Electric Power System Design for Reconfigurable CubeSat Clusters

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***Abstract*—This project presents the design and implementation of a high-efficiency Electric Power System (EPS) for CubeSat missions. The system addresses key challenges in space-based power management such as limited surface area for solar collection, battery longevity, space constraints, and radiation-induced failures. A custom analog-based switching topology and MPPT solar charging circuit are used to maximize power efficiency, safety, and mission reliability. Simulation and testing validate the effectiveness of the approach. A 4-layer PCB layout integrates all components for flight readiness.**

***Index Terms*—CubeSat, Electric Power System, MPPT, LTC3652, LTC4415, Single-Event Upset, SEU, Analog Switching, PCB Design**

I. Introduction

The purpose of this project is to design and implement a high-efficiency Electric Power System (EPS) that can reliably support the operation of a CubeSat throughout the duration of its mission. The EPS is the core system responsible for powering all onboard subsystems, and its performance directly impacts the mission's success and longevity. The main objective is to deliver a compact, efficient, and reliable EPS capable of harvesting solar energy, managing power distribution, and safely storing energy in onboard batteries. The system must maintain stable voltage levels, protect components from electrical faults or any single-event upset, and provide real-time power monitoring while operating under space and weight constraints inherent to CubeSat platforms. The EPS must also prioritize energy efficiency to maximize battery life and extend the mission's operational time.

This project addresses several key challenges:

- Maximizing energy conversion efficiency from limited solar panel surface area.
- Managing power storage and distribution for variable subsystem loads.
- Mitigating Single-Event Upsets (SEUs) caused by space radiation.
- Operating within strict space and mass constraints.
- Ensuring system stability and safety in high-temperature environments.
- Providing real-time monitoring and control to adapt to orbital power conditions.

II. Literature Review

The first and most critical problem addressed in our design is the efficiency gap between the amount of solar energy that can be harvested and how much of that energy can be effectively stored in the batteries. To address this, we selected the SM401K08L monocrystalline solar cell, rated at 702 mW and 5.53 V, with physical dimensions of 90 mm × 40 mm. Two cells are connected in series to produce up to 1.4 W per pair. This configuration is significantly more space-efficient than other CubeSat approaches that rely on either a single large panel or many smaller panels, which often suffer from power losses due to wiring resistance and interconnect complexity. By integrating five series-connected pairs—mounted on the top and four sides of the CubeSat—and deploying them using a mechanism similar to antenna deployment systems, we can generate up to 5.5 W under full sun exposure.

To convert and store the harvested energy, we employed the LT3652 Maximum Power Point Tracking (MPPT) charger. This IC dynamically adjusts its input to extract the maximum available power from the solar panels. Unlike traditional EPS designs that connect the charger output in parallel with both the load and the batteries, our design isolates these paths to avoid overcharging risks. In parallel configurations, the battery may continue charging unnecessarily when the load is drawing current, even after the battery is full. Additionally, this setup causes the battery to operate in a narrow voltage range and frequently alternate between charging and discharging states, which accelerates degradation.

To overcome these issues, we designed a custom analog automatic power switch circuit. This circuit separates the energy storage into two independent battery units. One unit is isolated for charging, while the other supplies power to the load. The LT3652 is connected in series with the charging battery, allowing it to monitor charge conditions accurately. The switching mechanism uses an LTC4415 ideal diode and is controlled by a TLV3012B comparator, which senses solar panel voltage. When sunlight is available, the comparator toggles the switch to isolate the charging battery and route the load to the other unit. Once solar input is lost, the switch reverts, making the charged battery available to the system and isolating the other for recharging in the next cycle.

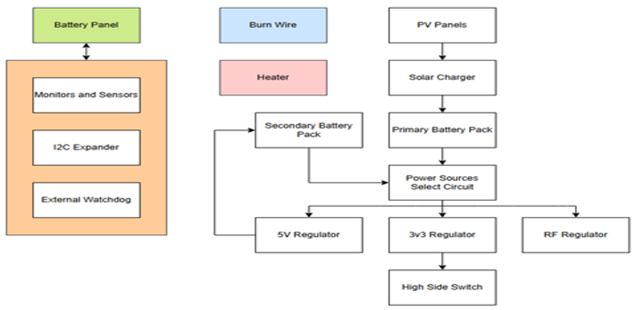


Fig. 1: Electrical Power System Block Diagram showing solar input, switching logic, MPPT charging, regulation, and battery units.

For efficient energy distribution, we used low-power regulators: the LTC3113 for 3.3V and the TPS61023 for 5V output. These deliver stable voltage rails for the CubeSat subsystems. A TPS1HC30 high-side switch protects the power path, and INA219 sensors are integrated to monitor current, voltage, and power in real time, providing telemetry to the main microcontroller.

To increase radiation resilience, the EPS logic minimizes reliance on digital microcontrollers and register-based logic. Instead, analog circuitry is used for core operations, significantly reducing susceptibility to Single-Event Upsets (SEUs)—bit-flipping events caused by high-energy particles in space. This analog-dominant architecture avoids runtime-dependent firmware and volatile memory, enhancing system robustness in radiation-prone orbits.

All components are selected to operate reliably up to 125°C, ensuring thermal resilience in lunar orbit conditions. Three temperature sensors are also added to the solar charger to compensate for panel voltage shifts due to thermal variations. The open-circuit voltage temperature coefficient of –13.92 mV/K is dynamically corrected, improving energy capture under fluctuating conditions—a feature rarely seen in comparable CubeSat systems.

For expanded control, we integrated a TCAL9539 I^2C expander, allowing the MCU to programmatically pull pins high or low. This enables manual overrides and control of subsystems, such as the thermal and deployment circuits. Additionally, LM74610 ideal diodes were added to prevent reverse current flow from the solar panels into the charging path.

Finally, the EPS board includes a burn-wire circuit for both antenna and solar panel deployment, as well as a battery heater circuit to maintain the batteries within optimal operating temperatures. Both circuits are controlled by the MCU through the I^2C expander, ensuring reliable execution of mission-critical functions across varying orbital environments.

III. Results and Discussion

To validate the performance and reliability of the power management system, we conducted multiple simulations and hardware tests focusing on the automatic switching topology, solar energy harvesting, battery behavior, and charging efficiency.

Using LTspice, I simulated the auto-switching power management circuitry. This design uses a TLV3012B comparator to control the enable pin of the LTC4415 power path controller, toggling between two battery units based on solar panel voltage levels. In the simulation, a pulse generator was used to mimic the behavior of the comparator, switching the control logic depending on light availability.

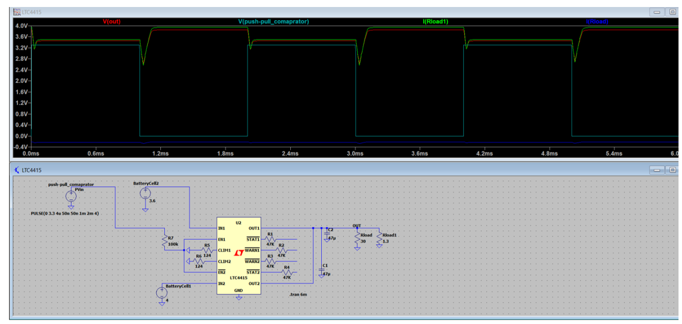


Fig. 2: LTSpice Simulation for the Auto-Switching Circuit

We tested different output capacitances to evaluate the voltage and current drop during switching events. When using an 80 μF capacitor at the output of the LTC4415, the simulation showed a 360 mV (11%) voltage drop and a 100 mA (10%) current drop. These transient variations are within acceptable limits and do not adversely affect the load. Further optimization using two 47 μF capacitors reduced these drops to 7%, confirming that the switching topology operates efficiently and can handle transitions without significantly impacting system stability.

In addition to simulations, real hardware components were evaluated. The solar panels were tested under standard illumination, and their current and voltage outputs matched rated specifications, validating our theoretical calculations. Similarly, the Li-ion batteries were tested to ensure their voltage, capacity, and charging behavior were within expected tolerances.

We also tested the LT3652 MPPT charger, which successfully activated its fault detection outputs. However, it failed to begin charging during early tests due to the exposed thermal pad not being properly connected to ground, a known requirement per the datasheet. Once addressed in the PCB layout, proper charging behavior is expected.

The use of flight-proven components throughout the EPS design, including the LTC4415, LT3652, TPS61023, and INA219, provided additional confidence in system reliability. Many of these ICs have heritage in previous CubeSat missions, further reinforcing their suitability for space applications.

We also conducted a power rating and efficacy study for our EPS. The energy conversion efficacy due to typical losses (resistance, wiring, and hardware) was estimated between 70% and 90%. Using this factor:

- A pair of panels in series: $1404\,\mathrm{mW} \times 0.8 = 1.1\,\mathrm{W}$

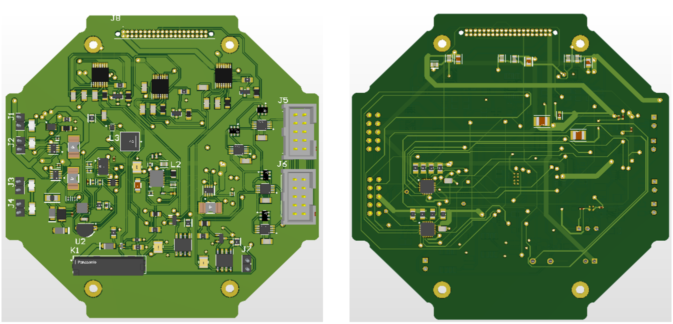
- Three series pairs: $3 \times 1.1\,\mathrm{W} = 3.3\,\mathrm{W}$
- Four series pairs: $4 \times 1.1\,\mathrm{W} = 4.4\,\mathrm{W}$

With five pairs of solar panels, the estimated total power generated is approximately 5.5 W under full sun exposure.

For storage, the system uses four 5000 mAh batteries, totaling 20 Ah. Based on a conservative energy availability estimate in Low Lunar Orbit (LLO)—where sunlight is guaranteed for at least 30 minutes per 2-hour orbital period—we expect to generate a minimum of 2 W per cycle. Assuming the load requires 1 W per hour, the power budget is sufficient to support basic CubeSat operations with redundancy, while also compensating for periods of eclipse or reduced solar exposure.

These results confirm that the EPS topology functions as intended, with reliable energy harvesting, intelligent switching, and regulated power delivery, while maintaining operational safety and extending battery and mission life.

In addition to simulation and component-level testing, a complete schematic of the entire Electric Power System was implemented, followed by full 4-layer PCB layout and routing. The board was designed to integrate all power generation, regulation, switching, and monitoring components into a compact, reliable form factor suitable for CubeSat deployment. Signal, ground, and power planes were carefully distributed across the four layers to optimize thermal performance, reduce EMI, and ensure power integrity. Input/output pins and onboard connectors were also included to support integration with the satellite's batteries, solar panels, and other subsystems. The layout emphasizes low-resistance paths for high-current traces, controlled impedance for signal lines, and overall electrical and thermal robustness. While the design is ready for fabrication and testing, a final round of routing refinement and design rule verification is required to ensure compliance with fabrication constraints and improve long-term reliability.



(a) Top layer view

(b) Bottom layer view

Fig. 3: CubeSat EPS PCB Design showing both top and bottom layout layers.

IV. Conclusion

This project successfully delivers a comprehensive and efficient Electric Power System (EPS) tailored to the constraints and requirements of CubeSat missions. By systematically addressing the core challenges in space-based power design, the final implementation demonstrates both innovation and reliability. The use of high-efficiency monocrystalline solar panels, coupled with an advanced MPPT charging system, ensures maximum energy extraction from the limited available surface area. The custom analog-based power switching topology enables intelligent battery management, avoiding harmful charge-discharge cycles and significantly extending battery life.

Space and mass constraints were overcome through a compact 4-layer PCB layout that integrates all subsystems including regulation, monitoring, fault protection, and thermal management into a single board. The design supports stable operation in extreme temperature environments, with all components rated up to 125°C and thermal feedback mechanisms included for improved energy conversion under changing conditions. Real-time power monitoring is enabled via low-overhead digital sensors and an I^2C expander, while critical safety functions like deployment and heating are directly controlled through onboard logic.

Importantly, the system minimizes dependence on microcontrollers and register-based digital logic, reducing vulnerability to radiation-induced Single-Event Upsets (SEUs) and enhancing overall mission resilience. With the full schematic implemented and a 4-layer PCB routed and ready for fabrication, the EPS is positioned as a robust, flight-ready solution. Once final routing refinements are completed, the board will be ready for manufacturing and integration. The design not only meets mission objectives for reliability and efficiency but also offers modular and scalable power architecture applicable to future CubeSat and small satellite platforms.

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