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A Review of Satellite Power Generation: A Sustainable Solution to CubeSats Energy Challenges

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***Abstract*—The power system is a critical subsystem of CubeSats, directly impacting their ability to operate autonomously and achieve mission objectives. Despite advancements in power generation, storage and distribution technologies, CubeSats face persistent challenges due to their compact size, limited for solar panels and exposure to harsh space conditions. This study aims to enhance CubeSats power systems by introducing a novel approach using Light Dependent Resistors (LDR) for solar tracking. These Resistors are lightweight, cost effective and consume minimal power, making them ideal for the constrained size and resource requirements of CubeSats. LDR- based system dynamically detects sunlight intensity and direction, enabling precise alignment of deployable solar panels to maximize energy capture. By addressing issues such as shading and misalignment, the proposed solution ensures continuous power optimization during varying orbital conditions, including eclipse periods. The system is integrated with existing power management technologies, such as Maximum Power Point Tracking (MPPT) and efficient DC-DC converters, to further improve energy efficiency. This approach not only mitigates power shortage but also extends the operational lifespan of CubeSats, supporting more ambitious scientific, commercial, and exploratory missions. The study provides a scalable and sustainable solution to CubeSats energy constraints, laying a foundation for the next generation satellite applications.**

Keywords—solar panels, DC-DC convertors, maximum power point tracking (MPPT), light dependent resistor (LDR), CubeSats.

I. INTRODUCTION

The power system of a CubeSat is a fundamental component that directly influences the satellite's ability to operate autonomously and execute its mission objectives[1]. As miniaturized satellites, CubeSats are constrained by strict size, weight, and power (SWaP) requirements, which necessitate innovative power management solutions to ensure efficient operation [2]. The harsh space environment further complicates this task, exposing the power system to radiation, extreme temperatures, and prolonged periods of eclipse. To address these challenges, CubeSat power systems are meticulously engineered to maximize power generation, optimize storage capabilities, and ensure reliable distribution to all onboard subsystems [3].

The primary source of power for CubeSats is photovoltaic solar panels, which convert sunlight into electrical energy [1]. Given the limited surface area available for solar cells, the choice of materials and panel configurations is critical for maximizing energy output [2]. CubeSats often employ high-efficiency cells, such as multi-junction gallium arsenide, to optimize power generation within the constraints of their compact design [4]. Energy storage is equally important, as rechargeable lithium-ion or lithium-polymer batteries are used to supply power during eclipse periods when the satellite is in the Earth's shadow. These batteries must be carefully managed to avoid overcharging or excessive depletion, which can lead to system failure [5].

The power distribution system plays a vital role in regulating voltage levels and protecting the satellite's subsystems from overcurrent conditions. DC-DC converters are employed to adapt power to the appropriate levels required by different components [2], while Maximum Power Point Tracking (MPPT) algorithms are used to ensure solar panels operate at peak efficiency under varying solar conditions [4]. Thermal management solutions, including radiators, heat pipes, and thermal coatings, are necessary to dissipate heat generated by the power system and maintain a stable operating temperature range for all components [6].

As the space industry has evolved, there has been a shift from large, traditional satellites to smaller, more compact platforms like CubeSats, which are now widely used in applications ranging from Earth observation and telecommunications to scientific research and technology demonstration. The affordability, versatility, and rapid development cycle of CubeSats have made them popular choices for both commercial and educational purposes.

However, designing an effective power system for CubeSats presents unique challenges. Unlike larger satellites, CubeSats face strict limitations on size, weight, and power (SWaP), which restrict the available surface area for solar panels and the capacity for energy storage. Furthermore, CubeSats experience variable power demands depending on their mission profile and environmental conditions, such as eclipses and different orbital altitudes.

Technological advancements in these areas, such as increased solar cell efficiency, improved battery materials, and adv anced power management techniques like Maximum Power Point Tracking (MPPT), have significantly enhanced the capabilities of modern CubeSats [4]. Nonetheless, further innovation is required to address ongoing challenges related to power efficiency and reliability, especially as CubeSats are

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deployed in more demanding missions, including deep space exploration and large satellite constellations.

This paper explores the current state of CubeSat power systems, highlighting recent technological advancements, challenges, and potential solutions for optimizing power management. By addressing these key areas, the research seeks to contribute to the development of more efficient and reliable power systems that can support the expanding range of CubeSat applications. Effective solar tracking systems are essential to maximize energy efficiency and ensure mission success. Among the various tracking technologies, Light Dependent Resistors (LDRs) present a promising solution due to their simplicity, low power consumption and cost effectiveness. LDRs function by detecting variations in light intensity enabling precise adjustments to the orientation of solar panels to maximize sunlight exposure.

This paper explores the critical aspects of CubeSats power systems, the rest of the paper is organized as follows: Section II addresses the important of CubeSats power system: Section III describes the CubeSats power generation; Section IV describes the tracking technology; Section V explores on the thermal management challenges; Section VI addresses the power management and distribution challenges; and Section VII introduces the Light Dependent Resistors for sun tracking in satellite altitude determination systems.

II. The Importance of CubeSat Power System

The power system is one of the most critical subsystems in CubeSats, as it ensures the satellite's ability to perform its intended functions throughout the mission. Given the unique challenges of space environments and the compact nature of CubeSats, the power system plays a crucial role in enabling mission success. Here are several key reasons why CubeSat power systems are essential:

A. Enabling Satellite Operations

The power system provides the necessary electrical energy to operate all onboard subsystems, including communication, payloads, altitude control, and data processing. Without a reliable power source, the satellite would be unable to carry out its mission objectives [2].

For CubeSats, where space and weight are limited, the efficiency of the power system directly impacts the satellite's overall performance. An optimized power system ensures that even with minimal power generation and storage, the satellite can still complete its tasks.

B. Sustaining Continuous Functionality

A well-designed CubeSat power system allows the satellite to maintain continuous operation during varying orbital conditions, such as alternating periods of sunlight and eclipse. Effective power management ensures that energy generated during sunlight is stored and used efficiently during shadow periods when solar power is unavailable.

This capability is crucial for CubeSats in Low Earth Orbit (LEO), which experience frequent transitions between sunlight and darkness. Ensuring a stable power supply prevents disruptions in satellite operations and data collection [7].

C. Maximizing Mission Lifespan

The power system provides the necessary electrical energy to operate all onboard subsystems, including communication, payloads, altitude control, and data processing. Without a reliable power source, the satellite would be unable to carry out its mission objectives [2].

The power system significantly influences the satellite's lifespan by determining the endurance of energy generation and storage components, such as solar panels and batteries. For example, batteries degrade over time due to the repeated charge and discharge cycles. This impacts performance of the satellite in the long-term [8].

By optimizing the power system for efficiency and durability, the mission lifespan can be extended, providing more value and data from the CubeSat. This is especially important for scientific and commercial missions that seek to maximize returns on investment.

D. Facilitating Energy Efficiency and Power Optimization

Energy efficiency is critical for CubeSats due to their limited size and weight. The power system must be designed to optimize the generation, storage, and distribution of energy to minimize losses and ensure maximum usage [9].

Techniques such as Maximum Power Point Tracking (MPPT) for solar panels, efficient power converters, and strategic power scheduling help optimize energy use, allowing CubeSat to make the most of its limited power resources.

III. The CubeSat Power Generation

Power generation is a fundamental aspect of CubeSat design, as it provides the primary source of energy required for satellite operations [10]. Given the limited size, weight, and available surface area on CubeSats, generating sufficient power to support the satellite’s subsystems is a challenging task [2]. The primary method of power generation for CubeSats is the use of solar panels, although alternative methods may also be considered for specific mission requirements [4]. This section will explore the key components, technologies, and challenges associated with CubeSat power generation.

A. Solar Panels as a Primary Power Source

Photovoltaic Cells: CubeSats typically rely on photovoltaic (PV) cells to convert sunlight into electrical energy [4]. These cells are made of semiconductor materials, such as silicon or gallium arsenide, which generate electricity when exposed to sunlight [11]. The choice of solar cell material affects the overall efficiency and performance of the power generation system.

Types of Solar Cells

- **Monocrystalline Silicon Cells**: Commonly used due to their relatively high efficiency and availability. They offer a balance between cost and performance, making them suitable for many CubeSat missions [12].
- **Gallium Arsenide (GaAs) Cells**: Provide higher efficiency compared to silicon-based cells and better performance in the harsh space environment. However, they are more expensive, which may limit their use to higher-budget or deep space missions [13].
- **Multi-Junction Solar Cells**: These cells have multiple layers that each absorb different wavelengths of light, leading to higher overall efficiency. They are particularly useful for missions with high power demands but come at a higher cost [14].

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B. Factors Affecting Solar Power Generation

- **Surface Area Constraints**: The compact size of CubeSats limits the amount of space available for mounting solar panels, which directly impacts the amount of power that can be generated [2]. Deployable solar arrays are often used to increase the available surface area, though they add mechanical complexity to the satellite [15]. Orbital
- **Dynamics and Sunlight Availability**: The amount of sunlight reaching the CubeSat depends on its orbit. For instance, Low Earth Orbit (LEO) satellites experience frequent periods of eclipse, during which they cannot generate power. Solar panel orientation and tracking mechanisms may be used to optimize sunlight exposure during orbital passes [16].
- **Solar Cell Degradation**: Over time, solar cells degrade due to exposure to radiation, micrometeoroid impacts, and thermal cycling in space [16]. This degradation reduces the efficiency of power generation, which must be considered during the mission design phase [9].

C. Deploable Solar Arrays

- **Fixed versus Deployable Panels**: CubeSats can be equipped with fixed solar panels mounted on the body, or deployable arrays that unfold once the satellite reaches orbit. Deployable arrays increase the available power-generating surface but require additional mechanisms and introduce potential points of failure [14].
- **Innovative Deployment Mechanisms**: Various deployment methods, such as hinged arrays, flexible solar panels, and roll-out solar sails, are used to optimize power generation while maintaining a compact form factor during launch [15].

D. Maximum Power Point Tracking (MPPT)

- Optimizing Power Output: MPPT technology is used to ensure that solar panels operate at their maximum power output regardless of changes in sunlight intensity or temperature. MPPT algorithms adjust the electrical load connected to the solar panels to achieve optimal performance. MPPT significantly enhances the efficiency of solar power generation, maximizing the usable power for satellite subsystems [16]

IV. The CubeSat Solar Tracing Technology

CubeSats use solar tracking technology to maximize the efficiency of their solar panels by aligning them towards the sun as much as possible. This technology is critical for ensuring a consistent power supply to the satellite's systems, given the limited size of CubeSats and their solar panels. Here is an overview of the main components and methods used in solar tracking for CubeSats:

A. Attitude Determination and Control System (ADCS)

- The ADCS is a crucial system in CubeSats that manages their orientation in space. It consists of sensors and actuators that measure the satellite's orientation and apply forces to adjust its position [24].
- Sensors like sun sensors, magnetometers, and gyroscopes help to determine the satellite's current orientation, while actuators such as reaction wheels, magnetic torquers, or control moment gyroscopes adjust their altitude [25].

B. Solar Sensors

- Sun sensors measure the direction of incoming sunlight. They can be fine sun sensors that give precise information or coarse sun sensors for general alignment.
- The data from these sensors is used by the ADCS to orient the solar panels towards the sun.

C. Actuators for Orientation Control

- Reaction Wheels: Use spinning masses to change the orientation of the CubeSat. When the wheels spin in one direction, the satellite rotates in the opposite direction [18].
- Magnetic Torquers: Generate magnetic fields that interact with Earth's magnetic field to change the satellite's orientation [19].
- Control Moment Gyroscopes: Work similarly to reaction wheels but can exert higher torque, making them useful for larger orientation changes [20].

D. Active and Passive Tracking

- Active Tracking: Uses the ADCS to continuously adjust the satellite's orientation based on sun sensor data. This approach is more precise but consumes more power [21].
- Passive Tracking: Uses the satellite's natural motion and pre-programmed maneuvers to orient the solar panels toward the sun. It's less precise but can save power [21].

E. Two-axis and Three-axis Tracking

- Two-Axis Tracking: Adjusts the orientation of the solar panels in two directions (azimuth and elevation) to optimize sunlight exposure. It's common in CubeSats where weight and complexity constraints limit the use of more advanced systems.

V. Issues with Satellite Solar Tracking System

Satellite solar tracking systems face several challenges that can impact their performance, reliability, and efficiency. Here are some common issues:

A. Point of Accuracy and Stability

- The accuracy of the satellite's attitude determination and control system (ADCS) may be insufficient for precise solar tracking, leading to suboptimal orientation of solar panels [23].
- External factors like disturbances from Earth's magnetic field, gravity-gradient forces, or solar radiation pressure can destabilize the satellite's orientation [23].

B. Power Consumption

- Active solar tracking requires power for the operation of sensors, actuators, and the ADCS. The energy consumed by these systems can reduce the net power gain, especially in smaller satellites with limited power budgets.

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- Balancing power use between the ADCS and other satellite subsystems can be challenging, particularly when there are high power demands..

C. Sun Sensors Limitations

- Sun sensors can experience errors due to reflections or stray light from the satellite's body, which may cause false readings [24].

In eclipse periods when the satellite is shadowed by Earth, sun sensors cannot function, requiring the satellite to rely on pre-determined tracking algorithms or gyroscopes.

VI. Implementing LDRs on CubeSats with Deployable Solar Panels



Fig. 1. CubeSat with deployable solar panel

CubeSats with deployable solar panels are designed to maximize the surface area available for sunlight capture while still fitting within the compact size constraints of the satellite during launch. Once in orbit, these solar panels unfold to increase power generation, which is crucial for meeting the energy demands of onboard systems. The deployment mechanisms can involve spring-loaded hinges, motors, or other mechanisms that ensure reliable panel unfolding.

We are developing an innovative LDR (Light Dependent Resistor) system tailored to enhance the performance of South African CubeSats equipped with deployable solar panels, helping them overcome the critical issue of power shortages. While current South African CubeSats, such as ZACube-1, ZACube-2, and the MDASat constellation, rely on fixed solar panels and basic power management systems, our new LDR-based system introduces advanced sun- tracking and energy optimization capabilities.

Key features and benefits

A. Enhanced Sun-Tracking forr Optima Power Generation

- Our system leverages multiple LDRs strategically placed on the deployable solar panels to accurately detect the sun’s direction and intensity. This real-time data will enable the satellite to continuously adjust its orientation, ensuring the panels face the sun at the best angle to maximize energy collection.
- This dynamic adjustment will be particularly useful during orbital changes or in varying light conditions, ensuring that the satellite generates sufficient power to maintain operations throughout its mission.

B. Power Management Optimization to Prevent Power Shotages

- By monitoring sunlight exposure across all solar panels, the LDR system will identify shading or misalignment issues and adjust the satellite's orientation to restore optimal sunlight exposure. This ensures a continuous flow of energy, preventing power loss and keeping batteries fully charged for critical operations.
- The system will be especially beneficial during eclipse transitions, where maintaining battery reserves is essential for uninterrupted operation.

C. Reliable Deployment Verification nd Issue Detection

- The LDR sensors will confirm the successful deployment of the solar panels by detecting changes in light intensity as the panels unfold. In case of partial deployment or misalignment, the system will alert the satellite’s control system to initiate corrective actions, ensuring full energy collection.
- If partial deployment or other issues arise, the system will identify inconsistent sunlight exposure across different LDRs, allowing for corrective actions to be taken quickly to restore full power generation capability.

D. Continuous Tracking and Spin Monitoring

- The LDR system will help manage the CubeSat's power usage by detecting transitions between sunlight and darkness, enabling efficient power-saving measures during periods in Earth's shadow.
- It will also provide real-time data on the satellite's spin rate and orientation by monitoring changes in sunlight exposure, aiding in attitude control and ensuring consistent solar panel alignment.

VII. Anticipated Performance and Efficiency Enhancements of LDR-Equipped CubeSats for Solar Energy Management

The anticipated results regarding the effectiveness of an LDR-based system in optimizing solar energy management for CubeSats with deployable solar panels will be focusing on:

A. Sun Tracking and Attitude Determination

- **Result**: The LDR will measure the intensity of sunlight hitting the satellite. By using multiple LDRs positioned at different orientations on the CubeSat's surface, you can estimate the direction of the sunlight.
- **Application**: This information can help determine the satellite's orientation relative to the Sun, which is useful for attitude control and stabilizing the CubeSat.

B. Power Management Optimization

- **Result**: LDRs can help assess the optimal orientation for the CubeSat's solar panels by indicating the side receiving the most sunlight.
- **Application**: The satellite can adjust its orientation to maximize power generation by positioning solar panels to face the Sun more directly.

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C. Earth Observation and Photometry

- **Result**: The LDR could detect changes in light intensity as the CubeSat passes over different parts of the Earth (day-night transitions, changes in surface reflectivity).
- **Application**: It could be used for basic photometric observations, detecting light pollution, or even measuring the reflectivity of different terrains. While the data would be relatively coarse, it can still provide useful insights for some environmental monitoring applications.

D. Orbital Position Estimation

- **Result**: By recording the timing and pattern of light intensity variations (such as sunrise and sunset events in orbit), the CubeSat can infer its orbital position.
- **Application**: This information could help verify or complement data from other sensors used for determining the satellite's orbit.

E. Eclipse Detection

- **Result**: The LDR would notice a sharp drop in light intensity when the CubeSat enters the Earth's shadow.
- **Application**: This could be used to trigger power-saving modes, prepare for temperature drops, or log the duration of time spent in the Earth's shadow.

The integration of the LDR on the CubeSat is expected to enhance the satellite's ability to detect changes in light intensity, providing valuable data for determining the satellite's orientation relative to the Sun. This will improve attitude determination and control capabilities, leading to more precise operations, such as solar panel alignment and optimized power generation.

VIII. Conclusion

In addressing the persistent energy crisis faced by CubeSats, the incorporation of Light Dependent Resistors (LDRs) offers a sustainable and innovative solution for optimizing satellite power generation. The LDRs enable precise detection of light intensity changes, allowing for accurate solar tracking and optimal orientation of solar panels. This enhancement leads to maximized energy absorption from the Sun, ensuring that the CubeSats can consistently generate sufficient power, even in challenging orbital conditions.

By improving power generation capabilities, CubeSats can sustain extended mission durations, support more power-intensive payloads, and enhance overall operational efficiency. Additionally, the increased power availability can facilitate onboard system redundancy, improve data transmission capabilities, and enable real-time attitude adjustments. This approach not only addresses the immediate energy requirements but also contributes to long- term sustainability by reducing reliance on energy storage systems and decreasing the frequency of satellite replacements due to power limitations.

Incorporating LDR-based solar tracking stands out as a practical and scalable strategy for the next generation of CubeSat missions, providing a robust pathway to overcoming energy limitations and enabling more ambitious scientific, commercial, and exploratory satellite applications.

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