Chapter 3
System analysis

Abstract

This chapter deals mainly with the analysis of the system. An important space is reserved to power sources in satellite: photovoltaic module and batteries. For both, the possible choices of connection are shown, with all advantages and disadvantages. In presentation of the photovoltaic module, a theoretical background is included. For the power supply the proposed layouts are analyzed in section 3.2.

3.1. Introduction

For the purpose of understanding function of the power supply, an analysis of the power subsystem has to be set. It is a requirement that the efficiency of the power supply to be as high as possible, considering thermal problems occurring in vacuum. In section 3.2, an overview of possible layouts of the power supply is done. In respect with efficiency, the best solution has been chosen for further implementation and deeper analysis, performed in the next chapter.

To obtain a robust system, the interface between the DC bus and the users must be examined. Protection of all users has to be implemented, also set up different priorities for users, according to their importance for the continuous functionality of the satellite.

3.2. Power supply topologies

Four different layouts have been proposed for the power supply.

In this section it will be explained the advantages and disadvantages for each of them and the best configuration is to be chosen.

In figure 3.1, the first possible configuration for the power subsystem is shown.

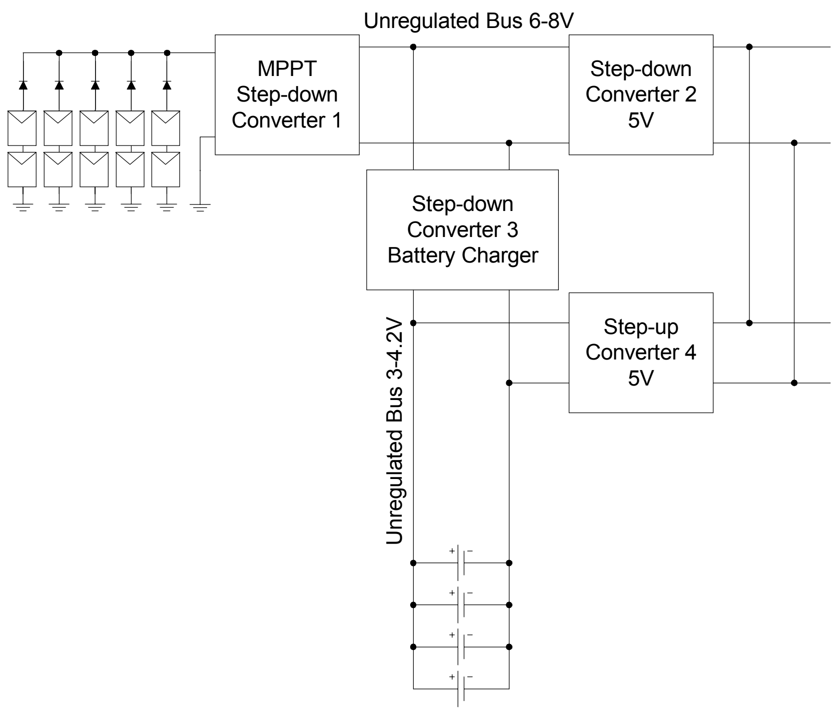


Figure 3.1 Proposal for power supply layout using 4 converters and 2 unregulated buses

In this configuration, four converters are to be used.

The MPPT converter is supplying the unregulated bus with voltage between 6V and 8V. This bus is feeding two step-down converters. One of them is charging the batteries and the other one realizes the 5V stabilized voltage used for OBC, ATC and camera. From the unregulated battery bus is supplied another converter for 5V. The 5V converter is working in parallel with the other one for a better redundancy.

Advantages:

- Good redundancy for 5V supply – there are two independent 5V sources

Disadvantages:

- Low efficiency – three converters are in series, final efficiency is product of each converter's efficiency
- Large amount of converters (4) – too big complexity
- Poor reliability – more components imply less reliability

In figure 3.2, the second possible topology is presented. Instead of the unregulated bus 6-8V, a 5V regulated bus is used. In this way is used one converter less.

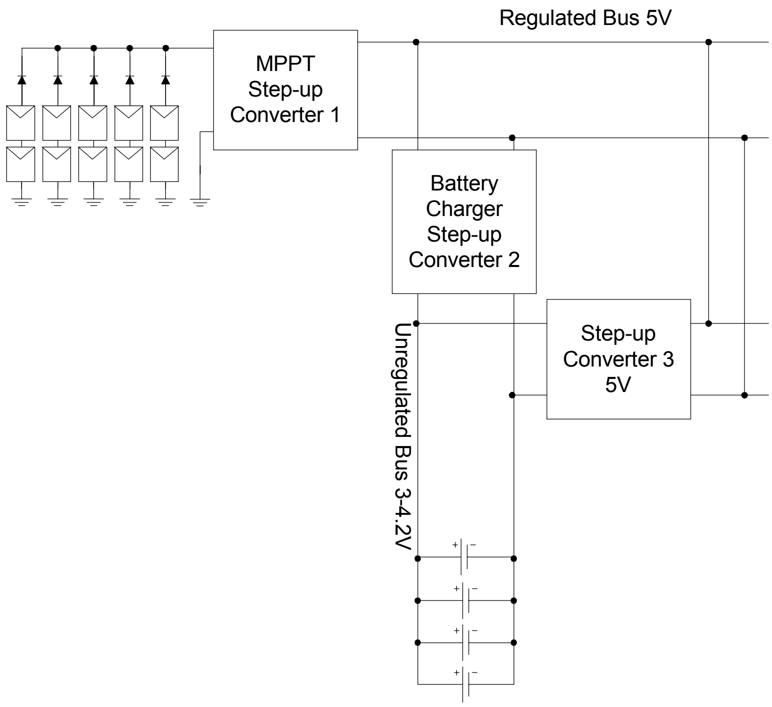


Figure 3.2 Proposal for power supply layout using 3 converters and an unregulated bus

Advantages:

- Good redundancy for 5V supply – there are two independent 5V sources (until batteries are charged)

Disadvantages:

- Low efficiency – again three converters in series

In the third case, presented below, the batteries are placed directly on the unregulated bus and the MPPT converter is also the battery charger. That results in one converter less, comparing with the other topologies.

The layout is depicted in figure 3.3.

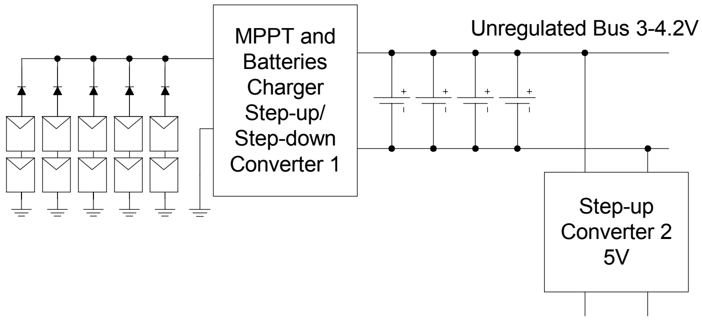


Figure 3.3 Proposal for power supply layout using 2 converters and an unregulated bus

Advantages:

- Good reliability – low number of components
- Good efficiency – only two converter in series

Disadvantages:

- There is not too wide variety of buck-boost converters, from which can be chosen proper one, in case of such a small input voltage.

The proposed layout for the power supply in the last case, is presented in figure 3.4. The configuration comprises two converters, one supplying the unregulated bus from the solar arrays. The second converter fed from the unregulated bus is stabilizing the voltage for the 5 V bus.

The first converter is controlled in order to achieve the maximum power point from the solar cells and to charge the batteries. Each battery string is using a protection circuit, which is disconnecting the battery string in case of overcharging, over discharging and over current.

The regulated 5V bus is supplied from a step-down converter fed by the unregulated bus. From the 5V bus each user is supplied using separate wires, but with common ground. Common ground is chosen because every user, which is connected to I^2C bus must use the same ground wire.

Protection circuits are provided for every load. The main function is to limit the output current to a safe level and to give a flag to the micro-controller unit (MCU), indicating an overcurrent. It can also be driven externally to connect or disconnect the user. The current is measured as housekeeping data for each user.

The protection for MCU is different than that for regular users. It is used a self-protected 5V voltage regulator with internal limiting and thermal shutdown features.

The MCU is used for gathering and computing the housekeeping data, taking decisions for connecting/disconnecting users in case of failure and communication with OBC.

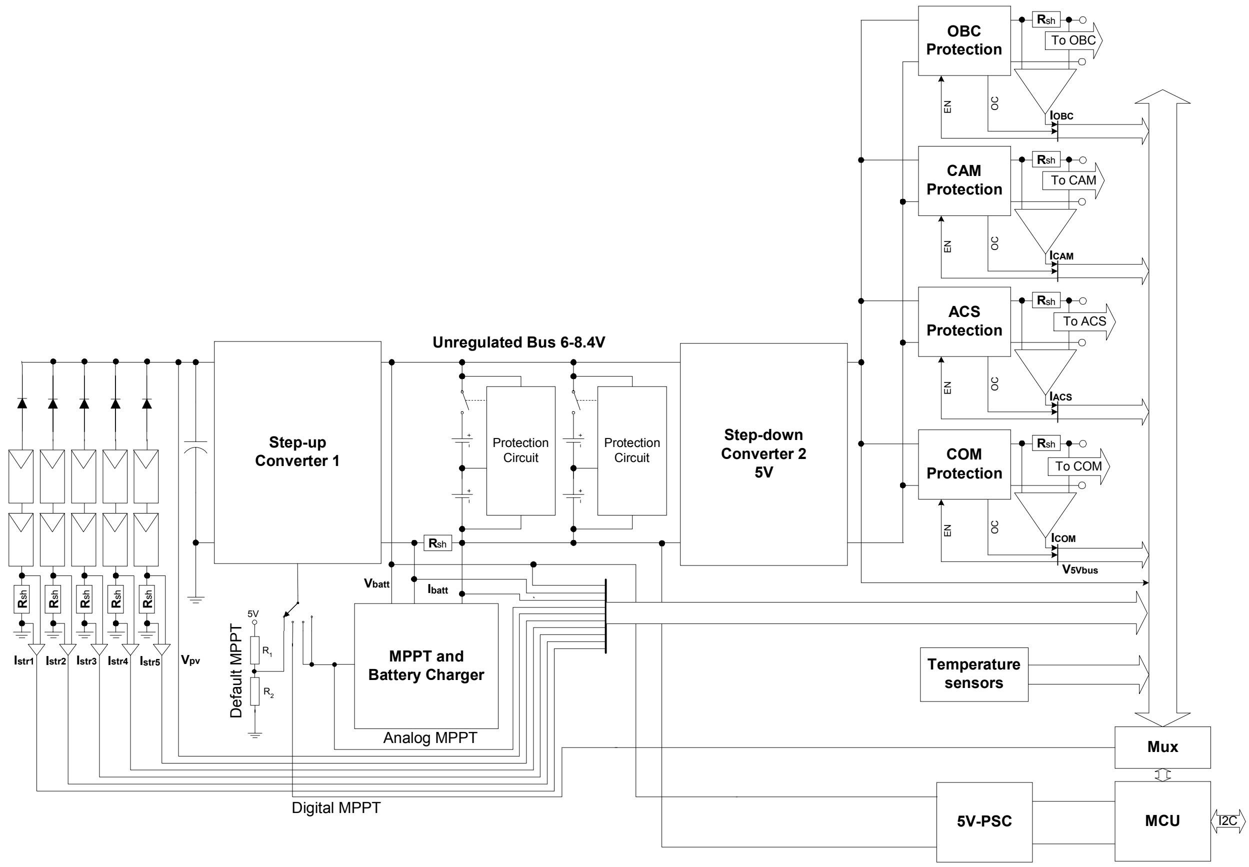


Figure 3.4 Proposed power supply layout using 2 converters and an unregulated bus

Taking into account all the advantages and disadvantages, for the presented configurations, it has been decided to use the last configuration, depicted in figure 3.4.

3.3. Power sources analysis

The Power Supply Unit (PSU) can be divided in three modules, as described in section 1.3: Photovoltaic module (PV), Battery unit (BAT) and Power Conditioning Unit (PCU). In this section, the first two modules will be analyzed, the third will follow in the next section. The reason of splitting the analysis in this way resides from the function fulfilled by each of the modules: PV and BAT are sources of energy while PCU main function is to provide loads with current from the common bus.

3.3.1. Photovoltaic considerations

Solar cells are composed of various semiconductor materials. Semiconductors are materials, which become electrically conductive when they are supplied with light or heat, but which operate as insulators at low temperatures. There are two effects that might provide the conversion of energy from sun into electric energy [*Fitzgerald, 2001*].

If a photon is incident upon a semiconductor then, if the photon energy is higher than the band-gap energy, the photon may be absorbed and an electron elevated from the valence band to the conduction band. This creates an electron-hole (e-h) pair; mobile charge carriers produced in this manner are called *photo-carrier*s. In a homogeneous semiconductor, the electron and hole will wander about (due to their thermal motion) and eventually recombine, either with each other or with other electrons and holes executing similar motion. When carriers recombine they annihilate each other and emit a photon corresponding to the band-gap energy. Under certain conditions the charge carriers may be collected before the combine to form a *photocurren*t. Depending on the material, band-gap energies range from several eV to a few tens of eV to. This process is called *photovoltaic effect.*

In the *photoelectric effect*, a photon strikes a metal and ejects an electron. No electrons will be ejected unless the photon energy, hf, exceeds the work function of the metal. (h is Planck's constant and f is the photon frequency). Unfortunately, work functions are typically 5-10 eV while most of the Sun's energy is concentrated in photons having energy 1-2 eV. Thus, the photoelectric effect would not be able to extract energy from most the Sun's radiation, and hence, would be very inefficient at converting sunlight to electric energy.

Ideal characterization and basic parameters of solar cells

The simplified equivalent circuit of a solar cell consists of a diode and a current source that are connected in parallel, as shown in figure 3.5.

The current source generates the photocurrent I_{ph}, which is directly proportional to the solar irradiance S and also temperature T. The p-n transition area of the solar cell is equivalent to a diode that is also integrated in the figure 3.5. In shadow, a solar cell is just a diode.

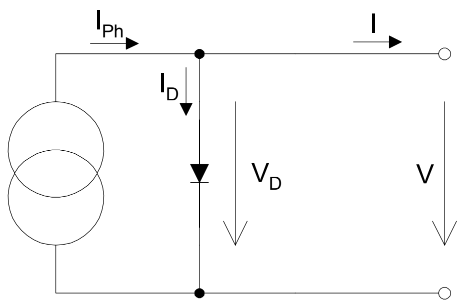


Figure 3.5 Simplified equivalent circuit of the solar cell.

The current-voltage characteristic of an ideal diode is given by the following formula:

$$I_D = I_{rs} \cdot (e^{\frac{q \cdot V_D}{A \cdot k \cdot T}} - 1) \tag{3.1}$$

where, I_{rs} is the reverse saturation current,

q = 1.6 x 10^{-19} [C] is the fundamental unit of charge,

k = 1.38 x 10^{-23} [J/K] is Boltzmann's constant,

A is diode quality factor (1÷5, 1 means ideal p-n junction),

V_D is voltage drop across the diode [V],

T is absolute temperature [K], 0°C = 273.15 K

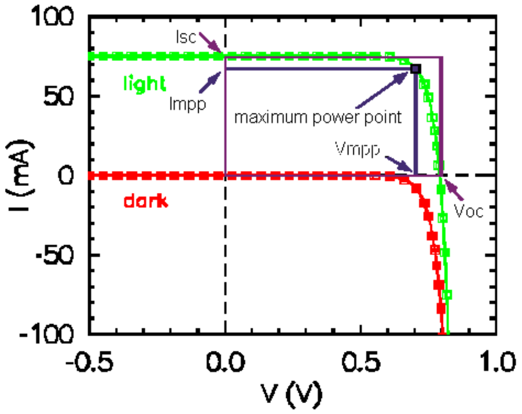
The theoretical behavior under illumination is represented by

$$I = I_{Ph} - I_D \tag{3.2}$$

where I_{Ph} represents the photo current, I_D is diode current described above.

In figure 3.6a are illustrated I-V characteristics of ideal cell in two different positions [*Fitzgerald, 2001*]. The dark color curve shows an ideal solar cell that is shadowed. The light color curve in figure 3.6a shows the I-V characteristic of an ideal solar cell measured under 1000 W/m^2 illumination. For an ideal solar cell, the I-V characteristics are simply shifted down due to the light-generated current, I_{ph}. In case of shadowed cell can appear a situation of negative current through the solar cells. This is due to the behavior of the solar cell acting like a p-n junction in parallel with a current source. In order to avoid this inadvertent situation can be used a string diode which is connected in series with solar cell in negative polarization (figure 3.6b).

On the I-V curve are shown some points typical for solar cell. The *open circuit voltage* V_{OC}, the *short circuit current* I_{SC}, the *maximum power point voltage* V_{MPP}, the *maximum power point current* I_{MPP}. Then can be defined these parameters typical for solar cells.



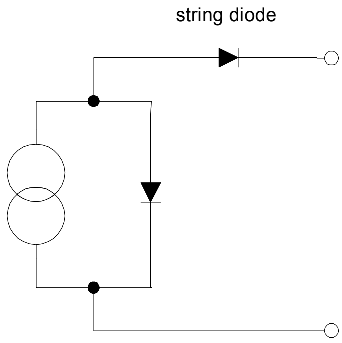


Figure3.6 a) I-V curves for solar cell b) solar cell with string diode

The *fill factor* as a ratio of maximum power and product of short circuit current and open circuit voltage, is given by:

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}} \tag{3.3}$$

The fill factor is always less than unity; the closer it is to unity the better the quality of the solar cell. One of the most important characteristic about a solar cell is its energy conversion efficiency, η:

$$\eta = \frac{Maximum\_electric\_power}{incident\_light\_power} \tag{3.4}$$

Real solar cell, influence of the temperature and incident light over I-V curve

In figure 3.7 is shown the equivalent circuit for real solar cell. In real solar cells a voltage loss on the way to the external contacts could be observed. This voltage loss could be expressed by a series resistor R_S. Furthermore leakage currents could be observed, which could be described by a parallel resistor R_P. For description of this circuit can be used relations mentioned above with proper modifying involving also influence of temperature.

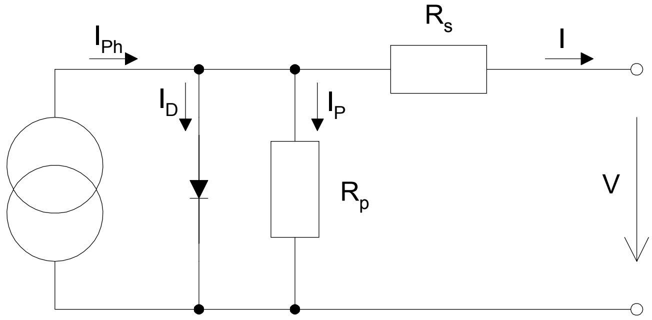


Figure 3.7 Circuit diagram for real solar cell

Equation (3.5) relates the I-V characteristics of a real diode to a number of device parameters [*Hussein et.al., 1995*]:

$$I = I_{Ph} - I_D - I_P = (I_{SC} + k_i \cdot (T - T_{ref})) \cdot \frac{S}{100} - \\ - I_{RR} \cdot (\frac{T}{T_{ref}})^3 \cdot e^{\frac{q \cdot E_G}{A \cdot k} \cdot (\frac{1}{T_{ref}} - \frac{1}{T})} \cdot (e^{\frac{q \cdot (V + I \cdot R_S)}{A \cdot k \cdot T}} - 1) - \\ - \frac{V + I \cdot R_S}{R_P} \tag{3.5}$$

Where, I_{SC} is short circuit current [A],

k_i is short circuit current temperature coefficient,

T is cell temperature [K],

T_{ref} is cell reference temperature [K],

S is solar radiation [mW/cm^2],

I_{RR} is reverse saturation current at T_{ref} [A],

q is the charge of an electron, equal with 1.6 x 10^{-19} [eV],

E_G is the band-gap energy of the semiconductor used in the cell [eV],

k is Boltzmann's constant, equal with 1.38 x 10^{-23} [J/K],

A idealizing factor (1÷5, 1 means ideal p-n junction),

R_S is series resistance of the cell [Ω],

R_P is shunt resistance of the cell [Ω].

Most of the parameters of the solar cell show a temperature dependency. The general equation to calculate the temperature coefficient *TC* for a value *y* is:

$$TC(y) = \frac{1}{y} \cdot \frac{\partial y}{\partial T} \tag{3.6}$$

In case of linear connection between *y* and temperature, then the equation (3.6) can be rewritten:

$$TC(y) = \frac{1}{y(T_0)} \cdot \frac{y(T_1) - y(T_0)}{T_1 - T_0} \tag{3.7}$$

The short circuit current is increasing a little at rising temperatures, while the open circuit voltage is lower (-0.4 [%/K]) [http://www.emsolar.ee.tu-berlin.de/lehre/english/pv1]. Therefore the power output is decreasing for increasing temperatures. The power loss is around 0.3-0.5 % per degree Celsius, so for an increase of 30°C in temperature the power is decreasing by 9-15 % as depicted in figure 3.8 [*Masoum et. al.*].

After absorption of the incoming radiation in the solar cell a portion of it is converted into electricity and diverted. The remaining heat flow gets from the cell through the encapsulation to the surface of the module (steady state heat flow) or increases the temperature of the module (non-steady state heat flow).

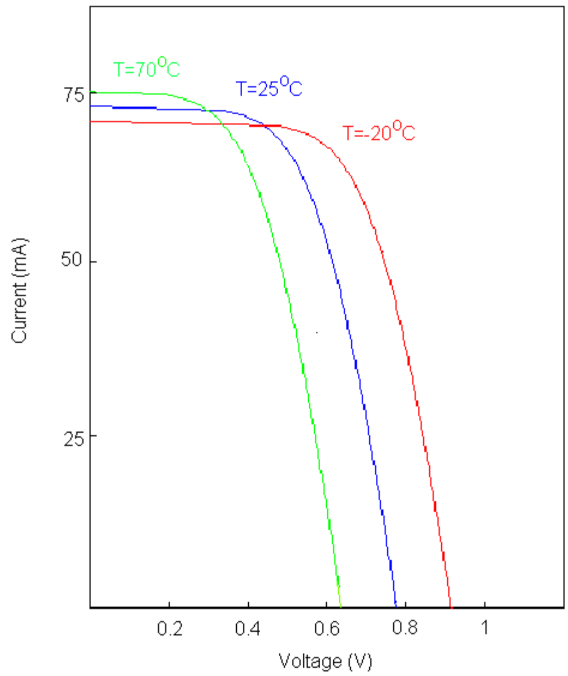


Figure 3.8 I-V curves dependent on temperature

The power that is obtained from solar cell is depended on the angle of incident light. In figure 3.9 is described a situation with changing angle φ [*Hishikawa et al., 2000, p.1465*].

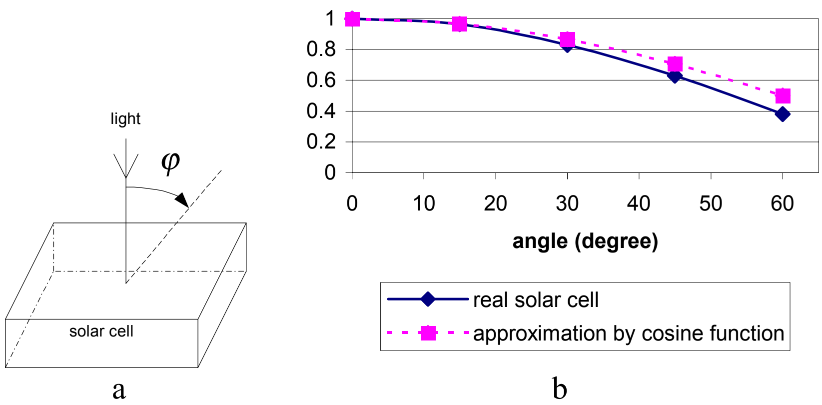


Figure 3.9 a) changing of the angle of incident light b) dependency of power from solar cell on angle of incident light

For description of this situation cannot be used any exact mathematic function. The best and also the most accuracy function used for this is cosine function. In figure 3.9b is shown per unit values of power from cell dependent on incident light for both real cell and cosine approximation. Approximation is accurate until approximately 15-degree angle.

Physical realization of solar cells

In these days can be found a lot of different structure of solar cells on markets. In order to choose proper cell for certain application must be compare behaviors together with prices. Nowadays there are three possible ways of internal structure: single, double and triple junction. More junctions indicate better efficiency due to cover wider spectrum of incident light. That, on the other hand, also implicates higher prices for those junctions.

The most efficient single junction space solar cell was fabricated from Galium-Arsenide (GaAs) substrate, which has a band-gap close to the theoretical ideal spectrum. It occurs also single junction fabricated from Germanium (Ge) substrate. Then on this substrate is applied a junction from GaAs. This junction can cover wavelength at intervals approximately 700-900 nm. It means that in this interval has the single junction the best quantum efficiency.

In order to cover also another wavelength is possible to add more junctions. The most often used material for this junction is Indium-Galium-Phosphorus (InGaP). In this case is possible to obtain energy from 300-650 nm interval of wavelength. If it is added directly on the substrate Ge junction, which forms third junction, the energy from 900-1600 nm could be also taken into account (figure 3.10).

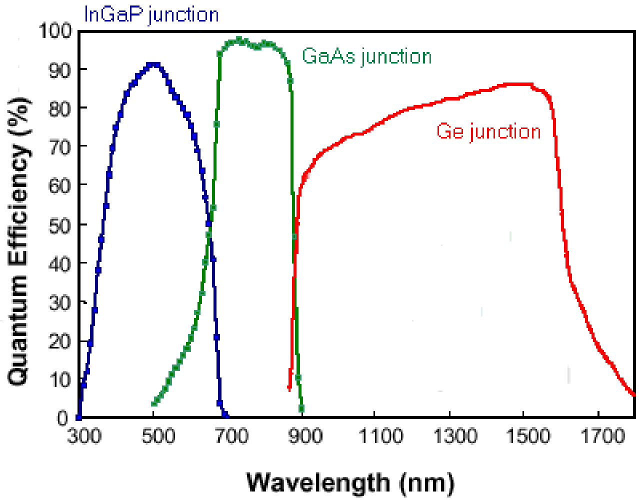


Figure 3.10 Different wavelength covered by typical triple junction solar cell
[www.emcore.com]

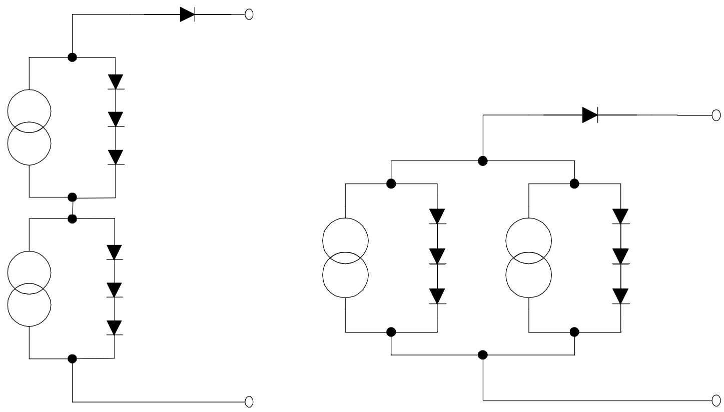
Connection of solar cells

There are two typical ways to connect solar cells to one module. Both of them have some advantages and also disadvantages.

In figure 3.11, series (a) and parallel (b) connection of the solar cells, into one module, are presented.

For the serial connection case, on the output from this connection can be obtain voltage which is sum of both cells and the current same for both cells. This is usually used in order to yield sufficient DC voltage for realizing higher conversion efficiency of converters.

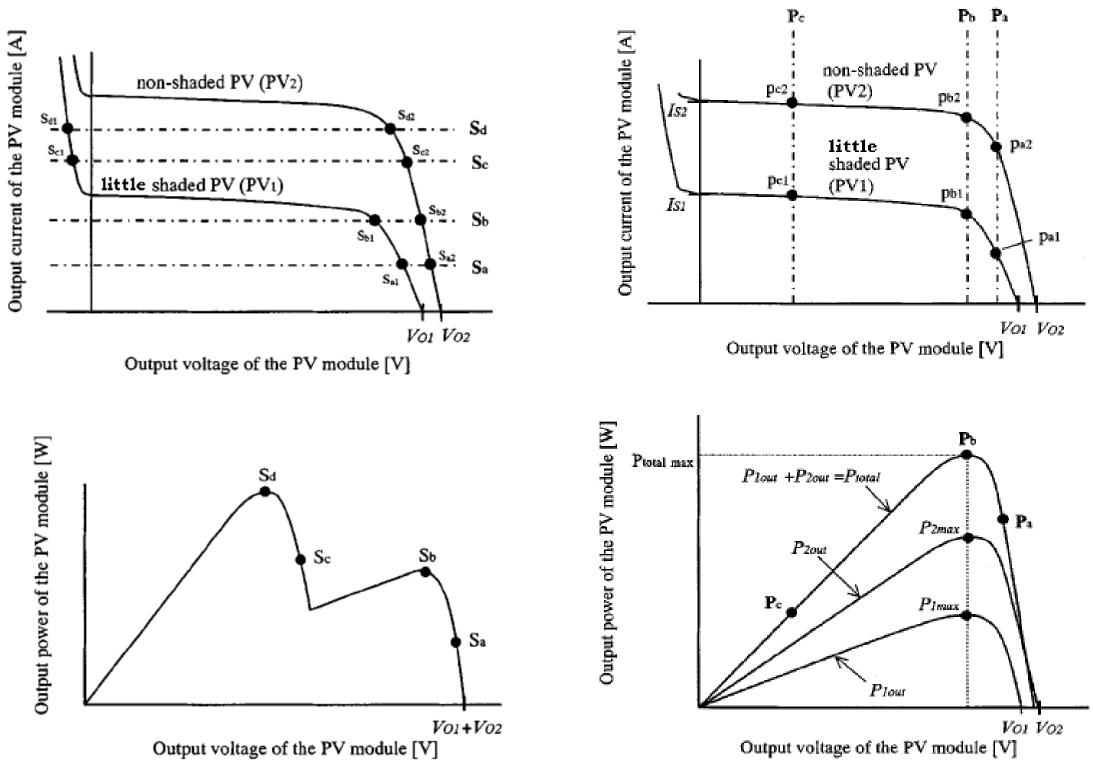
For the parallel connection case, on the output from this connection can be obtain current which is sum of both cells and the voltage same for both cells.



a b

Figure 3.11 Serial (a) and parallel (b) connection of two solar cells with string diode

The difference between the two connections resides in the shape of the output current and voltage.



a b

Figure 3.12 Characteristics for two cells connected in series (a) and parallel (b)

For the serial connection, operation point for each cell is given by intersection of lines that are parallel to the x-axis (shown in figure 3.12a, up). When the output current is increased from zero to maximum current, the operation point is moving progressively from S_a>S_b>S_c>S_d. In the last two points, for instant, the little shaded solar cell has the negative voltage and it causes power loss. That is the reason for such a shape of power curve, shown on the figure 3.12a, bottom.

For parallel connection, the operation point for each cell is given by intersection of lines which are parallel to y-axis (shown in figure 3.12b, up). When the output current is increased from zero to maximum then the operation point is moving progressively from P_a>P_b>P_c. This points that not only the non shaded but also the little shaded cell can operate in area where can generate power. Then the final output power is sum of the power of each cell [*Shimizu, et. al, 2001*].

As it was mentioned before, for better behavior in supplying the satellite systems, is recommended to use cells in parallel connection. But for higher voltage is recommended to use serial connection. If the string diode is broken down then is conducting. In case of series connection is lost only one cell. In parallel connection appears a shortcut circuit and are lost all cells. For the current application it was decided to use on each side cells connected in series and then all sides connected in parallel as depicted in figure 3.13.

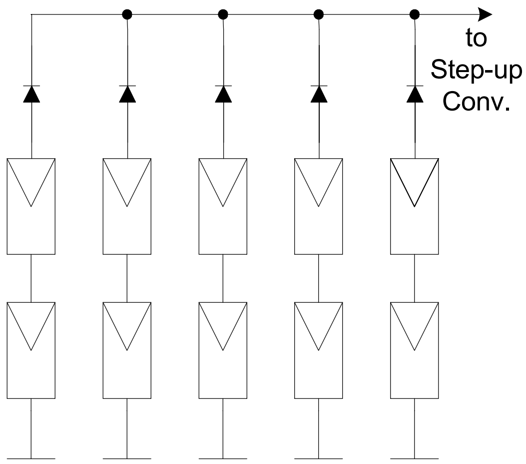


Figure 3.13 Final connection of solar cells

3.3.2. Input power calculation

Input power is influenced by a few factors. One of them is represented by type of energy source. As defined in chapter 2, section 2.3.1, there are three main sources of power in space. Due to the triple junction technology used in solar cells infrared radiation can be also taken into account. The input power, for one side of the satellite, considering only solar radiation, is:

$$P^*_{in1} = P_{sun} \cdot n \cdot A \cdot \eta \tag{3.8}$$

where, P_{sun} is the amount of energy radiated by Sun (Table 2.1), n represents the number of cells on one side, A is area of one cell and η represents the efficiency of solar cells. The efficiency, considered in calculations, is EOL (End Of Life) efficiency (25%).

The numerical value for the power is:

$$P^*_{in1} = 1353\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \cdot 2 \cdot 0.00273\left[\mathrm{m}^2\right] \cdot 0.25 = 1.845\ [\mathrm{W}] \tag{3.9}$$

Losses caused by Schottky diode, at maximum power point, are:

$$P_{diode} = \langle I_{diode} \rangle \cdot \langle V_{diode} \rangle \quad , \quad P_{diode} = \frac{P^*_{in1}}{n_s \cdot V_{mpp}} \cdot V_{diode} \tag{3.10}$$

where V_{diode} is the voltage drop on a diode, V_{mpp} is the maximum power point voltage (which is a function of the incoming sunlight) and n_s is the number of serial solar cells in one string.

Replacing in equation (3.10) numerical values, the power dissipated in diode, for one side, is:

$$P_{diode1} = \frac{1.845\ [\mathrm{W}]}{2 \cdot 2.08\ [\mathrm{V}]} \cdot 0.3\ [\mathrm{V}] = 0.133\ [\mathrm{W}] \tag{3.11}$$

Then, the one side input power becomes:

$$P_{in1} = P^*_{in1} - P_{diode1} = 1.845 - 0.133 = 1.712\ [\mathrm{W}] \tag{3.12}$$

Furthermore, the power input is function of satellite position toward the sun, because illuminated area is changing after the way the satellite is spinning.

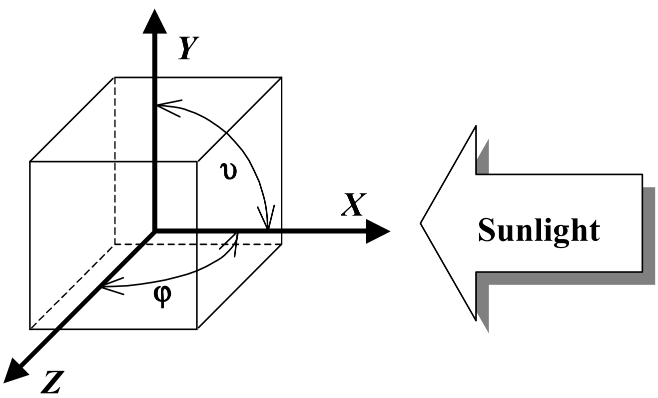


Figure 3.14 Definition of angles used for computation of input power

A function which will describe the illuminated area in dependency with angle have to be found. This function represents projection of side walls surface to plane normal to the Sun. For this simulation, Matlab software has been used and angles used in this program are shown in figure

3.14. Maximum three sides can be illuminated at a time. The area coefficients are defined for these three sides, as follows:

$$A_x = \cos(\varphi)\cdot\sin(\upsilon) \;,\quad B_y = \sin(\varphi)\cdot\sin(\upsilon) \;,\quad C_z = \cos(\upsilon) \tag{3.13}$$

This equations represent spherical coordinates.

[http://www.math.montana.edu/frankw/ccp/multiworld/multipleIVP/spherical/body.htm]

The total power available is the sum of powers for all sides:

$$P = (A_x + B_y + C_z)\cdot P_{in1} = (\cos(\varphi)\cdot\sin(\upsilon) + \sin(\varphi)\cdot\sin(\upsilon) + \cos(\upsilon))\cdot P_{in1} \tag{3.14}$$

The average power, calculated by a program in Matlab as an arithmetical average of all resulting values (Appendix A), is:

$$P_{av} = 2.48 \text{ [W]} \tag{3.15}$$

But satellite has only five sides covered by solar cells, then the average power will be only 5/6, under the assumption that all sides are equally exposed to the Sun:

$$P_{av} = 2.48 \cdot \frac{5}{6} = 2.07 \text{ [W]} \tag{3.16}$$

Result of the input power as a function of the angles of incident light is plotted in figure 3.15.

Maximum value obtained from Matlab is:

$$P_{max} = \sqrt{3} \cdot P_{in1} = 2.965 \text{ [W]} \tag{3.17}$$

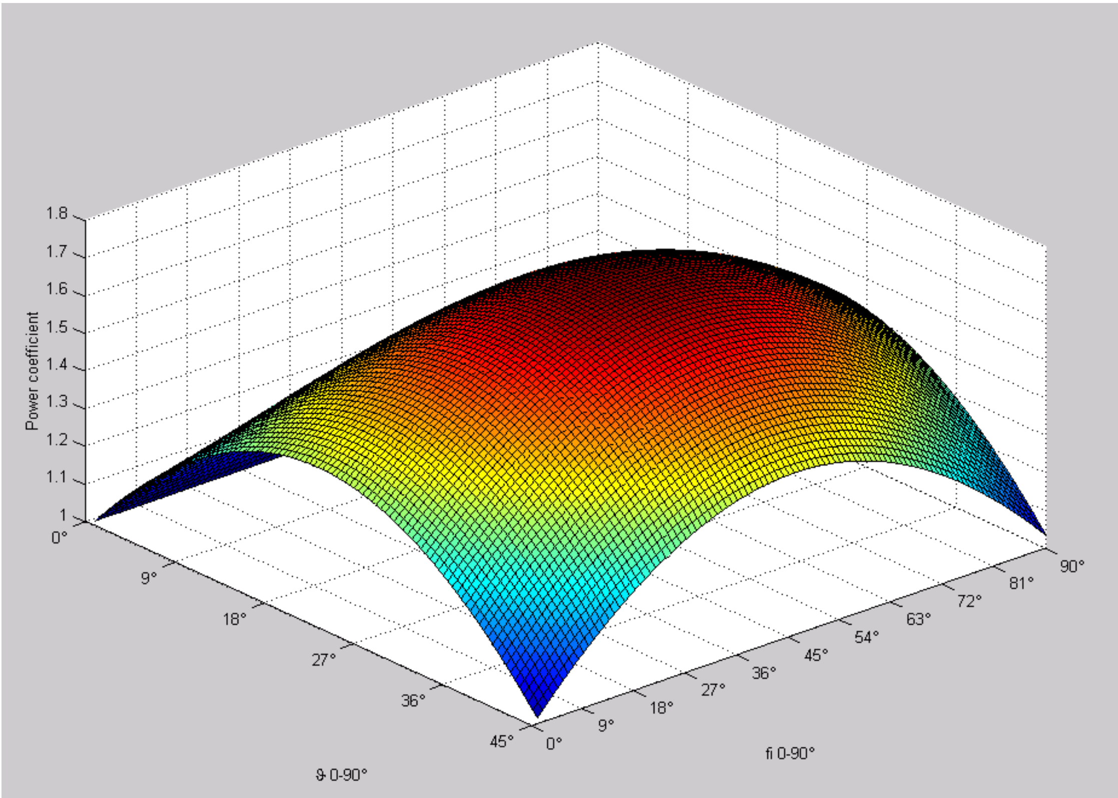


Figure 3.15 Input power as a function of incident light angles

And special case for two sides illuminated :

$$P_{in2} = \sqrt{2} \cdot P_{in1} = \sqrt{2} \cdot 1.712 = 2.42\ [\mathrm{W}] \tag{3.18}$$

In calculation of the input power, performed above, only the visible spectrum of the light, emitted by Sun has been considered. The Earth as a space object is source of energy and one of radiated components of this energy is in spectrum from 700 to 1000 nm. This energy is accepted by satellite during the whole orbit also in eclipse. That means that solar cells may convert this radiation into electrical power all the time. Some specific conditions must be fulfill for it. First, at least one of the sides with cells must point to the Earth and level of obtained current and voltage must be sufficient to drive switches (using of capacitor is necessary to accumulate power before MPPT). When the satellite is not in shadow there is no problem, energy from the Sun is summarized with infrared energy, so it adds a small amount of power in the system.

Input power from infrared radiation, for one side, is:

$$P_{IR}^{*} = P_{IR\_Earth} \cdot n \cdot A \cdot \eta \tag{3.19}$$

where, P_{IR_Earth} represents the amount of infrared energy radiated by the Earth (Table 2.1), n is the number of cells on one side, A is area of one cell and η represents the efficiency of solar cells. Like for equation (3.9), the efficiency is considered to be 25%.
Replacing numerical values in equation (3.19), yields:

$$P_{IR}^{*} = 237\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \cdot 2 \cdot 0.00273\left[\mathrm{m}^2\right] \cdot 0.25 = 0.324\ [\mathrm{W}] \tag{3.20}$$

Analogical to the equation (3.17) maximum of this value, when three sides are illuminated, must be

$$P_{m\mathrm{IR}} = 0.324 \cdot \sqrt{3} = 0.560\ [\mathrm{W}] \tag{3.21}$$

If the albedo radiation is considered, the provided power is:

$$P_{ALB}^{*} = P_{ALB\_Earth} \cdot n \cdot A \cdot \eta \tag{3.22}$$

where, P_{ALB_Earth} represents the amount of albedo energy radiated by Earth (Table 2.1), n is the number of cells on one side, A is area of one cell and η represents the efficiency of solar cells (25%). Replacing in equation (3.22) corresponding numerical values, it yields:

$$P_{ALB}^{*} = 406\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \cdot 2 \cdot 0.00273\left[\mathrm{m}^2\right] \cdot 0.25 = 0.554\ [\mathrm{W}] \tag{3.23}$$

and maximum value obtained from albedo is

$$P_{m\mathrm{ALB}} = \sqrt{3} \cdot 0.554 = 0.960\ [\mathrm{W}] \tag{3.24}$$

In calculation of infrared and albedo power, the specific levels of radiation can be found in chapter 2, table 2.1. If the values for infrared and albedo power are considered, this will give to the power subsystem a plus power of 0.878 [W] per one side.

3.3.3. Battery unit

According to the specifications batteries must be light and in minimum size. Two types of batteries are usually used in this kind of application: Lithium Ion (Li-Ion) and Nickel Cadmium (NiCd). Former satellites used NiCd batteries. The main advantage of these batteries is a longer lifetime, but in comparison to Li-Ion they are heavier and larger. Li-Ion offers a significant advantage of energy density and no memory effect. This was the main argument for choosing Li-Ion batteries. A comparison between usual types of batteries is shown in table 3.1.

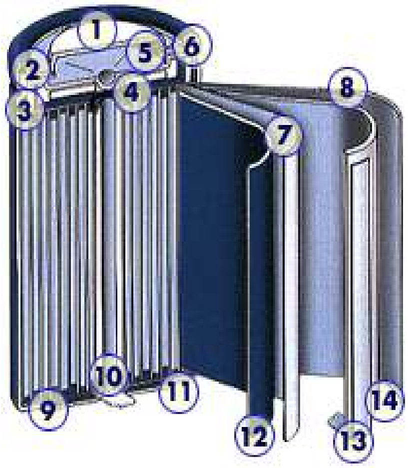
Type	NiCd	NiMH	**Li-Ion**
Nominal voltage [V]	1.2 V	1.2 V	**3.7 V**
Density of energy [W·h/l]	140	180	**200**
Density of energy [W·h/kg]	39	57	**83**
Max. discharging current	20C	4C	**2C**
Self disc.[% per day]	1 %	1,5 %	**0,5 %**
Charging time (the fastest)	15 min	30 min	**1 h**
Thermal range for charging [°C]	0 to +50	0 to +45	**5 to+ 45**
Thermal range for discharging [°C]	-20 to +50	-20 to +50	**0 to +40**
Resistance against overcharging	Low	Low	**Middle**
Cathode material	NiOOH	NiOOH	**LiCoO2**
Anode material	Cd	alloy	**C**
Max number of cycles	1000	500	**400**

Table 3.1 Comparison of different types of batteries [http://www.mobil.cz/]

Theoretical background for Lithium Ion battery

A cell of a Li-Ion battery consists of a carbon-based negative electrode and a lithium transition metal oxide positive electrode. Upon charging, lithium ions are extracted from the positive electrode material and inserted into the negative electrode material. Upon discharging, the reverse process is taking place. Hence, the basic electrochemistry of the cell involves only the transfer of lithium ions between the two insertion electrodes. Due to the high cell voltage of up to 4V, the specific energy of this battery system is very favorable in comparison to the other known and commercialized secondary battery systems; however, an organic electrolyte solution must be used in the case of the lithium-ion battery.

Lithium-ion batteries are constructed by using a lithium oxide cathode and a carbon compound anode, with a high polymer separator and a non-aqueous electrolyte between the poles. Minute spaces are designed between the electrode materials to allow the lithium-ions to enter.

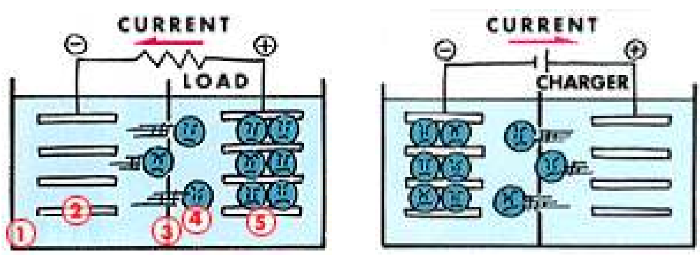


1.Cathode cover
2.Gasket
3.Insulator
4.Cathode lead
5.Safety vent
6.PTC
7.Separator
8.Separator
9. Insulator
10.Center pin
11.Anode container
12.Cathode
13.Anode lead
14.Anode

Figure 3.16 Section through a Li-Ion battery [http://www.sony-media.com/en/technical/lithium-ion.html]

The way that a Li-Ion battery works is depicted in figure 3.17. Basically, as the battery is charged and discharged, the Lithium-ions shift back and forth between the cathode and anode.

DISCHARGING **CHARGING**



1.Electrolyte (organic solvent)
2.Cathode (lithium oxide)
3.Separator
4.Lithium ions
5.Anode (carbon compound)

Figure 3.17 Illustration of Li ions movement [http://ecl.web.psi.ch/lithium]

Power budget during one time period

The power budget will be computed taking in account the worst situation, when the satellite is in shadow for 35 minutes and transceiver is transmitting data for 15 minutes. Whole orbit lasts 100 minutes. In the table below are stated the consumers, the working time and the energy needed.

No.	Consumer	Power [W]	Time [s]	Energy [J]
1	OBC	0.46	6000	2760
2	Transmitter	9	900	8100
3	Camera	0.3 (while shooting)	10	3
4	Attitude Control	0.25	6000	1500
	Total	**-**	**-**	**12363**

Table 3.2 Power consumption for users, in the worst case

The energy is computed using the following formula:

$$E[\mathrm{J}] = P[\mathrm{W}] \cdot t[\mathrm{s}] \tag{3.25}$$

If it is considered a total efficiency for the converters η = 75%, the minimum available power will result:

$$E_{total} = \frac{E}{\eta} = \frac{12363\ [\mathrm{J}]}{0.75} = 16484\ [\mathrm{J}] \tag{3.26}$$

The Sun will provide energy for 65 minutes and the average input power will be around 2.07W (without albedo and infrared). So, the power obtained from solar cells is equal with:

$$E_{sun} = P_{av} \cdot t_{sun} = 2.07[\mathrm{W}] \cdot 65 \cdot 60[\mathrm{s}] = 8073\ [\mathrm{J}] \tag{3.27}$$

In this case the energy needed from the batteries is:

$$E_{batt}^{n} = E_{total} - E_{sun} = 16484[\mathrm{J}] - 8073[\mathrm{J}] = 8411\ [\mathrm{J}] \tag{3.28}$$

One battery fully charged can provide an energy of:

$$E_{batt} = \left(\frac{(U_{\max} + U_{\min})[\mathrm{V}] \cdot C[\mathrm{Ah}]}{2} \right) \cdot 3600[\mathrm{s}] = \left(\frac{(4.2+3)[\mathrm{V}] \cdot 0.92[\mathrm{Ah}]}{2} \right) \cdot 3600[\mathrm{s}] = 11923\ [\mathrm{J}] \tag{3.29}$$

where, U_{max} and U_{min} represents the limits of the voltage range for a Li-Ion battery and C is the capacity of the battery. Data for the batteries can be found in Chapter 2, section 2.3.2.

This yields to a needed number of batteries of:

$$n = ceil\left(\frac{E_{batt}^{n}}{E_{batt}} \right) = ceil\left(\frac{8411}{11923} \right) = ceil(0.705) = 1 \tag{3.30}$$

It can be seen from this results that one battery is giving enough power for one whole orbit if the solar panels are also used. But for avoiding to drain the batteries and also have a backup in case of failure will be used four of them.

If the batteries are particular discharged, to recharge them, the same amount of power must be obtained from the solar panels. If every load except OBC and ATC is off, the power consumption is:

$$E_{OBC} + E_{ATC} = 2760[\mathrm{J}] + 1500[\mathrm{J}] = 4260\ [\mathrm{J}] \tag{3.31}$$

This means that in each orbit the amount of energy:

$$E_{charge} = E_{sun} - E_{OBC} = 8073 - 4260 = 3813\ [\mathrm{J}] \tag{3.32}$$

is available to recharge batteries. Taking in account that there are four batteries, the energy requested for recharging from the solar panels is:

$$E_{charge}^{r} = \frac{n_{batt} \cdot E_{batt}}{\eta_t} = \frac{4 \cdot 9072[\mathrm{J}]}{0.8} = 45360\ [\mathrm{J}] \tag{3.33}$$

where η_t is the total efficiency of the MPPT converter series with the battery charger.

The time necessary for recharging the batteries, considering that every load is cut off after taking a picture and transmitting, will be:

$$t_{ch} = \frac{E_{batt}^{r}}{E_{charge}} \cdot 100 = \frac{8411[\mathrm{J}]}{3813[\mathrm{J}]} \cdot 100[\mathrm{min}] = 220.59\ [\mathrm{min}] \tag{3.34}$$

From this results can be seen, that if the OBC uses 0.46W it will take more than 2 orbits to recharge batteries back to initial state. The more OBC uses the idle mode with 5mW power consumption, the less time is needed to recharge them. Than the conclusion is that it is possible to take and send one picture daily, because we can transmit 4 times per a day. This is exactly what we need for sending one picture per a day.

Connection of batteries

There are three possibilities how to connect batteries: series, parallel or combination of both. If they are connected in parallel (figure 3.18), the voltage will be the same, but the current capability will be four times higher.

$$C_{parallel} = n \cdot C_{batt} = 4 \cdot 0.92\ [\mathrm{Ah}] = 3.68\ [\mathrm{Ah}] \tag{3.35}$$

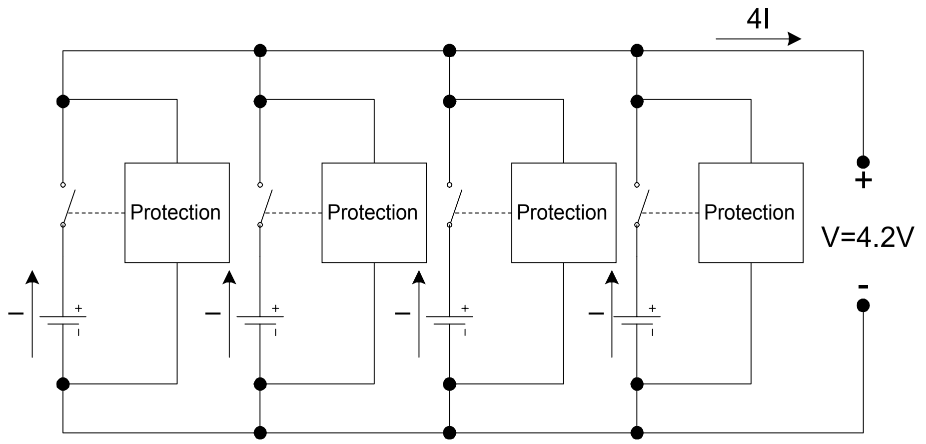


Figure 3.18 Parallel connection of the batteries

The reliability of parallel system is good, because when protection circuit will disconnect one battery, the other three can be still used. The only disadvantage of this configuration is the low voltage level.

If the batteries are connected in series (figure 3.19) the voltage level will be four times higher and the current will be the same.

$$V_{serial} = n \cdot V_{batt} = 4 \cdot 4.2[\mathrm{V}] = 16.8\ [\mathrm{V}] \tag{3.36}$$

Reliability of this system is lower because if the protection circuit is disconnecting one battery, the whole string might be lost.

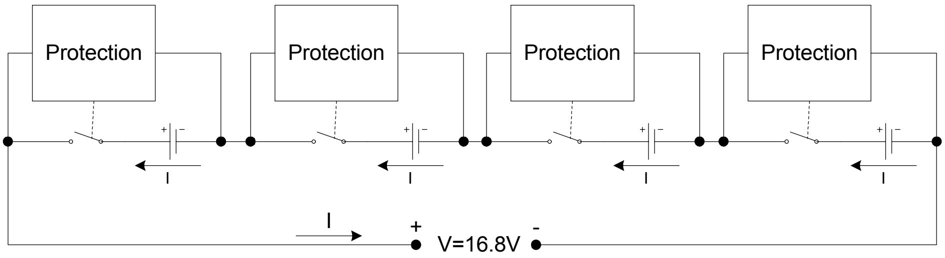


Figure 3.19 Serial connection of batteries

Last possibility is to use combination serial and parallel. Current and voltage levels will be:

$$\begin{gathered} C_{parallel} = n \cdot C_{batt} = 2 \cdot 0.92\ [\mathrm{Ah}] = 1.84\ [\mathrm{Ah}] \\ V_{serial} = n \cdot V_{batt} = 2 \cdot 4.2[\mathrm{V}] = 8.4\ [\mathrm{V}] \end{gathered} \tag{3.37}$$

Realization can be seen on a picture below:

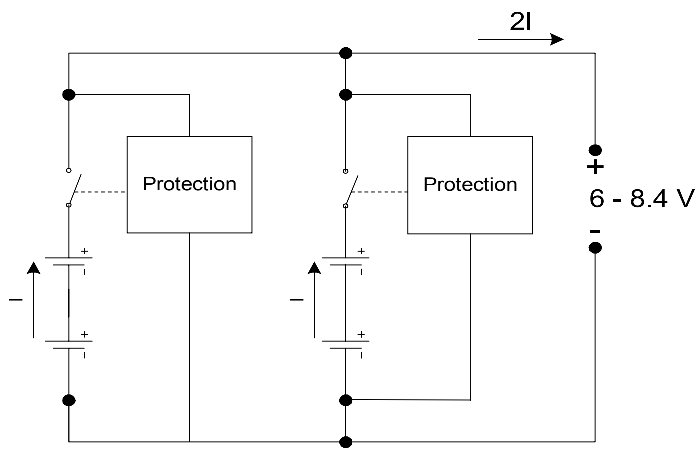


Figure 3.20 Serial and parallel connection of batteries

The last connection was chosen as the most suitable, despite the disadvantages of serial connection. Instead of this, the voltage level is higher and a step down with high efficiency converter may be used.

Position of batteries

Because of the temperature dependence, position of batteries is very important. All the batteries should have the same temperature for having the same operation parameters. Otherwise, can appear disequilibria between batteries and this situation is unwanted. It has been taken in consideration a thermal shield for them, in idea of a thermal stabilization and connection between batteries. Batteries are the largest component of the system and can be arranged in one pack of four or in two packs of two, function of available space in the cube and the thermal conditions.

For a better control of the satellite attitude, the center of mass must be placed as possible as in the middle of the satellite. Because of the large volume of the batteries and the thermal considerations, these should be placed as much inside the satellite as possible.

3.4. Power conditioning module analysis

3.4.1. Maximum power point tracker

Maximum power point tracker is an electronic device, which optimizes the point of operation of the solar cells in order to achieve maximum power delivered from the solar cells.

The output of a PV module is characterized by a performance curve of voltage versus current, (figure 3.21). The maximum power point of a PV module is the point along the I-V curve that corresponds to the maximum output power possible for the module. Maximum power point tracking enables PV arrays, to operate at its maximum power point.

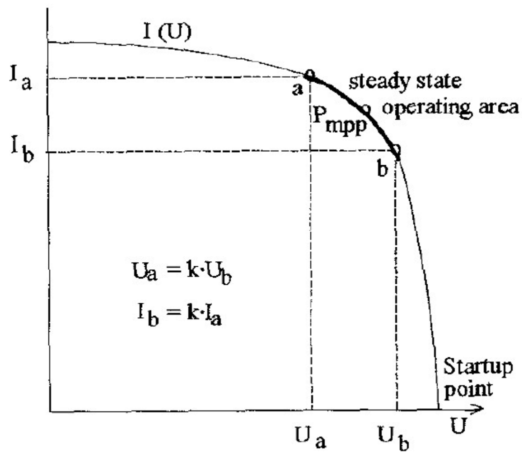


Figure 3.21 I-V isolation solar panel characteristic

There are several factors that will influence the amount of power gain one can expect; these factors are cell temperature, conversion losses, amount of available sunlight, cell structure and blocking diodes.

Some power is lost in the conversion from the voltage at the maximum power point to battery voltage. The efficiency of most maximum power point tracking units is usually around 93%. For crystalline modules, voltage will drop about 2.4mV/°C per cell. This yields a voltage drop of 1.73V, and shifts the I-V thus lowering the maximum power point closer to the battery voltage. As sunlight diminishes from the standard test condition of 1000W/m^2, the voltage corresponding to the maximum power point drops slightly, but the main component in the decrease of available power is the decrease in available current. In the case of amorphous silicon modules, the I-V curve will change current more dramatically as the voltage changes throughout the battery voltage and maximum power point ranges. This will translate into less gain seen by using the maximum power point tracker. Battery voltage will also play a major role in the amount of increased watt-hours one can expect from a module or array using a maximum power point tracker.

In practice are a lot of possibilities to implement a MPPT. An analog implementation of the MPPT (Maximum Power Point Tracker), which is to be used is stated in figure 3.22 [*Snyman, p.1243, 1993*].

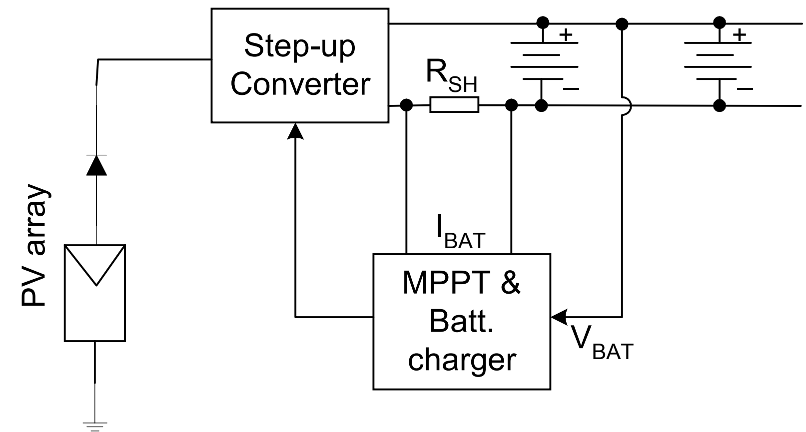


Figure 3.22 Analog implementation for MPPT

It is a feed-forward control, which combines a programmable current limit with a battery voltage limit to provide a constant current for charging the batteries. Only the output current is used as a feed-forward control parameter. The voltage regulation loop is converted into an overvoltage protection loop. This overvoltage protection loop becomes active only when the output voltage rises above a predetermined limit. Positive feedback of a signal proportional to the output current of the converter is therefore used as the input control signal to the current regulator (integrated in MPPT & Batt. charger, in figure), to perform maximum power point tracking. When the overvoltage loop is active, no maximum power point tracking can be performed.

The fundamentals of the maximum power point tracker are:

- When the time constant of changes in the output voltage of the converter is small compared to the switching period of the switching element, it is only necessary to maximize the output current of the converter in order to track the maximum power point of the PV array.
- Maximization of the output current by means of feeding the output current back in a positive way, is obtained since the I-V characteristics of the PV array are responsible for negative feedback when the output current tends to exceed the optimum current for the maximum power delivered by the PV array.
- Voltage feedback from the load is only necessary to protect the load against overvoltage

3.4.2. Converters used in power supply

For this given application is needed to be made only DC to DC conversion of energy. For this reason the types of converters to be used are: step-down (buck), step-up (boost) and step-down/step-up (buck-boost). For all the converters presented below is presumed that are working in continuous-conduction mode [*Mohan, p. 164, 1995*].

Step-down (buck) converter

As the name implies, a step down converter produces a lower average output voltage than the input voltage V_d. In the figure 3.23 can be seen a principle scheme for a buck converter.

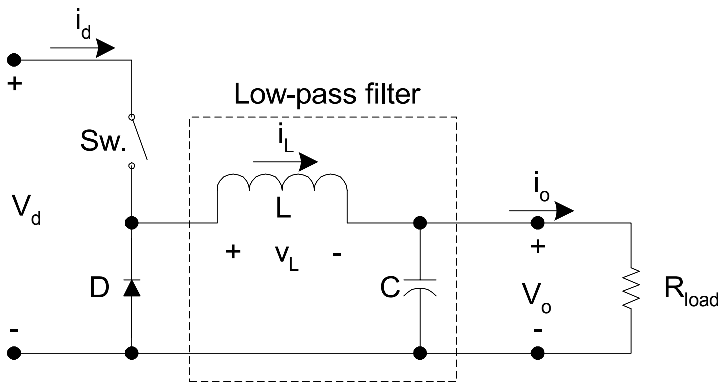


Figure 3.23 Step-down DC-DC converter

By varying the duty ratio t_{on}/T_s of the switch, V_0 the output voltage can be controlled (where t_{on} is conduction period for the switch and T_s is switching period). The voltage on the diode is fluctuating between 0 and V_d, but this is not acceptable in most of the applications. For this reason a low-pass filter is necessary.

During the interval when the switch is on (figure 3.24a), the diode becomes reverse polarized and the input energy is going to the load and in the same time is stored in the inductor. When the switch is turned off (figure 3.24b), the energy stored in the inductor will flow to the load through the diode.

The following equations imply that the areas A and B from the figure 3.24 must be equal. Therefore,

$$(V_d - V_o)\cdot t_{on} = V_o \cdot (T_s - t_{on}) \tag{3.38}$$

or,

$$\frac{V_o}{V_d} = \frac{t_{on}}{T_s} = D \tag{3.39}$$

This means that the output voltage varies linearly with the duty ratio for the switch for a given output voltage.

Neglecting the power loses caused by the circuit elements, the input power P_d equals with the output power P_o.

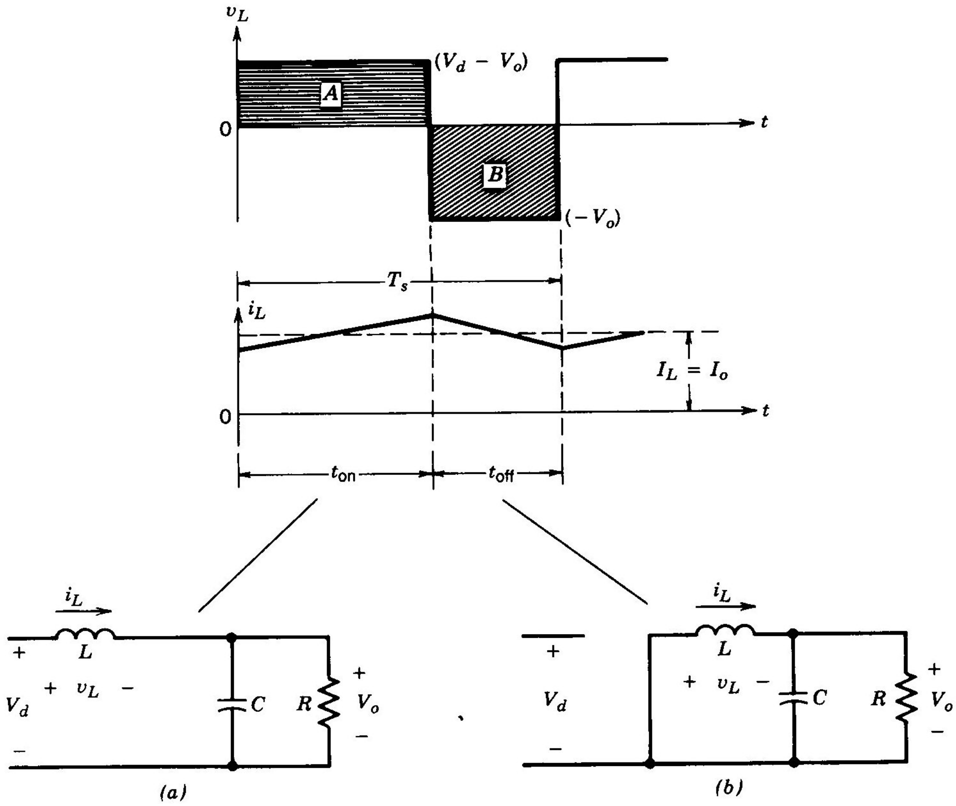


Figure 3.24 Step-down converter equivalent circuits when switch is turned on (a) or off (b).

It yields,

$$V_d \cdot I_d = V_o \cdot I_o \tag{3.40}$$

and

$$\frac{I_o}{I_d} = \frac{V_d}{V_o} = \frac{1}{D} \tag{3.41}$$

Therefore, in the continuous-conduction mode, the step-down converter is equivalent to a dc transformer where the turn's ratio of this equivalent transformer can be continuously controlled in a range from 0 to 1 controlling the duty ratio of the switch.

Step-up (boost) converter

As the name implies, the step-up converter produces a voltage higher than the input voltage V_d. In the figure 3.25 can be seen a principle scheme for a boost converter.

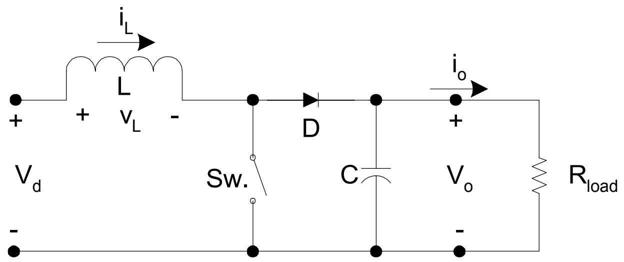


Figure 3.25 Step-down DC-DC converter

When the switch is on, the diode is reverse polarized isolating the output stage and the energy is stored in the inductor. When the switch is turned off, the load is receiving energy from the inductor as well as from the input.

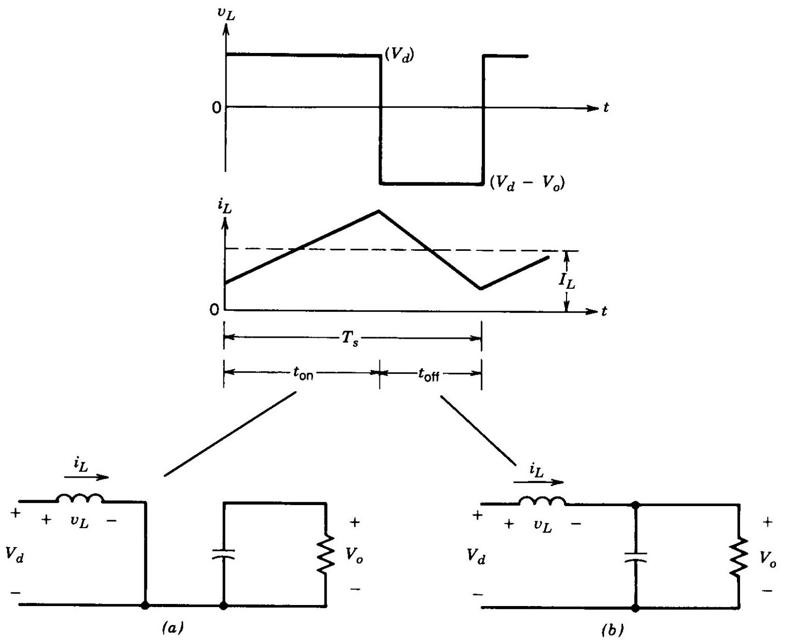


Figure 3.26 Step-up converter equivalent circuits when switch is turned on (a) or off (b).

Since in steady state the time integral of the inductor voltage over one time period must be zero,

$$V_d \cdot t_{on} + (V_d - V_o) \cdot t_{off} = 0 \tag{3.42}$$

Dividing both sides of equation (3.42) by T_s, and rearranging terms yields:

$$\frac{V_o}{V_d} = \frac{T_s}{t_{off}} = \frac{1}{1-D} \tag{3.43}$$

Assuming a lossless circuit, the input power P_d must be equal to the output power P_o:

$$V_d \cdot I_d = V_o \cdot I_o \tag{3.44}$$

Using formula (3.43), equation (3.44) yields:

$$\frac{I_o}{I_d} = \frac{V_d}{V_o} = 1 - D \tag{3.45}$$

3.4.3. Power supply interfaces

Power Bus

This bus should be used for transferring the electrical energy from the power subsystem to the users. Because PSU must also provide protection for each load, there are two possibilities in designing them:

- Protections can be mounted to each user's board and then there will be only two wires for supplying power to the users, but PSU must drive these protections with some logical/analog signals and it means high data traffic between the PSU and the users.
- All protections are put together to the PSU board. The advantage of this solution is that each user has its own power bus wire and it is more reliable to concentrate all the protections in one place, because connectivity problems between the protection circuits and MCU will disappear.

As a conclusion, it is more reliable to put all this protection circuits to one place where PSU system assure on/off on demand from OBC and/or also assure to turn off load in case of short circuit or overcurrent. It implies needs for independent wire for each user in the satellite. If short circuit occur there will be a higher voltage drop on the bus and that is why it is a better solution not to use common ground wire, but independent ground to each user. But because every user connected to I^2C bus must use the same ground wire, in that case, even though it is a worse solution it has to be used common ground.

Finally, the power bus will consists of four wires with 5V voltage and a common ground for all users.

Data Bus

I^2C bus used for data communication in the satellite is bi-directional 2-wire bus. Data flowing through this bus can be divided to two main categories.

From the first category, there is data to/from protection circuit, consisting in four flags describing safety status of each user (it means that user can be only turned on or off):

- status of the OBC
- status of the ACS
- status of the camera circuits
- status of the communication circuit

If the OBC send a flag to the PSU, PSU must react as fast as possible and turn on/off appropriate user. Other situation is if the protection circuit turns off the user, because of failure, a flag should be set and send to the OBC and it will decide what's going next. If the OBC is the user who has been turned off, this flag should be send to the OBC after a timer turn on power again only to tell the OBC that something went wrong.

Second category of data are housekeeping signals, this data might be used in other parts of the satellite like ACS, but their main task is to provide information to the OBC and help it to realize what is going on in the PSU. Also from the OBC this housekeeping data might be send to the ground station. From these conditions result high need for proper selected sensors, because after something wrong happen, the only way how to debug the system from the ground is from housekeeping data. The best solution is to measure all currents and voltages around the PSU, last but not least are thermal sensors, which must stick on the most dissipating parts of the satellite.

Each user can put at least one sensor to its system. All these signals will be presented as 12-bits numbers, except temperatures, which will be 8-bit in binary-complement format.

- currents from each solar panel (5 sensors)
- voltage on the solar panels (1 sensor)
- current flows from the MPPT (1 sensor)
- voltage on the batteries (1 sensor)
- voltage on 5V regulated bus (1 sensor)
- current flowing to each user (4 sensors)
- thermal sensors on most dissipative points in the satellite inc. PSU (7 sensors)

A summary of all the signals and sensors is depicted in figure 3.27.

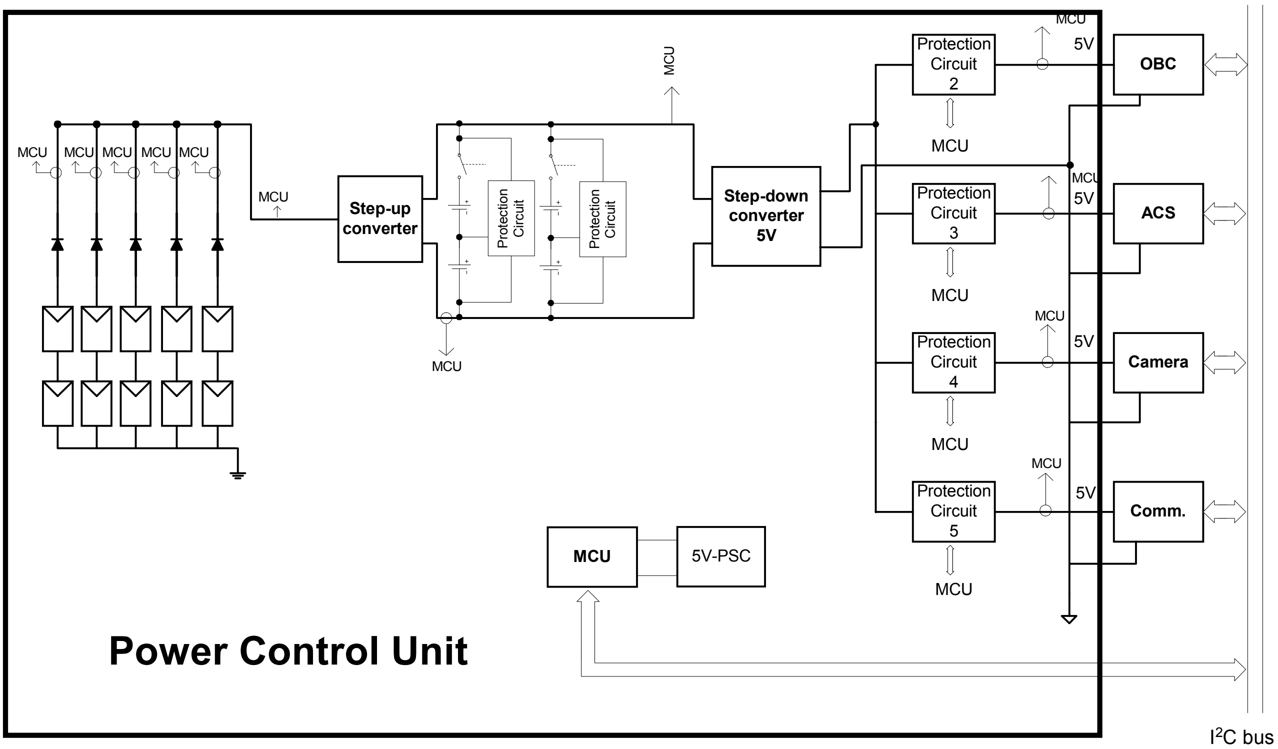


Figure 3.27 Power supply unit interfaces and sensors

3.5. Summary

This chapter presents the implementation solution of the power supply.

A few possible layouts are shown and the most reliable one is chosen. The final scheme of the power supply is presented in figure 3.4 and the way that different parts are interconnected and are working is explained. It is necessary a more accurate analysis for some of modules. This is to be used, further, in analysis of MPPT and power sources.

In section 3.3, the input power from the solar arrays is computed.

- Average input power, per one side: $P_{av} = 2.07$ [W]
- Albedo radiation power, for one side: $P^*_{ALB} = 0.554$ [W]
- Infrared radiation power, for one side: $P^*_{IR} = 0.324$ [W]

It is shown that the most favorable situation, in respect with the power, which can be delivered to users, is when three sides of the satellite are illuminated by Sun. Also, from characteristic of the solar cells, it is deducted that a certain amount of power can be delivered considering the infrared and albedo energy radiated by Earth. This quantity is calculated and it has been proposed as a mission statement to verify it through housekeeping data that will be send back to Earth. The power sources, photovoltaic module and rechargeable batteries, respectively, are inspected. A theoretical background about photovoltaic and batteries is presented, as well as an overview of different possibilities of implementation, existent on the market. Concerning the application and the specifications for the system, batteries are chosen to be Li-Ion type. Converters used in power supply are analyzed in section 3.4.2. It is not an exhaustive analysis, when appropriate components will be selected, a more accurate analysis will be perform.

The interfaces of the power supply (power interface and communication bus with OBC) are analyzed in section 3.4.3.