Electrical Power Subsystem

1 Power Introduction

The **electrical power subsystem** (EPS) often makes up 20-40% of the spacecraft mass and is therefore important. When designing the subsystem, attention should be given to a lot of parameters, like **power level**, **current type** (alternating current (AC) or direct current (AC)), backup and so on. Of course also general parameters like cost, weight, reliability and such are important.

When designing an EPS, first a **power budget** should be made. This is a list of all electrical apparatus on board, with for every part the power it needs in every operating mode.

An EPS usually consists of four parts. The **power source** provides power. The **power storage** stores it (normally used when the power provided/needed is not constant over time). The **power management** controls and converts power, if necessary. Finally the **power distribution** brings the power to the on-board equipment.

There are many types of energy sources. The **sun** can provide power due to radiation. **Nuclear** energy comes from the decay of atoms. Finally **chemical** energy comes from a chemical reaction between certain elements. Energy sources can also be **external** (like the sun) or **internal** (like chemical energy). The advantage of external power sources, is that they don't contribute to the mass of the spacecraft.

2 Solar Power

Let's go into a bit more detail on solar power. When the sun is used as power source, often **solar arrays** are used. A solar array is a **photo-voltaic** device. Solar arrays can be mounted on the spacecraft, or be deployable. The latter has as advantage that the cells can be directed more to the sun. If the solar array is not pointed to the sun, a correction factor needs to be taken account. The recieved solar power then isn't $\Phi = 1371 W/m^2$, but will become $\Phi_{actual} = \Phi \cos\theta$, where θ is the **incidence angle** of the solar array with respect to the sun.

When using solar cells, the **efficiency** η needs to be taken into account, defined as

$$\eta = \frac{P_{out}}{P_{in}}, \tag{2.1}$$

where P of course denotes the power. The **voltage** V and **current** I solar cells provide, depends on how they are connected. Placing cells in series increases the voltage, while placing cells in parallel increases the current. A series of cells is called a **string**. A series of strings is called a **section**.

When designing a solar array, **eclipses** need to be taken into account. In this time period, no energy is received form the sun. Let's suppose t_e, P_e and η_e are the eclipse time, power needed during eclipse and path efficiency during eclipse (going via the battery), respectively. t_d, P_d and η_d are the same for the day-time period. The power needed during day-time P_{sa} to operate the spacecraft and load the battery can now be found using

$$P_{sa} t_d = \frac{P_e t_e}{\eta_e} + \frac{P_d t_d}{\eta_d}. \tag{2.2}$$

When calculating the number of solar cells, the **degradation** should be taken into account. A solar panel won't provide the same amount of power over the years. Therefore there is a so-called **degradation factor** δ, giving the decrease in power production per year. The part of power left after a number of years x is then given by $(1-\delta)^x$.

3 Batteries

A **battery** is a series of voltaic cells. They can be rechargeable (**secondary batteries**) or non-rechargeable (**primary batteries**). Non-rechargeable batteries only provide power for at most a day, so they are therefore almost only used in launchers.

A measure of how much power a battery can deliver, is the **capacity** C, given by

$$C = \frac{E}{V} = \frac{Pt}{V} = It, \tag{3.1}$$

where E is the energy provided. The required capacity of a battery that is used to cope with ellipses can be found using

$$C = \frac{P_e t_e}{V\, DOD\, \eta_t}, \tag{3.2}$$

where DOD is the **depth of discharge** (the part of the battery that can be discharged) and η_t is the **transmission efficiency**.

Just like in a solar cell, the battery cells can be put in series or parallel. The amount of cells that are put in series n depends on the cell power V_{cell} and the required battery power V_{bat}, according to

$$n = \frac{V_{bat}}{V_{cell}}. \tag{3.3}$$

The number of cell strings put in parallel m can then be found by using

$$m = \frac{C_{bat}}{C_{cell}}. \tag{3.4}$$

The total number of battery cells is then simply the product of n and m.

To find information about the battery mass and volume, we need the **specific energy** E_{sp} (energy per unit mass) and the **battery cell volume** E_δ (energy per unit volume). The mass and volume can then be found using

$$M = \frac{E}{E_{sp}}, \qquad V = \frac{E}{E_\delta}, \tag{3.5}$$

where V now denotes the volume.

Energy from the sun can also be used without solar arrays. By using **solar thermal-electric systems** the radiation is turned into heat, which is then turned into energy. There are two methods to do the latter part. In **static methods** there are no moving parts. Although the efficiency is low, the reliability is high. In **dynamic methods** there are moving parts, which can cause vibrations. Also leakage is a danger. Although the efficiency of dynamic methods is higher, the static methods are preferred.

4 Other Power Sources

Let's look at the other power sources. First we consider **fuel cells**. This is a chemical energy source. Fuel cells give a relatively high power, for a relatively short duration (about a month). The fuel cell mass consists of the dry mass M_{fc} and reactants M_r. If P_{sp} is the specific power, and C_r is the **reactant consumption rate**, then the total fuel cell mass is

$$M = M_{fc} + M_r = \frac{P}{P_{sp}} + EC_r. \tag{4.1}$$

In a **nuclear-electric source** first heat is generated. This heat is then converted to electricity. A lot of excess heat is also created, so this needs to be disposed of. A downside of this kind of power source is that the amount of power it provides decreases as time passes by. This happens according to

$$P_t = P_0 e^{-\frac{\ln 2}{\tau_{1/2}} t}, \tag{4.2}$$

where $\tau_{1/2}$ is the **half-life** of the radioactive isotope used in the reactor.

5 Power Management and Distribution

The task of the **power management and distribution** (PMD) is to make sure that all the equipment on board gets power, with the right type and voltage.

We can determine several types of PMDs. In a **regulated system** bus power and voltage are fully regulated. In an **unregulated system** only on-off switching of strings is possible. It is a simple system, applied for low mass missions. Other more complicated types are **quasi regulated systems** and **hybrid systems**.

In a PMD the electrical current goes through various parts. Every part has an efficiency η_i. To find the efficiency of the entire path, all the efficiencies simply need to be multiplied.

When using a battery, often a **battery charge regulator** (BCR) and a **battery discharge regulator** (BDR) are present. The BCR adjusts the incoming voltage and current in such a way that battery charging is optimal. This causes the battery life to increase. However, the path efficiency decreases, because the current needs to take an extra step. The BDR does a similar thing as the BCR, but now for the on-board equipment instead of the battery.