Preliminary results for energy harvesting maximization with focus on heater control of batteries in nanosatellites

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INTRODUCTION

Orbit + Attitude → Irradiance

Governs the temperature and available energy.

Irradiance → Temperature & energy

May require thermal control to avoid failure, especially at battery.

Power Budget

Voltage of battery, voltage of solar panels, EPS architecture, DET, PPT models ...

Attitude model + Thermal model + Electrical model → Efficiency model

Heater operation coupled to power system to find maximum efficiency of EPS.
- Warmer photovoltaic panel and battery reduces the performance;

- Battery has minimum operational temperature, usually around 0°C (charge) and -20 °C (discharge);

- DET (Direct Energy Transfer) is a simple architecture for EPS where the battery is parallel to the solar panels.

- Trigger of tasks to keep solar panels close to their maximum power point;
**Thermal model:** Numerical and analytical; 
*Inputs:* Orbital parameters, attitude, geometry, design, and heater setpoint. 
*Outputs:* irradiance, temperature of solar panels and power of heater.

**Electrical model:** Analytical. 
*Inputs:* irradiance (solar flux), temperature (solar panels), power of heater. 
*Outputs:* Battery voltage, power on solar panels.

Figure 1 - Overview of the thermal and electrical model.
**METHODOLOGY: Thermal model**

**Algorithm:**

\[
\text{if } T_{\text{bat}} < T_{\text{set}} + \Delta T \\
\quad P_H = 1; \\
\quad \Delta T = 5; \\
\quad \text{else} \\
\quad P_H = 0; \\
\quad \Delta T = 0; \\
\text{end}
\]

- **Heater** ($P_H$): 0-1 W
- **Setpoint** ($T_{\text{set}}$):
  - 0°C, 5°C, 10°C

**Orbit & attitude (UDF of ANSYS CFX):**
Altitude of 650 km, noon-midnight circular orbit, attitude of nadir.

**Irradiance (UDF of ANSYS CFX):**
Solar flux, albedo and radiation from Earth.

**Transient temperature field (ANSYS CFX, FVM):**
\[
\dot{E}_{\text{in}} - \dot{E}_{\text{out}} + \dot{E}_{g} = \dot{E}_{\text{acu}}
\]

**Temperature at battery (MATLAB):**
\[
T_{\text{bat}}(t) = \left[ P_H(t) + \dot{E}_k(t) + \sum_{i=1}^{5} q_r(t) \right] \frac{\Delta t}{mc} + T_{\text{bat}}(t-1)
\]
- **Heater power**
- **Heat conduction**
- **Radiation (Gebhart method)**
**METHODOLOGY: Electrical model**

State of charge (SoC): $\text{SoC}(t) = \text{SoC}(t_0) - \frac{1}{C_n} \int_{t_0}^{t} \text{I}_{\text{bat}} \, dt$

Battery charge current ($I_{\text{bat}}$): $I_{\text{bat}} = -[I_{\text{SP}} - (I_{\text{heater}} + I_{\text{load}})]$

Battery discharge current ($I_{\text{bat}}$): $I_{\text{bat}} = I_{\text{heater}} + I_{\text{load}} - I_{\text{SP}}$

Heater current ($I_{\text{heater}}$): $I_{\text{heater}} = \sqrt{\frac{P_H}{R}}$

Solar panel current ($I_{\text{SP}}$): $I_{\text{SP}} = I_{\text{ph}} - I_D \left[ e^{\left( \frac{V_{\text{bat}} + I_{\text{SP}} R_S}{n V_T} \right)} - 1 \right] - \frac{V_{\text{bat}} + I_{\text{SP}} R_S}{R_p}$

**Figure 2: EPS simplified circuit diagram.**
Quasi-cyclic behavior: Previous temperature impacts in the following ones.

Heater also acts out of the eclipse: Shadow is between 1840-3990 s and 7700-9850 s.

Higher setpoint require more time with heater on: Upright ramp in the temperature relates to the heater on.

1W heater keeps the battery at safe temperature: Usually the lower acceptable temperature is 0°C.

Figure 3 - Behavior of heater and temperature at battery at 8th - 9th run.
Heater and battery energy:
The power to operate the heater is greater than solar panels, which drives energy of battery.

Voltage drop:
The charge loss decreases the battery voltage up to 200 mV.

Support of solar panels:
The voltage drop is attenuated out of eclipse by the power of solar panels.

Higher the setpoint, higher the charge loss:
Only the minimum setpoint returns the state of charge to the initial point.

Figure 4 – Power of heater and voltage at battery at 8th - 9th run.
**RESULTS**

**Non symmetric power input:**
Before the shadow (hot satellite) the power input is smaller than after (satellite cold).

**Small variation of energy due to battery voltage:**
- $T_{\text{set}} = 0^\circ\text{C}$: 8.224 kJ and 8.149 kJ =100 %;
- $T_{\text{set}} = 5^\circ\text{C}$: 8.262 kJ and 8.230 kJ ≈100.7%;
- $T_{\text{set}} = 10^\circ\text{C}$: 8.262 kJ and 8.290 kJ ≈101.1%.

**More power input with higher setpoint:**
The voltage battery in these regions is closer to the point of maximum power of the panels.

![Figure 5 – Power input from solar panels at 8th - 9th run.](chart)
Accurate energy models must consider the orbit, attitude, irradiance, temperature of solar panels and thermal control.

Within the tested setpoints, only the setpoint at 0°C was not critical for the battery voltage after two orbits.

Variations in the power consume of the heater impacts in the battery voltage and in the energy input.

The heater control may optimize the battery voltage to operate the solar panels near their maximum power point.
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THANKS!

Any questions?
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