DISTRIBUTED ELECTRICAL POWER SYSTEMS

IN CUBESAT APPLICATIONS

by

Robert Burt

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of

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in

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Approved:

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UTAH STATE UNIVERSITY
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ABSTRACT

Distributed Electrical Power System

in Cubesat Applications

by

Robert Burt, Master of Science

Utah State University, 2011

Major Professor: Dr. Charles M. Swenson
Department: Electrical and Computer Engineering

The single bus voltage distributed architecture is the mainstay architecture for small satellite spacecraft. Even large satellites follow this architecture. While they may have more than one voltage that is distributed, such as a high voltage bus and a low voltage bus, within a subsystem, there is usually one bus voltage. Each subsystem component is responsible for further regulation or point-of-load regulation. The Nanosatellite class, and more particularly the cubesat, have broken away from this norm and overwhelmingly implement a centralized architecture. With the advances of small, highly efficient, monolithic dc-dc converters, this thesis researches the possibilities of implementing the distributed architecture at the cubesat scale. The goal is to create a very efficient electrical power system design that has a high degree of utility, allowing it to be used for multiple missions, without having to redesign the system every time.

(83 pages)

PUBLIC ABSTRACT

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The cubesat spacecraft was conceived over ten years ago. Since that time, close to 100 cubesat satellites have either been launched or are in the process of construction. Although started as an educational teaching tool, the cubesat is gaining popularity in the satellite industry and is making inroads as a standard architecture for many nano and pico satellite applications. The electrical power system for the cubesat class satellites almost exclusively conforms to a centralized architecture.

This thesis researches the potential of using a distributed architecture for the cubesat power system. There are several key advantages of a distributed architecture that are desirable. Design reuse is one well known advantage and it is exploited almost exclusively in larger spacecraft. However, since the first cubesats were very simplistic in their electrical power system design, custom centralized architectures were initially selected and made sense. As the cubesat standard begins to proliferate, the need to have a

non-custom, generic electrical power system design that can be reused over and over again is needed to support the ever increasing design complexities.

To begin the research, an electrical power system survey is discussed that provides insight into the current state-of-the-art in cubesat electrical power system design. Next, an actual cubesat electrical power system design based on the centralized architecture is broken down into its individual components. A complementary design is then created using a distributed architecture. The two designs are analyzed, compared, and contrasted. The results are presented and discussed as part of the research.

I dedicate this effort to my wife and kids. To my wife because of her patience and love. To my children because of the time spent going to school rather than participating in their various activities. I love them all and would not have done this without their support.

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I wish to thank the many people who have helped to make, not only this thesis but, my whole post graduated education possible. The list below is only partial:
Pat Patterson and the Space Dynamics Laboratory provided encouragement and financial assistance for this effort. Dr. Charles Swenson worked to provide study and research material outside of the USU normal curriculum. Chad Fish and the DICE team allowed access to detailed cubesat design information. Brett Larsen assisted in assembling the test board converter. Yvonne Polak and Joel Drake, technical writers, helped format the document for publication. To each of these individuals and others, I owe my gratitude.

Robert Burt

CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS, NOTATIONS AND DEFINITIONS

ADCS	Attitude Determination and Control System
AFRL	Air Force Research Laboratory
BCR	Battery Charge Regulator
CPU	Central Processing Unit
DET	Direct Energy Transfer
DICE	Dynamic Ionospheric Cubesat Experiment
DVM	Digital Volt Meter
EPS	Electrical Power System
ESR	Equivalent Series Resistor
FPGA	Field Programmable Gate Array
GPS	Global Positioning System
I^2R	Power Loss Defined as the Current Squared Times the Resistance
IC	Integrated Circuit
LDO	Low Drop Out
MPPT	Maximum Peak Power Tacking
PnP	Plug-n-Play
POL	Point-of-Load
PPT	Peak Power Tracking
SDL	Space Dynamics Laboratory
SOIC	Small-Outlined Integrated Circuit
UUT	Unit Under Test

CHAPTER 1

INTRODUCTION

The cubesat, or Nanosat class satellites, have traditionally used highly integrated Electrical Power System (EPS) electronics designed to optimize for power. For the cubesat to become a mainstay bus used for real world missions, the EPS must not only be efficient but flexible. The ideal EPS design is one that meets the power requirements of a specific mission, and can then be used multiple times in different mission scenarios, without having to be redesigned for each mission. Distributive architectures are flexible. They have enable modular designs that result in greater design reuse, while still meeting system requirements of varying satellite payloads and spacecraft configurations; but can they be efficient?

The charge pump is of interest for this research. In addition to standard dc-dc converters, the charge pump will also be considered as the distributed Point-of-Load (POL) converter. The point-of-load converter is one where the converter is located near the load that it sources power to. The load can be a card or it can be a component or sub-circuit element on a card. The charge pump is typically only used in low-power applications. The cubesat is exactly that, a low-power application. The charge pump may also be preferable in magnetic sensitive applications and therefore has some utility outside of efficiency and architecture.

A. *Thesis Purpose*

The history of cubesat spacecraft now spans over a decade. There have been many cubesats launched during that period of time. The purpose of this master's thesis is to

create a viable distributed EPS design for use in cubesat class or Nano class satellites. The distributed architecture is common to larger spacecraft, but really has not been used on smaller class satellites. This thesis researches the distributed architecture and attempts to show that it can be used effectively on cubesat class, or the more general Nano class satellites, to enable a high degree of utility, and at the same time, maintain the high degree of efficiency required by these small spacecraft.

B. *Electrical Power System Architecture*

The basic components of the EPS are the energy source, energy conversion, power regulation and control, energy storage, and distribution [1]. Figure 1.1 shows a simple block diagram of these components.

The primary energy source for nearly all cubesats is the sun. Solar arrays are used to convert the solar energy to electrical energy. High efficiency converters are used for regulation and control. Secondary or rechargeable batteries are used for energy storage. Electronic switches or relays are used to distribute the power to the loads. Other implementations of these basic components can be, and are, used for cubesats. The

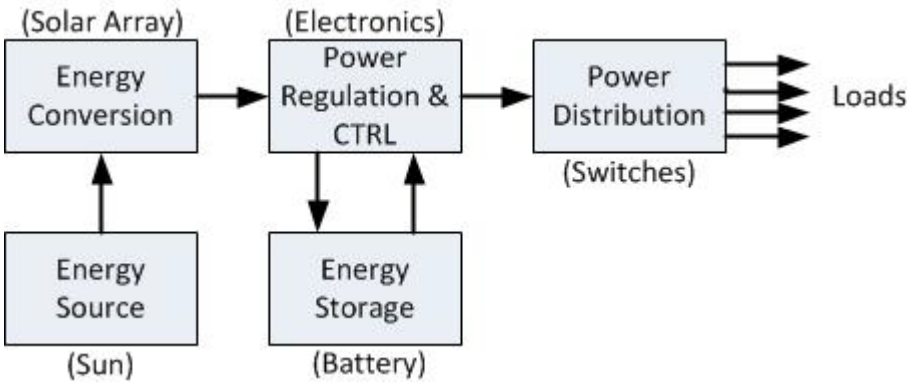

Fig. 1.1: Spacecraft EPS standard block diagram.

literature review, discussed in Chapter 2 of this paper, confirms the most common component configuration, by far, is what is described above. The focus of this thesis is the power regulation and control block and how it can be optimized for both efficiency and utility in cubesat or Nanosat implementations. This thesis also discusses the Power Distribution block as it relates to centralized and distributed architectures.

There are many different variants of the regulation and control block. However, most can be lumped into two categories: Direct Energy Transfer (DET) and Peak Power Tracking (PPT). The DET architecture connects the solar array directly to the load(s). This style requires that the solar array, loads, and battery be voltage matched. When optimized, and under the right conditions, this is ultimately the most efficient since there are no other intermediate components to dissipate power. Since conditions are seldom ideal, especially over long mission durations, the Peak Power Tracking (PPT) architecture is often used. The PPT architecture inserts a series regulation device between the solar array and the loads. The regulator regulates the current extracted from the array such that it maintains the solar array at its peak power point. Advantages of this architecture are that the solar array can be decoupled from the load, allowing simpler array designs. The PPT architecture does not rely on matching the array to the loads, and as such, optimization is obtained over a much broader set of conditions. The down side of the PPT is the added complexity of the controlling electronics. Under many conditions, it is debatable if peak power tracking wastes more power, with the added circuitry and complexity, than is saves. Regardless of what type of energy transfer architecture is selected, the power must ultimately be distributed and regulated to the

required voltage for each spacecraft component.

The power distribution function is typically considered part of the EPS in modern spacecraft. However, it is almost always assumed that each downstream component will provide some type of local regulation to meet its needs. Voltage regulation done at the EPS is usually only for the EPS components. Very large spacecraft (greater than 5000 watts), such as the international space station, may distribute more than one bus voltage to different modules with different voltage/power requirements. For smaller spacecraft, 28 volts has been the de facto industry standard voltage. This bus voltage is distributed to the various loads of the spacecraft and it is left to the load, or load component, to further regulate the bus voltage down to the many different voltages required by modern electronic components [1].

1) *Power System Architecture Utility:* Several common themes were uncovered in the EPS review to be discussed in Chapter 2. Institutions that planned to build follow on cubesats expressed a desire to redesign the EPS so that it could be used over a wider range of missions. Most cubesat EPS designs are custom and unique to the specific mission. Because the designs were so unique or custom for the application, they were not directly usable for the next cubesat design. Most of them require redesign to accommodate the next mission.

The key to greater utility, over a wide range of configurations, is a common standard within the cubesat industry. When all subsystem components share the same interface standard, these components can be reused in different configurations with little or no change to the component. The components can be termed modules and the advantages of

modularity begin to be realized on the scale where the common interface is implemented. Standards allow the industry to move forward without each individual company having to do the ground up implementation on its own [2]. The electrical power system is no exception to this rule. One of the most common interface standards for satellites has been the 28 volt bus, which enables a distributed architecture. Figure 1.2 shows a typical distributed EPS architecture. There are many components built to this 28 volt standard giving the spacecraft systems engineer many options to choose from when considering a spacecraft design. The utility of the standard interface is realized. A centralized EPS architecture, shown in Fig. 1.3, can also have a standard interface, but the more buses that are included in the interface the more complex it becomes. Ultimately, there are fewer components that will fit the specific interface standard and utility drops off accordingly.

2) *Centralized Electrical Power System:* The most common EPS architecture for

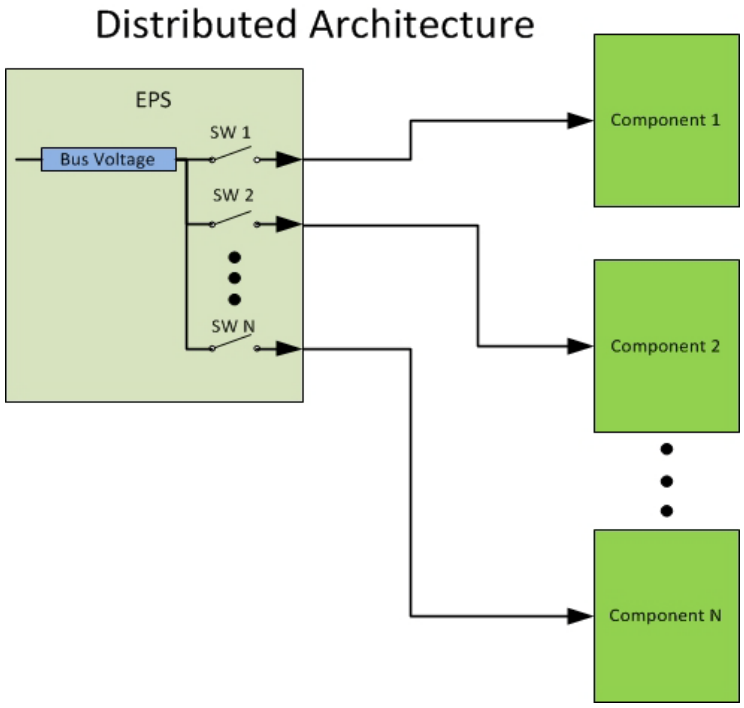

Fig. 1.2: Distributed architecture.

cubesats is centralized. A centralized architecture distributes all or most of the voltage rails used by the cubesat from one central location. In addition to the battery bus, the typical cubesat will distribute a 5.0V bus, a 3.3V bus, and occasionally a third regulated voltage. Some centralized systems will implement point-of-load regulation for special voltages not provided by the EPS card. Depending on the degree of allowable voltage ripple, a Low Drop Out (LDO) regulator is often the choice to convert to the new, lower voltage. The primary advantage of the centralized architecture is that fewer regulators are required since one regulator can provide the same regulated voltage to multiple subsystems or components. One disadvantage is that the regulator must be sized to fit all of the loads and potential loads that will be connected to it. Therefore, the designer must size the regulator for the worst case expected load. This usually means that when the

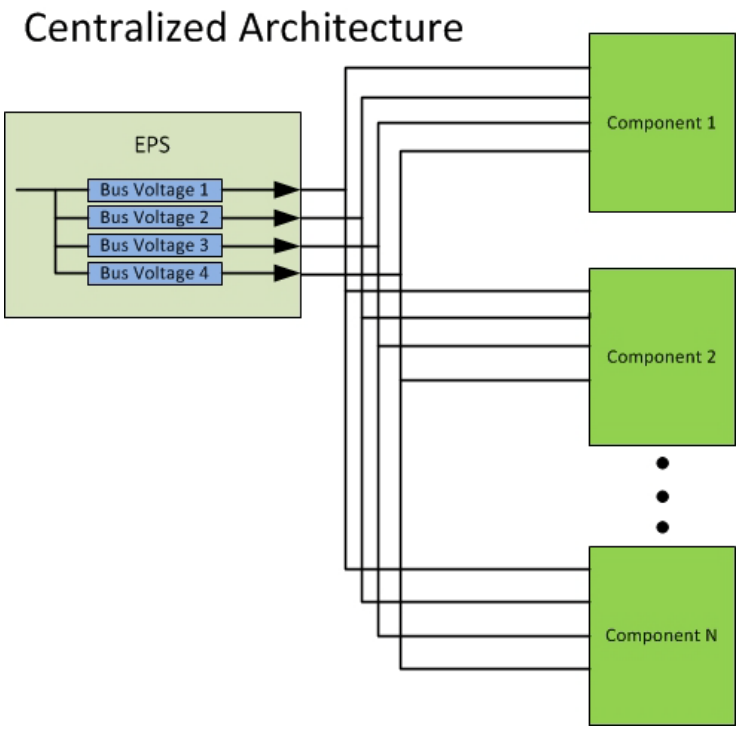

Fig. 1.3: Centralized architecture.

worst case load is not connected, the regulator is operating down on its efficiency curve, or in other words, is not optimized. The next section provides an example of a centralized system.

a) *DICE EPS Overview and Performance:* Utah State University and the Space Dynamics Laboratory collaborated to build the Dynamic Ionospheric Cubesat Experiment (DICE) cubesat. The electrical power system uses one of the most common designs commercially available. It follows the pumpkin cubesat standard [3]and was designed and built by Clyde Space LTD. This EPS is the typical centralized architecture. In addition to the 8.2 volt main battery bus, it also distributes regulated 5.0V and regulated 3.3V. The design employs a peak power tracking algorithm to regulate the solar array. Figure 1.4 shows a block diagram of the DICE EPS [4]. There is a dedicated Battery Charge Regulator (BCR) for three separate solar array inputs. The output of the BCRs pass through a series of switches designed to disconnect the battery, loads, and secondary regulators from the power source per requirements set forth by the various launch providers and documented in the CubeSat Design Specification [5]. After the switches are three outputs. The first is the unregulated battery bus. The other two are regulated 5.0V and 3.3V, respectively.

The battery is a 2SnP lithium-polymer cell chemistry where “n” indicates the number of parallel strings and each string has two cells in series. This battery configuration equates to a maximum voltage of 8.4 volts per string. The EPS is designed to charge the battery to a maximum of 8.3 volts which allows for a longer life or more battery charge/discharge cycles. Once the battery is charged to the maximum voltage, the BCR

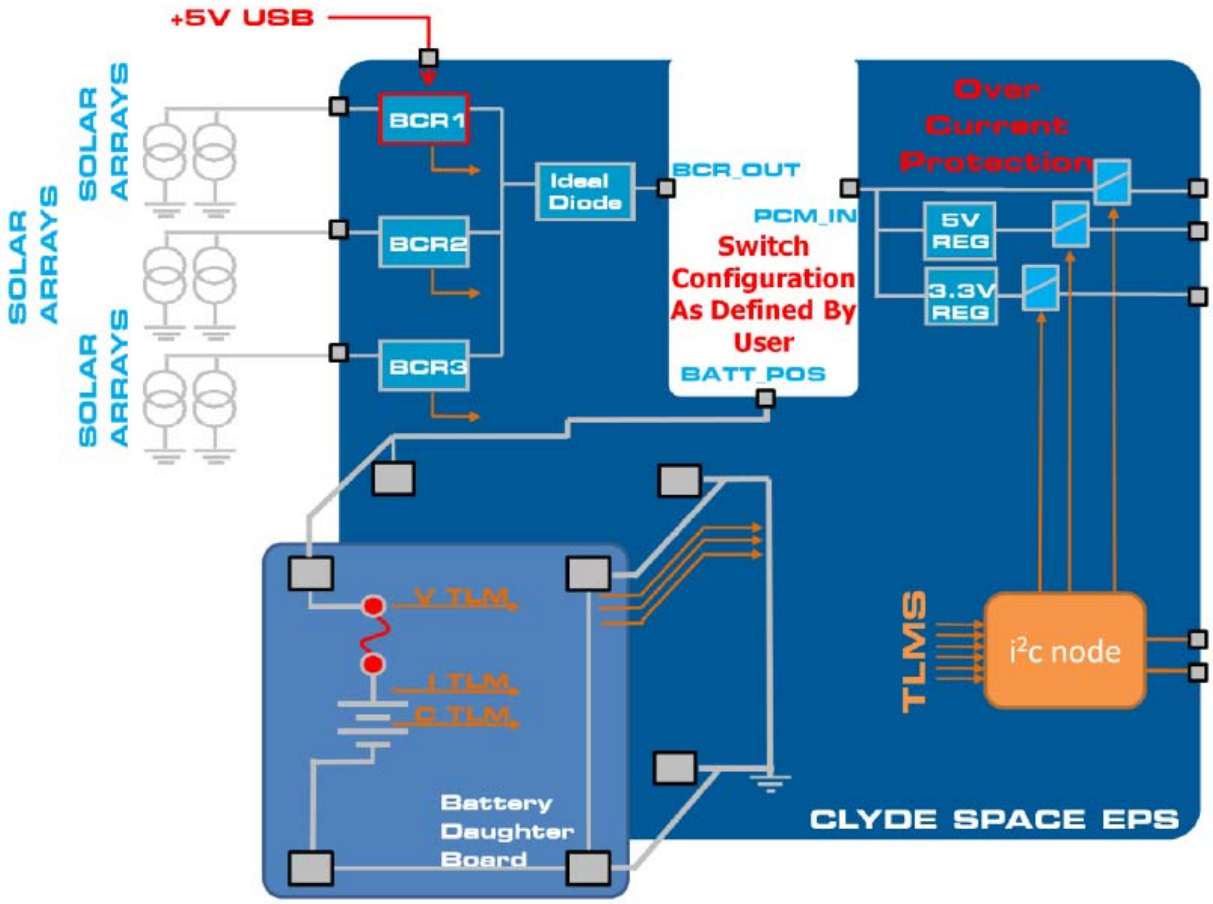

Fig. 1.4: Clyde Space EPS – centralized architecture used on the DICE cubesat.

maintains the voltage at that level. The sun regulated battery bus is output directly to the loads. Two switching regulators provide 5.0V and 3.3V as well.

The EPS manufacture gives the efficiency of the BCRs and regulators without counting the power draw from other card components into the calculation. They rate the converter at greater than 90% at full load.

b) *DICE Battery Charge Regulator Efficiency:* The Space Dynamics Laboratory (SDL) measured the BCR efficiency, shown in Fig. 1.5, by monitoring both the input voltage and current and connecting a load to the battery bus. The load is also

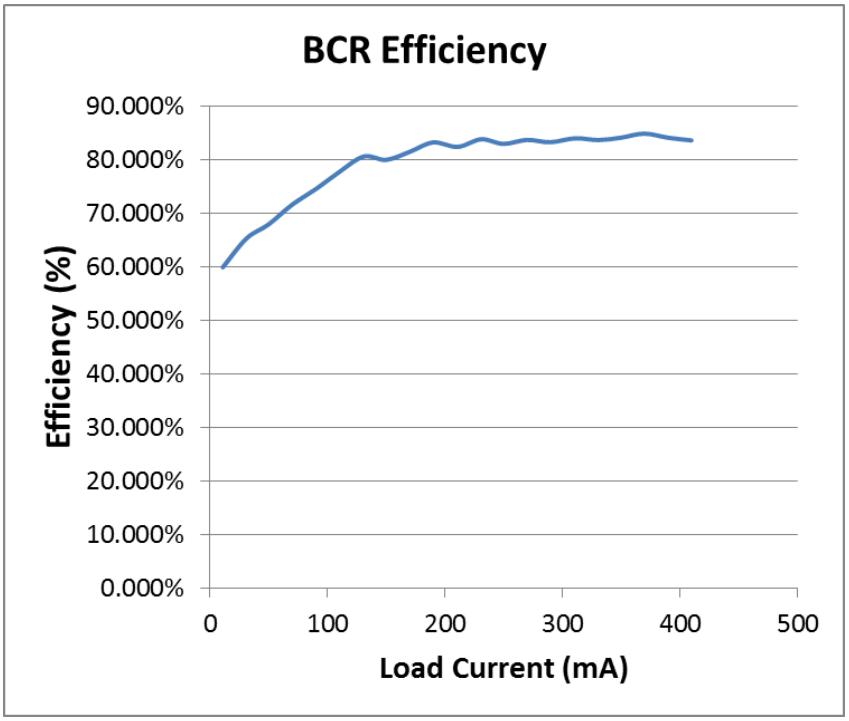

Fig. 1.5: DICE BCR efficiency plot.

monitored for voltage and current. No load is connected to the secondary regulators. SDL accounts for the secondary regulator current draw based on information provided from Clyde Space. This secondary current is subtracted out in the efficiency calculation. The plot shows that the BCR flattens out in the low eighties. This is less than the stated 90% of the data sheet. There may be some other inaccuracies in the SDL measurement, but a common comment observed from the power system research in Chapter 2, Section D, is that switched converter performance seldom matches the manufactures specification. The data from this chart will be used later in this thesis to compare and contrast with the new distributed design given in this research.

c) *DICE 5.0V and 3.3V Regulator:* Both the 5.0V and the 3.3V regulators use buck type switching regulators. The stated efficiency from the Clyde Space is 90% at

full load. Full load for the 5.0V regulator is 1.2 amps. Full load for the 3.3V regulator is 1 amp. The regulators are selected and sized based on the worst case anticipated load for each bus. The exact part number is unknown, so values provided by Clyde Space could not be verified against the Integrated Circuit (IC) manufactures efficiency ratings. The test data shown in Fig. 1.6 and Fig. 1.7 indicate that the 3.3V regulator is approaching 90% and the 5.0V regulator exceeds 90%. If the test data had gone all the way to full load for the 3.3V regulator, it is likely that it too would have reached the 90% value. One lesson important to note from this data is that the manufacture stated efficiency should not be used for critical calculations unless the converter was optimized for the given load. An efficiency curve with actual data is preferred. The best case is when the data is generated from the actual card itself rather than standalone specs from the IC manufacture. The designer can erroneously use the higher efficiency number for

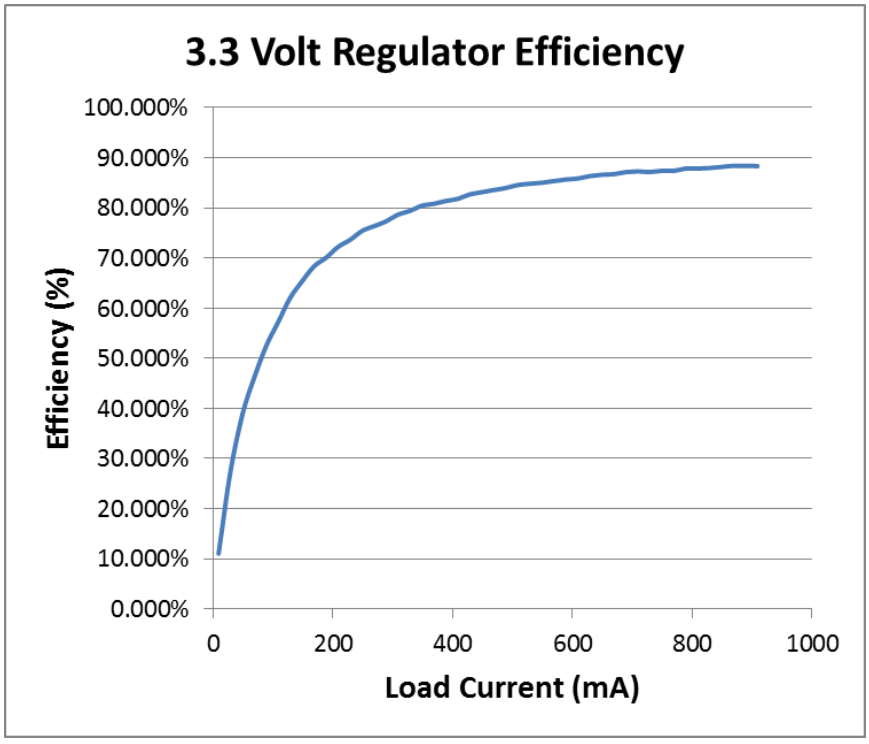

Fig. 1.6: DICE 3.3V regulator efficiency.

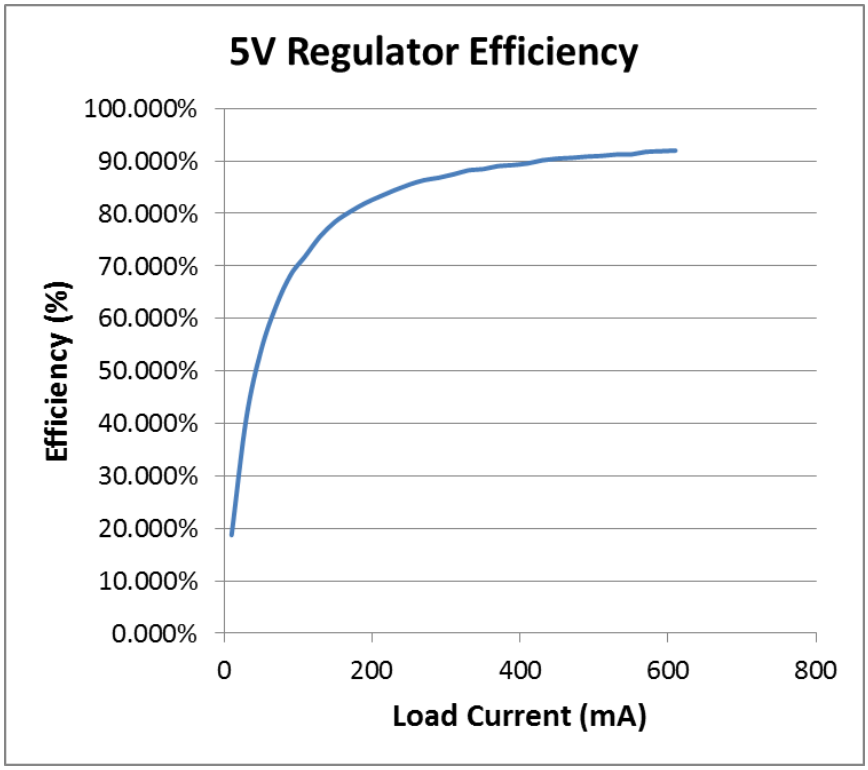

Fig. 1.7: DICE 5.0V regulator efficiency.

all loads when a lower number should apply. This can cause errors in the power budget and subsequent analysis.

d) *DICE Power Budget:* The DICE power budget is shown in Table 1.1. The power budget is based on measurements and estimates of the power requirements for each subsystem or load. The budget is an orbit average power generated from the percent of time the load is on per orbit. Both margin and contingency are added into the budget to allow for errors in estimations. One of the problems associated with an off-the-shelf centralized architecture is that the systems engineer does not know in advance the load each voltage will require. Therefore, it is almost certain you will not be operating at the peak efficiency of the regulator. For the system using point-of-load regulation, the load is known or is learned as the system is being designed. It can therefore be better

optimized.

3) *Distributed Electrical Power System in Cubesats:* The review of the cubesat electrical power system, detailed in Chapter 2, shows that no current cubesats are employing single voltage, sun regulated, distributed architectures for the EPS. The most information available about distributed cubesat architectures is from publications about Cubeflow. Cubeflow is a variant of cubesats, designed to meet the standard size requirements, but they take a unique approach in how the cubesat is mechanically configured. The structure of the cubesat is hinged such that it can be unfolded and laid out flat. A power hub is embedded inside the structure panels. This architecture is based on an Air Force Research Laboratory (AFRL) Plug-n-Play (PnP) concept [6]. The concept heavily relies on distributed architectures to work. Each load in a PnP system has its own dedicated switched power input of 28 volts. The Cubeflow design attempts to mimic this power architecture at the cubesat level [7].

The Cubeflow design has been implemented in demonstration form, but has not been flight proven. At the publish date of the paper, they used a table top power supply to provide the system with 5.0V rather than use a functional EPS controller. However, the concept is the same and demonstrates the interest in creating a cubesat class EPS system that can distribute the unregulated battery voltage to the different spacecraft loads as the only voltage rail. The Cubeflow EPS design recommends only three components for the simple system: solar panels, batteries, and battery charge regulators. The Cubeflow design classifies the power distribution as separate and implements it on a separate embedded circuit card. Although not specifically stated in the paper, it is assumed that

Table 1.1: DICE POWER BUDGET.

Power (mW) Component	Power Peak	Power mWatts	Duty Cycle %	Orbit Average	10% Contingency	% Margin	Margin	Total Power
ADCS Card		160	100%	160.00	16.00	10%	17.6	193.60
PIC CPU		60	100%	60.00	6.00	10%	6.6	72.60
Comm Tx		9300	3%	279.00	27.90	10%	30.69	337.59
Comm Rx		80	100%	80.00	8.00	10%	8.8	96.80
Magnetometer		10	0%	0.00	0.00	10%	0	0.00
GPS		950	5%	47.50	4.75	10%	5.225	57.48
Torque Coils		750	0%	0.00	0.00	10%	0	0.00
Sun Sensor 1		25	100%	25.00	2.50	10%	2.75	30.25
EPS		285	100%	285.00	28.50	10%	31.35	344.85
Payload		300		200	20	10%	22	242
Magnetometer		90	100%	90.00	9.00	10%	9.9	108.90
DC-Probe		40	100%	40.00	4.00	10%	4.4	48.40
E-Field		40	100%	40.00	4.00	10%	4.4	48.40
Motor Control		100	0%	0.00	0.00	10%	0	0.00
Payload Controller		30	100%	30.00	3.00	10%	3.3	36.30
Orbit Period		**Average Power**		**1136.50**			**Power w/Margin**	**1375.17**

subsequent voltage regulation occurs at the point-of-load.

The EPS functional concept for the Cubeflow design is right in line with this thesis design, but the Cubeflow mechanical implementation is somewhat difficult to utilize the full volume without some interesting board stack configurations.

For the distributed architecture to really work, point-of-load conversion must be the standard. Each spacecraft subsystem or card is responsible for regulating its own lower level bus voltages. Because of this, it is critical to understand the various point-of-load converters available on the market and which ones will provide the greatest efficiency, smallest footprints, and best opportunity to optimize. Part of this research is focused on that topic and is discussed in Chapter 3.

C. *Thesis Overview*

This research began with a literature review of existing cubesat EPS systems. The primary goal was to see if any of the spacecraft had flown a distributed EPS architecture. The secondary objective was to compile a list of information about the different EPS

systems for quick reference. Chapter 2 shows the results of this literature review and survey. Chapter 3 presents the results of the switching converter test board. This board was created to allow for the design, build, and test of several different switching converter types with an emphasis on the charge pump. This thesis and the distributed architecture depend on effective and viable point-of-load regulation. Without it, the distributed architecture is not recommended.

Chapter 4 presents a reference design for a distributed EPS for cubesat or Nanosat applications. This section focuses primarily on the regulators, and power distribution to form the EPS. The power source and power storage are referenced but not discussed in detail. This chapter also provides an analysis of the distributed reference design as compared to the more common centralized architecture found in most modern cubesats.

Finally, Chapter 5 contains a summary of conclusions. It also provides thoughts and ideas about future areas of research in this area.

Throughout this thesis, the terms Nanosat and cubesat are used interchangeably. In fact, they are not the same. The cubesat is a subset of the Nano satellite class. The cubesat is defined to fit within specific size, mass, and volume constraints. The cubesat is a Nanosat, but a Nanosat is not necessarily a cubesat. Where differences are important, they will be differentiated.

CHAPTER 2

CUBESAT EPS REVIEW

This research begins with a review of various cubesat EPS designs. The primary starting point for information was what could be found on the internet [8]. Attempts were made to find websites for each known cubesat. Websites were searched for documentation describing the electrical power systems. Many different EPS parameters were collected in a spread sheet to create a cubesat power system data base. The primary parameters collected were those that had to do with architecture types. The main goal was to find out which cubesats used a centralized architecture and which ones used a distributed architecture. A secondary goal was to see if peak power tracking was more prevalent than direct energy transfer. Other collected information included how many voltage buses were distributed, what the bus voltages were, and how large the cubesat was. Data on battery and solar array types were also items of interest. In total, 52 cubesats were reviewed. Information on the electrical power system for 33 of the 52 cubesats was found. Table 2.1 provides a complete list of the cubesats included in this review. Finding information means that some, but not necessarily all, of the information sought after was found. As one would expect, most of the information comes from university or university affiliated institutions. Some information from non-university affiliated cubesats was available, but much less, as they often consider their designs to be proprietary. A complete list of the documents cited in this review are found in the bibliography [3, 8-27].

Table 2.1: CUBESATS IN THIS REVIEW.

Name	Organisation	Size	Architecture	Dist/Cent	# of Buses	Bus Voltages
CUTE-I	Tokyo Institute of Technology	1U	DET	Centralized	3	5R, 3.7bat, 3.3R
XI-IV	University of Tokyo	1U	DET	Centralized	3	5R
XI-V	University of Tokyo	1U	DET	Centralized	4	5, 3.8bat
CanX-1	University of Toronto, Canada	1U	DET/PPT			
CanX-2	University of Toronto, Canada	3U	DET			
DTUsat	University of Denmark	1U		Distributed	1	3.6R
AAU	Alborg University, Denmark	1U	MPPT	Centralized	1	5R
QuakeSat	Stanford University	3U	DET	Centralized	2	5R, -5R
Ncube 1	Norwegian University of Science and Technology	1U				
Ncube 2	Norwegian University of Science and Technology					
UWE-1	University of Wurzburg, Germany	1U	PPT			
CUTE-1.7	Tokyo Institute of Technology	2U	PPT	Centralized	4	3.3R,5R, 6R,3.8Bat
ION	University of Illinoise	2U	PPT			
Sacred	University of Arizona	1U		Centralized	2	5R,3.3R
KUTEsat	University of Kansas	1U		Centralized	3	5R,3.3R, 12bat
ICE Cube 1	Cornell University	1U	PPT			
RINCON	University of Arizona	1U				
SEEDS 1	Nihon University, Japan	1U	DET		1	5R
SEEDS 2	Nihon University, Japan	1U	DET			
HAUSAT	Hankuk Aviatin University	1U		Centralized	3	5R, 3.3R, 3.6bat
MEROPE	Montana State University	1U	PPT	Centralized	5	5R,-5R,6R, 8R,5R,5R
AeroCube-1	Aerospace Corporation	1U				
CP2	Cal Poly	1U	PPT	Centralized	4	
CP1	Cal Poly	1U	DET	Centralized		
ICE Cube 2	Cornell University	1U	PPT			
Mea Huaka	University of Hawaii	1U				
GeneSat-1	Center for Robotic Exploration and Space Technologies	3U				
CP3	Cal Poly	1U	PPT	distributed	6	3R,3R,3R,3R,3R, 3.7bat
CP4	Cal Poly	1U	PPT	distributed	7	3R,3R,3R,3R,3R, 3.7bat
AeroCube-2	Aerospace Corporation	1U				
CSTB-1	Boeing	1U				
MAST	Tethers Unlimited	3 - 1U				
Cape-1	University of Louisiana	1U				
Libertad-1	University of Sergio Arboleda, Columbia	1U				
Delfi-C3	Delft University of Technology, Holand	3U	DET	Distributed	1	12R
AAUsat-2	Alborg University, Denmark	1U				
Compass One	Fachhochschule Aachen, Germany	1U	PPT	Centralized	3	3.3R,5R,5R
AeroCube-3	Aerospace Corporation	1U				
Hawksat-1	Hawk Institute of Space Sciences	1u				
Pharmasat-1	Santa Clara University, Nasa	3U				
Polysat CP6	Cal Poly	1U				
Aggiesat-2	Texas A&M	1U				
BEVO 1	University of Texas at Austin	?				
Explorer1Prime	Montana State University					
Hermes	Colorado Space Grant Consortium	1U	DET	distributed	4	7.4R,7.4R,5R,3.3R
KySat	Consortium of Kentucky Universities	1U	PPT	Centralized	3	12bat,5R,3.3R
AtmoCube	University of Trieste, Italy	1U	DET	Centralized	6	3.3R,5R,6R,-6R,-100,3.3R
e-st@r	Politecnico di Torino, Itally	1U	PPT	Centralized	3	7.4bat,5R,3.3R
Goliat	University of Bucharest, Romania	1U	DET	Centralized	>1	7.4bat, others
OuFTI-1	University of Liege, Belgium	1U	DET	Centralized	3	7.2bat,3.3R,5R
DICE	Utah State University	1.5U	PPT	Centralized	3	7.2bat,3.3R,5R
Colony 1	Pumpkin	3U	PPT	Centralized	3	7.2bat,3.3R,5R

A. *EPS Review For Distributed vs. Centralized Architecture*

Table 2.2 shows the number of systems that use the centralized architecture as opposed to the distributed architecture. The centralized systems are very standard in that they produce most all of the regulated bus voltages required for the satellite and then bus them out to the individual loads. Each load has access to the bus voltage. Load switching is not typically associated with this type.

The distributed systems, identified in the review, are unique and listed as distributed because they did not fit the classical centralized architecture. Each of the distributed designs is discussed in greater detail in the following paragraphs.

Cubesat 1: This cubesat employs a lithium-ion battery for power storage and operation during the eclipse [18]. The battery output is regulated using a sepic (buck-boost) type converter. The newly regulated bus is then distributed to the various system loads where point-of-load regulators are used to lower the voltage to the required level. A battery charge regulator is used to charge the battery and source power to the main bus regulator during sun lit portions of the orbit. Power delivered to the loads must pass through two regulators and is subject to the associated losses. This design is a good example of a distributed design. There is no information explaining why the designers decided to regulate the distributed buses. Regulation at this level is less power efficient but more space efficient.

Table 2.2: CENTRALIZED VS. DISTRIBUTED ARCHITECTURES.

EPS Architecture Type	**Quantity**
Centralized	20
Distributed	5

Cubesats 2 and 3: These cubesats were built by the same organization [10]. The same EPS was used both times demonstrating a higher level of utility through component reuse. This design provided a dedicated 3 volt converter on each switched bus. Each bus was dedicated to a specific load per a distributed architecture. It was then left to the load to further regulate the switched bus voltage if required. There is no information as to why the voltage regulation is done on the power board rather than all of it at the load. Unlike the first example, each of these distributed buses has its own dedicated converter. The same amount of board space is required to place the converters at the load as at the EPS board.

Cubesat 4: This cubesat is interesting in that there is no battery for operation through the eclipse [15]. The bus is powered up new each time the satellite comes out of eclipse and into the sun. There is one 12 volt regulated bus that is distributed to all of the subsystems. Each subsystem is responsible for regulating all of its own lower level required voltages. There is only one regulator that the power is required to pass through prior to reaching the load.

Cubesat 5: This cubesat is similar to cubesats 2 and 3 in that it provides a dedicated regulated output to each of the defined loads [23]. It is slightly different in that each output is a different voltage. Because the outputs are dedicated to only one load, it was considered distributed. However, it is given a low rating as far as utility goes. The custom bus outputs would likely require change if the design were to be used on a different cubesat. Again, no information was found that suggests why the regulation was performed on the EPS card rather than at the point-of-load. From a board space point of

view, there is no difference in placing the regulators at the load. Placing the regulators at the loads, and distributing a single bus voltage, would have greatly increased the design utility.

There was one other cubesat EPS design that was classified as centralized in the review count that potentially could have been classified as distributed. The design had only one output voltage, 5V, which was regulated on the EPS card. The voltage was then "bused" to each of four loads without any on/off control. So although there was only a single output voltage and a single bus, it was classed as centralized because the regulation occurred locally on the EPS card and more importantly the single output voltage was bused to four separate loads.

None of the cubesats, classified as distributed in the review, distributed an unregulated battery bus as the sole output. Cubesats 1, 4, and the one centralized cubesat distribute a single bus and are closest to what the proposed architecture is that has the greatest utility and the lowest power loss at the EPS card itself.

B. *Power System Review for DET vs. PPT Architecture*

Table 2.3 shows the number of cubesats that employed the two main types of EPS architectures. It is split quite evenly between DET and PPT. There was one cubesat listed as "Other" because it actually used both DET and PPT on the same cubesat due to

Table 2.3: CUBESATS WITH THE LISTED EPS ARCITECTURE TYPE.

EPS Architecture Type	Quantity
Direct Energy Transfer	13
Peak Power Tracking	15
Other	1

different sized arrays. The PPT design was used on a panel that was a different size than the rest. The PPT converter enabled it to operate at the same voltage level as the other larger panels.

The very first few EPS systems that were launched consisted of DET EPS architectures. However, for later designs, the peak power tracking architecture appears to be the favorite. The need to squeeze the maximum power from the arrays is no doubt the motivation for the PPT designs. DET designs are still viable and are being used for current cubesat missions.

C. *Power System Review for Bus Voltages*

There were two other main power system parameters collected in the review. First, is the number of voltage buses that each cubesat outputs. Second, the voltage rail values, both regulated voltages and unregulated battery voltages. The most common number of buses for each cubesat is three, as shown in Table 2.4.

Table 2.5 shows the number of cubesats that use the listed regulated voltage. There is a pretty wide spread, but the obvious most common regulated outputs are 3.3V and 5.0V. There was one cubesat that generated a negative 100 volt output but it was not listed in

Table 2.4: CUBESATS WITH THE LISTED NUMBER OF VOLTAGE BUSES.

Number of Buses	Quantity
One Bus	3
Two Buses	2
Three Buses	10
Four Buses	4
Five Buses	1
Six Buses	2

Table 2.5: CUBESATS WITH THE LISTED REGULATED VOLTAGE OUTPUTS21

Common Regulated Bus Voltages	Quantity
3 Volt Regulated	2
3.3 Volt Regulated	13
3.6 Volt Regulated	1
5 Volt Regulated	17
-5 Volt Regulated	2
6 Volt Regulated	3
-6 Volt Regulated	1
7.4 Volt Regulated	1
8 Volt Regulated	1
12 Volt Regulated	1

the table due to the extreme oddity of the voltage value. The documentation did not state what the voltage was for, but it is assumed to be unique to the payload. This list is not comprehensive for regulated voltages used on cubesats. Many cubesats alluded to the fact that further voltage regulation takes place at the load in the form of point-of-load converters. Linear regulators were specified for use at these loads.

Table 2.6 lists the common battery bus voltage used on the cubesats and the number of cubesats that used those voltages. A one cell or two cell series connected lithium-ion cell type was dominant. Every cubesat, that information was available for, used Lithium chemistry batteries for energy storage. They also all used solar cells for energy generation. The one exception was noted earlier in this section in that it did not use a

Table 2.6: CUBESATS WITH THE LISTED BATTERY BUS VOLTAGES.

Common Battery Bus Voltages	Quantity
4.1 Volt Battery	5
8.3 Volt Battery	6
12.3 Volt Battery	2

battery at all and simply shut down during the eclipse and rebooted itself during the sunlit portion of every orbit.

D. *Power System Review Conclusions and Insights*

One insight from the power system review is that most of the EPS cards are custom designs. There were a few that used an off-the-shelf design, but most of them are unique. This is not altogether unexpected since the original purpose of the cubesat was a teaching tool for universities to help students learn fundamentals of spacecraft design. However, if cubesats are to take on a more operational purpose, then having a generic design that can be used for more than one custom application is important.

Throughout the review, a common expression was a desire to redesign the EPS to be more common or modular for use on more than one cubesat and more than one payload type [20]. The ultimate goal would be to create an EPS design that is considered "off-the-shelf." This is the same thing as greater utility over a wide range of missions and bus designs.

There is at least one EPS manufacturer that markets commercial EPS units. They have followed the de facto bus standard made popular by Pumpkin and the cubesat kit. Clyde Space is able to sell non-custom EPS units to customers that conform to the cubesat kit standard [28]. Once again, they demonstrate that a standard is essential to greater utility.

Another interesting comment in the literature review is that converter performance is often lower than manufacture specification. Nowhere in the review did anyone provided reasons why the performance was lower. From experience, the stated specifications in

manufacture data sheets are often best case or they are single point efficiency numbers rather than actual curves. These efficiency numbers are obtained through optimization of the load, the inductors, capacitors, and other components in the circuit. Optimization is not a trivial process and usually requires “tweaking” to the completed design. When the typical engineer completes the design, it is rare that the circuit will be sufficiently optimized. Many times, optimization at the rated peak load is not even possible if the engineer has to account for a wide range of loads. This is commonly the case with centralized bused designs where multiple loads can cause a large variation in load currents to the central bus.

Lastly, it was noted that not one cubesat, where information was available, distributed just the sun regulated battery bus. In all cases, the voltages leaving the EPS cards were regulated. This is very different from typical small satellite configurations where the 28 volt battery bus is distributed to the various loads and each load is expected to regulate its own lower level voltages [1].

In the report on the Power Supply for the AAU cubesat [21], advantages and disadvantages of various EPS architectures were discussed. This was done as a precursor to them selecting the final architecture for their cubesat design. They looked at various topologies using different numbers of switching converters. Like all other EPS designs, they selected a two converter design, where the last converter outputs a regulated bus voltage used by all loads. They discussed the single converter design with a distributed battery bus, but dismissed it because the output bus would be the same as the battery voltage or in other words, unregulated. They therefore included the second regulator to

obtain a regulated bus. In Chapter 4, an unregulated, single battery voltage distributed bus output design is presented and analyzed. The design allows the load to implement the second regulating converter rather than doing it on the EPS controller card. The advantages of the later design are listed below.

1. The unregulated battery bus is usually higher voltage than the subsequent regulated voltages. Therefore, there is less I^2R losses in the interconnect cabling. Or, a smaller gauge wire can be used.
2. Placing the regulator at the point-of-load allows the designer to optimize it for the single load. The load variation at the point-of-load is usually smaller than at the system level. This allows a converter to be selected specifically for that load and then optimized.
3. Point-of-load regulators are typically smaller and require smaller inductors and/or capacitors as compared to a multi-load single bus regulator.
4. It is possible to isolate specific loads by using point-of-load converters. Isolated converter topologies can be used if required. Even without full isolation, each load is less subject to interference from other loads.
5. Simple and consistent ON/OFF control can be implemented. Since only one voltage is distributed, the switch design for each bus is the same.
6. The utility of this distributed architecture would be significantly increased if a common battery voltage standard could be established.

The primary disadvantage is that it takes more regulators to do the same thing. If there are four loads, it would require four separate regulators located at each load rather

than a single regulator located at the EPS. This disadvantage can be mitigated by the vast assortment of low-power regulators currently available. Each load regulator can be smaller and tuned for its specific application where the larger single regulator encounters difficulties.

CHAPTER 3

POINT-OF-LOAD REGULATION

Point-of-load regulation is a requirement for the distributed architecture design. Many commercially available point-of-load converters were researched for their possible use in a distributed design. Seven different devices were ultimately selected for the test board design [29-35]. The research focused on low-power, high efficient, switch mode type converters with a special point of looking at inductorless converters, otherwise known as charge pumps. There is a fairly wide assortment of low-power charge pump converters with outputs ranging from tens of micro amps up to a few hundred milliamps. At current levels above this, the inductor-based converters offer the best selection. The main goal was to find an assortment of low-power devices that could be used in different configurations as point-of-load converters. Converters were procured and built into a test board where converter performance parameters could be measured. The purpose of the test board was threefold: first, to determine the "as designed" efficiency of the converters; second, to learn how difficult it is to complete the design; and third, how much board space these small converters consume.

The next few subsections describe the different kinds of converters reviewed and experimented with. The test board and the test results, from the research, are also discussed.

A. *Inductor-based Switching Converters*

The inductor based switching converter is by far the most common. The research

focused on very low-power converters that had internal switches also known as "monolithic." The rationale was to optimize for low-power requirements of the cubesat loads, to simplify the design, and keep the required board real estate to a minimum. There are four main types of converter functions: buck, boost, buck-boost, and invert. Each function may be used or a combination thereof, depending on input and output power voltage and power requirements. The inductor based converter is best suited for point-of-load applications that require the greatest amount of power. Most all inductor based converters reviewed were rated for greater than 500 mW. As small as it sounds, it is actually quite large for cubesat POL applications. The DICE power budget, shown in Table 1.1 for reference, shows more than half of the loads are less than 500 mW. Only the transmitter is greater than 1 watt. Further insight down to the board level would indicate that loads for specific buses are even smaller. To get the best efficiency from the converters, we want to be closer to their rated maximum loads. For this reason, the inductorless converter or charge pump was considered for use in these ultra-low-power applications.

B. *Inductorless Switching Converters (Charge Pump)*

The charge pump switching converter becomes an ideal POL device for extremely low-power applications such as the cubesat. Like the big brother inductor based switching converter, the charge pump comes in four main varieties: buck, boost, buck-boost, and invert. The charge pump power range goes from a few milliwatts up to about a watt. Typically, only two or three capacitors are required. At the low power required by cubesat loads, often a ceramic capacitor can be used to keep foot prints to a minimum.

On the research test board, the charge pumps were found to be very simple compared to the inductor based counterpart.

C. *Point-Of-Load Test Board Design*

Seven different converters were selected for implementation on the test board. Five of the seven were charge pumps. One sample from each of the four main converter types was selected. Some of the converters were configurable to operate in multiple functions.

The data sheet for each component was consulted for the design and implemented according to the recommended or typical configuration for each case. All seven converters were implemented onto a single circuit card. A jumper was placed on the input power for each individual circuit to enable, and power, only one regulator at a time. The board construction is four layers. The top and bottom layer are for signal routing while the two inner layers are power and ground planes.

Figure 3.1 shows the test board layout. Tight component placement was attempted for each localized converter to get an idea of the circuit board footprint required to implement the POL converters. Each of the selected converter devices is available in multiple packages. Smaller packages than the ones selected for the test board are available. Since the test board was hand built, larger parts were purposely selected such that they could be assembled without special surface mount soldering equipment. In all cases, surface mount components were still selected. When available, Small Outline Integrated Circuit (SOIC) packages were selected. Since board space is an issue, it should be noted that much smaller packages are available. It is the capacitors and the inductors that begin to dominate the overall footprint rather than the IC controller chip.

Figure 3.2 and 3.3 show the schematic design of the test board. For each circuit, a jumper select is included on the input for power and an output header is installed where a load can be connected. These two components would not normally be installed on a real board but they accounted for a lot of the board space. All components, except a capacitor for circuit 4 (U3), were placed on the top side of the board. Placing more parts on the bottom side of the board would have made the layout more compact. The overall board dimensions are 3.8 x 2.5 inches. The board space required for each circuit varied somewhat but was around 0.3 square inches. This could have been further reduced had the smallest possible device packages been used for all component types (controller ICs, resistors, and capacitors). The inductors were the only parts that looked like it would be more difficult to reduce. With inductors and capacitors, the higher the frequency, the smaller the component. The down side is that switching losses increase and become dominate at the highest frequencies. A trade exists here for the circuit designer to potentially trade efficiency for board space. The smallest footprint for the test circuit, outlined in red in Fig. 3.1, was about 0.07 square inches excluding the input and output headers.

For the charge pumps, a minimum of two capacitors are required and usually three. There are many different charge pump topologies but nearly all wanted an input capacitor, which in some cases could be eliminated, depending on your proximity to the main source. The charge pump converters also all required a fly back capacitor or a switching capacitor that acts as a temporary charge storage location. An output capacitor or filter capacitor is also required to minimize output ripple on the voltage bus. Each

data sheet provides information on the capacitor selection criteria. Close adherence to the criteria will produce a better quality, higher efficiency design. The capacitor selection process was not difficult for the charge pump devices. One of the great advantages of the low-power, high switching speed devices is that capacitor values can be kept low. This also allows for the use of extremely low Equivalent Series Resistance (ESR) ceramic capacitors in most instances.

In addition to the input and filter capacitors, the inductor based designs use an inductor as an energy storage element. The capacitor and inductor selection process is coupled and is more difficult than the charge pump capacitor selection process. However, the process is still quite straight forward for the low-power class. For both of

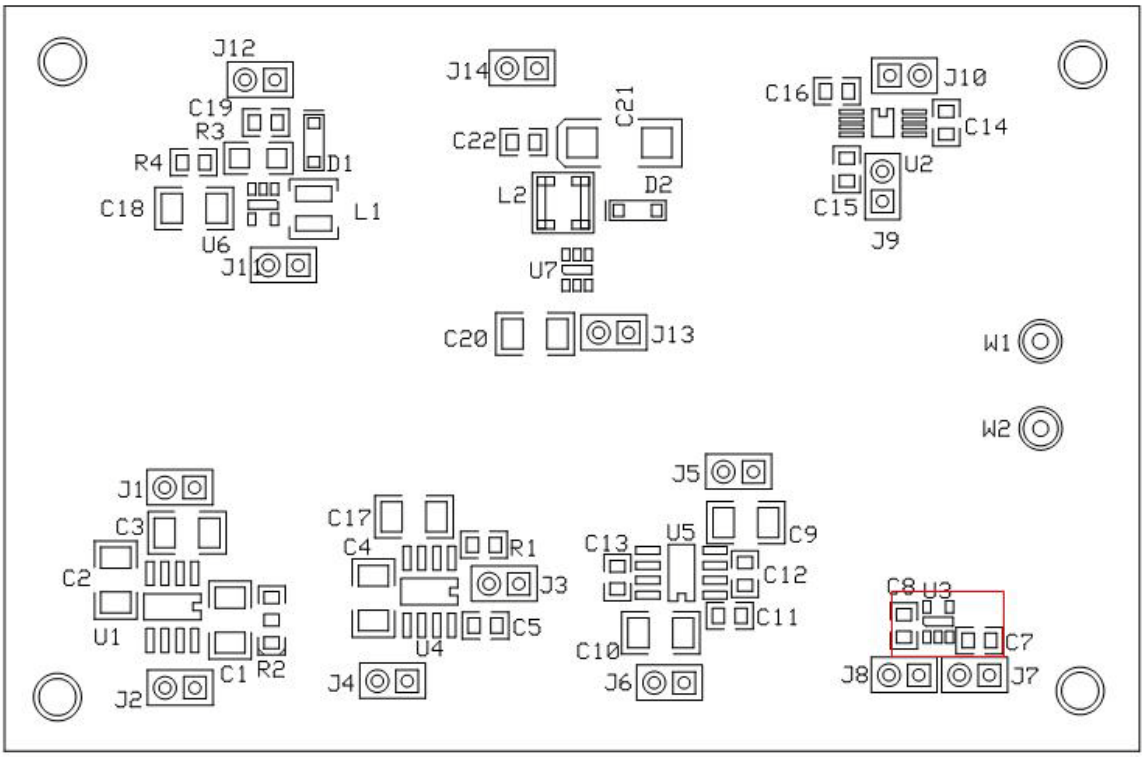

Fig. 3.1: Point-of-load converter test board.

the inductor based converters on the test board, the switching element was internal to the IC controller similar to the charge pumps. This eliminates one more variable in the design process.

D. *Point-Of-Load Converter Board Test Results*

Each converter was tested separately by using the enable jumper on the input of each circuit. Without any load connected, both the input and the output voltage of the Unit Under Test (UUT), were measured using a Digital Voltage Meter (DVM). A current monitor was also placed in series with the input power supply to obtain no-load input currents for each circuit. An oscilloscope was used to measure the ripple at both the input and the output. Figure 3.4 shows the test configuration and Table 3.1 provides the test results.

In the "No Load" state, all of the converters performed as expected. All of the converters were within specification on the no load input currents, voltages, and power ratings listed on the data sheets. The ripple voltage for both the input and the output was a little bit of a surprise. This value was not specified in most of the data sheets. However, some of them showed waveform outputs that describes the expected ripple. The surprise comes from dealing more with linear regulators rather than with switching regulators. For those unaccustomed to switching regulators, they will need to ensure that the ripple inherent in the switching converters is acceptable. By varying the input and the output capacitance, the respective ripple voltage can be reduced or increased if desired. Often, it is a trade between higher ripple voltage and larger, more expensive capacitors. Application of a load will likely decrease ripple due to increased parasitic capacitances.

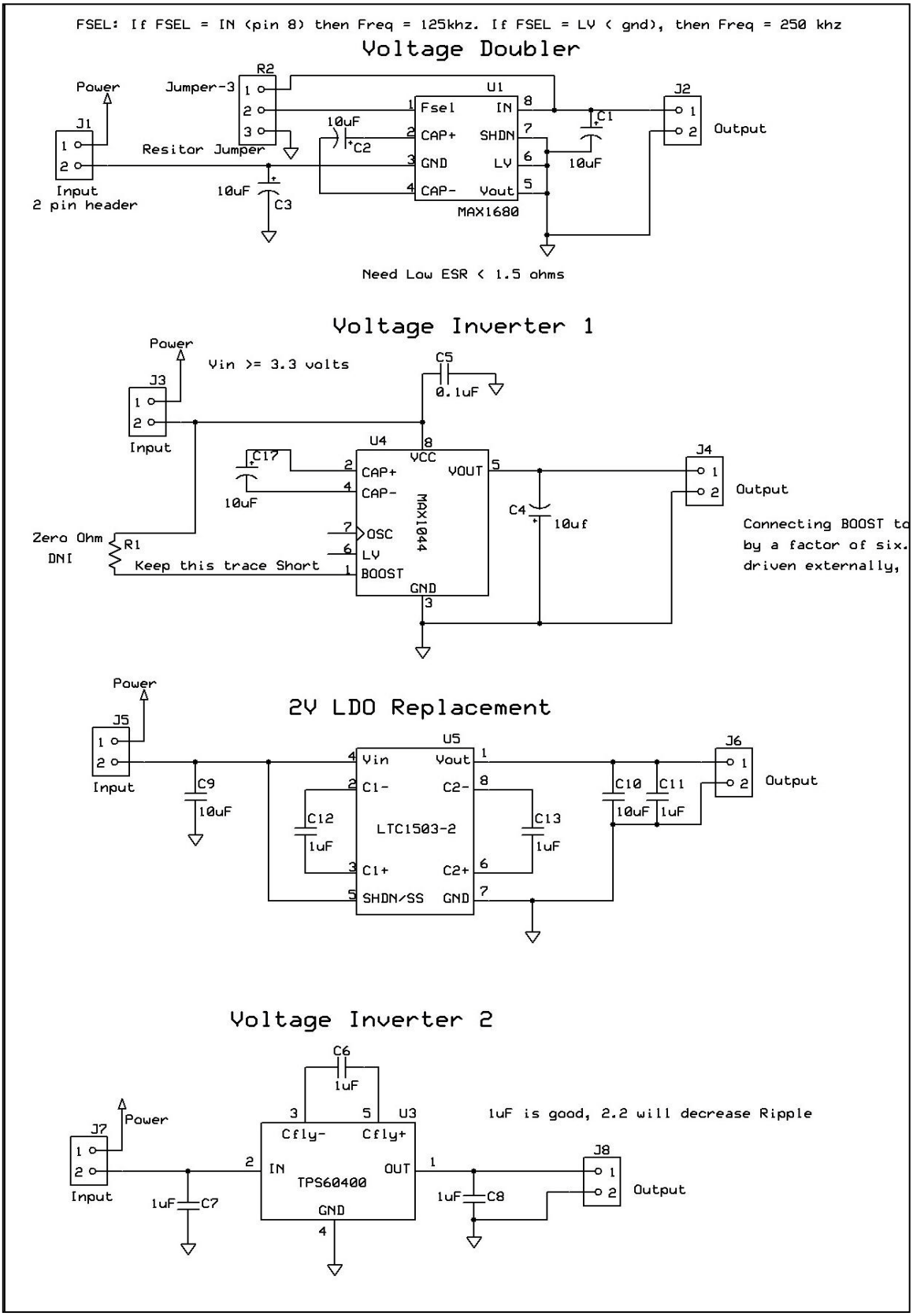

Fig. 3.2: Test board circuits part 1.

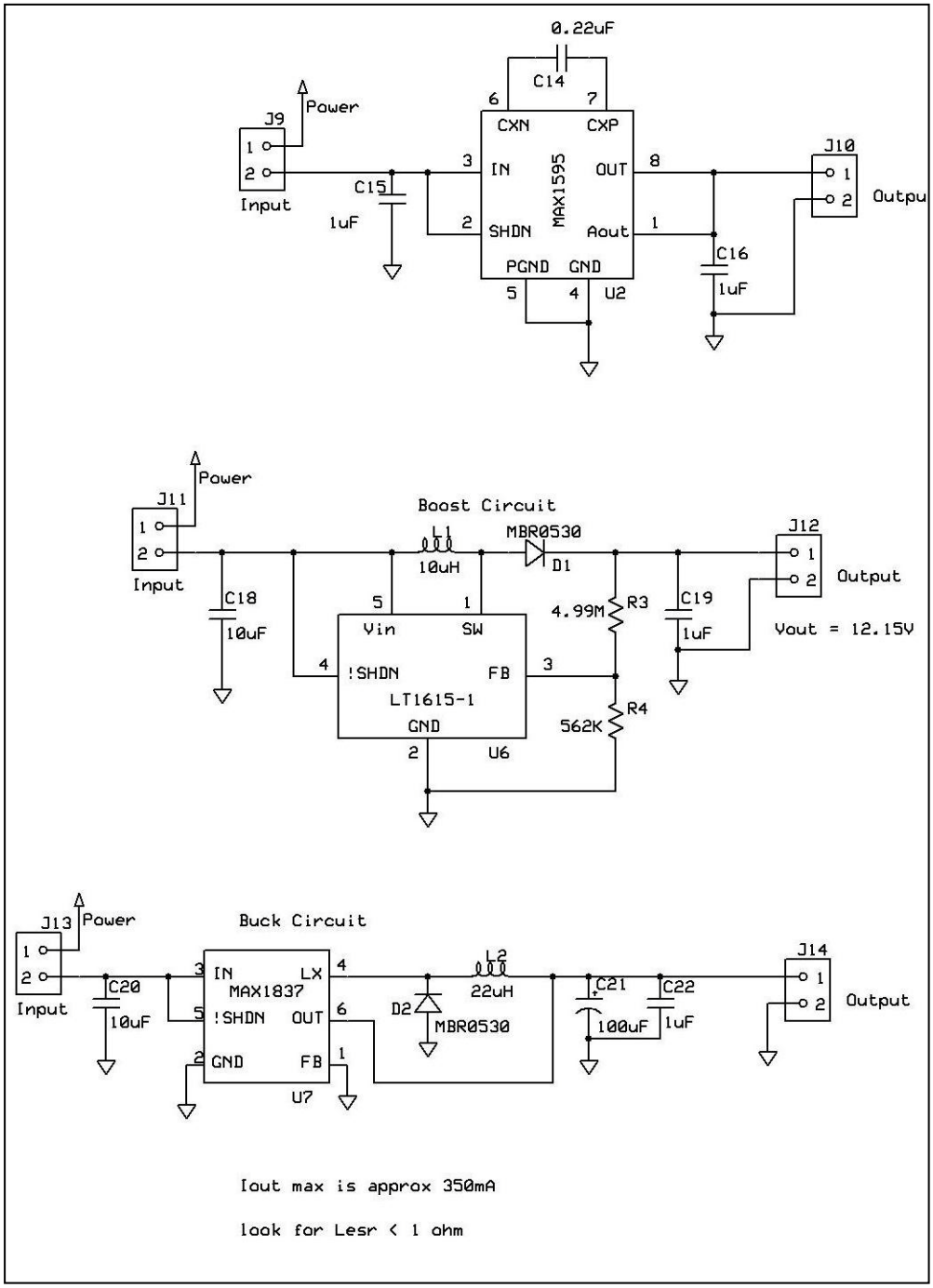

Fig. 3.3: Test board circuits part 2.

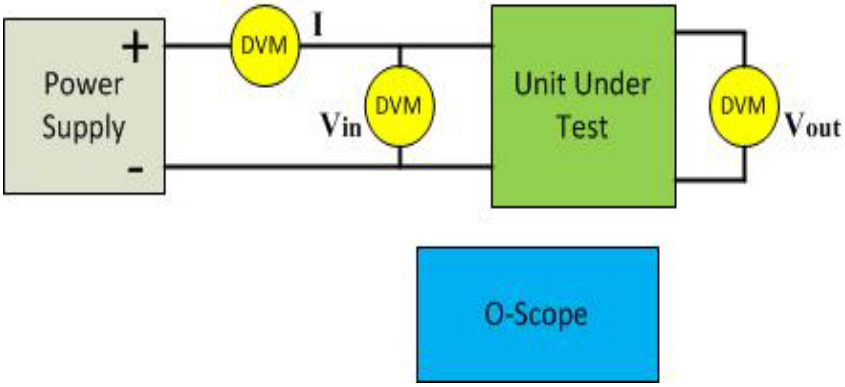

Fig. 3.4: Point-of-load circuit board test setup for no load measurements.

Next the converter efficiency was measured. Again, the converters were all run one at a time. An electronic load was installed on the output of the UUT as shown in Fig. 3.5. The electronic load allowed for very precise control of the load current. The constant current mode of the electronic load was used to obtain a steady load current. Output power was calculated by multiplying the output current and voltage. The input power was calculated by measuring both the input voltage and current, using digital volt meters, and multiplying them together. Efficiency is then the ratio of output power to input power expressed as a percentage. A nominal load point was picked to measure the output ripple for comparison to the no load measurement. In all cases except one, the ripple went down under load as expected. The exception was not re-verified. The initial measurement is assumed erroneous.

Appendix A contains the efficiency measurement data collected from the test board

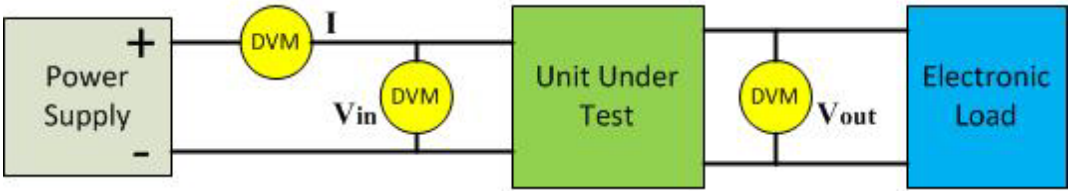

Fig. 3.5: Point-of-load circuit board test setup for efficiency testing.

Table 3.1: NO LOAD TEST RESULTS FOR POINT-OF-LOAD TEST BOARD.

Device	Input Voltage	Output Voltage	Input Ripple	Output Ripple	Input Current
MAX1680	5	9.97	237mv p-p	180mv p-p	2.87 mA
MAX 1044	5	-5	55mV p-p	30mV p-p	40 uA
LTC1503	5	2.01	200 mV p-p	200 mV p-p	20 uA
TPS60400	5	-5	155 mV p-p	100 mV p-p	120 uA
MAX1595	5	3.46	400mV p-p	300mV p-p	120 uA
LT615-1	5	12.45	55 mV p-p	600mV p-p	30 uA
MAX1837	5	3.34	370mV p-p	150mV p-p	10 uA

for each converter. The one item of note is that the input voltage drops as the load current is increased for each converter table data. This is because of the internal series resistance of the DVM used to measure the input current. The series resistance, in the milliamp mode, is measured at 1.86 ohms. This becomes an input voltage factor and was accounted for in the efficiency measurement. Table 3.2 is a summary of the measured efficiencies from the different regulators. This table only shows the peak efficiency. The summary suggests that the charge pump converters are indeed a viable solution for point-of-load converters.

Table 3.2: POINT-OF-LOAD PEAK EFFICIENCY.

Device	Type	Function	Efficiency Percent	Ripple (mV P-P)
MAX1680	Charge Pump	Doubler	96%	170
MAX1044	Charge Pump	Inverter	93%	28
LTC1503	Charge Pump	LDO Replacement	78%	160
TPS60400	Charge Pump	Inverter	93%	14
MAX1595	Charge Pump	Buck-Boost	66%	330
LT1615-1	Inductor	Boost	87%	NA
MAX1837	Inductor	Buck	87%	147

The voltage doubler and inverters exhibited excellent results with efficiencies greater than 90%. The low drop out converter replacement also performed very well by comparison to a typical linear regulator. Of course, the voltage ripple would have to be taken into consideration for many applications. However, where the ripple can be tolerated, this type of charge pump is recommended over an LDO for efficiency sake. The buck-boost charge pump performance was on the low side. The data sheet provides two efficiency curves at two different input voltages, neither of which was used for the test. The data sheet showed that peak efficiency could be as low as 67% which is effectively what was measured on the test board. The data sheet also shows that the device could produce results as high as 86% depending on the input voltage. A different input voltage was not tested to confirm this. For the inductor based converters, peak efficiencies were measured to 87%. However, the LT1615-1 device, or boost converter, did not perform over its full specified load range. As the load was increased, the output voltage quickly fell out of regulation. A failure analysis was not performed to confirm the root cause of the anomaly. On the other hand, the buck converter performed very well.

E. *Conclusions*

The commercially available charge pump is a very good fit for POL converters in the low-power cubesat application. One drawback to the commercially available charge pump is the limited input voltage range. There is very little selection of parts for input voltages greater than 6 volts. With this limitation, it forces the cubesat power engineer to design around a parallel battery system. Multiple battery cells can be placed in parallel,

but you are limited to 1 cell in series, assuming lithium-ion battery chemistry. There is nothing wrong with a battery this size. Some of the cubesats referenced in Chapter 2 used bus voltages in this range. It is a constraint never-the-less. A second drawback is limited options for regulated output voltages. There are some charge pumps with fixed outputs, but fewer that have an adjustable output range. The ones that do exist suffer from poor regulation efficiency. The combination of the charge pump and the inductor based converter may be the compromise and is application specific.

The charge pump can be a more efficient solution over the LDO regulator. Many times a linear regulator is used to generate voltages for digital electronics such as Field Programmable Gate Arrays (FPGA), Central Processing Units (CPU), logic, and memories. For these applications, an analysis and decision must be made to determine which component is best suited. The digital electronics are usually tolerant of low level ripple, and the process of implementing a charge pump versus an LDO is not much more complex. The charge pump will likely consume less board space since the device will use less power, and therefore can be packaged in a smaller package. Where ripple cannot be tolerated, such as high accuracy analog circuits, the linear regulator is still the converter of choice.

The charge pump design is very easy to implement using components commercially available. After the proper function is determined, the process of sizing the flyback capacitor and filter capacitors was not difficult. The data sheets provided adequate information along with recommendations and limits. For charge pumps that performed simple functions, such as doubling or inverting, the circuit designer has to pay attention

to the voltage droop that can occur as a function of load. These types of converters perform no active feedback regulation and the output will be reduced as the load current increases.

The use of a charge pump allows you to eliminate the inductor. The inductor is often the largest component in a system. The low-power charge pump is designed to be very small and consume a minimal amount of board space. As stated earlier, the controller IC and integrated switch will likely be the smallest device. The capacitors and inductor, if necessary, will dominate the calculation for board space requirements. For the low-power POL devices, the 0603 and 0805 body style ceramic capacitors could be used. With parts this small, it allows you to drop multiple POL regulators onto a circuit card design as required for optimization.

Although the integrated converters, both inductor and charge pump, are quite straight forward in their implementation, a bread board circuit of the converter design is still recommended. Doing so will allow the circuit designer to become familiar with any subtle characteristics of the device. It will give the designer an opportunity to learn how to configure, characterize, and optimize the performance of the converter. This information will be important when calculating power dissipation for the given circuit card designs.

In comparing the charge pump against the converter with an inductor, the charge pump appears to be a simpler design. There was one less storage element requiring selection and optimization. It is easier to optimize one energy storage element than two, especially when the two elements are coupled closely. The inductor based converter is

more flexible in buck, boost, and buck-boost type designs. A wider input range is available and better efficiency can be obtained in regulated applications.

There is a tremendous selection of inductor class converters commercially available. However, the selection diminishes quickly down at the very low-power end. The best approach is a combination of the different converter options. A distributed EPS, wherein only one unregulated voltage is distributed throughout the spacecraft, requires local voltage conversion at the loads. A typical spacecraft load will require several different bus voltages. The low-power combination of charge pumps and inductor based switching regulators, used as point-of-load regulators, enables efficient operation and a high degree of utility.

CHAPTER 4

DISTRIBUTED DESIGN ANALYSIS AND COMPARISON

This section outlines and describes a distributed EPS with point-of-load converters. Parts of this design have been built and tested as isolated components. Most of the design is still just paper. This design targets the DICE spacecraft described in Chapter 1, Section B.2. This distributed design attempts to provide all of the same voltages generated on the DICE spacecraft card sets. If a complete redesign were to take place, further optimization could likely be realized. However, for the sake of analysis and comparison, the original design loads have been used. To evaluate the impact of charge pumps, an attempt will be made to incorporate them into this distributed design. Efficiency will be given precedence over other parameters. However, if a charge pump can be used, it will be evaluated.

A. *EPS Analysis and Comparison Approach*

The goal of the comparison is to show that an optimized distributed EPS can be realized such that the efficiencies of the distributed design are not significantly different than the centralized system efficiencies with its inherently non-optimized converters. If the design can be shown to be at least equal, or close to equal, then the advantages of the single voltage, distributed bus will allow for the sought after high degree of utility, and reuse, in the EPS design.

The analysis and comparison of power systems performed by the students at the University of Aalborg [21] resulted in a distributed architecture except they did the

regulation all local to the EPS card. The regulated buses were distributed to the downstream electronics. The assumption is that subsequent regulation took place locally at the point-of-load. Their analysis looked only at the initial stage of the power conversion chain and did not include all of the secondary and later stages. Looking at the entire spacecraft power system helps provide perspective not available by just looking at the first stage.

The comparison mechanism will use power converter models, assembled in MatLab Simulink®. The approach is to model the existing DICE power architecture and the distributed EPS design using measured efficiencies from the actual converters and data sheet values provided by the manufacture. Both architectures will be modeled using the same loads and local voltages. The differences will be in the architecture and the ability to optimize the distributed system.

B. *Power Generation – Power Storage*

It is not within the scope of this thesis to go into detail on the power generation and storage blocks other than a brief description. This design will assume photovoltaic power generation and lithium-ion batteries for power storage.

The solar arrays are constructed using high efficiency triple junction solar cells. There are two primary vendors in the United States that both make similar cells. The Emcore BTJ and the Spectrolab UTJ cells each provide about 28% efficiency at beginning of life. The standard cell size is 26.6 cm^2 and nominally produces 1 watt per cell. The DICE spacecraft reference design uses four 1.5U solar array panels, each populated with three solar cells. This results in power generation of three watts per panel

assuming direct illumination and a normal sun vector to the panel. Greater power can be generated if more than one panel is being illuminated at the same time depending on the axis tilt of the spacecraft.

The battery selection is much greater. Lithium-polymer, due to its high energy density and thin shape, has become the battery type of choice for cubesat applications. Standard lithium-ion cells are also frequently used. The DICE reference design uses the lithium-polymer cell manufactured by Varta. This is a 1.3 A-h battery cell. The DICE reference design uses four cells configured as 2S2P, providing a 2.6 A-h battery at 8.26 volts maximum.

For the analysis, both the battery and the solar array will be assumed constant, and modeled as ideal DC sources. The intent is to remove the effects of these components from the architecture comparison.

C. *Battery Charge Regulator*

The battery charge regulator used in the DICE reference design is manufactured by Clyde Space Ltd. This regulator has been independently characterized for efficiency by measurements in the laboratory. The measured efficiencies are used throughout this analysis. The BCR used for the distributed EPS design is assumed to have the same performance characteristics as the Clyde Space device. The BCR effects will be the same for both designs forcing the differences to be due primarily to architecture, and downstream component optimization to highlight the effects of point-of-load converters.

D. *Distributed EPS Design Details*

The primary feature of the distributed EPS is the single battery dominated bus. This

bus is sun regulated; meaning that it is regulated to a fixed voltage during the sunlit portion of the orbit or once the battery end of charge voltage is reached. The bus is unregulated during the eclipse portion of the orbit. The battery state of charge determines the bus voltage for this time period.

For this analysis, and simplicity, we will assume a constant voltage. The battery dynamics can be added later to the model for increased fidelity. However, the battery dynamics are not required to compare the first order impact of the distributed EPS to the centralized approach and are omitted in this analysis. Figure 4.1 shows the block diagram for the DICE (centralized) power delivery system for the Attitude Determination and Control System (ADCS) Interface Board. This board is used as an example of the difference between the centralized design and the distributed design. Note that all three buses, battery and the two regulated buses, are used on this board. The battery bus is further regulated to obtain an analog plus and minus rail. The 5.0V and 3.3V rails are used directly on the card. The green blocks represent switching converters. The orange

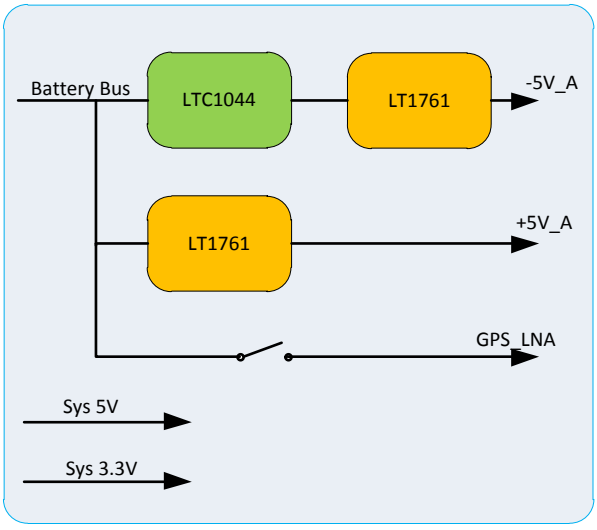

Fig. 4.1: DICE ADCS power block diagram.

blocks represent linear regulators. Linear regulators were used in noise sensitive areas where the voltage ripple of a switching regulator was not acceptable. Figure 4.2 shows the block diagram for the distributed configuration equivalent. For this configuration, three additional converters are required. A 3.3V converter and a 5.0V converter generate the voltage rails previously provided from the DICE EPS. One additional 3.3V buck converter is used for the Global Positioning System (GPS) for load optimization.

The GPS 3.3V load is approximately 300mA and is too great for the local board regulator to handle. In an ideal world, the GPS would provide its own point-of-load conversion directly from the battery input. Since it does not, it is provided here. The DICE design used a solid state relay to switch 3.3V power to the GPS. The new point-of-load 3.3V regulator can be considered as replacing that relay since it has a shutdown feature. From a board real estate point of view, the regulator is larger than the solid state relay, but not significantly.

For the analysis, a power block diagram, similar to ADCS, was generated for each card in the DICE design. A second block diagram was then generated that showed the power implementation assuming a single distributed bus. These block diagrams are contained in Appendix B.

E. *EPS Analysis Models*

There are three main Simulink models that include a DC-DC converter, a linear regulator, and a load cell. Each of these models is configurable so they can be made to represent many different components. The components are connected together in the same configuration as the block diagrams outlined in the previous section. In addition to

the three custom model components, typical SimuLink® source, sink, and interconnecting components are used.

1) *EPS Load Models:* For the analysis, there are resistive loads, constant current loads, and constant power loads. Since voltages are not allowed to vary in this analysis, the three kinds of loads are effectively the same. A constant power load is used for all cases since DICE load information is available as power, it simplifies the analysis. Because it is the intent of future work to increase the model fidelity, the load models do include current rise and fall time dynamics. However, the analysis results will only look at the values once all converters and loads have reached the steady state. Figure 4.3 shows the constant power load. V_{in} is the input voltage node and I_L is the load current output. A subsystem mask allows the user to define the power level of the model and the rise time. The model then determines the load current based on the voltage input and the

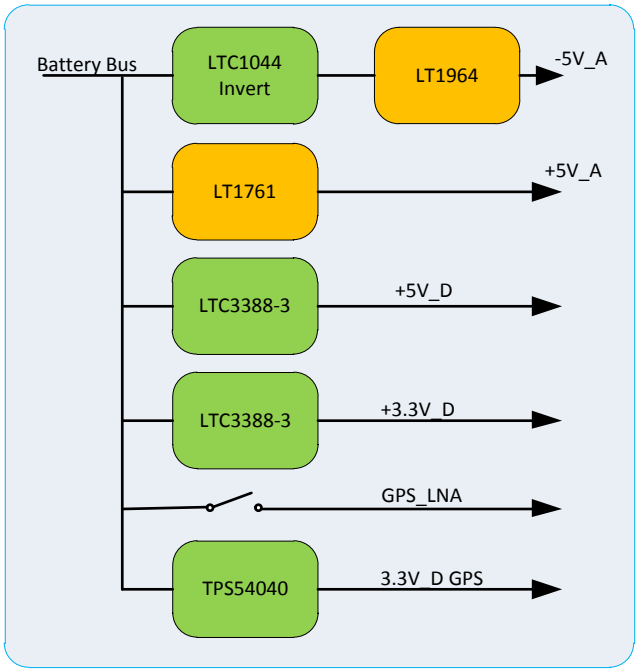

Fig. 4.2: ADCS distributed power block.

constant power rating.

2) *DC-DC Converter Models:* The DC-DC converter model mainly attempts to model the input and output loads based on the device efficiency. The model is low fidelity in that the only dynamics it models is the current output dynamics. The output voltage is constant and is set as a mask variable. Other mask variables include rise and fall times, output current range, output voltage range, and efficiency table data. Figure 4.4 shows the DC-DC converter model.

DS_Load is an input and defines the downstream load that the converter sees. The load is typically connected to this point. Vin is the input voltage for the converter. US_Load is an output and represents the upstream load that the converter places on an upstream power source. Vout is the second output. It is the output voltage of the regulator and, as stated earlier, is set as a constant. Eff_out is the third output of the model and represents the calculated efficiency of the block. The efficiency output comes from the data sheet tables or actual measurements if available. Efficiency tables are stored as MatLab variables and interpolated based on input and/or output voltages, and load currents to determine the efficiency parameter.

3) *Linear Regulator Models:* The linear regulator (see Fig. 4.5) is a simple component that models the efficiency of the device based on the input and output voltages, and currents. The output voltage, Vout, the current rise time, and the quiescent

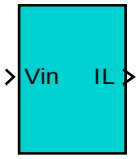

Fig. 4.3: Constant power load for use in the SimuLink® analysis.

current are set as constants through a model mask variable. Vin is the regulators input voltage. DS_Load is an input and represents the load seen by the regulator. US_Load is the load from the regulator presented to upstream power sources.

The load current calculation assumes the upstream current is equal to the downstream current plus the regulator's quiescent current consumption. The efficiency, Eff, is a simple calculation of power out divided by power in.

4) *Entire Power System Model:* Figures 4.6 and 4.7 show the top level model for the DICE design and the distributed DICE design. The simplification of the single bus is quickly obvious from the top level. Each DICE card is represented by a model block. Pushing down into each block, reveals the next level that contains the converter, regulator, and load models discussed above. The figures also show several other blocks used in the analysis to output load data to the workspace. These are there for analysis purposes and are not part of the DICE design.

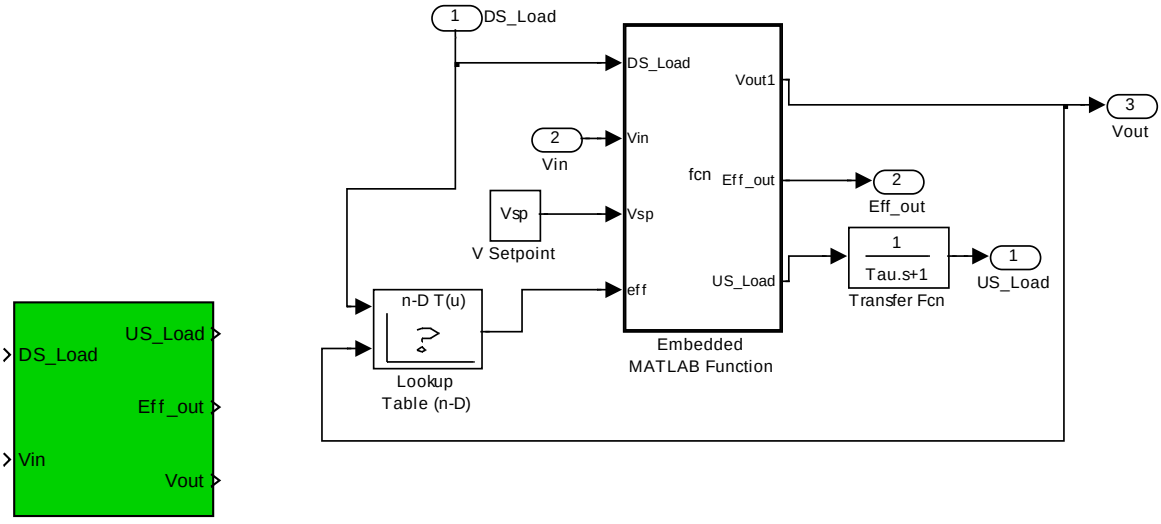

Fig. 4.4: DC-DC converter model for use in the SimuLink® analysis.

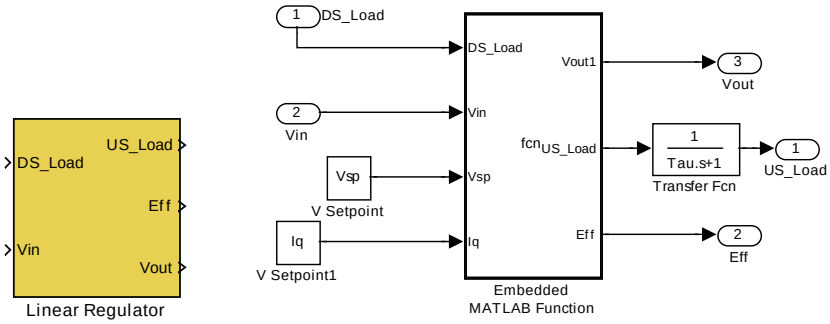

Fig. 4.5: Linear regulator model for use in the SimuLink analysis.

The distributed design is drawn with a single output bus for simplification. It is more correct to assume that there is a single voltage with multiple possible distributed switched outputs. The distributed EPS design can incorporate power distribution functions. Multiple buses, of the same voltage, can be output to individual loads. A higher fidelity model could easily incorporate the switch functions. For this analysis, different load currents for different cases were manually adjusted.

F. *Analysis Results*

In the analysis, an attempt to match the DICE power loads was performed. The power load for each DICE card was measured at each voltage bus. The sum of these loads was then considered to be the card power load. For the analysis, constant power loads were selected for each voltage rail, such that the power load of the card, including converter efficiency, matched the measured DICE load. While the matching is not exact, the same loads are used throughout the analysis to allow for a good comparison.

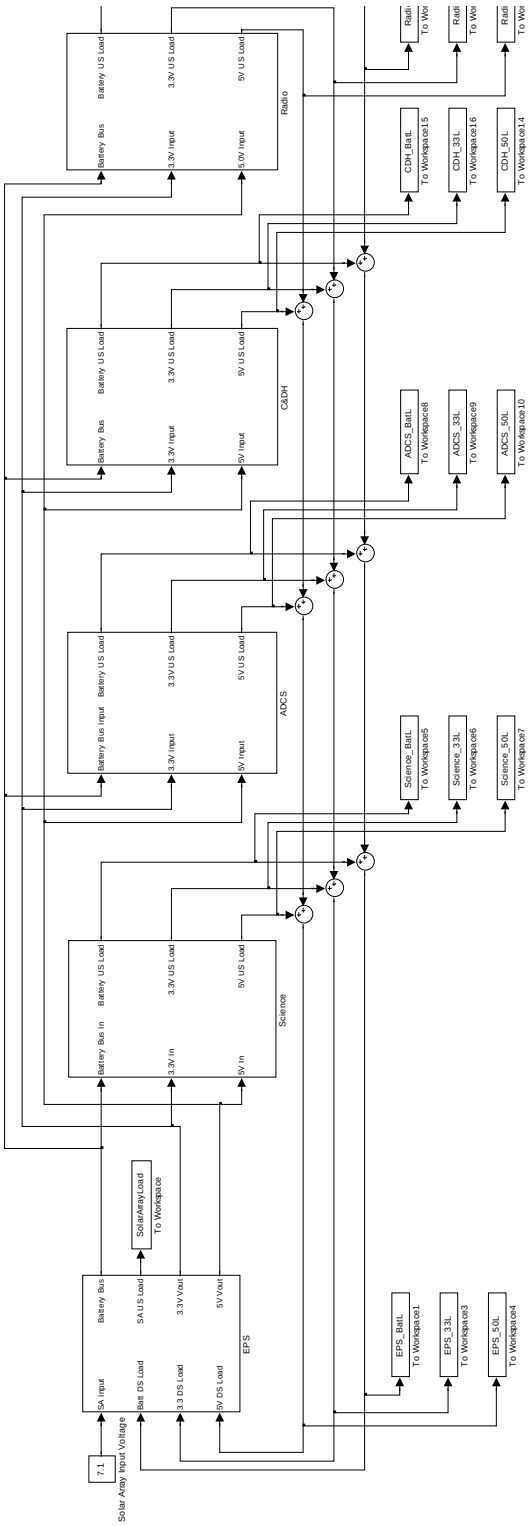

Fig. 4.6: DICE centralized power system design.

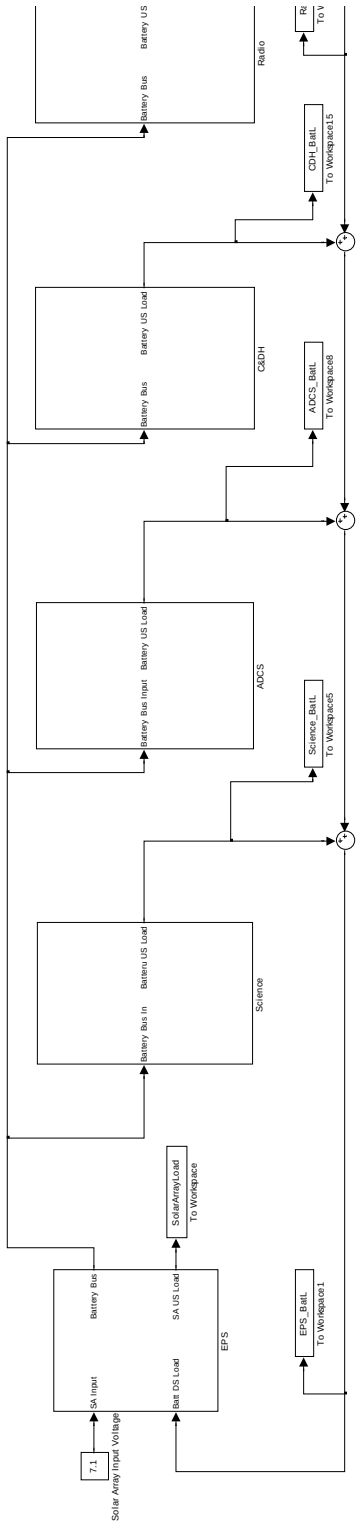

Fig. 4.7: DICE distributed power system design.

Table 4.1 is a summary of the Simulink® analysis for the DICE centralized design loads. Table 4.2 is the summary for the DICE distributed analysis. The first column, top section, lists the different cards. In the case of the Radio and the Science board, the power loads are divided because there is a significant change depending on what is powered. The next column, Fixed Load, is the load that the local power system on each card sees. In other words, it is the load downstream of any local power supplies. Where no power supplies exist on a particular bus voltage, for the given card, this column is the power for the specified power rail.

The next five columns, Case 1 through Case 5, are the individual power draws for each card based on the simulation. Where the value is "OFF," it indicates that the card or the function is turned off. The "Total System Load" row is the sum of each of the columns and represents the total load seen by the EPS card for that case. This value does

Table 4.1: DICE CENTRALIZED DESIGN CARD POWER SUMMARY.

	Fixed Load (W)	Case 1 Load (W)	Case 2 Load (W)	Case 3 Load (W)	Case 4 Load (W)	Case 5 Load (W)
C&DH	0.065	0.065	0.065	0.065	0.065	0.065
ADCS	0.158	0.198	0.198	0.198	0.198	0.198
GPS	1.022	OFF	1.022	OFF	OFF	OFF
Comm Tx	10.271	OFF	OFF	OFF	10.271	10.271
Comm Rx	0.117	0.117	0.117	0.117	0.117	0.117
Science Digital	0.12	0.193	0.193	0.193	0.193	0.193
Science Analog	0.175	OFF	OFF	0.338	OFF	0.338
Total System Load	12.045	0.573	1.595	0.911	10.844	11.182
Solar Array Load PWR		2.961	4.277	3.337	14.42	14.8248
BCR Efficiency	Pct.	83%	84%	84%	84%	84%
3.3V Efficiency	Pct.	87%	88%	87%	88%	88%
5.0V Efficiency	Pct.	15%	15%	15%	88%	88%

not include the EPS card loads and inefficiencies. The next line, Solar Array Load PWR, is the total power required for the entire spacecraft. In the real system, the battery would begin to provide power to the power loads for the high load cases. For this analysis, all of the power is brought out to the solar array for comparison.

The lower section of each table shows the efficiency for each EPS card converter. The centralized design shows the efficiency for the 5.0V and the 3.3V converter. These converters do not exist for the distributed design.

The results show that the distributed design has better efficiency than the centralized design. There are two reasons for the better efficiency. The first is poor converter optimization on the science board. The analysis shows more power consumption, in the distributed design, from every card except the science board. With the distributed design you should expect higher power consumption because the 3.3V and the 5.0V voltage rails are being created locally and the inefficiencies associated with the conversion is

Table 4.2: DICE DISTRIBUTED DESIGN CARD POWER SUMMARY.

	Fixed Load (W)	Case 1 Load (W)	Case 2 Load (W)	Case 3 Load (W)	Case 4 Load (W)	Case 5 Load (W)
C&DH	0.065	0.068	0.068	0.068	0.068	0.068
ADCS	0.158	0.207	0.207	0.207	0.207	0.207
GPS	1.022	OFF	1.099	OFF	OFF	OFF
Comm Tx	10.271	OFF	OFF	OFF	10.323	10.323
Comm Rx	0.117	0.125	0.125	0.125	0.125	0.125
Science Digital	0.12	0.154	0.154	0.154	0.154	0.154
Science Analog	0.175	OFF	OFF	0.252	OFF	0.252
Total System Load	12.045	0.554	1.653	0.806	10.877	11.129
Solar Array Load PWR		1.984	3.124	2.188	14.12	14.422
BCR Efficiency	Pct.	83%	84%	84%	84%	84%

accounted for locally on the boards. However, for the science board this is not the case. This is because the science board converters are oversized and not operating efficiently. In the distributed design, different converters were used that resulted in better efficiency, up to 86 mW less power consumption.

The second reason is the EPS board regulated voltage efficiency. Both the 3.3V and the 5.0V converters are high efficiency converters, but they require a relatively high amount of load current before they reach their peak efficiency. Even in the peak power mode for the system, the 5.0V converter has still not reached its peak efficiency. This is one of the primary flaws of a centralized design that is not optimized for a specific mission. If the EPS design would have been designed for this specific mission, it likely would have done better. However, since it is a common design, used for multiple cubesat missions, it has to be designed for the highest loads. It is therefore inefficient for missions that have lighter loads. For most of the DICE mission, the 5.0V converter efficiency is at a dismal 15%. From this analysis, it is fair to assume that even if the 5.0V converter was optimized for the maximum load requirement of the DICE mission, the efficiency still would not be as good as dedicated point-of-load converters. The load spread between the high load state and the low load state is great enough that it is difficult to find a converter that can cover the spread evenly at its peak. The 3.3V converter is better utilized but even it could benefit from point-of-load optimization.

One of the initial goals of the research was to determine if charge pumps could be effectively used in the distributed design. For the distributed DICE design, only one charge pump was used. The DICE mission uses a 7.2V nominal bus. At this voltage,

commercially available charge pump options are few. The other issue is that charge pumps are better suited for non-regulated applications where the output only depends on the input. High efficiency charge pumps are available but mostly for inverter or doubler applications. For the DICE mission, the science board specifications for the low level regulated voltages required linear regulation for the analog components. This eliminated the charge pump from several applications. If these requirements were relaxed, then the charge pump could have been used to increase the efficiency over the linear alternatives.

A lower bus voltage was initially considered for the distributed design. This would have enabled more opportunities for charge pumps. However, the decision was made to keep the bus the same as the centralized DICE design to enable better comparison. For a single bus voltage distributed design, a decision for what that bus voltage should be will have a large impact on available converters. It will also have an impact on what kind of efficiencies can be obtained at the point-of-load. The process of selecting the point-of-load converters, and generating efficiency data, showed that the lower the delta between the converter input voltage and output voltage, the greater the efficiency. Assuming lithium-ion battery chemistry for the distributed bus, the voltage rail options grow in increments of 3.6 volts. Based on the design and subsequent analysis, the recommended bus voltage is either 7.2 +/- 1.2 volts. Further work should be done to come up with the optimal cubesat bus voltage. A review of the different loads would shed more light on the optimal bus voltage.

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CHAPTER 5

CONCLUSIONS

The distributed EPS design is very flexible with a high degree of utility. The efficiency of the distributed design can be shown to be equal or close to that of an optimized centralized design. In the case of the reference design used in this analysis, the distributed design efficiency is better. The use of small, efficient, point-of-load converters, both charge pumps and inductor based converters, enables single bus voltage architectures for cubesat or Nano class satellite applications. This architecture is the same as that used in larger small sat applications, and is the key to a cubesat or Nanosat EPS design that can be used across multiple platforms and varying missions.

The cubesat industry almost entirely relies on centralized EPS designs. Most EPS designs have been custom designs. There are a few manufactures that make their designs available for commercial use. Most of these designs conform to the most common standard that uses three distributed buses. A single distributed bus would increase the EPS utility and allow its use in more cubesat designs.

Point-of-load converters are efficient and small. The down side of the distributed EPS is that more board space is required for voltage regulation on each card. To mitigate the impacts of more converters, small monolithic converters can be used, and require very little board space.

Standard inductor converters have an advantage over charge pumps in regulated applications. Their efficiency is usually greater and there is a much greater selection available over a wider array of input voltages. When charge pumps are used, they are

easier to configure since there is one less energy storage element to size. For inverting or doubling applications, the charge pump is a good choice and is easier to configure than the inductor based counterpart.

It is very insightful, for EPS designs, to perform full power system analysis. Looking at the power performance from the solar array down to the last converter before the load, gives you a very complete look at all of the power dissipation. It allows for identification of problem areas where further optimization can be made. Building a prototype design for each converter, with representative loads, allows you to completely characterize the performance of the selected converter. It helps identify issues early in the design process. Ultimately, if a distributed design is implemented, optimization can be done at a lower level.

A series connected, two cell lithium-ion battery was used in this analysis. The research would indicate that an 8.4 volt (two series cells) battery bus is the most common. While, it is still not clear what the optimal bus voltage is, based on the research, the optimal bus voltage recommendation would be 8.4 volts for all cubesats 2U and smaller. It appears that 12.6 volts (3 series cells) is a better choice for cubesats larger than 2U. A review of cubesat loads would be useful to help determine the optimal voltage. For example, the DICE radio initially required a higher bus voltage. They initially wanted greater than 9 volts. The requirement was subsequently lowered to accommodate the DICE battery bus voltage. Using a higher bus voltage would reduce the number of boost converters required in a system. However, the higher the bus voltage, the lower the converter efficiency is when that voltage is converted to low level

regulated voltages. For this reason, voltages above 12.6 volts are not recommended. If a standard voltage can be selected, then the greatest utility can be realized.

Full power system modeling is extremely insightful and useful for analyzing the power system performance. Further development of the EPS system level models to include system level dynamics would be valuable. The inclusion of a solar array model and a battery model would help perform reference mission EPS simulations to validate solar array and battery sizing. Further work in this modeling arena could provide a very valuable tool for the EPS designer in not only evaluating the EPS architecture and optimizing the system, but it could be very useful in performing mission simulations for the power system. Battery voltages could be modeled. Bus switches could be implemented and controlled based on mission scenarios. MatLab Simulink® appears to be a good tool for doing these types of dynamic modeling cases. MatLab allows for the inclusion of actual SPICE models into MatLab models when the proper tool packs are made available.

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APPENDICES

APPENDIX A

EFFICIENCY DATA

Table A.1: MAX1680 EFFICIENCY DATA.

Vin (Volts)	Input (mA)	Output (mA)	Efficiency Percent	Vout (Volts)	Ripple (mV P-P)
4.92	42.62	19.8	92%	9.78	
4.88	62.56	29.8	94%	9.67	
4.85	82.54	39.8	95%	9.56	
4.81	102.51	49.8	95%	9.45	
4.77	122.49	59.8	96%	9.34	
4.73	142.4	69.8	96%	9.23	170.00
4.70	162.34	79.8	95%	9.12	
4.66	182.3	89.8	95%	9.01	
4.62	202.28	99.9	95%	8.90	
4.59	222.22	109.9	95%	8.78	
4.55	242.18	119.9	94%	8.67	
4.51	262.12	129.9	94%	8.55	

Table A.2: MAX1044 EFFICIENCY DATA.

Vin (Volts)	Input (mA)	Output (mA)	Efficiency Percent	Vout (Volts)	Ripple (mV P-P)
5.00	0.923	0.8	86%	-4.96	
5.00	1.929	1.8	92%	-4.92	
4.99	2.935	2.8	93%	-4.87	
4.99	3.927	3.8	93%	-4.82	
4.99	4.934	4.8	93%	-4.78	
4.99	5.931	5.8	93%	-4.73	
4.99	6.935	6.8	92%	-4.68	
4.99	7.923	7.8	92%	-4.64	
4.98	8.929	8.8	91%	-4.59	
4.98	9.925	9.8	90%	-4.54	28.00

Table A.3: LTC1503 EFFICIENCY DATA.

Vin (Volts)	Input (mA)	Output (mA)	Efficiency Percent	Vout (Volts)	Ripple (mV P-P)
4.99	5.219	9.8	76%	2.01	
4.98	10.471	19.8	76%	2.01	
4.97	15.761	29.8	76%	2.00	
4.96	21.002	39.8	76%	2.00	
4.95	26.201	49.8	77%	2.00	
4.94	31.358	59.8	77%	2.00	
4.93	36.495	69.8	77%	2.00	
4.92	41.611	79.8	78%	2.00	
4.91	46.759	89.8	78%	1.99	
4.90	51.882	99.9	78%	1.99	160.00

Table A.4: TPS60400 EFFICIENCY DATA.

Vin (Volts)	Input (mA)	Output (mA)	Efficiency Percent	Vout (Volts)	Ripple (mV P-P)
4.99	4.993	4.8	93%	-4.831	
4.98	10.029	9.8	93%	-4.74	14
4.96	20.087	19.8	92%	-4.624	
4.94	30.137	29.8	90%	-4.494	
4.93	40.198	39.8	88%	-4.357	
4.91	50.235	49.8	85%	-4.226	
4.89	60.23	59.8	83%	-4.099	

Table A.5: MAX1595 EFFICIENCY DATA.

Vin (Volts)	Input (mA)	Output (mA)	Efficiency Percent	Vout (Volts)	Ripple (mV P-P)
4.98	10.339	9.8	64%	3.37	
4.96	20.741	19.8	65%	3.37	
4.94	31.234	29.8	65%	3.38	
4.92	41.703	39.8	66%	3.40	
4.90	52.307	49.8	66%	3.40	330
4.88	63.55	59.8	65%	3.38	
4.86	76.05	69.8	63%	3.36	
4.83	93.46	79.8	59%	3.34	
4.79	111.73	89.8	56%	3.32	
4.77	123.54	99.9	56%	3.33	
4.73	146.57	109.9	53%	3.32	
4.70	158.72	119.9	53%	3.32	
4.68	172.47	129.9	53%	3.32	

Table A.6: LT1615-1 EFFICIENCY DATA.

Vin (Volts)	Input (mA)	Output (mA)	Efficiency Percent	Vout (Volts)	Ripple (mV P-P)
4.86	75.38	24.8	82%	12.16	
4.79	114.8	49.8	84%	9.29	
4.74	142.2	74.8	85%	7.69	
4.77	124.47	99.8	87%	5.183	

Table A.7: MAX1837 EFFICIENCY DATA.

Vin (Volts)	Input (mA)	Output (mA)	Efficiency Percent	Vout (Volts)	Ripple (mV P-P)
4.96	20.127	24.8	83%	3.34	
4.92	40.5	49.8	84%	3.347	
4.89	60.94	74.8	84%	3.355	
4.85	81.42	99.9	85%	3.368	147
4.81	102.01	124.9	86%	3.367	
4.77	122.59	149.9	86%	3.36	
4.73	143.16	174.9	86%	3.349	
4.70	163.81	199.9	87%	3.334	
4.66	184.48	224.9	87%	3.315	
4.62	205.73	249.9	87%	3.291	

APPENDIX B

POWER DELIVERY BLOCK DIAGRAMS

Figure B.1 through Fig. B.8 contain the power delivery system block diagram for the existing DICE spacecraft.

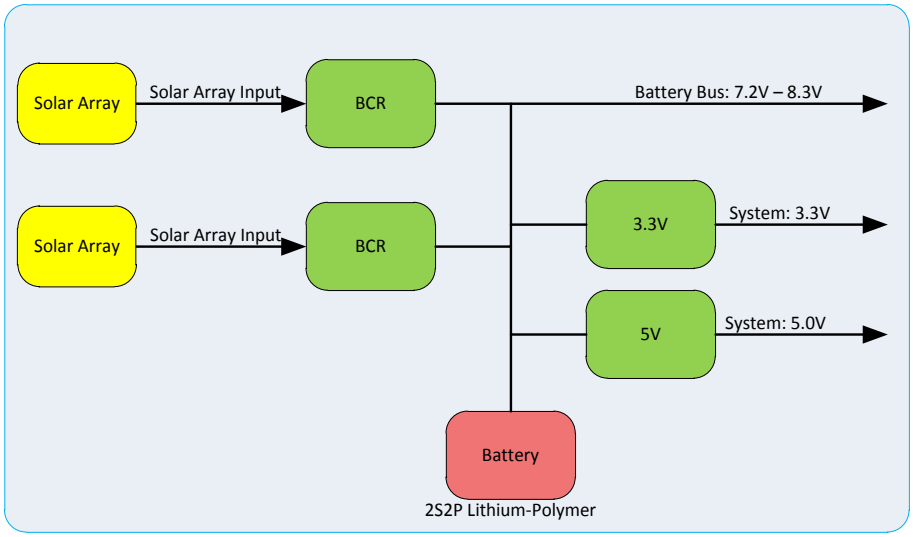

Fig. B.1: DICE EPS power block diagram.

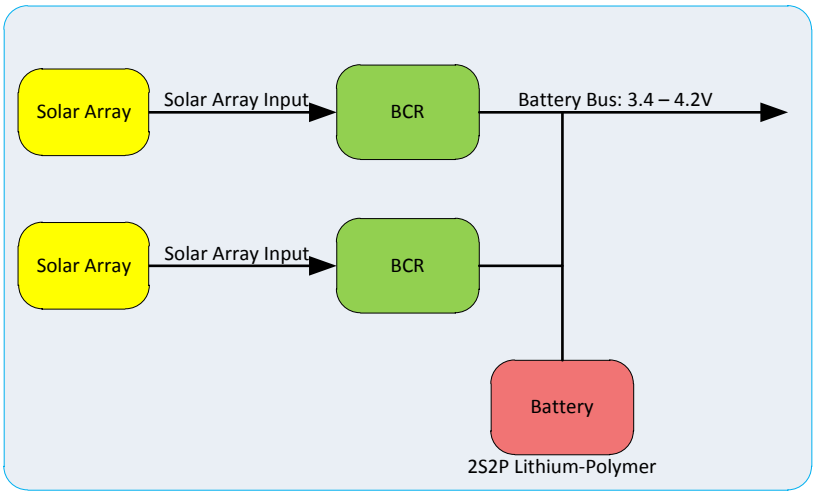

Fig. B.2: Distributed EPS power block diagram.

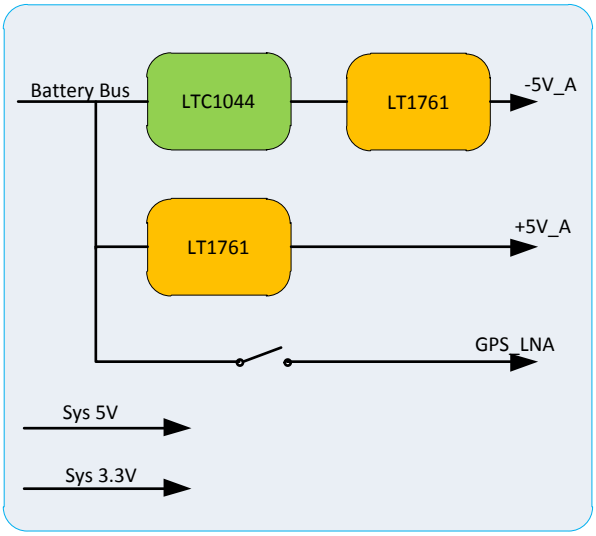

Fig. B.3: DICE ADCS power block diagram.

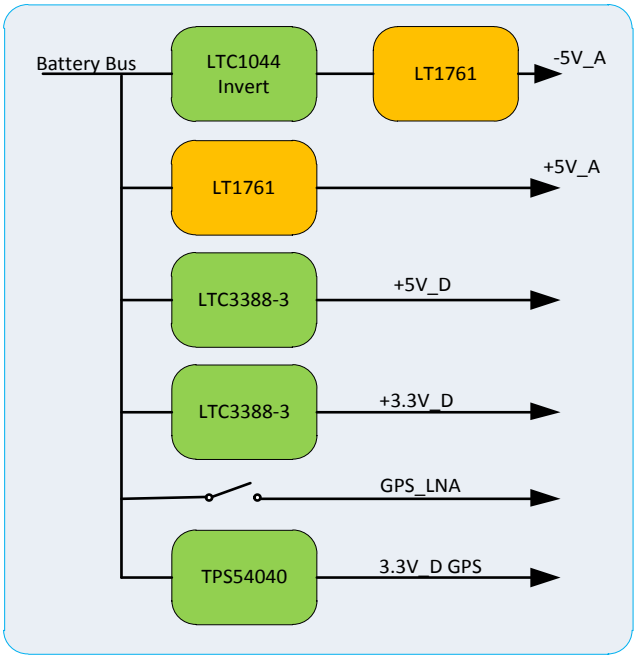

Fig. B.4: ADCS distributed power block diagram.

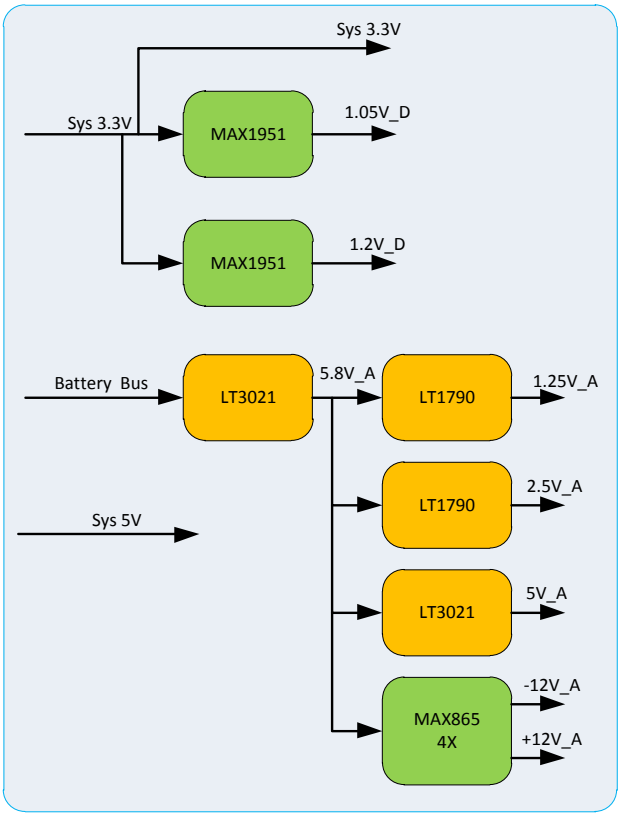

Fig. B.5: DICE science power block diagram.

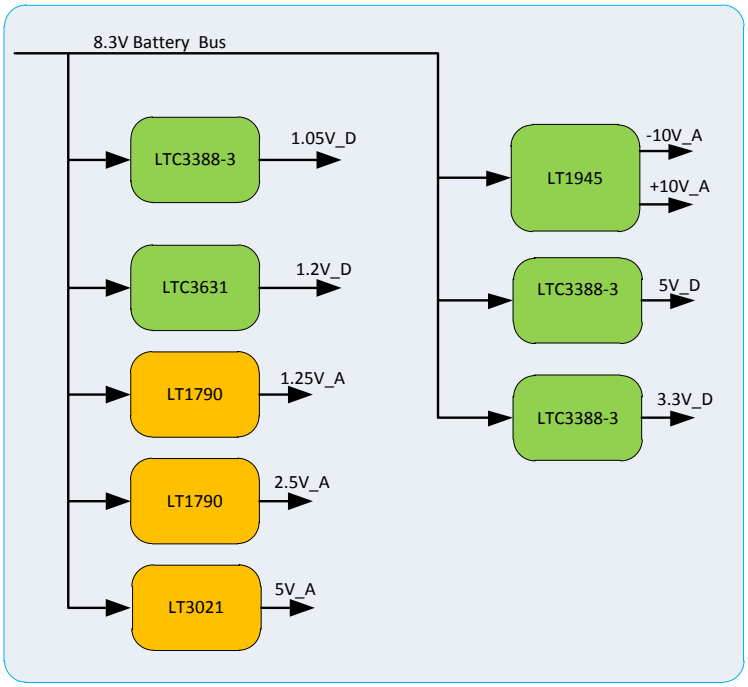

Fig. B.6: Science board distributed power block diagram.

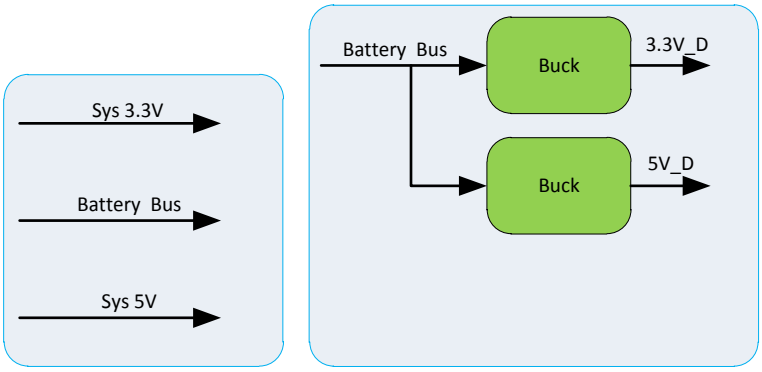

Fig. B.7: DICE CPU block diagram (left). CPU distributed block diagram (right).

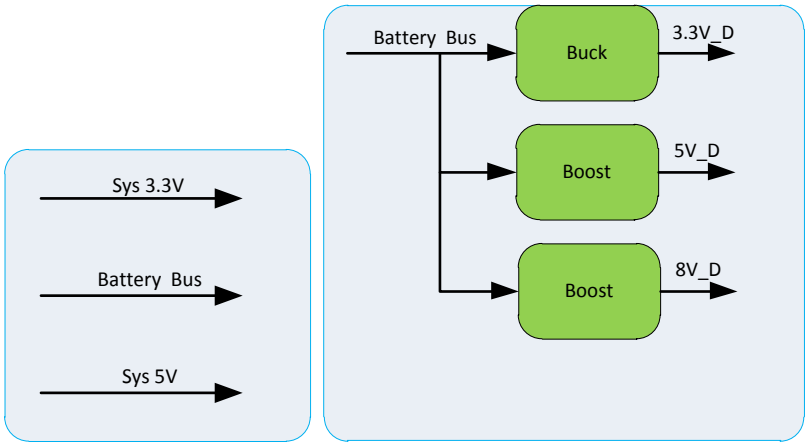

Fig. B.8: DICE radio block diagram (left). Radio distributed block diagram (right)