Spacecraft Power Systems

The Generation and Storage of Electrical Power

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Power Systems

- Batteries $\rightarrow$ Solar Cells + Batteries $\rightarrow$ Fuel Cells $\rightarrow$
  RTG $\rightarrow$ Nuclear Reactors $\rightarrow$ ?

- The Power System controls the generation, storage, and efficient use of power

- Must also provide protection against a failure in one circuit inducing a failure in other systems
Power System Design Drivers

- Customer/User requirements
- Mission, distance from the sun
- Spacecraft configuration
  - Mass constraints
  - Dimensional constraints
  - Launch Vehicle constraints
  - Thermal constraints
- Expected lifetime
- Attitude control system
  - Pointing
  - Effectors
  - Viewing
- Orbit
- Payload requirements
  - Power type, voltage, current
  - Duty cycle, peak load
  - Fault protection
- Mission constraints
  - Maneuver rates
  - G-loads
Power System Functional Block Diagram

Power Source
- Batteries
- Solar
- RTG
- Fuel Cells
- Nuclear
- R Dynamic
- Solar Dynamic

Source Control
- Shunt Regulator
- Series Regulator
- Shorting Switch Array

Power Distribution, Main Bus Control & Main Bus Protection

Power Conditioning
- DC-DC conversion
- DC-AC conversion
- Voltage regulator
- Battery charge control
- Voltage regulator

Load

Energy Storage Control

Energy Storage
Design Practice (1/2)

- Direct Current Switching
  - Switches or relays: positive line to an element with a direct connection to “ground’ on negative side
  - Therefore, element is inert until commanded

- Arc Suppression
  - Locate as close to the source of the arc as possible
  - Conductive cables, connectors, solar array edges, any current-carrying element should not be exposed to the ambient plasma

- Modularity
  - Simplifies testing
  - Easier element replacement
  - Reduces “collateral” damage
Design Practice (2/2)

- **Grounding**
  - Cause of some debate among EEs
  - Common ground cable preferable to individual component grounding
    - Easier to maintain a common potential
    - Less likely to disturb sensitive components
    - Can be difficult to do in large spacecraft
  - Sometimes it is necessary to completely isolate an element from other spacecraft noise

- **Continuity**
  - Avoid buildup of static potential; i.e., any voltage difference
  - Any shielding must have continuity and a common ground

- **Complexity**
  - KISS
Batteries: Definition of Terms (1/2)

- **Charge Capacity, \( C_{chg} \)**
  - Total electric charge stored in a battery; measured in amp-hours (e.g., 40A for 1 hour = 40Ah)

- **Energy Capacity, \( E_{bat} \)**
  - Total energy stored in a battery;
    \[ C_{chg} \times V_{avg} \] (Joules or watt-hours)

- **Average Discharge Voltage, \( V_{avg} \)**
  - (Number of cells in series) \( \times \) (Cell discharge voltage)

- **Depth of Discharge, DOD**
  - Percent of battery capacity used in discharge cycle
  - 75% DOD means 25% remaining
  - Try to limit DOD to promote longer cycle life
Batteries: Definition of Terms (2/2)

- **Charge Rate**, $R_{\text{chg}}$
  - Rate at which the battery can accept charge (amps/unit time)

- **Energy Density**, $e_{\text{bat}}$
  - Energy per unit mass stored in battery
  - Joules/kg or Watt-hours/kg

- **Two categories of batteries**
  - Primary
  - Secondary
Primary Batteries

- Long storage capability (missile in a silo)

- Dry (without electrolyte) until needed
  - Activation by introducing electrolyte into dry battery
  - Electrolyte may be solid at room temperature. Activate heater to melt electrolyte. (Thermal battery)

- Used for early major mission event
  - Short duration
  - May be isolated from major power bus
  - Usually non-rechargeable
  - Mass penalty
Secondary Batteries

- Typically, lower energy density, Rechargeable
- DOD management required
  - Will be in eclipse ~ 40% of orbit
  - 12-16 discharge/charge cycles per day
  - Battery degradation and lifetime reduction
  - Given spacecraft power usage and maximum allowable DOD for lifetime design:

\[
DOD = \frac{P_L t_d}{C_{chg} V_{avg}} = \frac{P_L t_d}{E_{bat}}
\]

- \(P_L\) = load power, Watts
- \(t_d\) = discharge time, hours
Recharge Rate

- Must manage charge rate
  - Too fast ➔ heat and damage
  - Too slow ➔ can’t make up discharge

- Rule of thumb
  
  - \[ R_{chg} = \frac{C_{cha}}{15h} = I_{chg} \] Charging current
  
  - I.E., a battery can accept about 1/15 of its total capacity per hour (conservative)

  - “Trickle” charge = \[ \frac{C_{cha}}{45h} \]
DOD Management

- Typically, a LEO spacecraft spends 40% of its time discharging and 60% charging.
- DOD during eclipse is limited by the rate at which it can be restored in sunlight.
- All expended energy must be restored or you will have a net drain.
- Driver ends up being the charge rate:
  - DOD limited to 7-8% per orbit.
  - Battery temperature can affect charge rate.
- Battery generally must be charged at a voltage > $V_{avg}$ (~20% higher) to restore full charge.
- This affects solar array design.
Solar Arrays

- Photoelectric Effect
  - Electrons are emitted from matter as a result of absorption of short wavelength electromagnetic radiation such as visible light.
- Originally limited to skin acreage
- Deployables offer more flexibility, but also more complexity

- Solar Cell Characteristics
  - 1st order: $V$ decreases as $T$ increases (and vice versa)
  - 2nd order: $I$ increases as $T$ increases
    - But only about 10% relative to the voltage drop
  - Therefore, overall power output is reduced: as temperature increases: $P = I \times V$
- May need radiators to remove excess heat
Maximum Power Point (MPP)

- Desirable to operate at the MPP if possible
  - Minimize mass and maximize efficiency

![Diagram showing a graph with a horizontal axis (I) and a vertical axis (V). The graph depicts the IV curve with an arrow indicating the Maximum Power Point (MPP). The area under the curve is highlighted as the maximum area rectangle.](image-url)
Sun Tracking

- Best, of course, if sun is normal to the array
- Cosine rule applies – up to a point

Up to 45-60° cosine function works, then falls off rapidly

Optimum
Beta and Alpha

- **Beta, β**
  - Angle between a line from the sun to the center of the earth, and spacecraft orbit

- **Alpha, α**
  - Apparent rotation of sun angle from spacecraft pov during its orbit. $\alpha = 0-360$
Solar to Electric Conversion

- Efficiency
  - Gallium arsenide solar cells (Ga-As)
    - More efficient (20%) and radiation tolerant
    - More expensive
  - Crystalline Silicon Cells
    - 11-16%, 18-20%, >20%?
  - Multi-junction (multi-layer cells)
    - Top layer converts light in the visible range
    - Bottom layer(s) optimized for infrared
    - Up to 30% efficiency
    - Not surprisingly, expensive
Radioisotope Thermoelectric Generator (RTG)

- Renders spacecraft independent of the sun
- Converts heat energy generated by radioisotope decay into direct current energy via thermoelectric effect
  - Plutonium 238, $^{238}$Pu
  - Strontium 90, $^{90}$Sr
- Expensive
- Complicated ground handling
  - Heat
  - Radiation
- RTG radiation detrimental to spacecraft electronics
Fuel Cells

- Direct conversion of chemical energy into electricity
- Like batteries, but more efficient
- Oxidizer and fuel fed into a cell
- Electricity generated from oxidation reaction in the cell
- Space applications use oxygen/hydrogen
- By product: water
- ~ 35% efficiency
Power Conditioning & Control

- Voltage from power source, especially solar arrays, may fluctuate

- Power conditioning functions
  - Control solar array output
  - Control battery charge/discharge cycle
  - Regulate voltage supplied to spacecraft systems

- Two types of systems
  - Dissipative (direct energy transfer, DET)
  - Non-dissipative (peek power tracking, PPT)
Dissipative Systems

- Simpler
- Not in series with array output

Diagram:

- Solar Array
- Shunt
- Battery Charge Controller
- Battery
- Spacecraft Loads

Shunt dissipates current in excess of instantaneous load requirement.
Non-dissipative Systems (PPT)

- In series regulation of solar power

- Usually reserved for large spacecraft
Additional Power Sources

- Nuclear Reactors
- Dynamic Isotope Systems
- Alkali Metal Thermal-to-Electric Conversion (AMTEC)
- Solar Dynamic