Distributed EPS in a CubeSat Application

Robert Burt
Space Dynamics Laboratory
1695 N Research Parkway; 435-713-3337
Robert.burt@sdl.usu.edu

ABSTRACT

Historically, cubesats have used a centralized Electrical Power System (EPS) wherein regulated and unregulated voltages are bused throughout the cubesat eliminating the need for further regulation. Typical EPS designs for larger spacecraft, almost always use a distributed architecture for the EPS. A high voltage, un-regulated or regulated, is distributed to the subsystems. These subsystems regulate the higher voltage to the required lower voltages required by the electronics. This distributed architecture was found to be difficult to scale when the satellite design shrunk from hundreds of kilograms and kilowatts down to handfuls of each.

Regulators can be optimized for non-varying loads. The more fluctuation in the load, the greater your inefficiencies become for the specific fixed point regulator. The designer must size the regulator to meet the highest load demand plus margin. This usually means the operating point, for the majority of the load cases, is far down on the efficiency curve. Thus, regulators that are specified at greater than 90% may in reality be operating at less than 60% in many cases. This paper investigates the use of high efficiency point of load converters, commonly available on the commercial market, in a distributed architecture for cubesat implementation.

INTRODUCTION

The cubesat, or Nanosat class satellites, have traditionally used highly integrated EPS 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 it also must be flexible. The ideal EPS design is one that meets the power requirements, and can be used multiple times in different mission scenarios, without having to be redesigned for each mission. Distributive architectures allow for greater flexibility in meeting the requirements of varying satellite payloads and spacecraft configuration, but can they efficiently be implemented in cubesats?

The history of cubesat sized spacecraft now span over a decade. There have been many cubesats launched during that period of time. The purpose of this paper is to report on research done in implementing a distributed architecture in cubesat or Nano class satellites using point of load DC-DC converters. The distributed architecture is common to larger spacecraft, but really has not been used on the Nano class satellites. 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. This study 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, maintains the high degree of efficiency required by these small spacecraft.

ELECTRICAL POWER SYSTEM ARCHITECTURE

The two main EPS architectures are centralized and distributed, each architecture having its advantages and disadvantages. Centralized architectures can be very space efficient with little waste but typically do adapt well to changes in requirements from mission to mission. A distributed architecture has the advantage of greater utility over a wider range of mission requirements and is usable in modular applications but it is often lacking in efficiency.

Centralized Electrical Power System

To date, the most common EPS architecture utilized by cubesats is the centralized architecture. 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 volt bus, a 3.3 volt 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 worst case load is not connected, the regulator is operating down on its efficiency curve, or in other words, is not optimized. Figure 1 shows a block diagram of a centralized architecture.

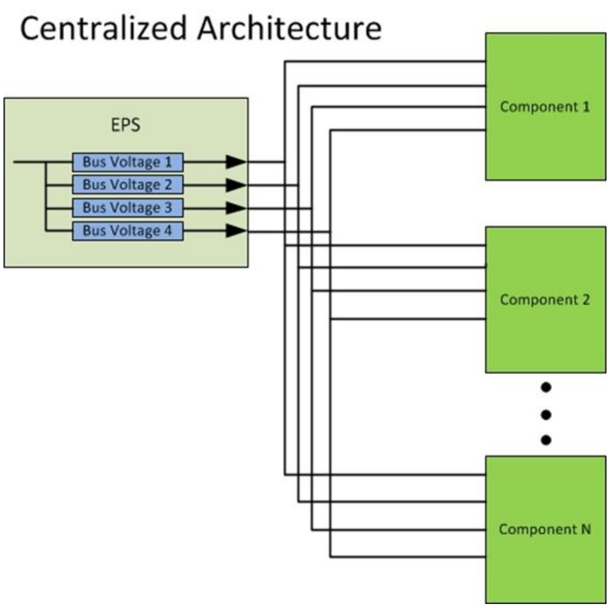

Figure 1: Electrical Power System Centralized Architecture

Distributed Electrical Power System

A distributed EPS, shown in Figure 2, typically distributes a single bus voltage to the different subsystems. Each subsystem has its own dedicated bus. Individual components can now be switched on and off without affecting all of the other subsystems or components.

A review of the cubesat electrical power system, discussed later in this paper, 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 cubesat 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 [1]. 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 [2].

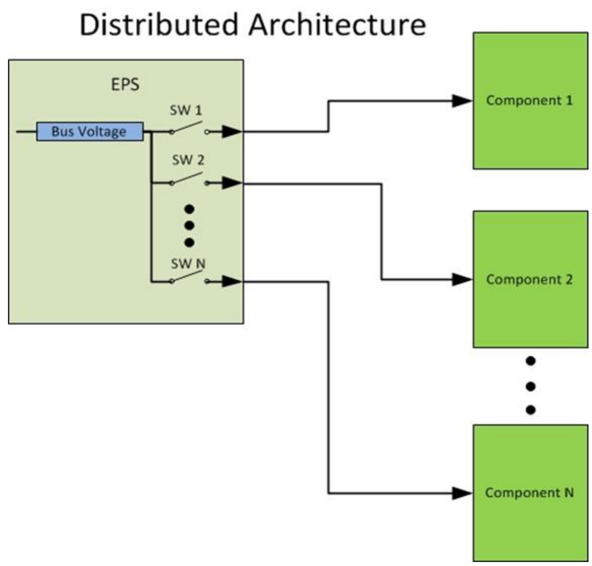

Figure 2: Electrical Power System Distributed Architecture

The Cubeflow design has been implemented in demonstration form but has not been flight proven. At the publish date of this paper, developers have used a table top power supply to provide the system with 5 volts rather than use a functional EPS design. 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. 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 [2], it is assumed that subsequent voltage regulation occurs at the point of load.

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

For the distributed architecture to effectively 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.

DISTRIBUTED EPS STATE OF THE ART

A search for cubesat EPS information was undertaken. A total of fifty two cubesats were reviewed. Information on the electrical power system for thirty three of the fifty two cubesat was found. 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.

Sufficient information was found to evaluate twenty five cubesats and to determine what type of EPS architecture they implemented. 80% of the cubesats implemented a centralized architecture, while only five of the twenty five, or 20%, used a distributed architecture. The next few paragraphs describe in detail those distributed architectures.

Cubesat 1 Distributed Architecture

This cubesat employs a lithium-ion battery for power storage and operation during the eclipse [3]. 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 regulated the distributed buses. Regulation at this level is less power efficient but more space efficient. This may have been a factor in the decision process.

Cubesat 2 & 3 Distributed Architecture

These cubesats were built by the same organization [4]. The same EPS was used both times demonstrating a higher level of utility through component re-use. 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 the EPS board. However, the ability to optimize for efficiency is increased with this design.

Cubesat 4

This cubesat is interesting in that there is no battery for operation through the eclipse [5]. 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. From the data, separate on/off control for each load is not provided as part of the EPS.

Cubesat 5

This cubesat is similar to cubesats 2 & 3 in that it provides a dedicated regulated output to each of the defined loads [6]. 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 power card rather than at the point of load. From a board space point of view, there would not have been any 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.

It is interesting to note that none of the distributed systems in the study actually distributed an unregulated battery bus as the only output. In all cases, a series regulator was inserted in the power path and all subsequent downstream converters pulled power through this series regulator. These distributed designs realized the utility of a distributed architecture but failed to optimize the efficiency. Efficiency can likely be optimized on a per mission basis but if the EPS manufacture wants an EPS, that can be used on multiple missions, without change, then eliminating this second regulator would help. Adherence to this design forces the load to perform all of its secondary voltage regulation. Again, there is more board space requirement at the load, but potentially much better efficiency.

The advantages of the single voltage, sun regulated, distributed battery bus are listed below. The following conclusions were drawn from the EPS review, experience building a point of load test board, and industry experience:

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 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. In the case of charge pumps, no inductor is required at all.

4. It is possible to isolate specific loads by using point of load converters. Isolated converters 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 of this sun regulated, distributed battery bus design 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.

EPS ANALYSIS AND COMPARISON

To validate the study, an analysis was performed. A cubesat, using a popular EPS that conforms to the Pumpkin Cubesat kit standard [7] was selected as the baseline. The spacecraft was built by students from Utah State University in conjunction with the Space Dynamics Laboratory. All electrical power designs were available such that a complete electrical power evaluation and comparison could be performed.

The goal of the comparison is to show that an optimized, single bus, sun regulated, 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 sun regulated, single voltage, distributed bus will allow for the sought after high degree of utility, and reuse, in the EPS design.

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 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.

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. As a result, the battery dynamics are excluded. The input voltage into a DC-DC converter is a factor in efficiency calculations. In this analysis, this factor is ignored. However, it is estimated that the efficiency change due to input voltage variation is small, based on the anticipated voltage change of two volts for a 2S2P battery configuration. For the bulk of the cases, the regulated voltages are less than the input battery bus voltage. As the battery voltage is reduced and gets closer to the desired output voltage of the regulator, the regulator efficiency typically gets better. A nominal 7.9 volts was used for the battery voltage for all of these tests.

For both designs, the same Battery Charge Regulator was used. This BCR was designed manufactured by Clyde Space Ltd. In the analysis, actual measured efficiency numbers for this BCR design were used. The differences in the comparison are all due to the differences in the EPS architecture downstream of the BCR.

Total Power System Block Diagrams

Block diagrams for power circuits were generated for the entire DICE spacecraft. The block diagram begins with the Solar array input voltage and ends at a load. The diagrams are divided by the natural boundaries formed by individual cards. Figure 3 shows the power block diagram of the ADCS interface card. The original design already incorporated some point of load conversion to generate the +/- 5 volt rails for analog circuits. The system 5 and 3.3 volt rails, coming from the EPS card, are used directly on this card. The battery bus is also passed through this card to the GPS receiver. Figure 4 shows the equivalent distributed design. 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 GPS for load optimization. For this 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 distributed battery bus.

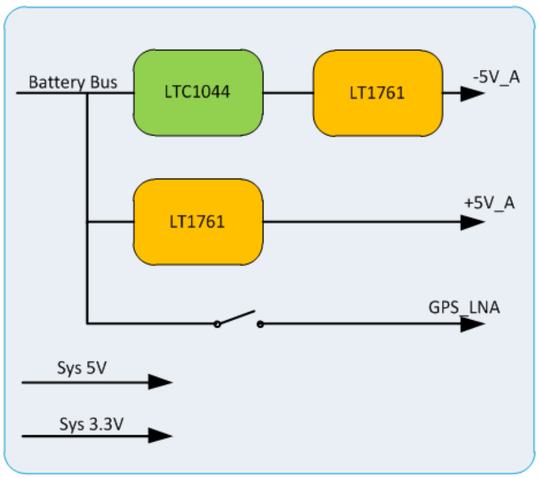

Figure 3: DICE ADCS Power Block Diagram

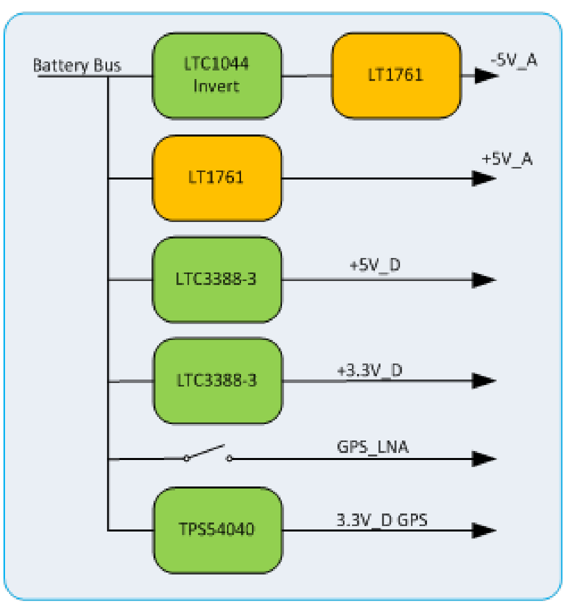

Figure 4: ADCS Distributed Design

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. Figure 5 shows the SimuLink® model used for the DC-DC converters. The model elements were connected to represent the baseline centralized design. A second circuit was connected to represent the distributed design. The same loads were used for each of the circuit analysis. The final comparison is based on this data

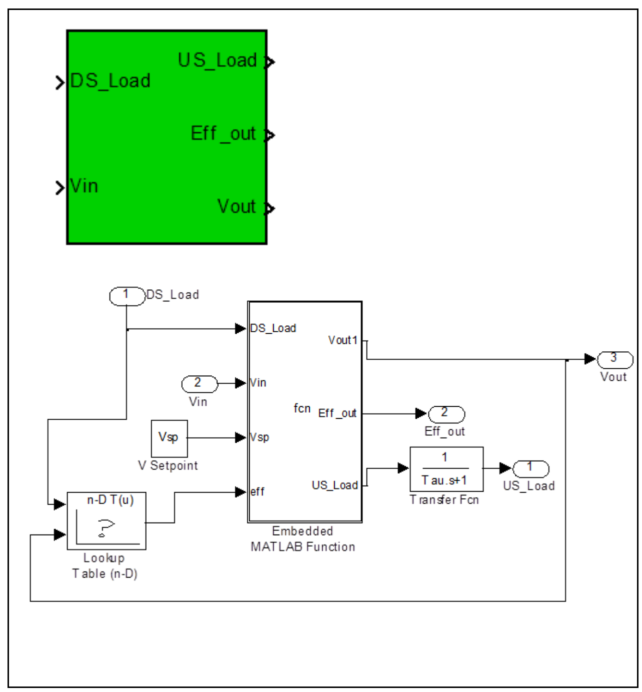

Figure 5: DC-DC Converter Model for use in the SimuLink® Analysis

EPS 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 isn't exact, the same loads are used throughout the analysis to allow for a good comparison.

Table 1 is a summary of the SimuLink® analysis for the DICE centralized design loads. Table 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 on or off. The next column, Fixed Load, is the load that the local power circuit, on each card, is subjected to. In other words, it is the load, downstream of any local power supplies. Where no local power regulators exist on a particular bus voltage or card, this column is the power load for the specified card. The loads for each power rail are summed together to obtain the "Fixed Load" value. Power efficiency for the card can be obtained by dividing the "Fixed Load" value by the "Case" value.

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 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.

Table 2: DICE Centralized Design 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%

Table 1: DICE Distributed Design 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%

The lower section of each table shows the efficiency for each EPS card converter. The centralized design shows the efficiency for the 5V 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 5V voltage rails are being created locally and the inefficiencies associated with the conversion is 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 86mW less power consumption.

The second reason is the EPS board regulated voltage efficiency. Both the 3.3 volt and the 5.0 volt 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 5.0 volt 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 volt converter efficiency is at a dismal 15%. From this analysis, it is fair to assume that even if the 5V 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.

STUDY 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 relies heavily 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 bused voltage rails. A single distributed bus would increase the EPS utility and allow its use in more cubesat designs.

Ultimately, the use of a distributed design comes down to a trade between utility and board real estate. Advances in commercial DC-DC converter technology, in both size and efficiency, has made this trade very viable and begins to mitigate the board space effects.

ACKNOWLEDGMENTS

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