ICTRL_PLUS
ICTRL_MINUS
VCTRL
SPV1040
C8
1nF
C9
1uF
R13
1K
R14
1K
C10-2
47uF
C10
47uF
R12
75mR
R8
680K
R9
360K
3.6 V
DD2
Vbat-
U1_Sense
Vbat+
V1
VIN-
VIN+
GND
VS
SDA
SCL
A1
A0
INA219
ADDR = 0x4a
3V3_A
I2C_SDA_PV
I2C_SCL_PV
CV1
100nF
Vbat-
Title
Side Chargers
Size
A4
Number
Revision
2
Date:
27.05.2012
Sheet of
NUTS EPS
File:
C:\Users\..\EPS_sideChargers.SchDoc
Drawn By:
Lars Erik Jacobsen



Title	Side Chargers 2		
Size A4	Number		Revision 2
Date:	27.05.2012	Sheet of	NUTS EPS
File:	C:\Users\..\EPS_sideChargers_2.SchDoc	Drawn By:	**Lars Erik Jacobsen**



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Size A4	Number	Revision	2
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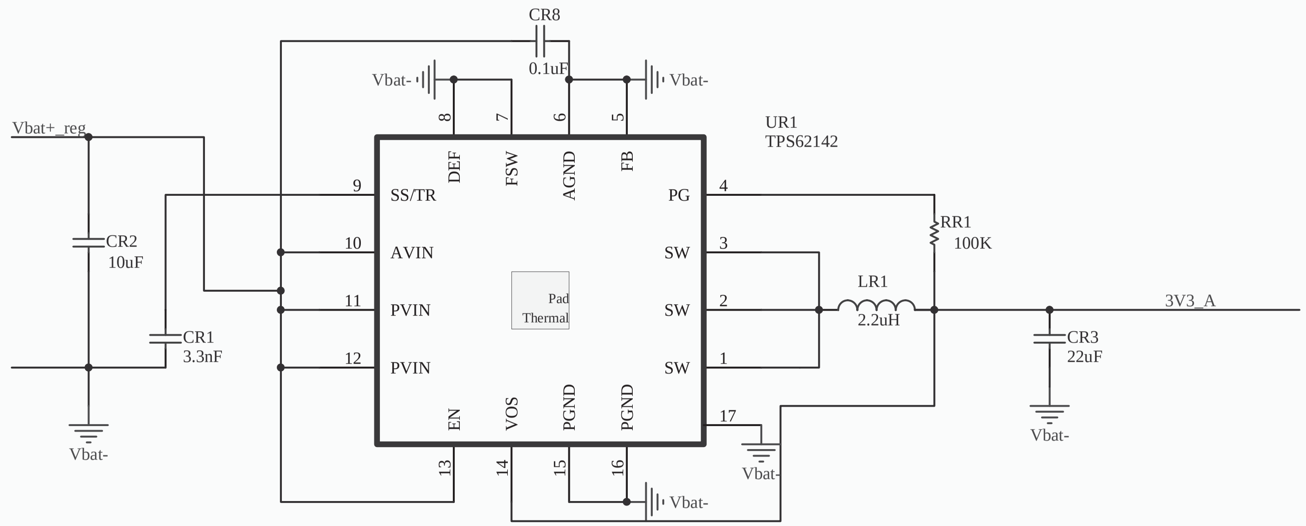
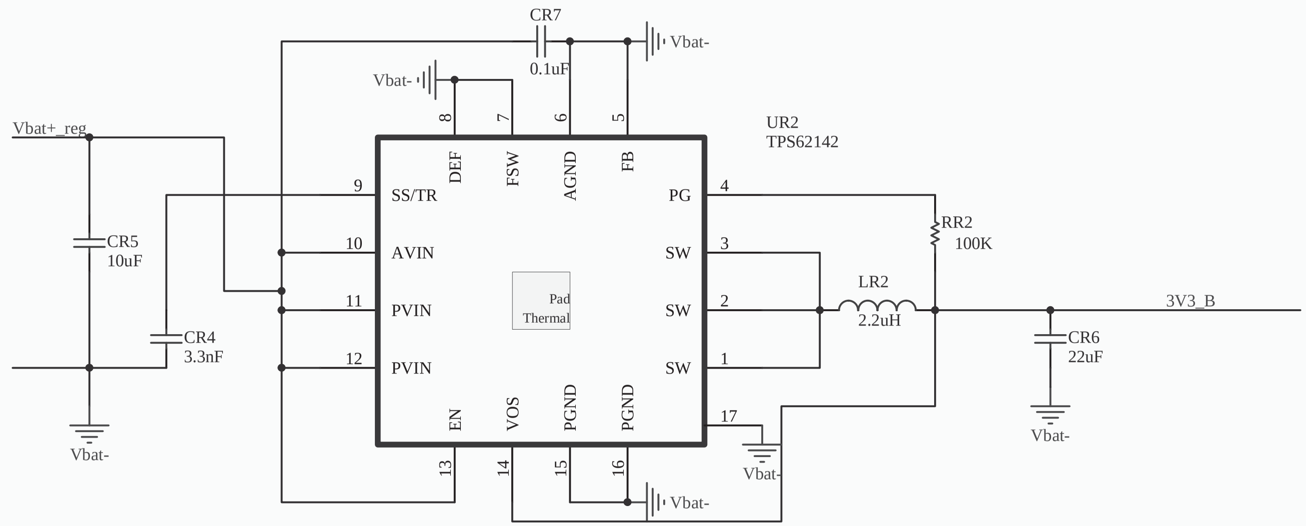
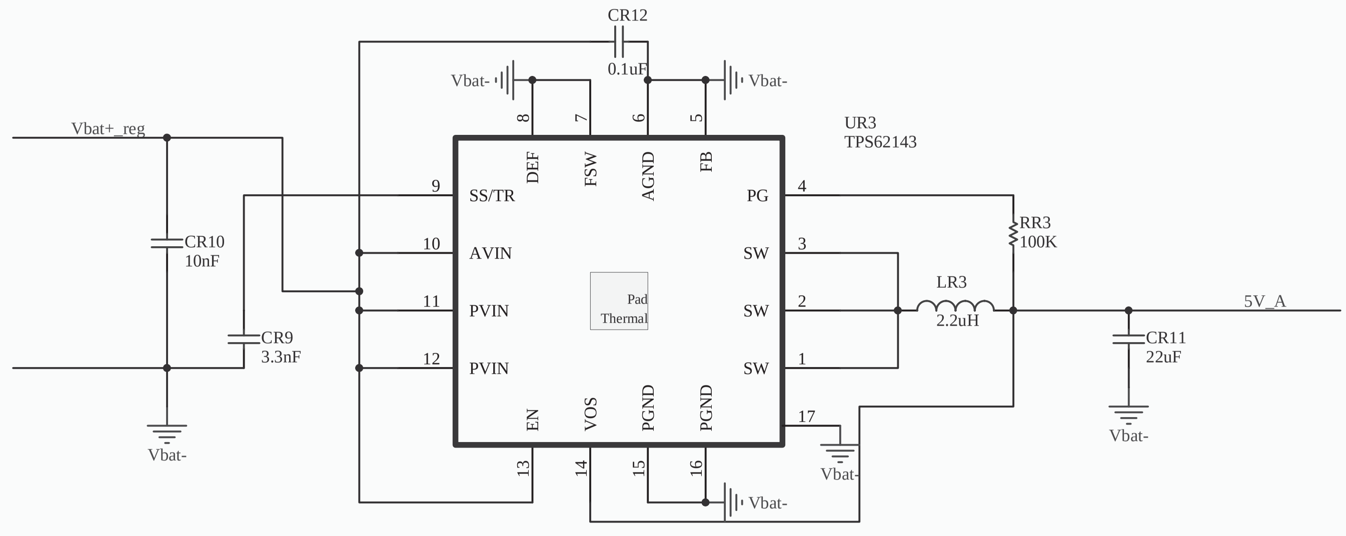
File: C:\Users\..\EPS_topChargers.SchDoc		Drawn By:	**Lars Erik Jacobsen**



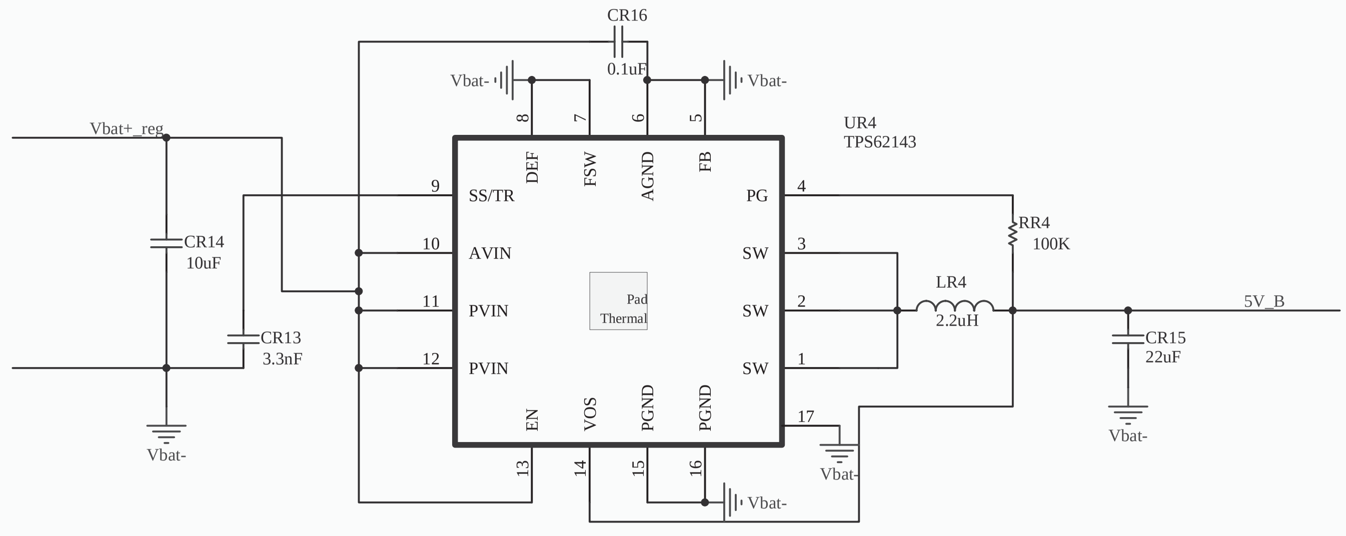
Title	3V3_A Regulator		
Size: A4	Number	Revision	2
Date:	27.05.2012	Sheet of	NUTS EPS
File:	C:\Users\..\EPS_3Vregulators.SchDoc	Drawn By:	Lars Erik Jacobsen



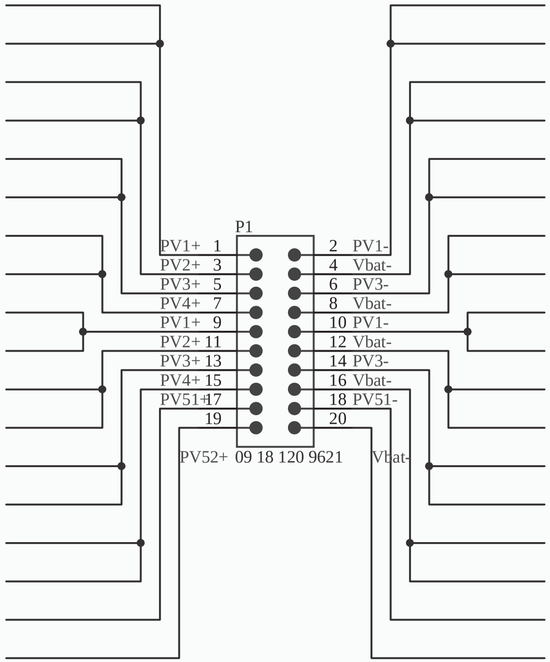
Title	**3V3_B Regulator**		
Size	Number		Revision
A4			**2**
Date:	27.05.2012	Sheet of	**NUTS EPS**
File:	C:\Users\..\EPS_3Vregulators_B.SchDoc	Drawn By:	**Lars Erik Jacobsen**



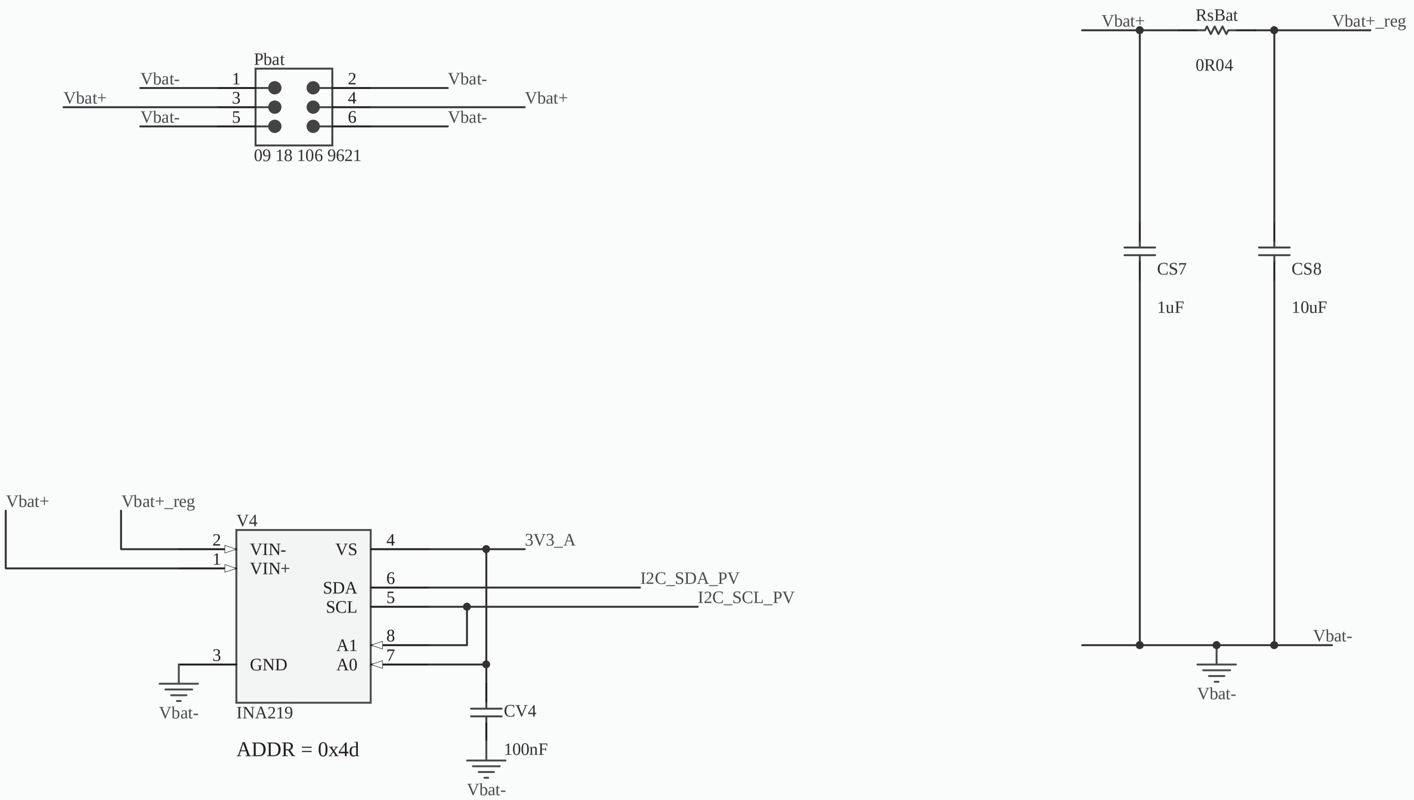
Title	5V_A Regulator		
Size: A4	Number	Revision: 2	
Date:	27.05.2012	Sheet of	NUTS EPS
File:	C:\Users\..\EPS_5Vregulators.SchDoc	Drawn By:	Lars Erik Jacobsen



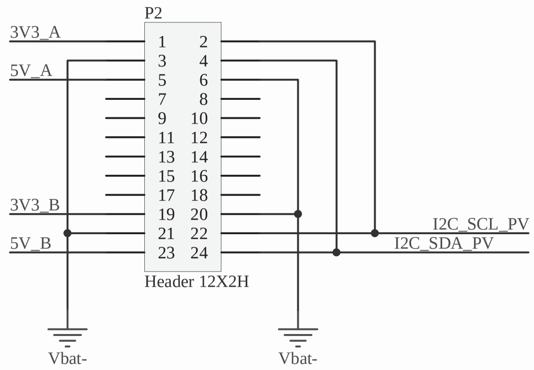
Title	5V_B Regulator			
Size A4	Number		Revision	2
Date:	27.05.2012	Sheet of	NUTS EPS	
File:	C:\Users\..\EPS_5Vregulators_B.SchDoc	Drawn By:	Lars Erik Jacobsen	



Title	**Solar Cell Connector**		
Size A4	Number		Revision **2**
Date: 27.05.2012		Sheet of	**NUTS EPS**
File: C:\Users\..\EPS_solarcell_con.SchDoc		Drawn By:	**Lars Erik Jacobsen**



Title	**Battery Connector with sensor**	
Size A4	Number	Revision **2**
Date: 27.05.2012	Sheet of	**NUTS EPS**
File: C:\Users\..\EPS_BatteryCon.SchDoc	Drawn By:	**Lars Erik Jacobsen**



Title	Backplane Connector		
Size A4	Number		Revision 2
Date:	31.05.2012	Sheet of	NUTS EPS
File:	C:\Users\..\EPS_Backplane_con.SchDoc	Drawn By:	Lars Erik Jacobsen

Appendix C

NUTS EPS

C.1 Assembly Drawing

The assembly drawing shows the position and orientation of the components on the PCB. Since the silkscreen on the PCB may not identify the location of a component, the assembly drawing can be very useful. The assembly drawing of the EPS module is presented in Figure C.1.

C.2 Bill of Materials

The Bill of Materials (BOM), is a list of all the components and their part numbers. A print-out of the BOM is presented in Figure C.2.

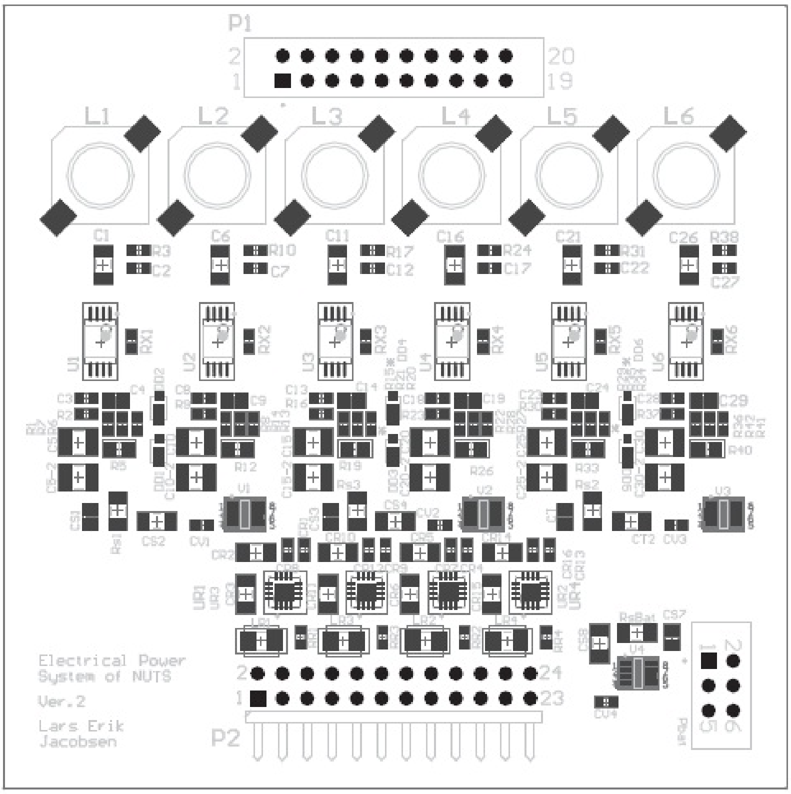


Figure C.1: Assembly Drawing of the EPS module.

NUTS EPS Revised: 07.05.2012

Item	Quantity	Designator	Description	Comment	Manufacturer	Part Number	Footprint
1	10	C1, C6, C11, C16, C21, C26, CR3, CR6, CR11, CR15	Capacitor	22uF	Murata	GRM31	C1206
2	12	C2, C3, C7, C8, C12, C13, C17, C18, C22, C23, C27, C28	Capacitor	1nF	Murata	GRM188	1608[0603]
3	10	C4, C9, C14, C19, C24, C29, CS1, CS3, CS7, CT	Capacitor	1uF	Murata	GRM21	C0805
4	12	C5, C5-2, C10, C10-2, C15, C15-2, C20, C20-2, C25, C25-2, C30, C30-2	Capacitor	47uF	Murata	GRM32	C1210
5	4	CR1, CR4, CR9, CR13	Capacitor	3.3nF	Murata	GRM188	1608[0603]
6	8	CR2, CR5, CR10, CR14, CS2, CS4, CS8, CT2	Capacitor	10uF	Murata	GRM31	C1206
7	8	CR7, CR8, CR12, CR16, CV1, CV2, CV3, CV4	Capacitor	100nF	Murata	GRM188	1608[0603]
8	6	DD1, DD2, DD3, DD4, DD5, DD6	Schottky Diode		Vishay	MSS1P3U-M3/89A	MICROSMP
9	6	L1, L2, L3, L4, L5, L6	Inductor	10uH	Panasonic	ELLATV100M	ELLATV
10	4	LR1, LR2, LR3, LR4	Inductor	2.2uH	Vishay Dale	IHLP1212BZER2R2M11	INDC3630X20N
11	1	P1	Flat Cable Connector (IDC), PCB Transition Connector, 2 Rows, Solder Pin, 20 Contacts	09 18 120 9621	Harting	09 18 120 9622	9181209621
12	1	P2	Header, 12-Pin, Dual row, Right Angle	Header 12X2H			HDR2X12H
13	1	Pbat	Flat Cable Connector (IDC), PCB Transition Connector, 2 Rows, Solder Pin, 6 Contacts	09 18 106 9621	Harting	09 18 106 9622	9181069621
14	6	R1, R8, R15, R22, R29, R36	Resistor	680K			1608[0603]
15	6	R2, R9, R16, R23, R30, R37	Resistor	360K			1608[0603]
16	18	R3, R6, R7, R10, R13, R14, R17, R20, R21, R24, R27, R28, R31, R34, R35, R38, R41, R42	Resistor	1K			1608[0603]
17	6	R5, R12, R19, R26, R33, R40	Resistor	0R075			6-0805_N
18	4	RR1, RR2, RR3, RR4	Resistor	100K			J1-0603
19	4	Rs1, Rs2, Rs3, RsBat	Resistor	0R04			C1206
20	6	RX1, RX2, RX3, RX4, RX5, RX6	Resistor	0R			1608[0603]
21	6	U1, U2, U3, U4, U5, U6	Battery Charger with MPPT	SPV1040	ST Microel.	SPV1040TTR	SPV1040xSOP65P640X265-8N
22	2	UR1, UR2	Voltage regulator 3.3V	TPS62142	Texas Inst.	TPS62142RGTT	TPS6214xQFN16
23	2	UR3, UR4	Voltage regulator 5.0V	TPS62143	Texas Inst.	TPS62143RGTT	TPS6214xQFN16
24	4	V1, V2, V3, V4	Voltage sensor	INA219	Texas Inst.	INA219AIDCNT	SOT23-8

Figure C.2: EPS Bill of Materials.