DESIGN AND VERIFICATION OF ELECTRICAL POWER SYSTEMS FOR FORESAIL SATELLITES BEYOND THE LEO

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ABSTRACT

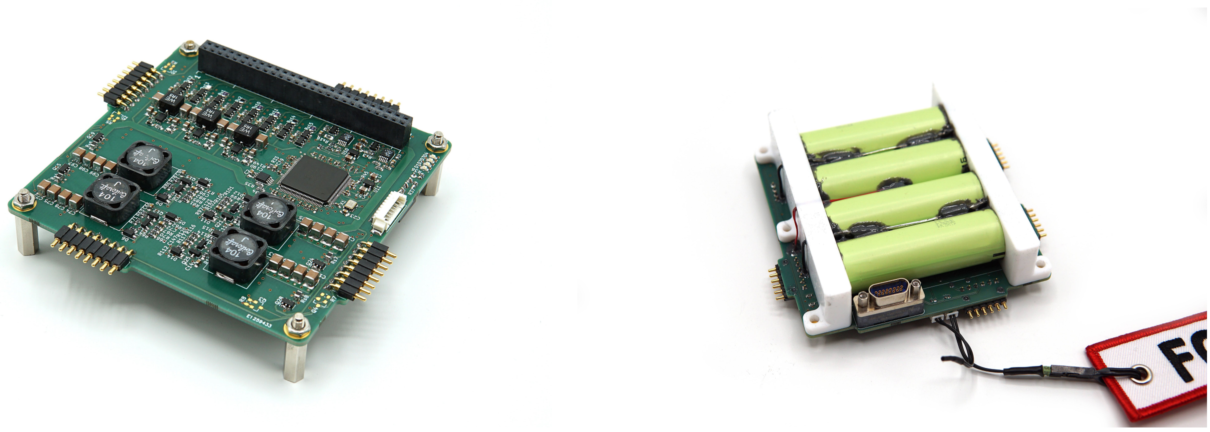
FORESAIL-1 and FORESAIL-2 are the first two small satellite missions under development by the Finnish Center of Excellence Research in Sustainable Space (FORESAIL) and will be launched to LEO and GTO, respectively. Mission requirements become more stringent with each consequent satellite, as the space environment becomes harsher with higher orbits and scientific/technological payloads increase in complexity and require more power to operate. Both satellites feature an Electrical Power System (EPS), entirely developed at Aalto University, Finland. The design goal has been to develop a system which can be easily adapted to changing mission requirements and allow flexibility in supply rail configuration for avionics subsystems and payloads. Testing and verification campaigns play a critical role in validating performance and reliability of the EPS.

1 INTRODUCTION

When designing a CubeSat platform, a hybrid approach is usually taken: some subsystems are built in-house, while others are commercial products. The electrical power system (EPS) often falls into the latter category, as a ready-made solution is not only cheaper and faster to obtain than developing and testing one in-house, but also a safer option from mission success standpoint as commercial solutions usually have proven flight-heritage. This was the case with the first Finnish small satellite, Aalto-1, which used a commercial-off-the-shelf (COTS) EPS procured from Clyde Space [1]. However, FORESAIL-1, the first small satellite mission of the Finnish Center of Excellence Research in Sustainable Space (FORESAIL), is moving away from the hybrid approach and uses a platform stack built completely in-house from scratch. This opens possibilities to optimize the design for a given mission, creating a more efficient and reliable system.

As the first satellite in the series, FORESAIL-1, will be launched to LEO, the EPS utilizes predominantly traditional COTS electronic components that are not designed with space environment in mind. While this is adequate for LEO missions and allows for agile and cost-efficient design, using non-radiation hardened components in consequent higher orbit missions will significantly reduce chances of their success. To address this, several design choices were made for FORESAIL EPS (see figure 1). First of all, maximum power point tracking (MPPT) battery charger is a custom built circuit instead of using a do-it-all COTS integrated circuit (IC), like ST's SPV1020. As will be shown in the next section, using a digital MPPT algorithm based on the output parameters of the switching converter, instead of the solar panel, allows MPPT and battery charge regulator (BCR) functionality to be combined into one. This reduces overall complexity of the EPS, improves its efficiency and reliability, and furthermore, makes the MPPT charger easily extendable to other CubeSats of different sizes. In addition, having a module build from several discrete components, instead of one IC, opens possibility to substitute components for radiation hardened counterparts when needed. Also, it is possible that an IC that fulfills changing mission requirements does not even exist, while a module built from discrete components can be adapted to almost any requirement.

Another differentiating aspect of FORESAIL EPS is a power distribution module (PDM). In traditional "centralized" power distribution, implemented by most small-satellite EPS', standard voltages like 3.3 V and 5 V are distributed to payloads as is. While centralized power distribution offers space and cost optimized design, it has several disadvantages. First of all, because many, if not most, of the subsystems and payloads are connected to the single switching regulator, the regulator usually runs at a lower efficiency as its component values are selected for the maximum possible load. Single regulator supplying multiple subsystems is also a potential single-point-of-failure. Secondly, supplying subsystems with a "use-as-is" standard voltage like 3.3 V will never meet all required system specification, such as transient load requirements, noise levels, absolute accuracy and so on, due to the distance between the voltage source and the load, and noise coupling on the way. Therefore, FORESAIL EPS opted to distribute "raw" voltages, nominally 3.6 V and battery voltage, to subsystems and payloads. This gives flexibility to subsystem and payload designers: if they only want to supply digital circuits without any special requirements in noise and accuracy specifications, when they can just use 3.6 V. Otherwise, they can efficiently step-down with an LDO to 3.3 V or less. In addition, FORESAIL EPS uses multiple switching regulators for 3.6 V voltage rails that allows to spread load over multiple regulators, improving efficiency, reducing thermal stress and reducing risk of single-point-of-failure.



(a) (b)

Figure 1. PCDU (a) and Battery Board (b)

2 DESIGN OF FORESAIL-1 EPS

The high-level block diagram of the FORESAIL-1 EPS is presented in figure 2. The incident solar radiation is harvested to electrical power by four solar panels, developed at Aalto University. Each solar panel consists from six to seven 32 % efficient space-grade GaAs solar cells manufactured by OCE. The cells are connected in series and glued to a thermally conductive PCB. Each panel is capable of producing up to 8.7 W at the beginning-of-life (BOL). The solar panels are connected to the array conditioning step-down regulators that perform maximum power point tracking (MPPT) and battery charging functionality. Extracted power is stored in the battery pack consisting of four Panasonic NCR-18650B lithium-ion cells connected in 2p2s configuration and further distributed through latching current limiting (LCL) switches to subsystems and payloads. Two kinds of voltage rails are provided: two unregulated battery voltage rails and six nominally 3.6 V regulated voltage rails.

The heart of the EPS is a COTS radiation hardened 32-bit ARM Cortex-M0 VA10820 Vorago MCU clocked at 20 MHz. Program image and configuration data are stored in 512 kB non-volatile SPI FRAM made by Cypress. Telemetry is collected with three 12-bit ADCs over SPI protocol. Communication with avionics subsystems is performed over hot-redundant RS-485 bus, while communication with the battery board is done over I2C bus. The power management stage is powered with a 3.3 V and a 1.5 V local LDOs that are behind resettable-LCL (RLCL). In addition, the EPS performs antenna deployment at the beginning of the mission.

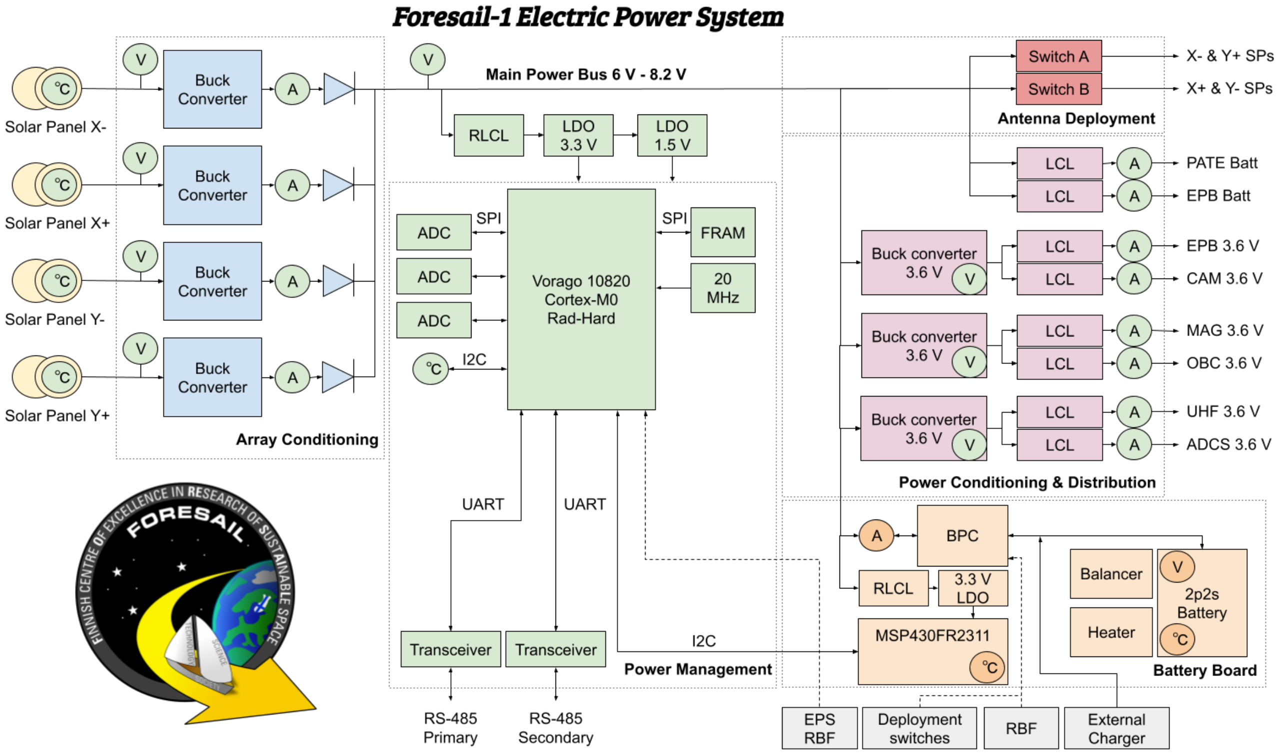


Figure 2. A high-level block diagram of the FORESAIL-1 EPS.

2.1 MPPT BATTERY CHARGER

The array conditioning stage of the Foresail-1 EPS is shown in figure 3. Its main components are a buck converter with a gate driving circuit, an ideal diode and a missing pulse detector circuit. The buck converter is controlled with the PWM signal, generated by the MCU that runs a custom MPPT battery charging algorithm. The ideal diode prevents the battery from discharging through non-illuminated solar panel and protects the main power bus from faults in the power conversion stage. Lastly, the missing pulse detector monitors the PWM signal and in the case of fault connects the solar panel directly to the main bus through the buck converter.

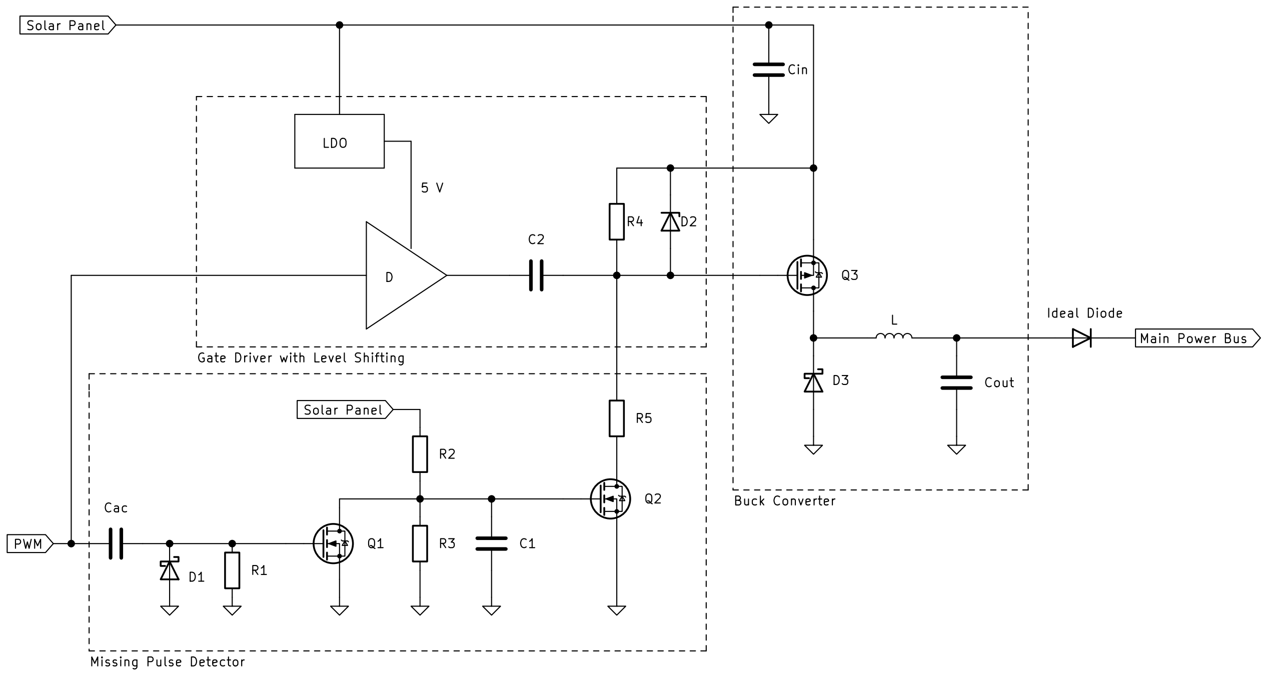


Figure 3. FORESAIL-1 Array Conditioning

Usually, a high-side switch (Q_3) in the buck converter is implemented with a n-type MOSFET, as it has lower on-resistance than its p-type MOSFET counterpart. On the other hand, having the high-side switch implemented with a p-type MOSFET provides two advantages. First of all, the solar panel can be directly connected to the main power bus by simply pulling gate to ground. This is useful in cases when gate driving is not anymore possible. Secondly, p-type MOSFETs seem to be immune to single event burnout (SEB) effects [2].

While driving a p-type MOSFET in high-side switch applications is easier than n-type counterpart, there are still several considerations to be made. Firstly, gate-to-source voltage needs to be limited not only to respect the maximum gate-to-source voltage rating given in data sheet of the device, but also to reduce likelihood of destructive single event effects from happening [3]. As there are limited selection of high-side gate drivers for p-type MOSFETs, since most of the step-down switching converters use n-type MOSFETs, the FORESAIL-1 EPS employs a simple level-shifting circuit made of a capacitor (C_2), a resistor (R_4) and a zener-diode (D_2) that can be used with most low-side gate drivers, which are plentiful. The level-shifting circuit shifts output of the gate driver by $V_{in} - 5$ V, where V_{in} is voltage at the source node of the p-type MOSFET and 5 V is the voltage supplied to the gate driver. Therefore, the maximum gate-to-source voltage is set by the supply voltage of the gate driver that can be in turn set by the LDO.

In space application, it is useful to be able to bypass the solar panel conditioning circuit and connect the solar panels straight to the main power bus. This can allow the mission to continue in some capacity, even if the MPPT controller has failed or battery pack power has been depleted. The missing pulse detector, presented in figure 3, turns the Q_3 on when the pulse-width modulated (PWM) driving signal goes missing. It consists of three subcircuits: a positive clamper (formed by C_{ac}, D_1 and R_1), a watchdog timer (Q_1, R_2, R_3 and C_1) and an output stage (Q_2 and R_5). The positive clamper passes the PWM signal unchanged, while blocking dc signals. The watchdog timer is responsible for detecting missed PWM signal within timeperiod set by the $(R_1||R_2)C_1$ time constant. If such event is detected, the output stage transistor Q_2 is switched on and gate of the p-type MOSFET will be pulled down to a voltage set by the voltage divider formed with resistors R_4 and R_5.

2.2 MPPT BATTERY CHARGER ALGORITHM

The MPPT battery charging circuit, presented in the previous section, is controlled digitally with MPPT charging algorithm, shown in figure 4. In fact, the algorithm does not strictly perform MPP tracking. Instead, it is a general purpose hill-climbing algorithm that steers the output current of switching regulator towards the target current. The algorithm is general purpose and does not depend on a switching regulator topology. In literature, similar algorithm was proposed by Shmilovitz [4].

The algorithm consists of three stages. In the first stage, charging mode is deduced based on two voltage thresholds: the upper threshold voltage for MPPT and the lower threshold voltage for charge limiting. If voltage at the main power bus is greater than the threshold voltage for charge limiting, the charger will enter into charge limiting mode. If, on other hand, voltage at the main power bus is less than the threshold voltage for MPPT, the charger will enter into MPPT mode. As can be seen, the algorithm has hysteresis in order to prevent oscillation between two modes. In the next stage, after the charging mode is deduced, the target for the output current is calculated. In case of the MPPT mode, the current is set to the largest possible values (infinity). On the other hand, if the battery charger is in the charge limiting mode, the target for the output current is set according to the P-controller. In the final stage, the output current is steered towards the target. To make sure that the operating point of the solar panel is always kept on the right hand side of the MPP in the P-V-curve, there are two additional comparisons in the last two decision diamonds. Keeping the operating point on the right hand side of the MPP is required so that the charging power can be steered to any target value. On the left hand side of the operating point, the minimum power output is set by the short circuit current of the solar cell, and the battery voltage.

There are two parameters that must be correctly selected for the proper operation of MPPT algorithm: update frequency (period) of the algorithm, and the amplitude (step size) of duty cycle perturbations. The first parameter is related to the transient performance of the switching converter. If measurements of the output current and voltage are made before transients have died out, the algorithm will not make a correct decision. The second parameter is related to the minimum duty cycle step size. In order for the algorithm to make a correct decision, power variation due to the perturbation of the operating point has to be higher than the variation due to external factors, such as irradiance, temperature and ADC quantization error. This parameters can be either estimated (see [5]), or, as in the case of the FORESAIL-1 EPS, experimentally deduced.

3 VERIFICATION OF FORESAIL-1 EPS

Verification model of the FORESAIL-1 EPS followed project's own internal verification model that is only loosely based on the ECSS test standards [6, 7]. Because FORESAIL-1 platform was newly developed, it first underwent a prototype phase followed by a functional testing phase, before moving to EQM and FM verification stages with an integrated satellite.

In the prototype phase, the subsystem is iteratively developed and tested until the intended functionality of the subsystem is achieved. During this phase, mistakes are more easier and cheaper to fix than later on in the project timeline. There is no standardized test plan document that needs to be followed.

In the functional testing phase, it is expected that the hardware design is fixed and only very minor details can be changed. Software development, on the other hand, continues until the very end. The goal of the functional testing is to qualify the prototype for FlatSat qualification. For this, the subsystem needs to demonstrate that it fulfills set requirements and that all functionalities are implemented and working.

During functional testing, several test campaigns were done, including:

- Panasonic NCR-18650B li-ion cells, selected for their flight heritage, were characterized. Characterization test plan was adopted from [8] and consisted of several environmental tests, such as vibration and thermal-vacuum, preceded and followed by capacity and internal resistance measurements. The battery cells showcased uniformity and passed all tests without problem.
- MPPT performance was verified outside in the Sun and optimal parameters were selected. The solar panel sweep results are shown in figure 5 and real-time performance of the MPPT algorithm is shown in figure 6.
- At the end of the functional testing, the EPS underwent total dose radiation test campaign. Results of the total dose campaign are documented in the following paper [9].

After the functional test phase is over, full functional testing with integrated CubeSat begins, first with EQM versions of the subsystems and payloads, and later with FM. During these stages, the integrated satellite undergoes various environmental tests: thermal and vacuum tests in thermal-vacuum chamber (TVAC) and vibration tests.

4 CONCLUSIONS

At the time of writing this paper, the FORESAIL-1 is undergoing the last week of the final testing before being shipped to Germany for integration. The satellite will be launched in the beginning of summer 2022. The design of the FORESAIL-2 EPS has already started and continues from where FORESAIL-1 EPS left off.

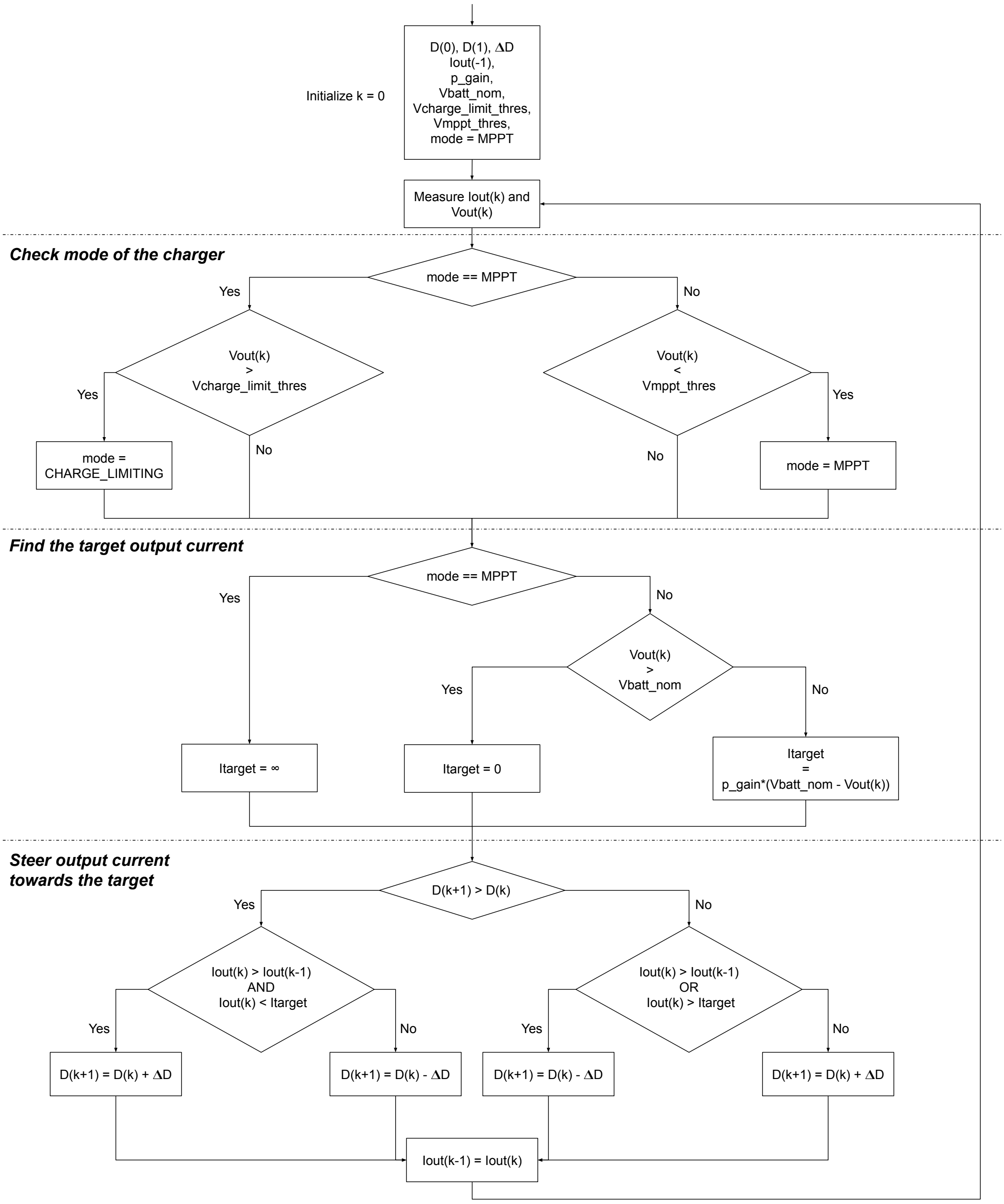


Figure 4. FORESAIL-1 MPPT Battery Charging Algorithm

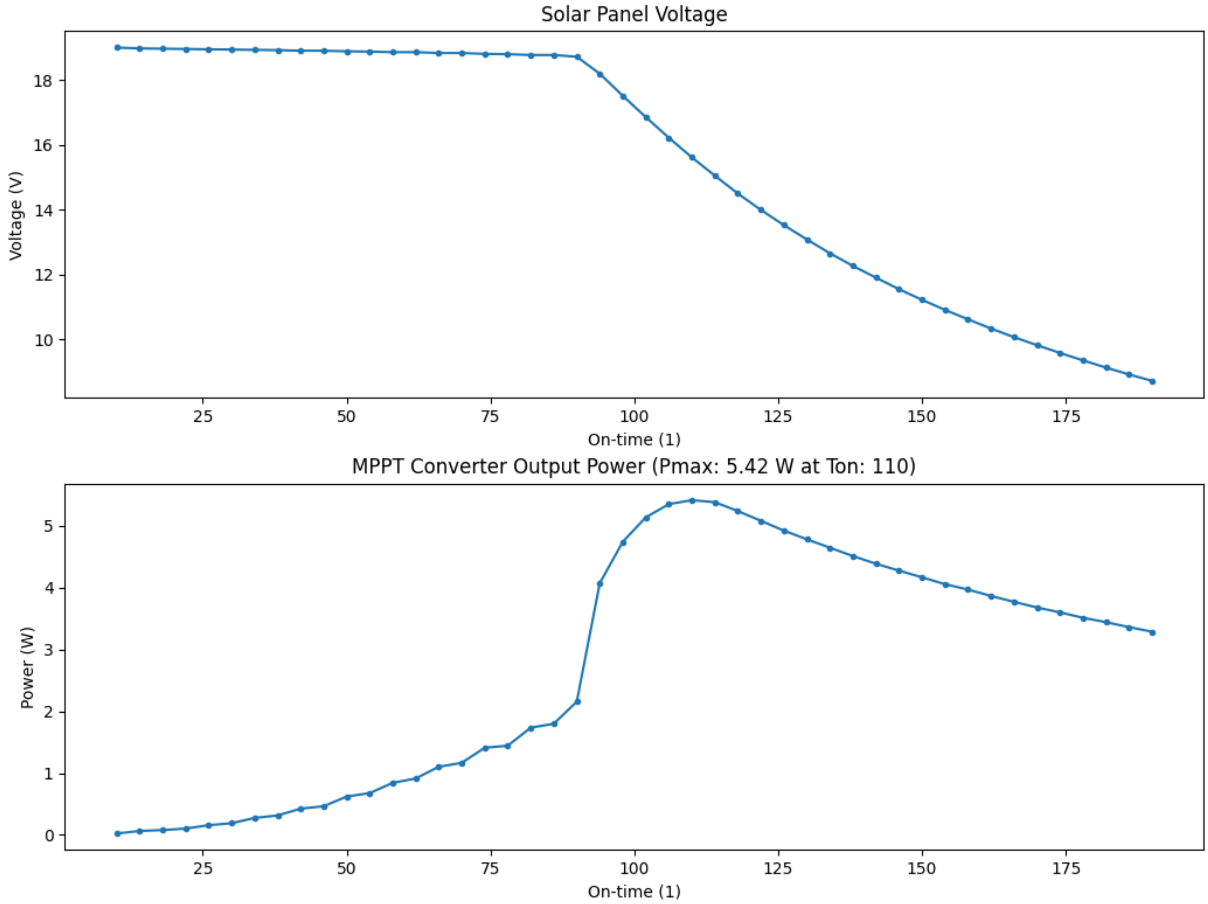


Figure 5. Panel sweep result. X-axes are on-time (unitless) of the PMOS switch from 0-200 (0 corresponds to 0 % duty cycle, or solar panels are disconnected from the main power bus, and 200 to 100 % duty cycle, or solar panels are fully connected to the main power power bus). The upper plot shows the voltage of the solar panel and the lower plot shows the charging power (output power of the MPPT converter) as the on-time is swept from 10 to 190 with step-size of 4. The maximum charging power is about 5.4 W.

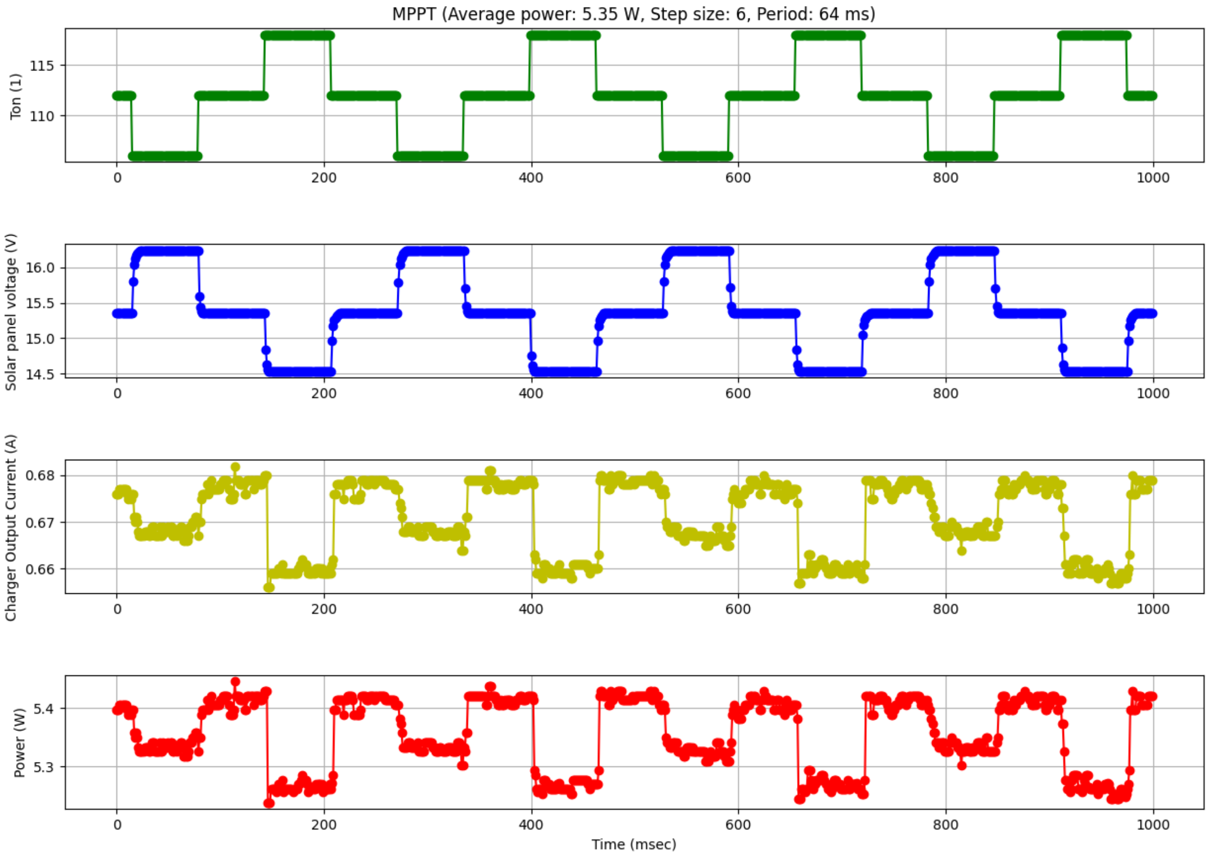


Figure 6. MPPT performance vs time in ms. Top subplot shows on-time of the PMOS. The second subplot contains solar panel voltage input. The third subplot contains MPPT converter output current plot and the lower subplot contains the charging power waveform. The step size is 6 and the MPPT period is 64 ms. The average charging power is 5.35 W.

References

[1] Jaan Praks et al. “Aalto-1, multi-payload CubeSat: Design, integration and launch”. In: *Acta Astronautica* 187 (2021), pp. 370–383.

[2] K Shenai, KF Galloway, and RD Schrimpf. “The effects of space radiation exposure on power Mosfets: a review”. In: *International journal of high speed electronics and systems* 14.02 (2004), pp. 445–463.

[3] European Cooperation For Space Standardization. *Space Produce Assurance. Derating - EEE components*. Standard ECSS-Q-ST-30-11C. Noordwijk, The Netherlands, Oct. 2011.

[4] D Shmilovitz. “On the control of photovoltaic maximum power point tracker via output parameters”. In: *IEE Proceedings-Electric Power Applications* 152.2 (2005), pp. 239–248.

[5] Nicola Femia et al. *Power electronics and control techniques for maximum energy harvesting in photovoltaic systems*. CRC press, 2017.

[6] European Cooperation For Space Standardization. *Space Engineering. Testing*. Standard ECSS-E-ST-10-03C. Noordwijk, The Netherlands, June 2012.

[7] European Cooperation For Space Standardization. *Space Engineering. Verification*. Standard ECSS-E-ST-10-02C. Noordwijk, The Netherlands, Mar. 2009.

[8] European Cooperation For Space Standardization. *Space Engineering. Li-ion battery testing handbook*. Standard ECSS-E-HB-20-02A. Noordwijk, The Netherlands, Mar. 2015.

[9] Kiril Cheremetiev. “Design of reliable Electrical Power System for Foresail-1 Small Satellite”. In: (2020).