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MAXIMIZING OVERALL ELECTRICAL POWER SYSTEM EFFICIENCY IN PICO/NANO-SATELLITES WITH INNOVATIVE PLUG-AND-PLAY BATTERY CHARGING SYSTEM

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Many CubeSat investigations are designing their own electrical power systems (EPS.) Due to the size constraints of the CubeSat standard, these EPSs, more often than not, implement Maximum Power Point Tracker (MPPT) systems to squeeze the most power possible out of the solar panels. While there has been significant focus on different MPPT techniques, little emphasis has been placed on what to do with excess power unused by the MPPTs other than storing it in lithium ion or lithium polymer chemistries-based batteries. Some investigations have implemented traditional bi-state Constant Current, Constant Voltage (CC-CV) battery chargers. This method is effective, maximizing battery lifetime. However, due to the variable nature of the net power available in space, this approach requires accurate orbit predictions and modelling to minimize unused power, and tends to allow for a large quantity of unused power to dissipate as heat in the solar panels. The system developed at UAHuntsville–for ChargerSat-1 uses high-efficiency USB power management ICs (PMICs) in a feedback loop to continually keep the MPPTs active by charging the batteries with a variable charge current. The system adjusts the charge current based on satellite current draw and MPPT output voltage. Overall, this load management system allows for large EPS efficiency increases compared to the bi-state method and, due to the modular nature of ChargerSat-1's hardware development, can be easily implemented in any 1U or 2U system using MPPTs.

I. PURPOSE

Today, Lithium-ion (Li-ion) and Lithium Polymer (Li-Po) batteries power nearly every electronic device that is not permanently tethered to the power grid. However, the notable energy density of these batteries, the reason that we use this chemistry over others, makes them dangerous. During the last decades, industry has nearly perfected the art of safely charging Lithium batteries. The most prevalent charging technique used for this chemistry is CC-CV charging. The majority of battery chargers on the market implement some variant of this charging profile. The technique safely charges the battery and does not significantly degrade battery lifetime. To achieve greatest efficiency, CC-CV charging requires a constant supply of power, which must be available to the charger for constant current mode. For Pico/Nanosatellites, this becomes an issue.

In their most simple form, 1U and 2U CubeSats are tiny boxes~~,~~ covered in solar panels, tumbling in Low Earth Orbit (LEO). Due to the tumbling motion, power output from their solar panels is never constant. Using this simple model of these Pico-platforms, a CC-CV charging profile is not ideal for these spacecrafts. A charging profile and a power management system -- such as the ones developed at UAHuntsville -- can accommodate variable charging currents that must be used for these systems to safely maximize all available power on orbit. A charging profile and a power management system that addresses these needs have been developed at UAHuntsville to safely maximize available power on orbit.

II. BACKGROUND

Damaging Lithium Batteries

All batteries degrade through use and over time. This damage is typically measured as a function of battery lifetime or the number of charge/discharge cycles it takes to degrade a battery to 70% of its beginning of life (BoL) capacity. Violent battery failure can occur if a battery experiences sustained over voltage~~,~~ or is allowed to overheat to the point of thermal runaway[1]. Battery management systems must prevent both of these scenarios from happening for safe operation of Li-ion and Li-Po batteries.

Constant Current – Constant Voltage Charging

The CC-CV charging profile is the safest and most prevalent charging profile used today. Figure 1 is an example of this profile for a Li-ion battery.

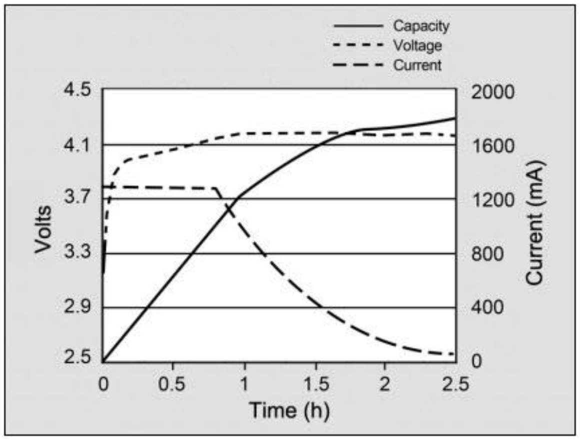

Fig. 1: Capacity as a function of charge voltage on a lithium-ion battery[1].

The first step is constant current mode, in which the current sourced to the battery is held constant while the voltage is allowed to rise until it reaches a threshold voltage usually between 4.0V and 4.2V. At this point, the charger transitions into the constant voltage mode, holding the cell voltage at the threshold voltage and enabling the current to drop off naturally until it is approximately 3% of the current during the constant current mode. This stage is often referred to as the Saturation Charge[1]. The saturation charge that replenishes the top 15% to 30% of the battery's capacity.

III. ON ORBIT POWER

On orbit power is at a premium for 1U and 2U CubeSats. Only a few watts of power can be generated from the limited solar collection area. If the CubeSat is tumbling, the power output from its solar panels will always be in flux. If a CC-CV charging profile is used, the CC current should be carefully selected through orbital modeling to maximize charger on-time and power stored in the battery.

Other important factors to consider when selecting the CC current include: solar array degradation due to radiation and thermal stressing, CubeSat power bus draw and mission lifetime. If the mission lifetime is short, the CC current can be set higher as solar array degradation will not start to affect charger on-time until after the mission has been completed. However, if the mission lasts longer than a few months, solar array degradation will noticeably affect solar power collection. Even with the most accurate models and mission planning, CC-CV battery chargers leave 20% to 60% of available power unused. CC-CV battery chargers must be fine-tuned on a mission-by-mission basis to maximize available power used.

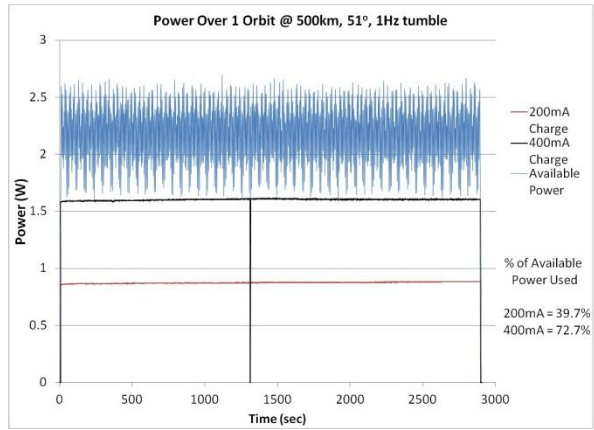

Fig. 2: (Blue) Solar power available at beginning of life (BoL) to ChargerSat-1, a 1U CubeSat, over one orbit. Model developed using data generated in STK. This chart does not show eclipse operations. The red and black curves represent the power required to charge a Li-Po battery, starting at 40% state of charger (SoC), at 200mA and 400mA CC respectively. Charging power data collected experimentally.

IV. POWER MANAGEMENT SYSTEM

The power management system developed at UAHuntsville is designed to draw the maximum amount of power from the solar panels when a CubeSat is not in eclipse. It controls how much power can be drawn from the solar panels by both the CubeSat bus and the battery chargers. The power management system -- including the load matching system and the power path controller -- can be thought of as two fundamental blocks that work together to optimize power throughput. These two blocks are the load matching system and the power path controller. One load matching system can control multiple power path controllers. Each power path controller is capable of outputting 10W, charging a battery at up to 1A. The power management system is a stand-alone system, requiring no inputs from other EPS systems to operate.

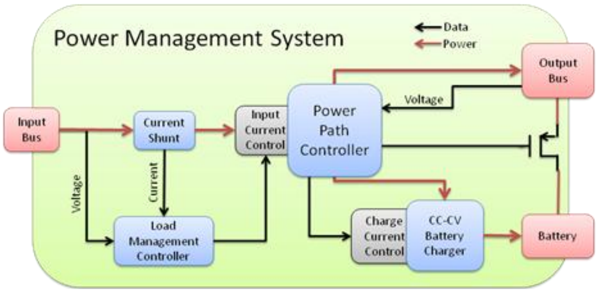

Fig. 3: Block diagram of the power management system in its simplest form. Power is sourced from the input bus at 4.5-5.5V. Black arrows represent data and red arrows represent power flow.

Load Matching System

The load matching system controls how much power can be sourced from the MPPTs and solar arrays. The load matching system treats the battery charger and CubeSat power bus as a single load through the power path controller. The system adjusts the amount of current available to the power path controller until the maximum power draw from the input bus is achieved. It then tracks the maximum power point of the entire input bus and adjusts the current as needed to maintain a lock. This allows the power management system to draw as much power as possible from the solar panels, adjusting the input current to the power path controller as the amount of available power from the solar panels changes.

The load matching system's controller operates under the same principle as certain maximum power point trackers. The load matching system uses an algorithm similar to the Incremental Conductance and Perturb and Observe methods of power point tracking. The load matching system determines how much power is passing through the power path controller by measuring the input current and input bus voltage. It then slightly adjusts the system's power draw and measures the resulting change. The system then uses derivative control to track the maximum power point of the input bus. This allows the load matching system to maximize power output from the solar panels, provided the batteries are not fully charged.

Power Path Controller

The power path controller directs the dissemination of the power. It determines where to send the power based on feedback from the load matching system and measurements from the CubeSat power bus. The system prioritizes the output bus over the battery charger.

The power path controller enables the output bus to draw as much current as it needs to preserve the output bus voltage. It then adjusts the charge current of the battery charger so that the current output from the power path controller meets the input current limit set by the load matching system. As the output bus current changes and the load matching system adjusts the input current limit, the power path controller modifies the charge current on the battery so the input current limit is never violated. The power path controller also automatically connects the batteries to the output bus through the FET (in figure 3) in the case that input bus voltage falls below the battery voltage. The power path controller and the load matching system work together to attempt to use all of the power available to the system. However, the battery charger will not attempt to charge a full battery.

Adaptive Current Charging

The charging profile used by the battery charger is a modified CC-CV charging profile. In the battery charger's "CC" mode, the power path controller directs the charge current. This allows the power management system to charge a depleted battery with any current available, up to a safety charge current threshold. It creates a dynamically changing charging current that adapts to variations in available input power and output bus power requirements. The battery charger's saturation charge stage performs normally unless power is needed by the output bus. In this case, the power path controller will siphon power from the battery charger to preserve the output bus. Load matching is less effective if the battery charger is in saturation charge as it is unable to sink all unused power into the battery charger. In this case, the load matching system will stop attempting to adjust the input power and will only respond to sharp decreases in input power.

The power management system will not charge the batteries at a higher current than is safe. In a case that the available current from the solar panels exceeds the safety charge current of the batteries, available power will go unused. For ChargerSat-1 this limit is 2A or 0.5C, which is three times what the 1U's solar arrays can produce in its deployed configuration. In this situation, the load matching system will stop tracking the input power and only attempt to adjust the power if the input power decreases continually for a set amount of time.

For 1U CubeSats with batteries larger than 3000mAh, approaching the safety charge current is not possible because the peak solar panel output will never exceed the power needed to enter this condition. However, this condition should not be ignored in 2U applications because peak solar panel output can exceed 5W. While charging at the safety charge current will not produce any adverse effects on the power management system or the batteries, overall EPS efficiency will be reduced in this condition because usable electrical energy will be dissipated thermally in the solar panels.

V. CHARGERSAT-1 POWER MANAGEMENT SYSTEM SPECIFICATION

ChargerSat-1 will fly the first prototype of the power management system developed at UAHuntsville. Chargersat-1 is a 1U CubeSat with 9 solar panels and is capable of producing a peak power output of 8W in its deployed configuration. ChargerSat-1's power management system uses one load matching system, two power path controllers and two 2000mAh Li-Po batteries. The power path controllers run in parallel to utilize all of the available power after the solar panels are deployed.

VI. CONCLUSION

The adaptive current charging profile and the power management system exhibit distinctive advantages over stand-alone CC-CV chargers. The adaptive current charging profile allows for a significant boost in overall EPS efficiency during "CC" mode by enabling access to all available solar power. The power management system can be dropped into any design because it is a stand-alone unit. It will automatically draw as much power as possible from the MPPT and it is suitable, without modifications, for any application with power inputs less than 20W. This reduces the need for the high-fidelity models required by stand-alone CC-CV chargers. Overall, the power management system delivers significant improvements over stand-alone CC-CV battery chargers.

VII. ACKNOWLEDGMENTS

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Mr. Phillip Pemberton, SHC
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Mr. Brad Partin, SHC
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[1] I. Buchmann, "Batteries in a Portable World: a handbook on rechargeable batteries for a non-engineer.", Cadex Electronics Inc. (2011).

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