RV College of Engineering®
Mysore Road, RV Vidyaniketan Post,
Bengaluru - 560059, Karnataka, India

principal@rvce.edu.in
www.rvce.edu.in
Tel: +91-80-68188110
+91-80-68188111
+91-80-68188112

antariksh

Phase-2 Assignment – Team Antariksh

Electrical Power Systems Task 2
By Pradhumna P Gupta

Solar Panel Electrical Characteristics

Solar panels are the primary power generation source for satellites in Low-Earth Orbit (LEO). Modern CubeSat solar cells operate at **1–3 W per unit area** in LEO with solar irradiance of ~1,367 W/m² (AM0). Silicon cells achieve 15–17% efficiency, while advanced triple-junction gallium arsenide cells reach 28–32% efficiency. Individual cells generate approximately 0.5–2.5 V at maximum power point (MPP), with current capacity ranging from 300 mA to 1 A depending on cell size and configuration.

Solar arrays are constructed by combining cells in series (to increase voltage) and parallel (to increase current) configurations, denoted as xSyP notation (e.g., 4S2P represents four cells in series, two strings in parallel). A typical 1U CubeSat panel operates at 4.8–16.8 V depending on configuration, delivering 2.4–19.3 W under nominal sunlight conditions. Cell efficiency degrades with temperature (~0.4%/°C), so thermal management is critical. Long-duration missions must account for radiation-induced degradation (~0.8%/year for typical space-qualified cells).

EPS Input Stage Protections

The electrical power system input stage protects against solar panel transients, reverse current flow, and overvoltage conditions. The primary protection mechanism is the **Maximum Power Point Tracker (MPPT)**, which actively adjusts solar array voltage and current to maintain operation at the optimal power point on the IV curve. Three independent MPPT channels are typical for 3-sided CubeSat configurations, enabling autonomous tracking on sun-facing surfaces.

Passive protections include **bypass diodes** (one per solar string) to prevent reverse current during eclipse or shadowing, and **series regulators** that limit input voltage to battery charger specifications. Overvoltage protection triggers at battery voltages exceeding 16.6 V, cutting input power to prevent damage. Undervoltage protection activates below 13.8 V, entering safe mode to protect critical subsystems. Over-current protection limits per-rail sustained current to ~2–2.5 A through series switches or fuses, with rapid shutdown (<100 ms) to mitigate thermal latch-up failure modes common to radiation-exposed semiconductors.

Battery Pack Basics

Lithium-ion (Li-Ion) batteries are the standard secondary power source for CubeSats, offering superior energy density (~250–276 Wh/kg for 18650 cells), long cycle life (500–1000 cycles), and proven spaceflight heritage. Individual cells operate within a narrow voltage window (2.5 V minimum, 4.1–4.2 V maximum) and nominal 3.6–3.7 V, requiring integrated protection circuits. Cell arrangements typically range from **2S (8.26 V nominal)** for compact 1U missions to **4S (14.4 V nominal)** for larger 3U CubeSats.
Typical CubeSat battery packs include 20–80 Wh capacity with discharge currents of 2–5 A sustained, supporting peak bursts to 10–20 A for transceiver transmissions. **Depth of Discharge (DoD)** is carefully managed: conservative designs limit DoD to 40% to maximize lifespan; aggressive designs allow up to 80% for shorter missions. Cell balancing between series strings ensures equal voltage distribution; coulomb counters or voltage dividers estimate state of charge (SoC) with ±5% accuracy. Battery thermal management includes heaters for cold-soak protection (typical operating range: −20°C to +50°C discharge) and passive venting or fuses to contain thermal runaway events.

Required Power Rails (5 V, 3.3 V, Bus)

Three main voltage rails distribute regulated power throughout the spacecraft:

Rail	Voltage	Current Capacity	Primary Loads	Regulation Method
3.3V	3.3 ± 0.3 V	2–5 A	Microcontrollers, sensors, transceivers	LDO or buck converter
5V	5.0 ± 0.5 V	1–5 A	Operational amplifiers, logic, experiments	Buck converter from Vbat
VBAT (Unregulated)	7.2–21 V (battery dependent)	5–10 A peak	High-power loads, heaters, thrusters	Direct battery (no regulation)

The 5V and 3.3V rails are always-on to support critical systems (OBC, communications). VBAT may be switched via field-effect transistors (FETs) for non-essential loads like experiment payloads, enabling power-gating strategies. Voltage ripple on regulated rails is typically <10 mV peak-to-peak, maintained by bulk capacitors (100–1000 µF) and feedback regulators with ~90% efficiency.

Common EPS Faults and Failure Modes

1. **Battery Overvoltage/Overcharge**: MPPT or charger failure causes cells to exceed 4.2 V, triggering thermal fuse activation and loss of power (unrecoverable failure).

2. **Battery Undervoltage**: Excessive discharge below 2.5 V per cell prevents normal charging recovery and triggers immediate system shutdown.
3. **Over-Current Transients**: Inrush current from load switching causes voltage sag on unregulated rails; inadequate protection allows surge currents to damage semiconductors (typical limit: 2–3 A per switched line).
4. **Thermal Latch-Up (SEL)**: Radiation-induced single-event latch-up in power switches causes runaway current that melts silicon; fast current-limiting protection (<100 ms shutdown) mitigates risk.
5. **Voltage Cross-Talk**: High-current transients (e.g., thruster activation) on shared ground planes induce voltage noise on adjacent rails, corrupting low-voltage analog signals.
6. **MPPT Tracking Failure**: Algorithm stalling or oscillation prevents optimal power extraction, reducing available power by 5–10%.
7. **Solar String Degradation**: Microcrack formation in cells or interconnect corrosion slowly reduces output power over 2–5 years in space.

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