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"Satellite Electrical Power System : A Review of Design,Operation and Optimization Techniques"

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1. ABSTRACT

This image presents a high-level overview of a spacecraft electrical power system. It shows how energy is generated, stored, managed, and distributed to different subsystems.

At the core, solar panels (solar array) capture energy from the sun. This energy is then regulated and routed through a power conditioning and distribution unit (PCDU), which manages how electricity flows within the system. The system also includes lithium-ion batteries that store energy for use when solar power is unavailable, such as during eclipses. Inside the PCDU, several components handle tasks like voltage regulation, battery charging control, and power distribution across different buses. These buses supply electricity to various loads, including low-voltage devices, secondary systems, heaters, and main system loads.

Additionally, the diagram highlights control and safety elements, such as logic units and release mechanisms, as well as monitoring features like temperature sensors. Overall, the figure explains how a spacecraft ensures a stable and reliable power supply by integrating solar generation, battery storage, and intelligent power management.

2. INTRODUCTION

Every spacecraft, whether it's a small satellite orbiting Earth or a probe traveling deep into space, depends on a reliable source of electrical power. Without it, none of the mission-critical systems—like communication, navigation, or scientific instruments—can function. The heart of this power system is usually a combination of solar arrays, which generate electricity, and batteries, which store energy for use when the spacecraft is in shadow or far from the Sun.

Modern spacecraft use Power Control and Distribution Units (PCDUs) to manage this energy. The PCDU acts like the central hub: it regulates the flow of power from solar panels, monitors and protects the batteries, and distributes electricity to all onboard equipment. Advances in technology, especially the adoption of lithium-ion batteries and smarter regulation techniques such as Maximum Power Point Tracking (MPPT), have made these systems more efficient, lighter, and longer-lasting than older designs.

As missions become more complex—ranging from CubeSats to large geostationary satellites—the design of spacecraft power systems has had to evolve. Engineers now focus on making these systems modular, scalable, and capable of handling unexpected conditions in space. Features like autonomous fault detection, intelligent load management, and redundant safety mechanisms are increasingly common, ensuring that spacecraft can operate reliably with minimal human intervention.

This review paper explores how spacecraft power systems have developed, with a focus on solar array regulation, lithium-ion battery integration, and the role of the PCDU. By looking at current designs and future trends, the paper highlights both the challenges and opportunities in building power systems that can support the next generation of space exploration.

3. DESIGN CHALLENGES

Design Challenges in Spacecraft Power Systems

Designing a spacecraft's power system is far from straightforward. Engineers face a unique set of challenges because space is an unforgiving environment, and every mission has strict requirements. Some of the main challenges include:

Weight and Size Limits

Spacecraft must be as light as possible to reduce launch costs. Power systems, including solar panels, batteries, and distribution units, need to deliver high performance while staying compact and lightweight.

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Reliability in Harsh Environments

Spacecraft operate in extreme conditions: radiation, vacuum, and wide temperature swings. Power systems must be designed to survive and function consistently for years without repair.

Efficient Energy Management

Solar arrays only generate power when exposed to sunlight. During eclipses or deep-space missions, batteries must take over. Balancing generation, storage, and consumption requires smart regulation and control.

Battery Longevity

Lithium-ion batteries degrade over time. Ensuring they last throughout the mission involves careful monitoring of charge/discharge cycles, temperature control, and protection against overcharging or deep discharging.

Complex Load Distribution

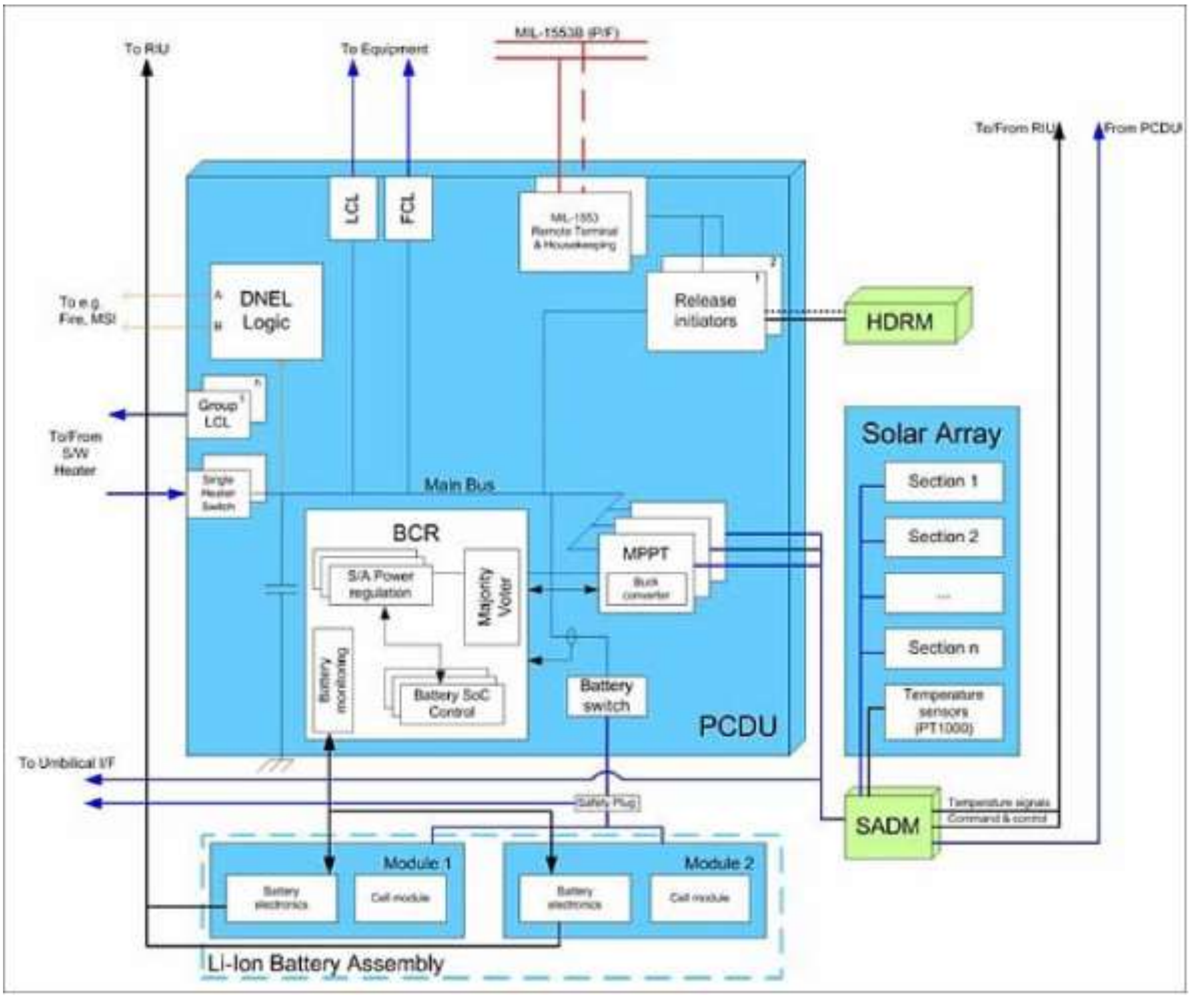
Different subsystems (communication, propulsion, instruments, heaters) require different voltages and power levels. The Power Control and Distribution Unit (PCDU) must handle this complexity while preventing overloads or failures.

Fault Detection and Redundancy

A single failure in the power system can end a mission. Engineers design redundant circuits, backup regulators, and autonomous fault detection to keep the spacecraft running even if something goes wrong.

Scalability Across Missions

From small CubeSats to large geostationary satellites, power systems must be adaptable.



Designing modular architectures that can scale up or down is a constant challenge.

4. DESIGN OF SATELLITE POWER SYSTEM

The Electrical Power System (EPS) is one of the most important parts of a satellite. Its main job is to generate, store, control, and supply electrical power to all the components inside the satellite. Without this system, the satellite cannot function properly in space.

In a satellite, electricity is mainly produced using solar panels (solar arrays). These panels convert sunlight into electrical energy. However, a satellite does not always stay in sunlight—it also passes through the Earth's shadow (called eclipse). During this time, the satellite uses lithium-ion batteries to supply power, which were charged earlier when sunlight was available.

The main control unit of this system is the Power Conditioning and Distribution Unit (PCDU). It manages the power by controlling voltage, charging and discharging the batteries, and distributing electricity to different parts of the satellite. Important components like Battery Charge Regulators (BCR), Maximum Power Point Tracking (MPPT), and Low Current Limiters (LCL) help in efficient power usage and protect the system from damage.

The system also includes control and monitoring parts like DNEL logic and remote terminals, which help in checking the system status and controlling different operations.

Safety devices such as release mechanisms and solar panel deployment systems (like HDRM and SADM) make sure that parts like solar panels open and work properly in space.

In simple words, the Electrical Power System makes sure that every part of the satellite gets proper and continuous power, which is necessary for the success of the satellite mission.

4.1 SOLAR ARRAY AND SADM

The Solar Array is the primary power source, typically divided into multiple sections to ensure that a failure in one panel doesn't compromise the entire mission. To keep these panels productive, the SADM (Solar Array Drive Mechanism) acts as a motorized joint that rotates the arrays to track the sun's position. By maintaining an optimal angle of incidence, it ensures the maximum amount of photon energy is captured throughout the satellite's orbital path.

4.2 THE PCDU (POWER CONTROL AND DISTRIBUTION UNIT)

Often called the "brain" of the electrical system, the PCDU is a highly integrated box that handles power conditioning, storage management, and distribution. It takes the raw, fluctuating electricity from the solar panels and transforms it into a clean, stable supply. It also acts as the central hub for the satellite's "housekeeping" data, communicating with the main flight computer via a MIL-1553B or similar data bus to report on the system's health.

4.3 BCR (BATTERY CHARGE REGULATOR) AND MPPT

The BCR is responsible for the health of the energy storage system. It monitors the battery's State of Charge (SoC) and regulates the incoming current to prevent overcharging. Integrated within this is the MPPT (Maximum Power Point Tracking) buck converter. This is an optimizer that constantly "hunts" for the ideal electrical operating point of the solar cells, ensuring that even as the panels get old or cold, the system extracts every possible watt of power.

Li-Ion BATTERY ASSEMBLY

The Battery Assembly serves as the satellite’s reservoir. Since satellites spend a significant portion of their lives in the Earth’s shadow (eclipse), these Lithium-Ion modules store excess energy gathered during the day to keep the spacecraft alive at night. They are built with redundant modules to ensure that if one cell fails, the others can continue to support the mission's energy demands.

4.4 MAIN BUS AND VOLTAGE REGULATORS

The Main Bus is the primary highway for electricity. It maintains the common voltage level that links the generators, the batteries, and the consumers. Because different instruments require different voltages, Secondary and Low Voltage Regulators act as step-down converters. They take the high-voltage power from the main bus and "clean" it for sensitive electronics, protecting them from noise and fluctuations.

4.5 PROTECTION AND LOGIC : LCL, FCL, and DNEL

To prevent a single equipment failure from destroying the entire satellite, the PCDU uses electronic "fuses" known as LCLs (Latching Current Limiters) and FCLs (Foldback Current Limiters). These components instantly cut off power to any device that starts drawing too much current due to a short circuit. For more extreme cases, the DNEL (Disconnect Non-Essential Loads) Logic acts as a survival instinct; if the battery gets dangerously low, it autonomously shuts down science payloads to save enough power for the radio and heaters.

4.6 DEPLOYMENT AND THERMAL CONTROL

During the launch phase, the solar arrays are folded tightly against the satellite body. The Release Initiators and HDRM (Hold Down and Release Mechanism) are specialized components that receive a high-current command from the PCDU to "fire" and deploy the panels once in orbit. Meanwhile, Heaters managed by dedicated switches within the PCDU ensure that the hardware doesn't freeze in the deep cold of space, using small amounts of electrical energy to maintain a stable internal climate.

4.7 COMMUNICATION AND DATA INTERFACES

The ML-1553B Data Bus serves as the primary communication backbone, allowing the power system to "talk" to the satellite's central computer. Inside the PCDU, the Remote Terminal (RT) & Housekeeping unit acts as an interpreter; it collects status data—such as current draws and voltage levels—and packages them into digital messages for the ground crew to monitor. This is often paired with a Remote Interface Unit (RIU), which handles the input and output signals for external hardware that isn't directly integrated into the main power box, ensuring every part of the satellite stays synchronized with the power budget.

4.8 RELIABILITY AND VOTING LOGIC

Because a single radiation-induced "glitch" in deep space could cause a total system shutdown, the PCDU employs a Majority Voter system within its control loops. This is a form of hardware redundancy where three separate circuits perform the same calculation (such as determining the battery's charge state), and the voter chooses the result that at least two of the three agree upon. This "two-out-of-three" logic ensures that even if one circuit fails or produces an error, the satellite continues to operate correctly without human intervention.

SENSING AND ENVIRONMENTAL MONITORING

To manage the extreme temperature swings of space, the system relies on PT1000 Temperature Sensors. These high-precision thermometers are strategically placed on the solar arrays and within the battery modules. The data they provide is critical because the efficiency of a solar cell and the chemical stability of a battery change drastically with temperature. If these sensors detect a drop toward freezing, the Heater Switches (including both single and group switches) are activated to divert small amounts of power to thermal blankets, preventing the hardware from reaching its breaking point.

4.9 GROUND OPERATIONS AND SAFETY

Before the satellite even leaves Earth, the Umbilical Interface (I/F) and the Safety Plug play a vital role. The Umbilical I/F allows engineers to power the satellite and run tests on the launchpad without draining the flight batteries. The Safety Plug is a physical "remove before flight" component that acts as a hard disconnect for the battery system. This ensures that the high-capacity batteries cannot accidentally discharge or cause a fire during integration, transport, or the high-vibration environment of a rocket launch.

4.10 INTERNAL BATTERY MANAGEMENT

Within the Li-Ion Battery Assembly, the architecture is further divided into Cell Modules and Battery Electronics. While the modules physically store the energy, the internal electronics perform "cell balancing." Since no two battery cells are perfectly identical, some might charge faster than others; the electronics bleed off excess energy from the "fast" cells to ensure the entire pack reaches full capacity safely. A heavy-duty Battery Switch acts as the final gatekeeper, capable of completely isolating the battery from the main bus in the event of a catastrophic electrical fault.

5.1 DESIGN OF EPS ELECTRICAL POWER SYSTEM

The design of a Satellite Electrical Power System (EPS) is a rigorous engineering process that ensures the spacecraft remains operational under extreme thermal cycles and radiation. The architecture is primarily composed of the energy source (Solar Arrays), the energy storage (Batteries), and the power management and distribution (Converters).

5.1.1 SOLAR ARRAY DESIGN AND SIZING

The sizing of a solar array begins with the determination of the power required during the daylight (P_d) and eclipse (P_e) portions of the orbit. The total power the solar array must generate during the sunlit period (P_sa) must be sufficient to power the spacecraft loads while simultaneously recharging the batteries.

The fundamental sizing formula for the solar array power is:

$$P_{sa} = \frac{\frac{P_e T_e}{\eta_e} + \frac{P_d T_d}{\eta_d}}{T_d}$$

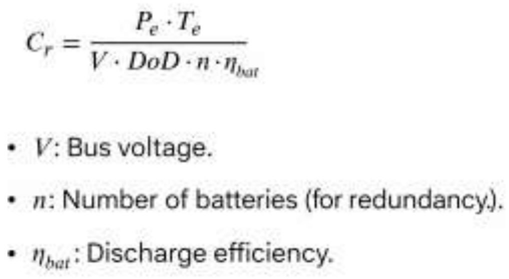
Te. Ta: Time spent in eclipse and daylight, respectively.

Ne. ha: Efficiency of the power paths during eclipse and daylight.

5.1.2 ENERGY STORAGE (BATTERY) SIZING

Energy Storage (Battery) Sizing Batteries provide power when the satellite is in the Earth’s shadow (eclipse). The most critical factor in battery design is the Depth of Discharge (DoD), which is the percentage of the total capacity used during a single cycle. Higher DoD reduces battery life significantly.

The required Rated Capacity (C_r) in Ampere-hours (Ah) is derived as follows:



$$C_r = \frac{P_e \cdot T_e}{V \cdot DoD \cdot n \cdot \eta_{bat}}$$

- V: Bus voltage.
- n: Number of batteries (for redundancy).
- η_{bat}: Discharge efficiency.

For a Low Earth Orbit (LEO) satellite, which may experience 5,000+ cycles per year, the DoD is usually kept low (20–30%), whereas for Geostationary (GEO) satellites with fewer cycles, it can be higher (60–80%).

5.1.3 POWER CONVERTERS AND REGULATION

The Power Control and Distribution Unit (PCDU) manages the voltage translation between the fluctuating solar array output and the steady bus voltage required by the payloads. This is achieved through DC-DC converters.

The efficiency of these converters (\eta_conv) is vital because lost energy is dissipated as heat, which is difficult to remove in a vacuum. The power output (P_out) of a buck or boost converter is:

$$P_{out} = \eta_{conv} \cdot V_{in} \cdot I_{in}$$

Most modern designs utilize Maximum Power Point Tracking (MPPT). The MPPT controller continuously adjusts the operating point (impedance) of the solar array to ensure it operates at the "knee" of the I-V curve, where the product of current (I) and voltage (V) is maximized:

$$\frac{dP}{dV} = 0 \Rightarrow I + V\,\frac{dI}{dV} = 0$$

6. OPERATION OF EPS

6.1.1 POWER FLOW CONTROL ARCHITECTURES

Operationally, satellites utilize one of two primary control architectures to manage the flow from the solar array to the bus: Direct Energy Transfer (DET) or Peak Power Tracking (PPT).

In a DET architecture, the solar array is connected directly to the bus, and a Shunt Regulator dissipates or switches off excess power when the array produces more than the load and battery require. The Sequential Switching Shunt Regulator (S3R) is a common operational choice here, providing high efficiency by only activating the number of solar array sections needed to meet the current demand.

Conversely, the PPT architecture uses a DC-DC converter (the PPT unit) to decouple the solar array voltage from the bus voltage. The operational logic follows the Maximum Power Point (MPP) of the array, which shifts based on temperature and aging. The control loop executes a "Perturb and Observe" (P&O) algorithm:

1. The controller slightly changes the converter's duty cycle (D).

2. It measures the change in power (\Delta P).
3. If \Delta P > 0, it continues in the same direction; if \Delta P < 0, it reverses.

The duty cycle D for a buck converter is governed by:

$$V_{bus} = D \cdot V_{sa}$$

6.1.2 BUS REGULATION AND DISTRIBUTION

The management of the Power Distribution Bus determines how payloads receive energy. Operations are categorized into Regulated and Unregulated buses. In an unregulated bus, the bus voltage (V_{bus}) is allowed to float with the battery voltage, which simplifies the hardware but requires all payloads to have wide-input-voltage converters.

In a regulated bus, the Battery Charge Regulator (BCR) and Battery Discharge Regulator (BDR) work in tandem to keep the bus voltage constant (e.g., at 28 +/- 1%). During the sunlit phase, the BCR controls the current flowing into the battery to prevent overcharging:

$$I_{charge} = \frac{P_{sa} - P_{load}}{V_{bat} \cdot \eta_{BCR}}$$

When the satellite enters eclipse, the BDR activates to boost the battery voltage to the bus level. The operation follows a multi-loop control strategy where the outer loop regulates voltage and the inner loop regulates inductor current to ensure fast transient response during high-power payload switching.

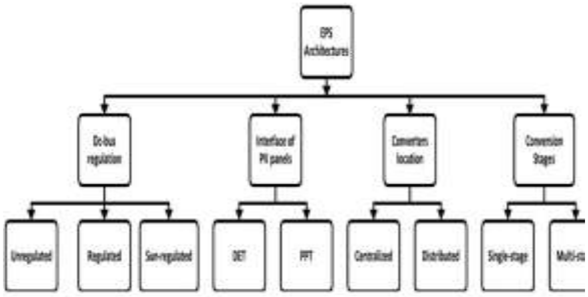
6.1.3 LOAD MANAGEMENT AND FAULT PROTECTION

Operational safety is maintained through the Power Distribution Unit (PDU), which employs Solid State Power Controllers (SSPCs) or Latching Current Limiters (LCLs). These devices act as electronic fuses that can be reset via ground command. If the bus voltage drops below a critical threshold (Undervoltage Protection), the EPS autonomously enters a "Safe Mode," sequentially shedding non-essential loads (load-shedding) based on a prioritized hierarchy:

Category 1 (Critical): Telemetry, Command, and Thermal Control.

Category 2 (Essential): Attitude Control.

Category 3 (Non-essential): Science Payloads and high-speed transmitters



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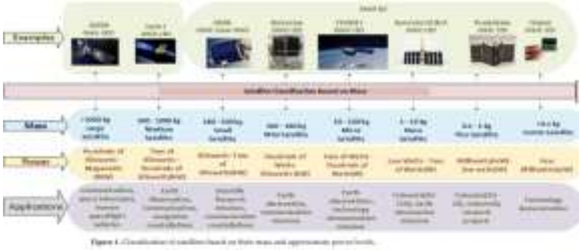
6.1.4 CLASSIFICATION OF EPS ARCHITECTURE



Satellites are commonly classified based on their mass, power requirements, and mission applications. This classification is essential for the design and optimization of onboard subsystems, particularly the Electrical Power System (EPS).

Based on mass, satellites are categorized into large (>1000 kg), medium (500–1000 kg), small (180–500 kg), mini (100–180 kg), micro (10–100 kg), nano (1–10 kg), pico (0.1–1 kg), and femto (<0.1 kg) satellites. As the satellite mass decreases, there is a corresponding reduction in system complexity, launch cost, and onboard resource requirements.

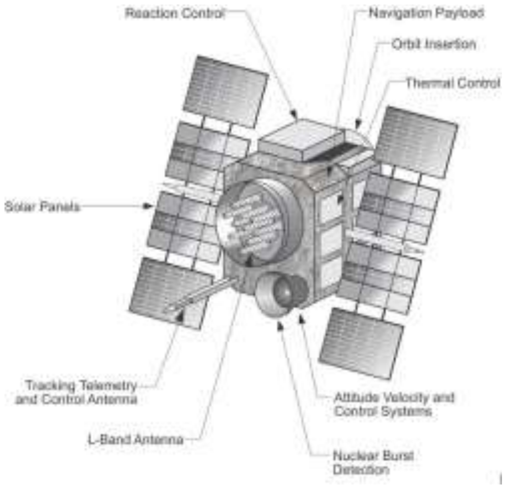
Power consumption varies significantly across these categories. Large satellites typically require power in the range of hundreds of kilowatts to megawatts, supporting high-demand applications such as communication payloads and space observatories. Medium and small satellites operate in the kilowatt range, while mini and micro satellites function with power levels ranging from tens to hundreds of watts. Nano, pico, and femto satellites are designed for ultra-low power operations, often consuming only milliwatts to a few watts.

The application domain also varies with satellite size. Large and medium satellites are primarily used for communication, navigation, and Earth observation missions. Small and mini satellites support scientific research and remote sensing applications. In contrast, nano and pico satellites, including CubeSats, are widely used for educational purposes, technology demonstration, and low-cost experimental missions. Femto satellites are mainly employed for highly specialized research and proof-of-concept studies.

This classification has a direct impact on the design of the Electrical Power System. Larger satellites require high-capacity solar arrays, advanced battery storage systems, and complex power management units. In contrast, smaller satellites rely on compact, energy-efficient power systems with optimized power consumption strategies. Therefore, understanding satellite classification is crucial for designing efficient and reliable EPS architectures tailored to specific mission requirements.

7. SATELLITE SUBSYSTEM AND PAYLOAD ARCHITECTURE.

The given diagram represents the overall structure of a satellite, showing its major subsystems and functional components required for operation in space. At the center is the main satellite body, which houses critical systems such as the navigation payload, orbit insertion system, and thermal control unit. The navigation payload is responsible for transmitting positioning signals, which are essential in systems like GNSS, while the orbit insertion system helps the satellite reach and maintain its designated orbit. The thermal control system ensures that all onboard components operate within safe temperature limits despite extreme space conditions.

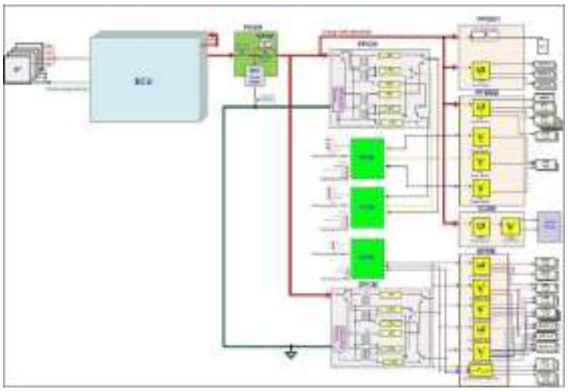


The satellite is equipped with multiple solar panels mounted on its sides, which generate electrical energy by converting sunlight into power. This energy is used to operate all onboard systems and is typically managed by the Electrical Power System. Communication with ground stations is achieved through antennas such as the L-band antenna and tracking, telemetry, and control (TT&C) antenna, which are responsible for sending and receiving signals, monitoring satellite health, and controlling its operations.

The diagram also highlights the attitude and velocity control system, which maintains the correct orientation and stability of the satellite in space. This system ensures that solar panels face the Sun for maximum power generation and that antennas are correctly aligned for communication. Reaction control mechanisms assist in adjusting the satellite's position and movement. Additionally, specialized components such as nuclear burst detection sensors may be included in certain satellites for monitoring space or defense-related activities.

Overall, this diagram provides a comprehensive view of how different subsystems within a satellite work together, including power generation, communication, navigation, control, and thermal management, to ensure efficient and reliable operation throughout the mission.

8. SATELLITE ELECTRICAL POWER DISTRIBUTION SYSTEM.



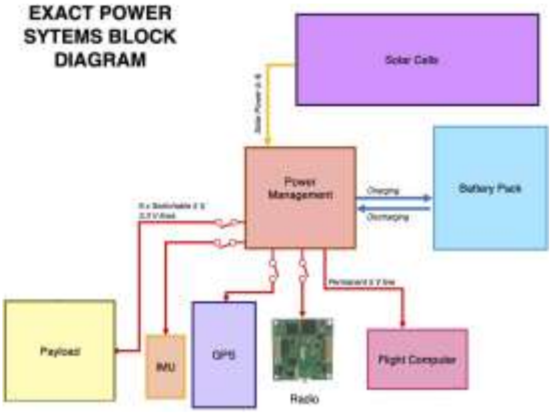
The given diagram represents a detailed architecture of a satellite Electrical Power System (EPS), focusing on power generation, storage, conditioning, and distribution to various onboard subsystems. The system begins with the solar panels (SP), which generate electrical energy from sunlight. This energy is directed to the Battery Control Unit (BCU), which plays a crucial role in managing the charging and discharging of the lithium-ion battery. The BCU ensures safe battery operation by controlling parameters such as voltage, current, and temperature. The generated power is also connected to a Power Supply Switching Module (PSSM), which acts as an interface between the solar array and the battery system. The lithium-ion battery stores excess energy and provides backup power during eclipse conditions when sunlight is not available. From this stage, power is supplied to the Power Conditioning Unit (PPCU), which is one of the most important components of the system. The PPCU converts and regulates the raw electrical power into different voltage levels required by various subsystems. It uses converters and transformers to provide regulated outputs such as +5V, +15V, and -15V, ensuring stable and efficient power delivery.

The regulated power is then distributed through multiple Power Distribution Modules (PDMs), such as PPDM1, PPDM2, and SPDM. These modules are responsible for distributing power to different satellite subsystems while also providing protection features like switching, isolation, and fault handling. Each PDM supplies power to specific loads, including communication systems, onboard computers, sensors, and payload instruments.

Additionally, control and interface modules such as PPIB, TCIB, and SPIB are included in the system to handle telemetry, telecommand, and data communication between the power system and the satellite's central processor. These modules ensure that the system can be monitored and controlled from ground stations. The system also includes a Telecommand Distribution Module (TCDM), which distributes control signals to different subsystems, enabling proper coordination and operation.

The architecture also supports critical subsystems such as heaters and payload equipment, ensuring that all components receive appropriate power under different operating conditions. Overall, this diagram demonstrates a highly organized and reliable electrical power distribution system in a satellite, where energy is efficiently generated, stored, regulated, and distributed to maintain uninterrupted operation throughout the mission.

9. SATELLITE ELECTRICAL POWER SYSTEM WITH POWER MANAGEMENT AND PAYLOAD DISTRIBUTION



The given diagram represents a simplified but practical block diagram of a satellite Electrical Power System (EPS), focusing on power generation, power management, energy storage, and distribution to onboard subsystems. In this system, electrical energy is generated by solar cells, which convert sunlight into electrical power. The generated solar power is supplied to the power management unit, which acts as the central controller of the entire system. This unit is responsible for regulating the incoming power, distributing it efficiently, and ensuring safe operation of all connected components.

The power management system is also connected to a battery pack, which stores excess energy generated during sunlight conditions. This stored energy is used during eclipse periods when solar power is not available. The system supports both charging and discharging operations, ensuring a continuous and reliable power supply. The diagram shows bidirectional power flow between the battery and the power management unit, indicating efficient energy storage and utilization.

From the power management unit, electrical power is distributed to different subsystems through multiple regulated output lines. These include several switchable 5V and 3.3V supply lines, which are used to power various onboard components based on operational requirements. Critical subsystems such as the flight computer receive a permanent 5V supply to ensure uninterrupted functioning, as it controls overall satellite operations.

Other important components powered by the system include the GPS module, which is used for positioning and navigation; the IMU (Inertial Measurement Unit), which provides motion and orientation data; and the radio system, which enables communication between the satellite and ground stations. Additionally, the payload, which represents the main mission-specific equipment, also receives regulated power from the system.

Overall, this diagram demonstrates an integrated and efficient power management approach in a satellite, where solar energy is generated, stored in batteries, and distributed through controlled voltage lines to ensure reliable operation of all subsystems. The design highlights the importance of power regulation, energy storage, and controlled distribution in maintaining the performance and stability of satellite missions.

10. CONCLUSION

In conclusion, the Electrical Power System (EPS) plays a vital role in the successful operation of satellites by ensuring continuous and reliable power supply to all onboard subsystems. This study highlights the importance of efficient power generation through solar arrays, effective energy storage using lithium-ion batteries, and proper power regulation and distribution using advanced power management units. The integration of components such as regulators, battery control systems, and distribution modules enables stable operation under varying environmental conditions, including sunlight and eclipse phases.

Furthermore, the analysis of different system architectures and block diagrams demonstrates how power is efficiently managed and supplied to critical subsystems such as communication units, navigation payloads, sensors, and onboard computers. The use of multiple voltage levels and controlled power lines ensures optimal performance and protection of sensitive electronic components.

Overall, a well-designed Electrical Power System enhances the reliability, efficiency, and lifespan of a satellite mission. With the growing demand for small satellites and advanced space technologies, the development of compact, energy-efficient, and intelligent power systems will continue to play a key role in future space missions.

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