NTNU
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Power System of the NTNU Test Satellite

Backplane Study and Design of the EPS

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Abstract

The NTNU Test Satellite (NUTS) project is aiming to launch a $10 \times 10 \times 20$ cm nanosatellite by the year 2014. The project has been on an experimental basis until last year. During the last year, students of the NUTS project have made huge progress in developing prototypes of the experimental studies from former students. This project work will focus on the power system of the NUTS satellite.

The power system of the NUTS satellite consists of a power distribution system, the backplane, and a power condition system, the Electrical Power System (EPS). This report describes an evaluation of the backplane power design solutions, and a design proposal of the EPS module. The power system is a critical part of the NUTS satellite, since the satellite will not operate without power.

The backplane is designed with flexibility, fault-tolerance and simplicity in mind. The design choices that are power relevant have been presented and discussed against possible alternatives. Through my study I have found the Backplane design to be a good solution, and its specifications impose requirements on the design of the power system of NUTS.

The work regarding the Electrical Power System (EPS) focuses on the battery charging and power conversion, and a proposal for the design of the module is provided. The EPS module features a battery charge regulator (SPV1040) with embedded Maximum Power Point Tracking (MPPT) algorithm and voltage regulators for the supply buses. An analysis of the solar cells and batteries is presented and some power calculations are provided. The analysis and design solution assumes a charge current of 1 A, and as a result the charging time of the battery bank has been calculated. An increase of the battery bank is suggested on account removing excess slave slots to increase the total power of the satellite. The proposed design provide a reliable and simple system, which complies with the design philosophy of the NUTS satellite project.

Preface

This report is a part of the specialization project TFE4520 Design of digital systems, and was accomplished during the autumn of 2011 at the Institute for Electronics and Telecommunications at NTNU. The project covers 15 student credits and is meant as a preliminary work to the master thesis.

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 Student Satellite. The main focus of this report is to get an understanding of the satellite power system, and to investigate the possibilities of designing an Electrical Power System (EPS) unit for energy harvesting, battery charging and voltage regulation.

The project began by reading earlier reports and master thesis' to get an overview of the satellite project. A thorough study of the recent work of the power system is performed to define the requirements of the EPS unit. The goal with this report is to form the foundation for further work with the implementation of an EPS unit.

I would like to thank the other students in the project group and project leader Roger Birkeland, for many good moments, advice, and discussions. 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, 20.12.2011

Lars Erik Jacobsen

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Chapter 1

Introduction

In the recent years there has been a growth in interest in space missions from several universities all over the world. Universities have traditionally been limited by the cost and time 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.

A nanosatellite, which this project is based on, is defined as an artificial satellite with a mass between 1 and 10 kg. This falls under the definition of small satellites which are usually passengers on larger satellite missions [4].

This new technology can drastically reduce the development cost and development time of small satellites by scaling down the design and make the 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 usually not considered for space missions can be taken into account when designing 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 primarly. Futhermore, there are many requirements and constraints that has 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, 3-6 months, the flexibility is much greater. As a result, factors like simplicity and power-efficiency will be favoured against the requirements of reliability and redundancy.

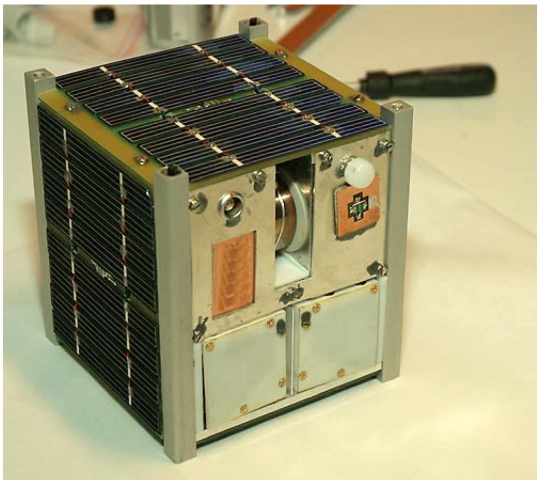

Figure 1.1: The Norwegian satellite NCUBE-2.

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 × 10 × 20 cm and weighing less than 2.66 kg, which conforms to the CubeSat Standard [1]. The satellite will carry a IR-camera for atmospheric observations as it's main payload. Other payloads are yet to be determined.

The NUTS project was started in September 2010, and is a part the Norwegian Satellite Program run by NAROM (Norwegian Centre for Space-related Education). This program involes three educational establishments, namely the University of Oslo (UiO), Narvik University College (HiN) and NTNU.

The main goal of this project work within the NUTS project is to evaluate the work of Dewald De Bruyn [2] and to provide a solution for the Electrical Power System (EPS) of NUTS. The two tasks are connected because to design and evaluate a solution for the EPS it is important to have an understanding of the Backplane designed by De Bruyn and Volstad [2, 5]. The EPS provides power to the backplane, which distribute this to the different modules. The EPS module is a very important part of the NUTS project, as it is the power supply for the entire 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 CubeSats with the dimensions $10 \times 10 \times 10$ cm and had a weight around 1 kg. Unfortunatly, 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 contraints concerning of a small student satellite [6]. In the following years there has been several students involved in the design and specification of the different sub-systems for the NUTS project. In this report, the main focus will be on the work of Dewald De Bruyn [2]. However, 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). This strategy was first presented in the Master's thesis of Lars O. Opkvitne [7].

The most recent contribution to the power management of the satellite is given in the Master's thesis of Dewald De Bruyn [2]. In his Master's thesis, 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 outline the necessary requirements and constraints for the Backplane and the EPS. De Bruyn also provides a prototype for testing the BCR (Battery Charge Regulator), which is an important part of the EPS module.

1.3 Scope and Disposition

As mentioned in Section 1.1, the main scope of this project is to evaluate the work of Dewald De Bruyn [2] and to provide a solution for the EPS of NUTS. Previous work in the NUTS project has mainly been theoretical work, with the exception of De Bruyns work on the backplane. This report presents an evaluation of De Bruyns work, his solutions and arguments. The evaluation will be focused at understanding the backplane functionality, with the work to be done on the EPS in mind.

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

Chapter 3 is dedicated to the evaluation of the backplane provided by De Bruyn. A short summary of De Bruyns design choices is presented and discussed with the design of the EPS in mind.

In Chapter 4, an overview of the EPS is presented. This includes the layout and the requirements for the EPS module. A discussion of the SPV1040 battery charge regulator is presented in this chapter.

In Chapter 5, a short discussion and conclusion with 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.

2.1 The CubeSat Standard

The CubeSat Standard [1] was developed by the Polytechnic University of California and Stanford University to ease the developement and deployment of nanosatellites. The standard includes the mechanical and electrical requirements. Some mechanical requirements from [1] 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.

The electrical requirements are provided to prevent interference with the launch vehicle, payloads or other CubeSats. Some important electrical requirements from [1] are:

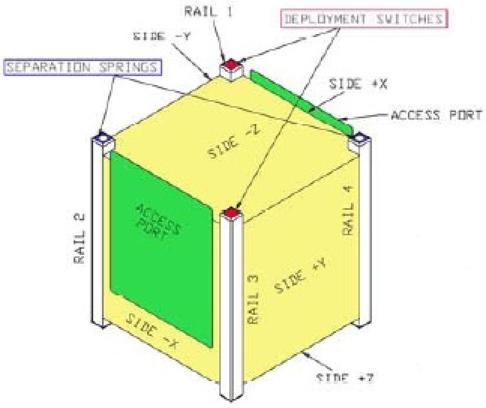

Figure 2.1: CubeSat specification [1].

- 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[1]. When the satellite is deployed from the P-POD the deployment switch is released. Although the satellite now has power, some operational requirements has to be fullfilled. 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

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[1] The P-POD is a deployment unit which releases the CubeSats into space. It is designed to push the CubeSats out, using a spring mechanism. It can contain 3 single, 1 double + 1 single, or 1 triple CubeSat.

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 calcutations on power- and orbit-estimates can be found in [2].

2.2.1 Power Supply

The power supply of the NUTS satellite consists of solar panels and batteries. The efficiency of the solar panels decrease when the temperature in the panels increase. Hence, the panels are most effective when the satellite returns from the eclipse and the temperature in the panels are low. For this reason the maximum power pointing tracking (MPPT) strategy, which will be discussed in Chapter 4, is considered for the EPS module to maximise the effect from the solar panels.

The batteries that has been evaluated for the NUTS satellite are the A123 APR18650M1A cells [8]. These cells are lithium-ferrite-phosphate cells ($LiFePO_4$). The reason for choosing lithium batteries over the traditionally nickel-cadmium (NiCd) batteries are 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% DOD[2] cycle. However, the main reason for choosing these $LiFePO_4$ battery cells over conventional Li-Ion battery cells is the number of possible charge cycles [2].

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 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 crusial for the total weight requirement of the satellite.

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[2] 100% Depth Of Discharge equals to the status empty in state-of-charge (SOC) of the battery.

2.2.2 Energy Storage

Rechargeable batteries are used on-board to provide power to the satellite when in eclipse. The purpose of the batteries is primarly to allow the IR-camera to take pictures while in eclipse. This requires power that the solar panels can not provide, because of the lack of irradiation from the sun when in eclipse.

For the NUTS satellite a battery pack of 4×1.1 Ah battery cells are proposed, where two and two cells are connected in series and the two series are connected in parallell. As a result, the battery pack has a capacity of 2.2 Ah at 6.6 V. The battery pack is discussed in more detail in Chapter 4.

2.3 NUTS Overview

The NUTS system is designed as a distributed architecture around the backplane, as shown in Figure 2.2. 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. However, the EPS module also has to be designed with the possibilty of receiving control commands from the on-board controller (OBC).

The system consists of two master modules and three slave modules. One of the master modules is the 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 [5].

The other master module is the Telemetry, Tracking & Control (TT&C) module, which provides the communication unit for the satellite. The module contains two radio tranceivers, 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 [9].

The slave modules of the satellite is the Attitude Determination & Control System (ADCS), EPS, and the payload. The ADCS module shall obtain

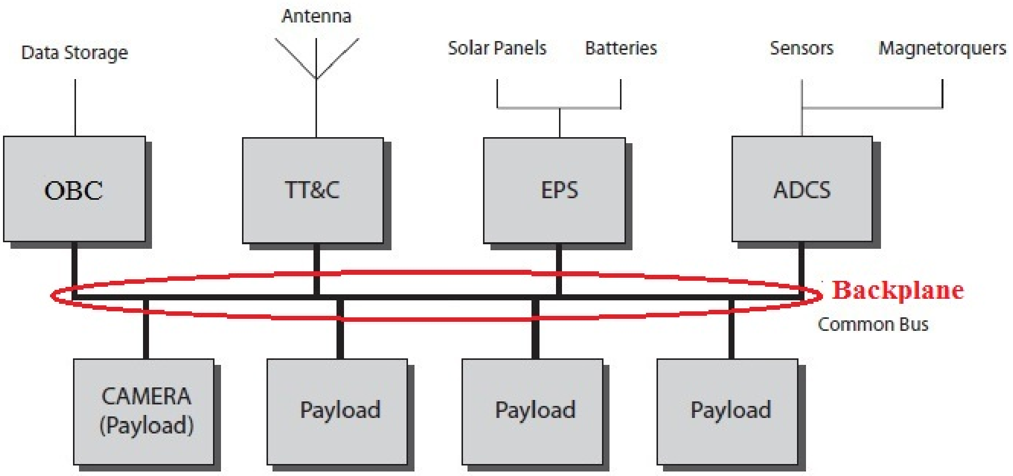


Figure 2.2: NUTS Sub System Modules.

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, is performed by Marianne Bakken and Snorre Rønning.

The EPS 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. The EPS module will be considered in Chapter 4 of this project report.

Chapter 3

Study of the backplane

During the spring semester of 2011 the NUTS project progressed a lot with the design and production of the backplane. The backplane serves as the main structure for the electronics in the satellite. The purpose of the NUTS backplane is to:

- Provide a physical connection to system modules
- Provide a common communication bus to system modules
- Provide power to system modules

A thorough understanding of the functionality and the design of the backplane is needed for the design of a electrical power system (EPS). In particular, one must consider the physical connection between the backplane and the EPS module, which differs from the others since it supplies power instead of receving power.

The backplane also includes functionality for protecting and power monitoring for each module. This allows the backplane to isolate different modules if a fault is detected.

This chapter presents some design and component choices of the backplane with regards to the power distribution of the satellite. These choices are evaluated and compared to alternatives.

3.1 Backplane implementation

In the implementation of the backplane several solutions were discussed. These solutions were based on the design and the use of components with compatible attributes.

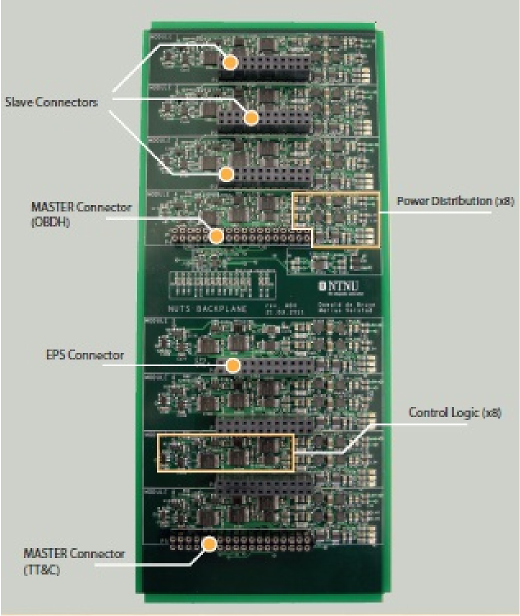


Figure 3.1: NUTS Backplane [2].

3.1.1 Design aspects

Power Supply OR-ing

For power supplies with $N + 1$ redundancy it is required to use OR-ing circuitry to isolate the main supply from the output bus in case of failure [10].

The power supply of the backplane is distributed by the use of dual redundant supply buses. An important design aspect presented in [2] was the use of special OR-ing controllers with transistors to solve the problem with current flowback into the regulators. The circuit of a transistor solution is shown in Figure 3.2a. The current flowback is a major hazard since it can cause the regulators to fail. The controlling circuit monitors the current flow through the transistor by measuring the voltage drop over the resistance in the transistor. By monitoring the current flow the controller can switch off the transistor as soon as the current becomes negative.

A simpler solution is to use diodes instead of transistors and controlling circuitry. The circuit of the diode solution is shown in Figure 3.2b. The disadvantage of using diodes is the loss in power due to the forward voltage of the diode. This is expressed as

$$P_{loss} = V_{fwd} \cdot I_{load}. \tag{3.1}$$

(a) Transistor OR-ing (b) Diode OR-ing

Figure 3.2: Power Supply OR-ing [2].

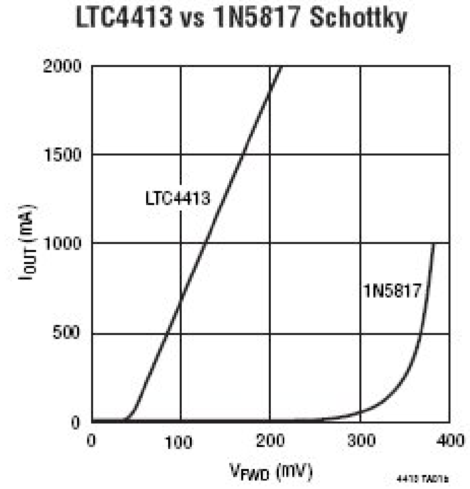


Figure 3.3: Transistor Or-ing (LTC4413) vs Diode Or-ing (Schottky) [3].

The factors of De Bruyn's choice was reliablity and the total power loss of a switch in currents, for which the transistor solution is superior. Figure 3.3 displays the difference in V_{fwd} for the transistor OR-ing and diode OR-ing, represented by the LTC4413 controller and the Schottky diode. As seen from the figure, the V_{fwd} of the diode solution is much higher than the transistor solution at equal currents. The power loss at 500 mA in a diode solution would be 187.5 mW, while the transistor solution would have a power loss of only 40 mW.

A low power consumption relaxes the demands on the EPS. Hence, this difference is a factor which affects the total power consumption. To have a solution that discards the possibility of a power waste of about 150 mW per switch is a good design methodology with power consumption in mind.

Current-limit Switch

The main purpose of the current-limit switch is to provide power switching and over-current protection. Over-current protection is important to detect when a module draws a too high current, and consequently disconnect this module from the power supply. If not, it can cause serious damage to the circuitry. As mentioned, a solution is a current-limit switch that opens when it detects that a too high current is drawn, and then breaks the connection to the module.

There are several ways of implementing an over-current protection. The simplest implementation would be to use a glass fuse. A major disadvantage of this implementation is that a physical change of the fuse is needed, and that will be impossible to do when the satellite has left the ground. The solution to be implemented has to have a current-limit switch with *reset* opportunities.

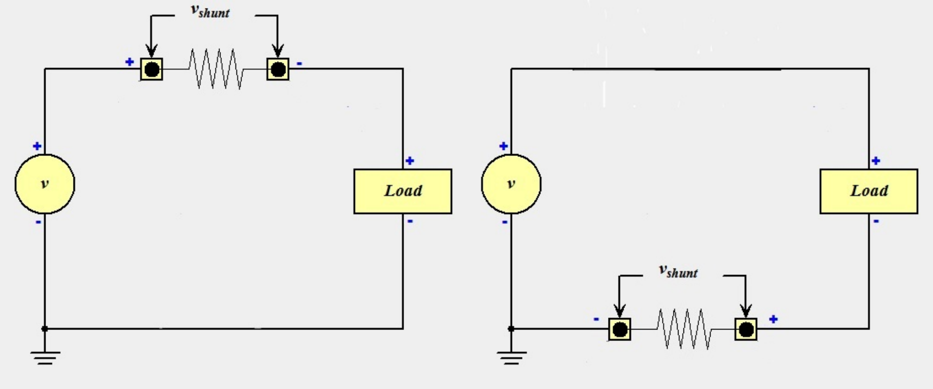
A possible solution is to use a thermal switch, which opens when it exceeds the threshold temperature and closes when the temperature has droped below the threshold. This implementation has two concerns. First, the switch has to be heated up before it opens. This allows a prolonged current draw which can cause damage to sensitive components of the circuit. Second, the switch will be placed in a vacuum environment where heat reduction is low. As a result, the switch may not return to closed position within the time the module or payload is needed.

The solution chosen for the backplane is a current-limit switch, MAX14523A from Maxim, which is a programmable current and voltage limit switch. It monitors the current flow to the load, and detects when the load current becomes to high and opens when the current reaches the programmed threshold. It also features a thermal protection for overheating and a reverse-current protection such that supply circuitry is safe [11].

Power Monitoring

Power monitoring is not a requirement for the design, however the power monitoring can be a useful feature for power management. By monitoring the power behaviour of each module the OBC or TT&C can issue a power down or shut off. This allows the masters to control the power consumption of the satellite systems and protect the batteries from over-discharging.

Power monitoring of the backplane was implemented by measuring the voltage drop over a shunt resistor. The shunt resistor is placed in series with the load so that all the current to the load runs through the resistor. The voltage drop across the shunt is proportional to the current flowing through



(a) High-Side Current Shunt (b) Low-Side Current Shunt

Figure 3.4: Power Monitoring: Current Shunt.

the shunt resistor. It is important that the size of the resistor is small since a large resistor can influence and disrupt the circuitry.

The component chosen for the backplane is the INA219 from Texas Instruments [12]. This component is a high-side current shunt and power monitor with an I^{2}C interface. A high-side current shunt refers to the path between the supply and load, while a low-side current shunt refers to the path between the load and ground, as presented in Figure 3.4. A high-side path is perferred over a low-side path, as it does not introduce problems with shifted ground potential. The low-side path also presents the problem of measuring the accurate current returned from the load to the supply. The current leakage to ground is not measured and can thus lead to a faulty measurement. Whileas the high-side current shunt solve these problems, it has a major drawback with common mode voltage. Common mode voltage has to be taken into account and adjustment of the instrument is important to get the right measurements. Failing to adress this problem can disrupt the result or even damage the measuring instrument.

3.1.2 Component choices

Keeping the complexity low and limiting the need for excess logic is important to limit the power consumption and mitigate the chance of errors. To find components that meet the functional requirements and at the same time keep the complexity low is thus an important part of the satellite design.

Power Supply OR-ing

The component chosen for power supply OR-ing on the backplane is the linear component LTC4413 from Linear Technology [3]. This controller has an operational voltage between 2.5V to 5.5V and can handle a current up to 2.6A. The advantages of the LTC4413 are its low reverse leakage current (1μA Max), it's small package size, and internal current-limit and thermal protection [3]. The controller is optimized with power consumption in mind.

However, there are many controllers which are less power consuming than the LTC4413, such as the Picor PI2121 [13] that has a lower on-resistance[1] which results in a lower voltage drop in the transistor, and thus lower power loss when a switch occurs. The PI2121 also has a lower continous power dissipation of 1080 mW in contrast to 1500 mW for the LTC4413, and hence the heat produced because of power dissipation is lower. Nevertheless, the PI2121 has some drawbacks when considering the NUTS project. For instance, the package size is over three times the package size of the LTC4413[2], which will result in more area usage of the backplane. It also has a 17 pin configuration and a larger operational voltage area, which can involve more complexity and discard the design philosophy of simplicity. Because of these facts this component seems inferior to the chosen component.

Current-limit Switch

As mentioned in Section 3.1.1, the component chosen as current-limit switch is the MAX14523A from Maxim [11]. The switch features a low 70 mΩ resistance and an adjustable current limit between 250 mA and 1.5 mA. The advantages of the MAX14523 are that it features an auto-retry function, thermal- and reverse-current protection. The thermal protection results in a shut down when the threshold temperature is reached, as described in Section 3.1.1. The reverse-current protection limits the current backflow to 2μA to protect the supply circuitry, since a high reverse current can cause damage to the regulators and in worst case damage the power supply for the entire satellite.

The auto-retry function is one of the major reasons for this choice of component. When the load current exceeds the programmed threshold, the timer t_{BLANK} starts counting. If the over-current condition persists after the "blanking time"[3], the switch opens and the "retry time" timer t_{RETRY} starts

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[1] The on-resistance is an important factor to determine the voltage drop in the transistor

[2] PI2121 package size: 33.4 mm^2. LTC4413 package size: 9 mm^2.

[3] Typically 17.5 ms.

counting. At the end of t_{RETRY}[4] the switch closes again, and if the fault still exists, the cycle repeats. As a result, the power consumption during a switch is reduced by 97% compared to continuous current limiting of for instance TPS203x from Texas Instruments [2]. The switch will remain on if the fault is removed.

The ratio between t_{BLANK} and t_{RETRY} is fixed at 32, according to [11]. This means that the average current during a prolonged over-current condition can be found by equation 3.2:

$$I_{load} = I_{lim} \cdot \frac{t_{BLANK}}{t_{BLANK} + t_{RETRY}} = \frac{I_{lim}}{32}, \tag{3.2}$$

where I_{load} is the current that runs through the load and I_{lim} is the current limit set by an external resistor.

The current limit is programmed using an external resistor. The size of this resistor, R_{SETI}, can be derived from an equation given in [11]:

$$R_{SETI}(k\Omega) = \frac{141400V}{I_{lim}(A)} - 2.48k\Omega. \tag{3.3}$$

De Bruyn [2] chose to implement a default limit resistor of 470 kΩ to each module slot on the backplane. This resistor size was decided with a current limit of 300 mA. Some of the other project participants has concerns about the limiter and want to know if the limit can be raised. The argument of De Bruyn is that this limit resistor should be specified for each module and fit the required peak current draw of the module. The evaluation of these limit resistors should be done when the final specifications of each module is realised. This will however cause a higher demand on the power supply which can shorten the lifetime of the batteries.

A future component for consideration will be the MAX14575 from Maxim [14]. It has the same basic attributes and functions as the MAX14523, but has a lower on-resistance of 50 mΩ, which reduce the power consumption per switch by 20 mW @ 1 A. As a result, the total power consumption is reduced by 160 mW. It also has a smaller package size of 2×2 mm, compared to 3×3 mm for MAX14523, which reduces the area on the backplane. However, when considering this it is important to evaluate the cost of time it takes to alter the backplane's electronics.

Power Monitoring

The component chosen for power monitoring is the INA219 from Texas Instruments [12]. As mentioned earlier, the INA219 is a high-side current

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[4] Typically 560 ms.

shunt and power monitor with a I^2C interface. The component also contains a programmable gain amplifier, an ADC and a multiplier. Multiplying a calibration value with the ADC allows the measured current to be directly read out in amperes. With an additional multiplier register it can calculate the power in watts by using the measured shunt current and bus voltage.

To get the best resolution for a measured current below 1 A a shunt resistor of 40 mΩ was chosen for the backplane.

3.1.3 Number of Modules

For the time being there is only five modules developed for the satellite, the OBC, TT&C, ADCS, EPS and the payload. An important consideration is whether the satellite needs the excess slave module slots on the backplane. Removing these will create more space, which can be useful if a larger battery bank is required or more area is needed for the payload, or even the antenna configuration. The removal of the slots will mean less circuitry, which results in less power consumption and less complexity. The reliability may also increase because the removal of the slots will remove possible failure points.

Chapter 4

Electrical Power System

This chapter presents the Electrical Power System (EPS), which together with the Backplane forms the power management solution of the satellite. An analysis of the solar cells and batteries based on power calculations is presented, and requirements and possible solutions for the EPS module are provided.

4.1 Overview

The EPS is the power system of the satellite, which is a critical part of the satellite. The purpose of the EPS module is to provide efficient conversion of the power radiated from the sun, battery charging and monitoring, and bus voltage regulation. The main task of the EPS is to provide regulated power supply to the satellite's backplane. Without power the satellite will not be able to operate, and as a result a main requirement for the EPS is reliability.

In Figure 4.1, the main architecture of the EPS module is presented. The solar panels are connected in pairs to Battery Charge Regulators (BCR), which charges the batteries with power from the solar cells. The batteries are then connected to four bus voltage regulators which provide regulated voltage to the backplane power rails. For battery charging and regulation an evaluation of the SPV1040 battery charger from ST Microelectronics is provided in Section 4.4.2. This approach offers a reliable and redundant system where a failure in a single regulator or damage to a solar cell, does not result in a total loss of power.

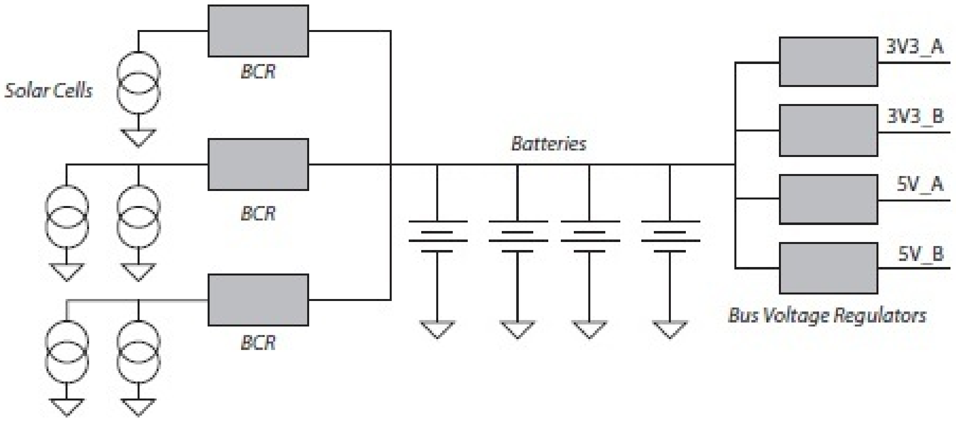

Figure 4.1: Electrical Power System architecture.

4.2 Solar Panels

The NUTS satellite will carry 18 solar cells from Azur Space [15]. Four cells on each side panel and two cells on the top panel. The solar cells will be connected to the battery charge regulator together in pairs of opposite sides to reduce the circuitry by limiting the number of regulators.

The solar cells harvest energy from irradiation of the sun. The amount of power the solar cells can produce depends on the solar power flux and the efficiency of the solar cells. The solar flux varies during the year, as a result an annual mean of $S = 1353$ W/m^2 is often assumed when designing a solar powered satellite system [16].

The average efficiency and area of the solar cell is about 29.1% and 30.18 cm^2, according to the datasheet [15], which results in a available mean power given by:

$$P = S \cdot area \cdot \eta = 1353W/m^2 \cdot 0.003018m^2 \cdot 29.1\% = 1.225W. \tag{4.1}$$

According to the datasheet [15], the voltage at maximum power pointing (MPP) is $V_{mpp} = 2.379$ V. As shown in equation 4.2, an output current from the solar cell of about 515 mA can be assumed if MPPT is implemented:

$$I_{mpp} = \frac{P}{V_{mpp}} = \frac{1.225W}{2.379V} = 515mA. \tag{4.2}$$

Here P is the mean power calculated in equation 4.1.

4.3 Batteries

The A123 battery cell chosen for the NUTS satellite has a nominal voltage of 3.3 V with the opportunity for a charge voltage of 3.6 V. The capacity of the cell is 1.1 Ah. As mentioned in Chapter 2, the NUTS satellite originally planned to use 4 battery cells, where two cells are connected in series and the two series are then connected in parallell. This configuration results in a nominal battery voltage of 6.6 V and a capacity of 2.2 Ah.

By removing the excess slots a larger battery bank can be implemented, as discussed in Section 3.1.3. A larger battery bank is desireable to increase the available power of the satellite. Since the satellite will operate on the voltages 3.3 V and 5.0 V, a larger battery bank voltage than the proposed battery bank is not required. As a result, an increase to 8 battery cells will imply a parallell connection of two of the battery bank configuration decribed in Chapter 2. This configuration will not increase the nominal voltage of 6.6 V, but the capacity will increase from 2.2 Ah to 4.4 Ah. This results in an available power of 29 Wh, compared to the 14.5 Wh of the former battery bank proposal.

However, an increase in battery cells will increase the charging time of the cells, as shown in Table 4.1. The table is calculated according to the equations in Appendix A. The charging time is calculated with a constant current of 1 A, which is the desired current from the solar panels. The real charge current is yet to be determined, since no real test of the solar cells has been accomplished. On the other hand, the charging time of the increased battery bank is still within reasonable limits since the satellite will not be performing major tasks every orbit.

The increase in number of battery cells will also result in a larger weight of the battery bank. However, the total weight of the satellite is currently way below the requirement of 2.66 kg from the CubeSat standard [1]. As a result, an increase in the number of battery cells is desireable, as it will increase the total power of the satellite and still within the functional requirements.

De Bruyn [2] found that the worst-case average power produced per orbit equals $P_{avg} = 3.43$ W. By using the equation

$$C_{used} = \frac{P_{avg}}{V_{nom}} \cdot t_{ecl}, \tag{4.3}$$

[2] found that the used battery capacity during eclipse equals to 0.3 Ah for a four cell battery pack with a nominal voltage of $V_{nom} = 6.6$ V. Here the t_{ecl} is the time in eclipse and is calculated using equation A.1 in Appendix A.

Battery bank	Capacity [Ah]	State-of-Charge [%]	Charge time [min]	# Orbit $\approx$ 61.1 min
4×1.1	2.2	86.1	132	2.16
6×1.1	3.3	90.7	198	3.24
8×1.1	4.4	93.0	264	4.32

Table 4.1: Charging time and SoC for different battery banks. Details on the calculations are given in Appendix A.

4.4 Requirements and Implementation

The requirements of the EPS module consists of providing a stable voltage regulation from the batteries to the voltage buses, and to provide a safe and reliable battery charge with power from the solar cells. This requires also protection circuitry for over-voltage and under-voltage, and a proper charging strategy. The EPS module shall also provide data about the available power and the battery state-of-charge for the OBC and TT&C master modules to use for power management of the satellite. Nevertheless, the EPS module shall have over-discharge protection to protect the battery from permanent damage. This circuit disconnects the batteries from the system when the batteries reach a dangerously low voltage level.

Constant Current Constant Voltage (CCCV) is a common battery charge strategy, which charges the battery with a constant current until it reaches a battery specified end-of-voltage, and is the strategy chosen for NUTS. It then gradually decrease the charge current while the battery voltage is held constant.

To receive maximum power from the solar cells, a Maximum Power Point Tracking (MPPT) algorithm is required. Since the solar cells I-V characteristic changes with the increase of irradiation and temperature, a tracking of the maximum power point is desireable to utilize the solar cells efficiently.

4.4.1 Bus Voltage Regulation

The main purpose of the EPS module is to provide two stable voltages to the rest of the system. To acheive this, the EPS will contain four step-down DC/DC converters. The converters shall convert the varying battery voltage to 2×3.3 V and 2×5.0 V stable bus voltages. Since the converters are a part of the power supply it is required that they include safety features such as over-voltage protection and short circuit protection. For the NUTS project, step-down DC/DC converters with preset output voltages of 3.3 V and 5.0 V and low power consumption is desireable to achieve a stable power supply.

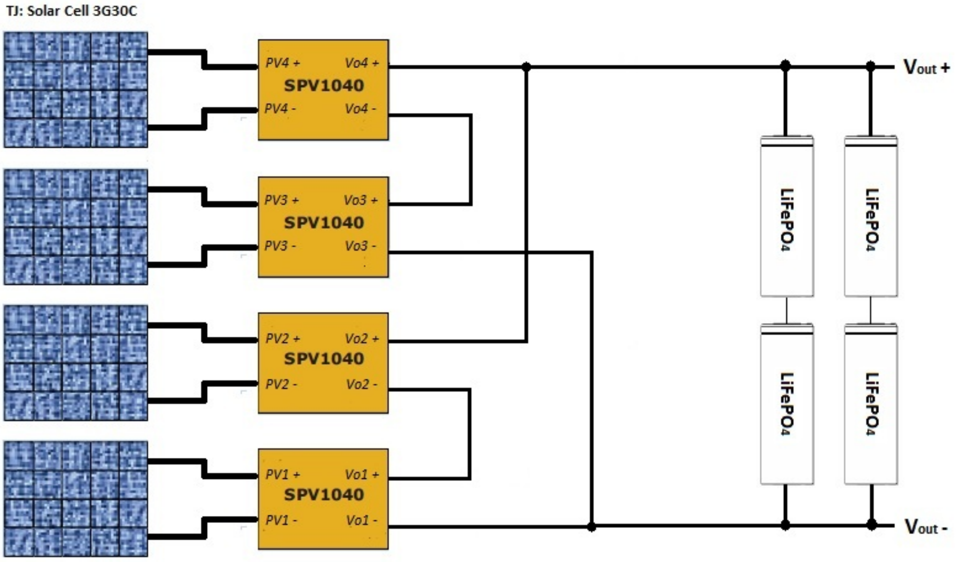

Figure 4.2: Battery charging circuit with 4 solar cells. This corresponds to one side panel of the NUTS. Solar cells from opposite sides will be connected to the same SPV1040 chip.

4.4.2 ST Microelectronics SPV1040 - Battery Charger

The SPV1040 is a high efficiency solar battery charger, and is a good option for the battery charging of the NUTS. It operates on an input voltage of 0.3 V to 5.5 V, and includes output voltage regulation, overcurrent and overtemperature protection. The charger includes the MPPT feature for maximum utilization of the solar cells and it uses the CCCV charging strategy.

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. This current is yet to be tested, however a average charge current of 1 A is desireable from the solar cells.

The charge termination voltage[1] of the batteries in the chosen configuration is 7.2 V, which is higher than the maximum output of the SPV1040. However, configurations can be made to accommondate this by for instance connecting two chips in series. A proposal for this design from solar cells to batteries is presented in Figure 4.2. To utilize the SPV1040 chip, a single chip needs to be connected to each solar cell. This requirement can be

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

verified by the produced voltage of the solar cell and the desired output voltage of the battery charger. The output of each SPV1040 chip will be set to 3.6 V, which will produce a charge voltage over the batteries of 7.2 V when two chips are connected in series, as shown in Figure 4.2. As mentioned in Section 4.2, the maximum power pointing (MPP) voltage of the solar cell is approximately 2.4 V, and as a result two solar cells in series will produce a MPP output voltage of 4.8 V. Since the SPV1040 is a step-up converter only, with a maximum output of 5.5 V, a configuration with two solar cells or more in series into a single chip will result in an unwanted need of extra step-up or step-down converters to achieve the charge voltage of 7.2 V. As a result, the use of the SPV1040 is only effective when each solar cell is connected to a single chip.

In compliance with the design philosophy of simplicity, the use of the SPV1040 will lead to a simpler design of the EPS module since it includes many of the attributes 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 it's utilization, the requirement of one chip per solar cell. This means that the NUTS project requires 18 SPV1040 battery chargers, which increases the cost of the project. However, the number of battery chargers can be lowered by connecting the solar cells on opposite side to the same SPV1040 battery charger. This will reduce the required number of battery chargers to 10, 8 to accommondate the side panels and 2 to accommondate the two solar cells on the top panel. This is justified as the irradiation will be high on the panels facing the sun, while it will be very low on the opposite side.

The advantages of using the SPV1040 includes the embedded MPPT feature and the voltage- and current protection features which is already implemented in the chip. An alternativ solution of the BCR, provided by De Bruyn [2], features seperate protection circuitry, a battery charger from Diode Inc., and an microcontroller for the MPPT algorithm implementation. Compared to the design proposal by [2], a simpler design that dosen'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 95%, which is 4% higher than the efficiency of the solution suggested in [2].

Chapter 5

Conclusions and way forward

In this project an evaluation of the Backplane power design solutions and a design proposal of the Electrical Power System was provided. An analysis of the solar cells' power and the capacity of the batteries with the regard to the EPS module was discussed. These analyses form the base for further work on the Electrical Power System of the NUTS satellite.

The power design choices and design layout of the backplane was discussed, and the power solutions were evaluated by comparison to alternative solutions. The layout was discussed with regard to the number of current modules produced for the NUTS satellite, and a reduction of slave slots were proposed to release space for an increased battery bank. To double the current battery bank will increase the total power of the NUTS satellite and not impose any problems regarding the size and weight requirements, and therefore it is a desireable solution for the NUTS satellite.

A design proposal of the EPS module implemented with the SPV1040 battery charger was choosen for its embedded MPPT algorithm and efficient and safe charging of the batteries. The design philosophy of simplicity and reliability is preserved and the design will provide the required charge and voltage regulation for the NUTS satellite.

Further work on the EPS module is firstly, to find an acceptable step-down converter for the bus voltage regulation. Secondly, it is required to implement the design into a CAD[1] tool and produce a prototype for testing. Finally, tests of the solar cells and batteries alone and together with the EPS module is required to define the available power, and to define the power budget of the EPS module, and the rest of the NUTS system.

The experience from this project is that alot of time were spendt on understanding the backplane, which resulted in less time for designing the

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[1] CAD - Computer Aided Design

EPS module. An afterthought is that I would have liked to have spendt more time on designing the EPS module, but a good understanding of the backplane is essential for the design of the EPS. With more time available, a thorough analysis of different step-down converters and an implementation of the design into a CAD tool with the necessary discrete components, would have been the top priorities.

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Appendix A

Formulas

The time in eclipse is given by

$$(t_{ecl})_{max} = 2a\sqrt{\frac{a}{\mu}} \arcsin \frac{R}{a}, \tag{A.1}$$

where $R = 6371$ km, which is the earth radius, $a = (R + Orbit_{height})$, and $\mu = GM = 398601\ \text{km}^3/\text{s}^2$ derived from the universal constant of gravitation $G = 6.6742 \times 10^{-11}\ \text{m}^3/\text{kg}^2/\text{s}^2$ and the earth's mass $M = 5.9736 \times 10^{24}$ kg. The $Orbit_{height}$ is the distance from the earth's surface to the orbit.

The state-of-charge (SoC) of the batteries is given by

$$SoC = (1 - \frac{\text{Used capacity of the batteries}}{\text{Total capacity of the batteries}}) \cdot 100\%, \tag{A.2}$$

where 0.3 Ah were used as used capacity during one eclipse, as given by [2]. The total capacity varies with the size of the battery bank.

The charging time is given by

$$T_{charge} = \frac{\text{Capacity [Ah]}}{\text{Charge current[A]}}, \tag{A.3}$$

where a charge current of 1 A were used for the calculations as indicated in Section 4.3.

The number of orbits used for charging is given by

$$\#Orbit = \frac{T_{charge}}{t_{orbit} - t_{ecl}}, \tag{A.4}$$

where t_{orbit} is the total time of an orbital circulation and t_{ecl} is the time spendt in eclipse during the circulation.