ELECTRICAL POWER SUBSYSTEM (EPS) DESIGN FOR A IU CUBESAT

1. INTRODUCTION

An Electrical Power System (EPS) is one of the most integral subsystems of any satellite. It is responsible for the generation, storage, conditioning, and distribution of electrical power to all other on-board systems, including the payload, on-board computer (OBC), communication (COMMS), and attitude determination and control system (ADCS). As a non-serviceable autonomous machine, a satellite's mission is entirely dependent on the continuous and reliable operation of its EPS.

This criticality is amplified in the context of a **1U CubeSat**. The CubeSat standard defines a "1U" unit as a cube measuring 10x10x10 cm with a maximum mass of 1.33 kg. These extreme constraints on volume, mass, and available surface area present significant challenges for the EPS designer. The limited surface area restricts the size of solar arrays, thus limiting power generation capacity. The mass and volume budget curtails the size and capacity of the batteries. Consequently, the design of an EPS for a 1U CubeSat is a rigorous exercise in optimization, prioritizing efficiency, energy density, and reliability above all else.

2. SUBSYSTEMS OF THE ELECTRICAL POWER SUBSYSTEM

A satellite EPS can be broadly segregated into three fundamental subsystems. Each of these contains more detailed components and functions critical to its operation. This is illustrated in the block diagram below:

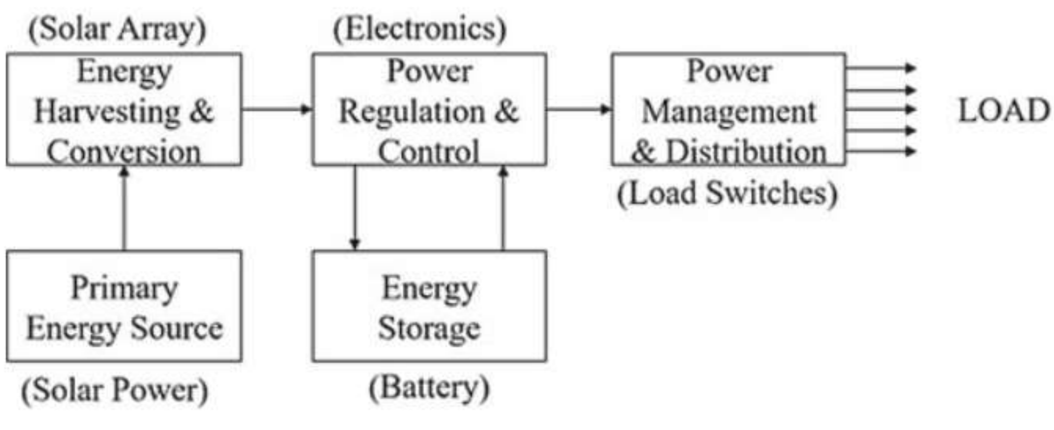


Figure 1: EPS Block Diagram

2.1. POWER GENERATION

The primary function of this subsystem is to convert incident solar energy into usable DC electrical power. This is the sole source of new energy for the satellite once it is in orbit.

2.1.1. Core Components

1. ***Photovoltaic (PV) Cells***

PV cells are semiconductor devices that operate on the photovoltaic effect. When photons from sunlight strike the cell, they excite electrons, creating an electron-hole pair. An internal electric field within the cell separates these pairs, driving a current through an external circuit.

A solar cell's output is not fixed. Its voltage and current vary depending on the load connected to it. This relationship is described by its characteristic I-V (Current-Voltage) curve.

- **Open-Circuit Voltage:** The maximum voltage a cell can produce (when no current is drawn).
- **Short-Circuit Current:** The maximum current a cell can produce (when the voltage is zero).
- **Maximum Power Point (MPP):** The "knee" of the curve where the product of voltage and current (Power = V x I) is at its absolute maximum. This is the optimal operating point for the cell. The goal of an efficient EPS is to force the solar array to always operate at this point.

While various technologies exist, the choice for a CubeSat is driven by efficiency (power per unit area).

- **Silicon (Si):** Lower efficiency (14-20%), but cost-effective and robust.
- **Gallium Arsenide (GaAs) - Triple Junction (TJ):** The industry standard for CubeSats. These cells have efficiencies of 28-30%+, generating nearly twice the power of Silicon for the same area. This is a critical advantage for a 1U CubeSat with only ~400 cm² of available surface area.

2. ***Solar Panels and Array Configuration***

Individual cells are wired together to form a panel. For cells in series**,** voltages add up and current stays the same. A typical 1U panel might have two 2.3V cells in series to produce a nominal 4.6V. On the other hand for cells in parallel, currents add up and voltage stays the same.

For a 1U CubeSat, panels are almost exclusively mounted directly to the 5 or 6 faces of the aluminium chassis. Deployable panels, while offering more power, introduce mechanical complexity and points of failure that are generally unacceptable for this form factor.

Each string of solar cells on a panel is connected in series with a **blocking diode**. This is a critical reliability feature. If one panel is in shadow, it stops generating power and can actually become a resistive load, draining power from the illuminated panels. The blocking diode is a one-way gate that prevents this reverse current, isolating the dark panel and preserving the power from the rest of the array.

2.1.2. Design Considerations

a. **Efficiency vs. Cost:** GaAs cells are significantly more expensive than Silicon, but their high efficiency is often a non-negotiable requirement to meet the power budget of a 1U mission.

b. **Degradation:** Over its lifetime, the solar array's performance will degrade due to radiation damage and thermal cycling. The EPS must be designed based on its **End-of-Life (EOL)** power generation, not its **Beginning-of-Life (BOL)** performance.

$$P_{EOL} = P_{BOL} \times (1 - Degradation\ Rate)^{Years} \quad (1)$$

c. **Number of Faces:** The face with the communications antenna (typically -Z) often has limited or no space for solar cells, reducing the total available power.

The Power Generation's output voltage and current profile directly drives the design of the Power Conditioning and Distribution Unit (PCDU), specifically the requirements for the MPPT charge controller. The total EOL power it can generate defines the absolute upper limit for the satellite's entire power budget.

2.2. POWER STORAGE

Power is stored for use during solar eclipse and to supply peak power demands (like radio transmission) that exceed what the Power Generation Subsystem can instantaneously provide.

2.2.1. Core Components

1. <u>Battery Cells</u>

Modern CubeSats almost exclusively use **Lithium-ion (Li-ion)** or **Lithium-Polymer (Li-Po)** cells. Their key advantages are:

- **High Specific Energy (Wh/kg):** They store the most energy for a given mass.
- **High Energy Density (Wh/L):** They store the most energy for a given volume.

These two factors are paramount for meeting the stringent mass (<1.33 kg) and volume (1000 cm³) constraints of a 1U CubeSat.

Key Terminology:

- **Capacity (Ah):** The amount of charge the battery can hold.
- **State of Charge (SoC):** The current remaining capacity, expressed as a percentage.

- **Depth of Discharge (DoD):** The percentage of the total capacity that is discharged in a single cycle. This is the most critical parameter for battery lifetime. A shallow DoD (e.g., 20%) results in a very long cycle life (many thousands of cycles), while a deep DoD (e.g., 80%) drastically reduces it. For a LEO mission lasting 1-2 years (5,000-10,000+ orbits/cycles), a low DoD is essential.

2. ***Battery Pack Configuration***

Cells are combined in series (S) and parallel (P) to create a pack with the desired voltage and capacity. For example, a **2s1p** configuration uses two cells in series. This provides a higher bus voltage (~7.4V nominal), which is more efficient because it reduces resistive (I^2R) losses in the wiring for the same amount of power delivered. (More voltage results in less current).

3. ***Battery Management System (BMS)***

This is the battery's essential life-support and safety system. It provides over-voltage (stops charging when full), under-voltage (disconnects loads when empty to prevent damage), and over-current protection. Similarly, it monitors battery temperature and can enable small resistive heaters if the battery gets too cold (charging Li-ion cells below 0°C can cause permanent damage).

Moreover, when cells are in series, tiny manufacturing differences cause them to charge and discharge at slightly different rates. Without balancing, one cell will hit its voltage limit before the others, limiting the usable capacity of the entire pack. The BMS uses small bleed resistors to equalize the charge across all cells, ensuring the pack ages gracefully and performs optimally.

2.2.2. Design Considerations

- **Capacity vs. Mass/Volume:** The fundamental trade-off. A larger battery provides more energy and allows for a lower DoD (longer life), but it consumes precious mass and volume budget.
- **DoD vs. Mission Life:** The designer must select a battery size and operational plan that ensures the DoD per orbit keeps the battery healthy for the total number of cycles required by the mission lifetime.

The battery's voltage range (e.g., 6.0V to 8.4V for a 2s pack) defines the required input operating range for all the DC/DC converters in the PCDU. The battery's maximum safe charge and discharge rates (C-rate) limit how fast the PGS can charge it and how much peak power the satellite can draw.

2.3. THE POWER CONDITIONING AND DISTRIBUTION UNIT (PCDU)

The PCDU acts as the intelligent hub of the EPS, managing the flow of power from source to storage to loads. It ensures that clean, stable, and protected power is delivered wherever it is needed.

2.3.1. Core Components

1. ***Battery Charge Controller (with MPPT)***

The goal is to operate the solar array at its Maximum Power Point. The MPPT controller is a specialized DC/DC converter that achieves this. The embedded microcontroller runs an algorithm like **"Perturb and Observe."** It slightly changes (perturbs) the operating voltage of the array and measures (observes) the resulting change in power. If power increases, it continues perturbing in that direction; if power decreases, it reverses. This process continuously "hunts" for the peak of the power curve, maximizing energy harvesting by 20-40% compared to a direct connection.

2. ***DC/DC Converters (Voltage Regulators)***

Voltage regulators take the unregulated, variable battery bus voltage and convert it into the stable, precise voltages required by the satellite's electronics (e.g., 3.3V for microprocessors, 5V for sensors and actuators). The most common type is a **buck (step-down) converter**.

Efficiency is a critical parameter in this case. A regulator's efficiency is the ratio of power out to power in ($\eta = P_{OUT}/P_{IN}$). An 85% efficient regulator wastes 15% of its input power as heat. A 95% efficient regulator only wastes 5%. For a power-starved 1U CubeSat, high efficiency is crucial to minimize wasted energy and reduce the thermal load on the satellite.

3. ***Power Distribution Switches***

Switches serve to control and protect each individual power output rail. These are not simple mechanical switches. They are integrated circuits often called **"e-fuses"** or intelligent load switches.

Advantages:

- **Resettable:** If a subsystem draws too much current and trips its switch, the OBC can command the switch to turn back on after a delay (unlike a physical fuse).
- **Current Limiting:** They actively limit the current to a pre-set maximum.
- **Telemetry:** They can report the actual current being drawn by the load, which is invaluable for on-orbit health monitoring.
- **Isolation:** They provide robust fault isolation. A short-circuit in a payload will only trip its own switch, protecting the rest of the satellite from a catastrophic failure.

2.3.2. *Design Considerations*

a. <u>Architecture (Centralized vs. Distributed)</u>

- **Centralized:** One main EPS board contains all the converters and switches. This is the standard for 1U CubeSats due to its simplicity and volume efficiency.
- **Distributed:** Power is distributed at the main bus voltage and small, local **"Point-of-Load" (POL)** converters are placed on each subsystem board. This can improve electrical performance but is more complex and voluminous.

b. <u>Switching Frequency</u>

- The DC/DC converters operate by switching transistors at high frequencies (hundreds of kHz to MHz). Higher frequency allows for smaller inductors and capacitors (good for volume) but can lead to higher switching losses (bad for efficiency). This is a key trade-off for the power electronics designer.

The PCDU is the heart of the satellite. It is entirely dependent on the Power Generation Subsystem and Power Storage Subsystem for power input. In turn, every single other subsystem in the satellite is entirely dependent on the PCDU for its conditioned and protected power. The PCDU's efficiency is a major factor in the overall energy balance and thermal design of the entire satellite.

3. THE EPS DESIGN PROCESS

A systematic process is the best approach for designing the EPS for a 1U CubeSat majorly driven by the mission requirements. The goal is to create a system that is perfectly balanced, where power generation, storage, and consumption are in harmony over the entire mission lifetime. The following steps outline this systematic process.

3.1. MISSION ANALYSIS AND REQUIREMENTS DEFINITION

<u>Analyse the Orbit:</u>

The mission's orbital parameters are the single most important input. Using tools like Systems Tool Kit (STK), the designer determines:

- **Orbit Period:** The total time for one revolution (e.g., ~95 minutes for a 500 km orbit).
- **Sunlight Duration (T_d):** The portion of the orbit where the solar panels can generate power.
- **Eclipse Duration (T_e):** The portion of the orbit where the satellite is in Earth's shadow and must run on battery power.

Define the Mission Lifetime

This involves defining how long the mission should take. This dictates the total number of charge/discharge cycles the battery must endure and the total radiation exposure the solar cells will receive. This is crucial for calculating component degradation.

Characterize the Loads

Every component that consumes power is a "load." The designer must create a comprehensive list detailing:

- **Voltage Requirement:** Does it need 3.3V, 5V, or can it run on the unregulated battery bus?
- **Power Consumption:** How many watts does it draw when active?
- **Duty Cycle:** What percentage of an orbit will this component be active? A radio transmitter might have a very high power draw but only a 5% duty cycle, while the OBC has a low power draw but a 100% duty cycle.

3.2. CONSTRUCT THE POWER AND ENERGY BUDGETS

With the requirements defined, the next step is to perform the core analysis. This is typically done in a detailed spreadsheet.

Create Operational Modes

A satellite doesn't do the same thing all the time. The designer must define different operational modes and calculate the total power consumption for each. Examples include:

- **Safe Mode:** The bare minimum power to keep the satellite alive (OBC on, receiver listening).
- **Nominal Mode:** Standard operations (e.g., ADCS active, sensors collecting data).
- **High-Power Mode:** A specific, power-intensive task (e.g., transmitting data to a ground station).

Calculate Orbit Average Power (OAP)

For the most demanding but sustainable operational mode, the OAP is calculated. This represents the average power the EPS must provide over a full orbit.

Orbit Average Power (OAP)

$$\boldsymbol{OAP_{load} = \sum P_{component} \times Duty\ cycle_{component}} \quad (2)$$

This sum is taken over all components.

Apply a Design Margin

No model is perfect. To account for uncertainties, component variations, and unforeseen operational needs, a healthy design margin of 20-30% is added to the calculated OAP_{load}. This becomes the target generation requirement for the solar array.

3.3. SIZE THE SOLAR ARRAY (POWER GENERATION)

The solar array must be sized to provide the target OAP while also recharging the energy used from the battery during the eclipse. Its performance is calculated at its End-of-Life (EOL).

Calculate Required Energy Generation

The total energy needed per orbit is the sum of the energy used by loads during sunlight and the energy needed to replenish the battery for what was used during eclipse. A simplified but effective equation is provided below.

Required Solar Array Power

$$\boldsymbol{P_{sa}} = \frac{\boldsymbol{P_d}}{\eta_{\boldsymbol{d}}} + (\boldsymbol{P_e} \times \frac{\frac{\boldsymbol{T_e}}{\boldsymbol{T_d}}}{\eta_{\boldsymbol{e}}}) \qquad (3)$$

Where:

$\mathbf{P_d}$, $\mathbf{P_e}$ = Average power consumed in daylight and eclipse.

$\mathbf{T_d}$, $\mathbf{T_e}$ = Duration of daylight and eclipse.

$\boldsymbol{\eta_d}$ = Efficiency of the power path from array to load (~95% for MPPT).

$\boldsymbol{\eta_e}$ = Efficiency of the charging and discharging path ($\boldsymbol{\eta_{charge}} * \boldsymbol{\eta_{discharge}}$, ~85-90%).

Account for Degradation

Solar cell efficiency degrades over time. The design must be based on the EOL power.

End-of-Life Power ($\mathbf{P_{EOL}}$)

$$\boldsymbol{P_{EOL}} = \boldsymbol{P_{BOL}} \times \boldsymbol{L_d}^{\boldsymbol{mission\ life\ in\ years}} \ (4)$$

Where $\boldsymbol{L_d}$ is the life degradation factor (e.g., 0.97 for 3% degradation per year). The P_sa calculated above must be what the array can produce at EOL.

Determine Physical Layout

The designer then checks if the required number of high-efficiency cells can physically fit on the available faces of the 1U CubeSat. If not, the process must be iterated.

3.4. SIZE THE BATTERY (ENERGY STORAGE)

The battery must be large enough to survive the longest eclipse without being discharged too deeply, which would shorten its life.

Calculate Energy Required for Eclipse

Required Eclipse Energy (C_{req})

$$\boldsymbol{C_{req}} = (\boldsymbol{P_e} \times \boldsymbol{T_e})/\eta_{\boldsymbol{discharge}} \quad (5)$$

Where $\eta_{discharge}$ is the efficiency of the DC/DC converters drawing from the battery (~90-95%). This gives the energy in Watt-hours **(Wh)** that the battery must deliver during eclipse.

Apply Depth of Discharge (DoD) for Lifetime

To ensure the battery survives thousands of LEO cycles, the C_{req} should only represent a small fraction of its total capacity.

Total Required Battery Capacity (C_{total})

$$\boldsymbol{C_{total}} = \boldsymbol{C_{req}}/\boldsymbol{DoD} \quad (6)$$

For a long-life LEO mission, a DoD of 20-25% is a standard design goal.

Select a Physical Battery

The designer then finds a commercially available battery pack that meets or exceeds the calculated C_{total} and fits within the allocated mass and volume.

3.5. ITERATE AND FINALIZE

If the required solar array is too large, or the battery is too heavy or voluminous, the design is not viable. The EPS designer must go back to the team and negotiate—"Can the radio transmit for 4 minutes instead of 5? Can we reduce the payload duty cycle?" This iterative loop continues until a balanced and physically achievable design is reached.

4. THE EPS ARCHITECTURE

The "architecture" refers to the high-level schematic of how the main EPS subsystems are interconnected. The choice of architecture is a fundamental design decision with significant implications for efficiency, complexity, and reliability.

The classification of the state-of-the-art CubeSat EPS architectures is shown in the figure below, which is done based on the following aspects:

(1) dc-bus voltage regulation

(2) Interface of PV panels

(3) Location of power converters

(4) Number of conversion stages

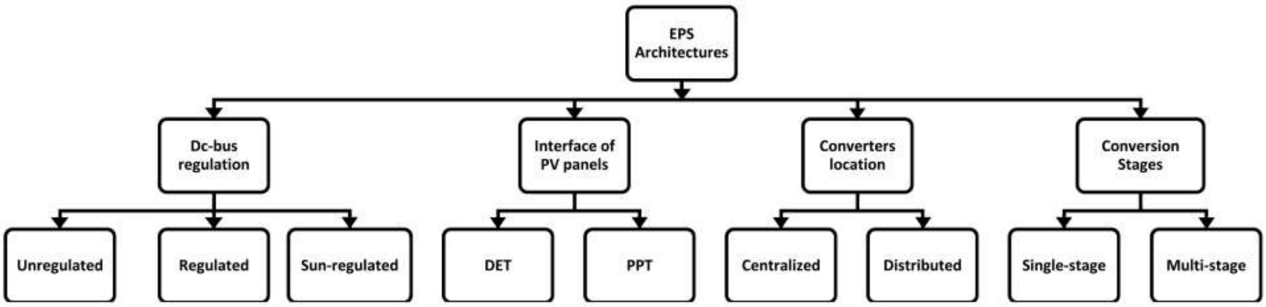


Figure 2: Classification of CubeSat EPS Architectures

The following are the most relevant for 1U CubeSat mission:

Key Decision Points for 1U:

4.1. PV INTERFACE (DET VS. PPT)

The PV panels are the main source of energy for the CubeSat and based on their interface, the EPS architectures are categorized into DET and PPT

4.1.1. Direct Energy Transfer (DET)

In this architecture, the PV panels with series diodes are directly connected to storage system and/or loads. It usually has a shunt regulator in parallel to the PV panel to divert the excess PV power when the battery is fully charged or when the load demand is less. The excess power is dissipated as heat inside CubeSat if resistor is used in shunt regulator otherwise it is dissipated on the PV panel. The reliability of shunt regulator is very important otherwise it results in loss of mission.

It is simpler, more reliable, fewer components. The PV panel is connected almost directly to the battery bus. However, it is inefficient as it does not operate the panel at its maximum power point.

4.1.2. Peak Power Tracking (PPT)

The architecture utilizes PV panels interfaced with dc-dc converters as shown in the figure below to achieve MPPT over wide range of operating conditions such as solar irradiation, PV panel temperature, and sun inclination angle.

On the generation-side, the PV panels on the opposite faces of CubeSat are connected in parallel and they are interfaced with dc-dc converter for maximum power point tracking (MPPT) under wide range of irradiation conditions and battery voltage. The type of dc-dc converter depends on the maximum power point (MPP) voltage of the PV panel and the battery voltage.

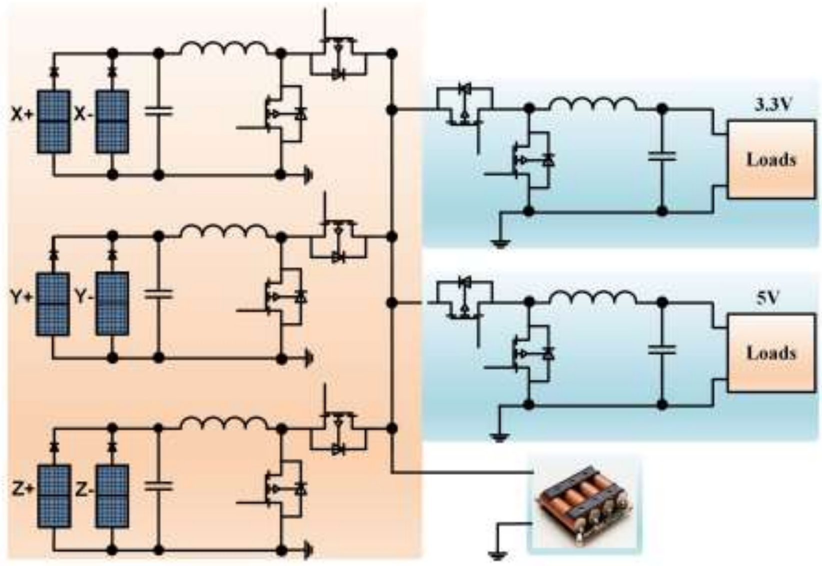


Figure 3: Peak Power Tracking (PPT) Architecture

It is widely used in CubeSat designs as they have limited power generation due to shorter sunlit periods and space constraints for using larger PV panels. The MPPT can be achieved by either digital micro-controller (MCU) or analog controllers. A MCU has advantages of simplicity and flexibility in tuning but it is more susceptible to failure due to radiation damage.

The analog controller with discrete components is considered more robust although not efficient as MCU. The CubeSat may implement analog controllers as main control or as back-up control to be used in case of MCU failure.

4.2. DC-BUS REGULATION (UNREGULATED VS. REGULATED)

The dc-bus acts as intermediate stage between PV panels, energy storage system, and loads. Based on the dc-bus voltage regulation, the EPS architectures are classified as: (1) unregulated dc-bus EPS, (2) regulated dc-bus EPS, and (3) sun-regulated dc bus

4.2.1. Unregulated Bus

The main power bus that feeds the satellite is the battery terminal. The bus voltage therefore varies with the battery's state of charge (e.g., from 8.4V down to 6.0V for a 2s Li-ion packs). There is no central regulator wasting power. Power flows directly from the battery to the loads. It is also more reliable as there is no single-point-of-failure main regulator.

However, all subsystems that require a stable voltage (like the 3.3V OBC) must have their own small, local DC/DC regulators.

The efficiency gains are critical, and the requirement for local regulators is a widely accepted and manageable trade-off all which makes it a dominant architecture.

4.2.2. Regulated Bus

A central, main DC/DC converter is placed after the battery to provide a constant bus voltage (e.g., a stable 5V) to the entire satellite. It simplifies the design of other subsystems, as they all receive a clean, stable input voltage. However, it introduces a constant efficiency loss (typically 5-15%) from this main regulator, which is always on. It also represents a critical single point of failure—if the main regulator dies, the entire satellite dies.

The efficiency penalty and reliability risk are generally considered too high for the benefit of a stable bus.

4.2.3. Sun-regulated Bus

In sun-regulated dc-bus architecture, the dc-bus voltage is regulated to reference value only during the sunlit period and during the eclipse period. The battery connects to the dc-bus via diode. It is also referred as partial regulated dc-bus or quasi regulated dc-bus.

4.3. CONVERTER LOCATION (CENTRALIZED VS. DISTRIBUTED)

Based on the location of power converters, the EPS architectures are categorized as centralized/concentrated and decentralized/distributed architectures as shown in the figure below:

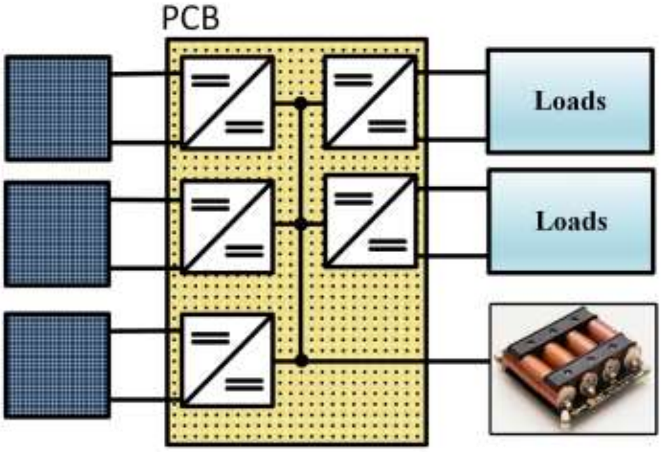


Figure 4(a): Centralized

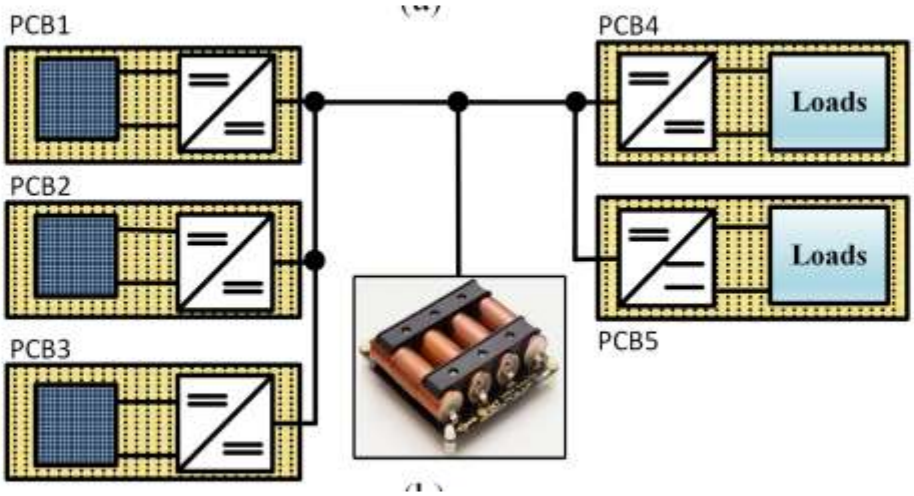


Figure 4 (b): Distributed

4.3.1. Centralized

In the centralized architecture of Fig. 4 (a), all the power converters along with the controllers are placed on a single printed circuit board (PCB) which connects to the PV modules, storage system, payloads, and subsystems through specific voltage rails.

It has been widely used in CubeSats due to simplicity, physical space efficiency, and several COTS EPS designs. In this architecture, fewer voltage regulators are required because multiple payloads and subsystems use same voltage rail.

One main disadvantage is that the voltage regulators must be designed for peak load demand and hence, the converter operates at lower efficiency for most of the time. Another disadvantage is lower reliability as the failure of one converter affects multiple subsystems.

4.3.2. Distributed

The distributed architecture has dc-bus supplied throughout the system and the power converters are placed close to individual subsystems and in some designs, MPPT converters are placed close to PV panels.

It utilizes several PCBs in the entire design and is commonly used in bigger satellites but has not become popular in CubeSats due to higher number of dedicated power converters.

5. RECOMMENDED ARCHITECTURE: EPS-6 (CENTRALIZED, UNREGULATED PPT)

This is the de-facto standard for commercial off-the-shelf (COTS) 1U EPS boards and has extensive flight heritage (GOMspace, Nanoavionics, etc.). The EPS-6 architecture is as shown below:

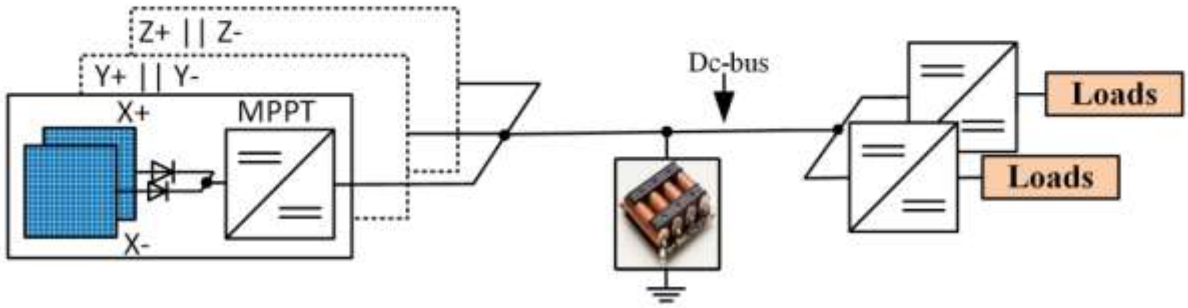


Figure 5: EPS-6 Architecture (PPT & Unregulated Bus)

Description:

- **PV Interface:** PV panels are connected to dedicated **MPPT converters**. Often, panels on opposite faces (e.g., +X and -X) are connected to a single MPPT converter.

- **Bus:** The outputs of the MPPT converters are connected directly to the battery, creating an **unregulated bus**.

- **Operation:** During sunlit periods, the MPPT converters charge the battery and supply power to the loads. If the battery is full, the MPPT converter throttles back. During eclipse, the battery directly powers the bus.

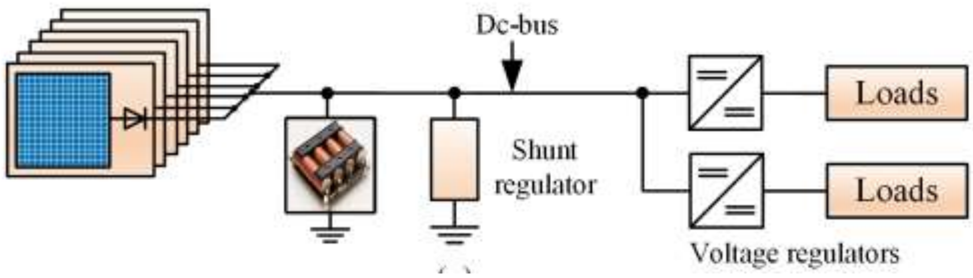
- **Distribution:** Point-of-Load (POL) converters tap off this unregulated bus to provide stable 3.3V and 5V rails to other subsystems.

Why it's ideal for 1U:

- **Efficiency:** PPT maximizes power from the small solar panels. The unregulated bus minimizes primary power conversion losses.
- **Simplicity & Volume:** The centralized design is compact and fits onto a single PC/104-form-factor board.
- **Reliability:** It's a proven design with significant flight heritage.

ALTERNATIVE ARCHITECTURE: EPS-1 (CENTRALIZED, UNREGULATED DET)

In case of EPS-1 shown in the figure below, the output of PV panels is connected to battery in parallel with shunt regulator and the load-side converters for further conversion. The PV panel’s output voltage is clamped to floating battery voltage and its output current depends on the I-V characteristics curve. The battery feeds to loads directly during the eclipse period and it has protection system to avoid over-current, over-voltage, and under-voltage conditions. It has higher conversion efficiency due to power conversion by just one dc-dc converter before feeding the load demand.



Use Case for 1U

This architecture is only suitable for missions with very low power requirements where simplicity and reliability are valued far more than power efficiency. Its lower component count is an advantage, but the power loss from not using MPPT is a significant drawback for most 1U missions.

6. CONCLUSION

The design of an Electrical Power System for a 1U CubeSat is a masterclass in compromise and optimization. It is a field where the immutable laws of physics intersect with the harsh realities of the space environment and the severe constraints of a miniaturized platform.

The design process is a systematic and iterative journey, rooted in a meticulous analysis of the mission's operational requirements. This analysis drives a quantitative budgeting and sizing process that dictates the specifications for every component, from the solar cells to the battery chemistry to the power regulators. The technological choices are unequivocally driven by the need for maximum efficiency and energy density, leading to the near-universal adoption of high-performance Gallium Arsenide solar cells and Lithium-ion batteries.

Architecturally, the 1U CubeSat community has converged on a topology that prioritizes efficiency above all else: a Peak Power Tracking system to ensure not a single milliwatt of precious solar energy is wasted, coupled with an unregulated bus to minimize conversion losses. Ultimately, the EPS is more than just a power supply; it is the foundational enabler upon which every scientific discovery, every transmitted data packet, and the very survival of the spacecraft depend. A well-designed EPS does not merely power a satellite—it makes the mission possible.