Design of Electrical Power System for Low-cost Ecological Nanosatellite

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ABSTRACT

EcoBeltSat is an innovative project of nanosatellite that develops a sustainable strategy to measure air pollution and provide data for future wind energy projects in Belt and Road countries. This strategic project is based on technological development concept proposed by China, which is initiated and conceived by students of Beihang University. The purpose of this paper is to design and evaluate the Electrical Power System (EPS), which is one of the critical subsystems of this project. This subsystem has been designed to provide power to the nanosatellite throughout the entire Low Earth Orbit (LEO) (500Km) using GaAs solar panels with 30% efficiency as power sources. During eclipse period, the nanosatellite is supplied via 3,2 Ah Li-ion battery pack. The proposed EPS model is based on a Direct Energy Transfer (DET) architecture with a single-stage PWM shunt regulator, unregulated and regulated buses. Some simulation results reveal the evolution process of EPS states and behavior and take into consideration the most common sources of EPS failure. The proposed model is useful to optimize subsystems architecture and having significant importance for nanosatellite design.

Keywords
- Power conservation
- Electrical Power system
- LEO orbit

1. INTRODUCTION

The designed EcoBeltSat-1 nanosatellite will be operated in Sun-Synchronous Orbit (SSO), with the ability to provide information of technical utility to generate solutions to environmental problems in countries belonging to the Belt and Road Framework. The project is designed by postgraduate students in engineering from Beihang University, located in Beijing, People's Republic of China. The design of this project takes into consideration the measurement and study of atmospheric and environmental variables, in terms of pollution (through the use of an atmospheric spectrometer) and surface winds and sea level (through the use of a GNSS-R, a reflectometry), which can be used in future generation plans of renewable energy systems, contributing to a clean environment [1]. The On Board Computer (OBC) interprets and acts on uplinked telecommands and sends a beacon and requested telemetry and files, it uses VHF/UHF amateur frequency bands and S frequency band to communicate with BUAA Ground station. The challenge is to achieve the mission despite a limited mass, volume and power. The nanosatellite operates on a strict power budget because of the power requirements and limitations in it, with limited sources (limited area for solar arrays, mass, and volume for batteries) [2]. This call for an efficient reliable design that guarantees the execution of all these tasks during all the mission life. The power subsystem is responsible for ensuring the power needs of all the subsystems. This includes generating power, conditioning and regulating power, storing energy for use during periods of peak demand or eclipse operation, and distributing power through the nanosatellite [2] [3].

The Electrical Power System (EPS) is composed by three main blocks: power sources, energy storage, and power management and distribution. The EPS design depends on the sun radiation profile during the mission and starts with the calculation of the solar panel dimension, the battery pack is assessed by receiving the power consumption from all the other subsystems and the payloads [3].

This paper is divided as follows: The first section describes the orbit design of EcoBeltSat. Then, the calculation of power budget and EPS design are presented in section two. In section three, the effectiveness of the chosen topology with the power balance are shown by simulation results for the EPS in orbit.

2. ECOBELTSAT ORBIT DESIGN

The mission orbit desired is a sun synchronous circular orbit with an altitude of 500 km, with local time descending node (LTDN) of 10:30. The orbit period was calculated using [3]:

\[ T = \frac{2\pi}{\sqrt{\frac{R^3}{\mu}}} \times 91.44 \text{ msn} \]  

with, \( \mu = 1.4324 \times 10^9 \text{Km}^3/\text{mtn}^2 \)
A = 500Km: orbit attitude. \( R_z + A = 6878.14 \text{Km} \)

To calculate the sunlight period and eclipse period \( \alpha \) angle is calculated first:

\[ \alpha = \arccos \left( \frac{R_z + A}{R_z + A} \right) = 22^\circ \]  

Than, fraction of time sunlight is 62% and fraction of time eclipse 37%.

The orbit design parameters are shown in Table 1, that is compound by inputs and results obtained from STK (System Tool Kit) simulation [1].
For analysis, EcoBelt orbit dynamic behavior were carried out from STK (System Tool Kit) and used as inputs on EPS model (see Figure 1).

At this orbit, $\beta$ angle oscillates between 35° and 70° (see figure 2).

### Table 1. Mission parameters

<table>
<thead>
<tr>
<th>Mission</th>
<th>Duration of Mission</th>
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<tbody>
<tr>
<td>LEO/SSO</td>
<td>10:30 (Local Time)</td>
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<tr>
<th>Orbit Parameters</th>
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<tr>
<td>Altitude (Km)</td>
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<tr>
<td>Semi-major axis (Km)</td>
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<tr>
<td>Eccentricity (e)</td>
</tr>
<tr>
<td>Inclination i (°)</td>
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<tr>
<td>RAAN</td>
</tr>
<tr>
<td>Argument of Perigee</td>
</tr>
<tr>
<td>True Anomaly</td>
</tr>
<tr>
<td>Orbit Propagator</td>
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<tr>
<td>Revolution Period T (mn)</td>
</tr>
<tr>
<td>Eclipse Period (mn)</td>
</tr>
</tbody>
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<tr>
<th>Phase Parameters</th>
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<tr>
<td>Number of Orbits per day</td>
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<td>Repetitively Period</td>
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<tr>
<th>Parameters of the Ground Station</th>
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<td>Ground Station Visibility Period (mn)</td>
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<table>
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<th>Visibility Parameters</th>
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<td>Passages Number</td>
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The EcobeltSat moods [1]

- **Safe mode** for charge battery when battery charge level is below than 40% of whole capacity and from each mood can enter to this mood when the condition occurs.
- **Recovery mode** is for attitude control to recover CubeSat attitude to the right precision that is defined according to the payload accuracy.
- **Normal mode**, all subsystems are ON instead payloads,
- **Communication mode** for send telemetry and payloads data and receive command from Ground Station,
- **Air pollution** is for measure pollution,
- **GNSS-R mode** is for measure wind severity and direction.
- In **Science payload** mode two payloads are ON for calculating air pollution and GNSS-R for finding the problem solution.

### 3. ECOBELT POWER BUDGET AND EPS DESIGN

The power budget estimation is devided into three categories: power consumption, power generation and power storage [4]. Then, these three estimations will be balanced to ensure that there is sufficient energy for EcoBelt to complete its mission.
3.1 Power Consumption

During the preliminary phase of the project, the equipment definition gave the minimum and maximum power consumption during one revolution and their operating voltages, for each mode of EcoBelt-Sat. Several modes (see section 2) and in each of them, can show which subsystems are activated or deactivated, in order to find a minimum and maximum power for EcoBeltSat. Figure 3 shows the loads power profile based on power consumption of each mode.

![Figure 3. EcoBeltSat Subsystems Power consumption](image)

3.2 Power Generation:

The power generation of Ecobelt during the sunlight time is due to the four-lateral solar panels, where the electrical power is generated and distributed to the devices, it recharges the battery and available to use during the satellite eclipse. The solar cell selected for EcoBeltSat are triple junction solar cells 3G30A space qualified technology from Azur Space, which having an efficiency of 30% and providing 2.411V output voltage and 504 mA output current at maximum power point [5].

The curve $I = f(V)$ and $P=f(V)$ simulation of solar cell, under constant condition of light and temperature, is shown in Figure 4 and 5.

![Figure 4. I=f(V) characteristic](image)

Since a satellite revolves around earth, its solar panels periodically supply power, the sun and eclipse phases alternate, and each panel can generate power only during the sun phase. The amount of power generated by a solar panel at $t$ depends on the angle between sunlight and the solar panel, and the angle is determined by the satellite’s position and attitude. Then, the amount of power generated by all solar panels in a satellite at $t$ is a function of attitude and the configuration of solar panels [6][7]. Figure 6 and 7 represents the power profile of EcoBeltSat solar array depending on $\beta$ and $\alpha$ angles.

![Figure 6. Power generated depending on $\beta$](image)
3.3 Power Storage

After the estimation of the required power of EcoBeltSat for different moods (see section 2.1), the capacity and the choice of the battery has been determinate [8]:

\[ \text{Capacity in energy} = (\text{total energy of charge}) \times (1 + \text{depth of discharge}) \]  

(4)

For a longer life duration of the battery a depth of discharge maximal of 70% is authorize. The chosen battery is Li-ion batteries, where the voltage during the discharge mode is obtained by [9]:

\[ V_{\text{batt}} = E_0 - R \cdot i - R_{\text{pol}} \cdot \frac{Q}{Q - \left( 1 - i_t - R_{\text{pol}} \right) \cdot Q} \cdot i_t \cdot \exp \left( -B \cdot i_t \right) \]  

(5)

And during charge mode,

\[ V_{\text{batt}} = E_0 - R \cdot i - R_{\text{pol}} \cdot \frac{Q}{Q - \left( 1 - i_t - R_{\text{pol}} \right) \cdot Q} \cdot i_t - Q \cdot 0.1Q \cdot i_t + A \cdot \exp \left( -B \cdot i_t \right) \]  

(6)

Where,

- \( R \): internal resistance;
- \( i \): battery current;
- \( R_{\text{pol}} \): polarization constant or polarization resistance;
- \( Q \): battery capacity;
- \( i_t \): actual battery charge;
- \( i' \): filtered current;
- \( A \): exponential zone amplitude;
- \( B \): exponential zone time constant.

The nominal current discharge characteristic simulation of LifePo4 3.2V nominal voltage and 3.2Ah capacity is shown in Figure 6.

4. ARCHITECTURE

The EPS model is based on a Direct Energy Transfer (DET) architecture with a single-stage PWM shunt regulator, unregulated and regulated buses [10] [11].

DET regulators are typically shunt regulators which holds the maximum bus voltage bellow some predetermined voltage, by deviating a portion of the current that would be supplied to the bus. This occurs because the PV power generation are designed based on EOL rather than BOL and, for worst-case scenarios, making necessary for some power deviation if the generation is bigger than the required by the battery and loads. High excess power should also be deviated after the spacecraft exit eclipses, when the PV peak power is higher than peak output power in normal sunlight operation.

The modeled topology is a PWM single-stage shunt regulator [13], as shown in Figure 9.
5. BALANCE OF TASKS POWER
The energy balance analysis is performed by simulating satellite power flow and energy account [12][14].

A model of the EPS in-orbit operation using the orbit data generated in STK (System Tool Kit) and the technical parameters of the EcoBeltSat solar array and battery unit.

The STK was used as the orbit propagator tool to generate a set of data with the sun incidence $\theta$ angles and the albedo reflection angle $\varphi$.

In the simulation, the battery DoD was set to 0% (SoC = 100%) at the beginning of the simulation and the DC/DC converter efficiencies to 94%. The mean values of 1353 W/m2 and 237 W/m2 for the solar constant and the Earth-emitted radiation, respectively, was used in the modal. The albedo factor has a temporal average of 0.3 like for most of spacecraft.

6. BATTERY TESTING
A characteristic test of charging/discharging Lithium-ion battery pack has been done for a 1.5A/2A with nominal voltage of 7.2V [4], as shown in Figure 12, which is equipped with a Protection Circuit Module (PCM). The role of the PCM is to protect the batteries against over-discharge and over-currents [13]. Battery depth of charge was limited to 30% in order to increase the life time and realibility. Figure 13 and 14 show the measured charging/discharging profile.
7. ACKNOWLEDGMENTS

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8. REFERENCES


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