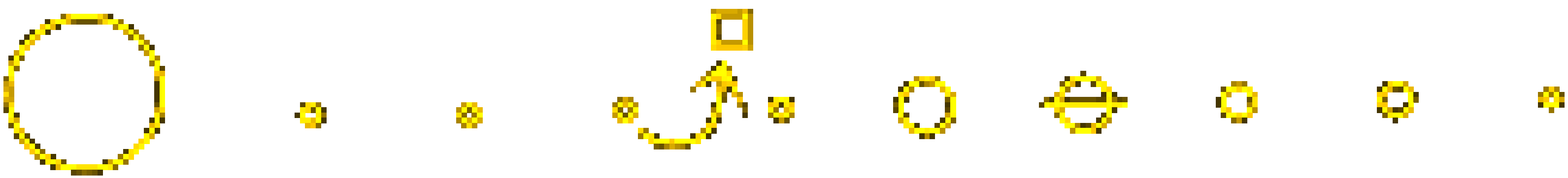
Cubesat Power Systems



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Agenda

- Introduction (11 slides)
- Power Budget (12 slides)
- Design of Cubesat Power Systems
  - Photovoltaic cells (17 slides)
  - Maximum Power Point Tracker (7 slides)
  - Batteries (3 slides)
  - Power conditioner and load-protection (4 slides)
  - Kill-switch (2 slides)
  - Structure (5 slides)
- What to look out for
  - Thermal design (3 slides)
  - Selection of components (2 slides)
  - Redundancy (1 slide)
- Appendix (2 slides)
- Exercises (2 slides)

Introduction

- The aim of the Cubesat Power System is to provide conditioned power for the Cubesat. This involves:
  - Continuous power generation for supplying the Cubesat
  - Power storage, for supplying the Cubesat when the main power generation cannot
  - Protection of the Cubesat in case of a fault situation

Introduction

- The Cubesat must somehow be supplied with electrical power. The power generation can be realised as:
  - Nuclear / thermal / electrical conversion
  - Chemical / electrical conversion
  - Light / electrical conversion
- The nuclear approach involves decaying of radio-active matter. The decaying results in heat-generation, which can be turned into electrical power by means of a thermo-generator (Peltier element).

Introduction

- The nuclear power generation is mostly used for deep-space (inter-planetary) missions because of its long-lasting capabilities.
- There exists a high risk of spreading of nuclear matter in case of a failed launch.
- The chemical approach involves batteries, which are charged before launch.
- The power-density for batteries are low, hence the weight of the satellite is increased to obtain enough power for the mission.
- The battery approach is only used for short missions (hours or days)

Introduction

- The third possible power source comes from the light irradiated by the sun.
- The light-power is converted into electrical power by means of photovoltaic (PV) cells.
- The PV cells is placed outside, around, the satellite.
- The power generated by the PV cells then becomes a function of the location of the satellite compared to the location of the Earth and the sun.
- The PV cells forms a very reliable power source and makes a light construction (tens of grams).

Introduction

- The generated power (from the nuclear- or PV-generator), must be stored for later use. This can be realised as:
  - Flywheels
  - Batteries
- The flywheel involves a wheel (cylinder or dish) revolving at high speed (thousands of RPM), hence the energy is stored as kinetic-energy.
- However, (de)accelerating the flywheel involves changes in inertia which will influence the satellite attitude!!! Hence two should be used.

Introduction

- The stored energy in the flywheel is given by:

$$E_{kin} = \tfrac{1}{2} \cdot J \cdot \omega^2$$

$$\omega = \frac{RPM \cdot 2\pi}{60}$$

$$J = k \cdot m \cdot r^2$$

$$k = \begin{cases} 1 \;\; for\ a\ rim \\ \tfrac{1}{2} \;\; for\ a\ solid\ dish / cylinder \end{cases}$$

where J is the mass of inertia, m is the mass and r is the radius of the dish / cylinder

Introduction

- The power can also be stored in batteries:

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**

The 'maximum number of cycles' includes totally charge - discharge operation, which do not occur.

Introduction

Power conditioning are necessary in order to provide ‘safe’ power (to protect and control) for the satellite.

- The conditioning circuit is responsible for turning on the satellite after deployment.
- The circuit turn the loads on and off by command from the On Board Computer (OBC).
- The conditioning circuit also turns off a load if its load-current exceeds a given threshold value. This could be in the case where a high-energy particle causes a transistor to transiently turn on.

Introduction

- The power generation should be based on photo-voltaic conversion of sunlight into electrical power. This is because the nuclear approach is to risky and the chemical approach cannot supply the satellite in more than a few days.

- The power storage should be based on Lithium Ion batteries, which has better performance compared to the flywheel, Nickel-Cadmium and Nickel-Metal-Hybrid batteries.

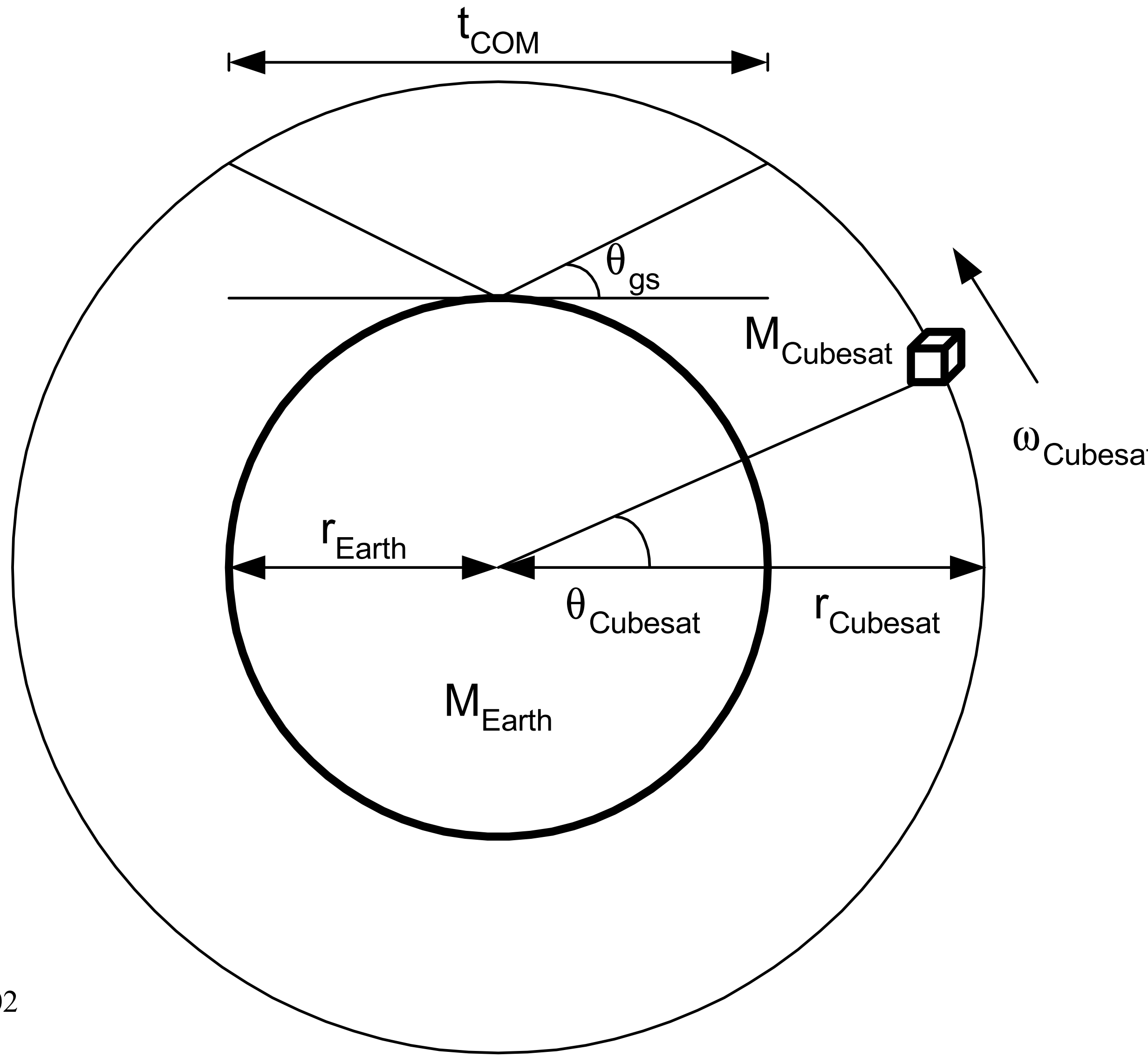
- A detailed control and safety circuit must be included in the satellite.

Power budget

Before moving on, we need to estimate the amount of incoming, outgoing and hence stored energy.

- The incoming power is a function of attitude.
- The outgoing power is a function of load demands.
- The stored power is equal to incoming minus outgoing.

Power Budget



Power Budget

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The Cubesat angle is given as:

$$\theta_{Cubesat} = \frac{v_{Cubesat} \cdot t}{r_{Cubesat}}$$

The velocity may be found by:

$$v_{Cubesat} = \sqrt{\frac{G \cdot M_{Earth} \cdot m_{Cubesat}}{r_{Cubesat}}}$$

where G is universal gravitational constant (66.7 10^{-12} Nm^2 kg^2). The angular velocity is then:

$$\omega_{Cubesat} = \sqrt{\frac{G \cdot M_{Earth} \cdot m_{Cubesat}}{r_{Cubesat}^3}}$$

Hence, one orbit takes:

$$t_{orbit} = \frac{2 \cdot \pi}{\omega_{Cubesat}}$$

Power Budget

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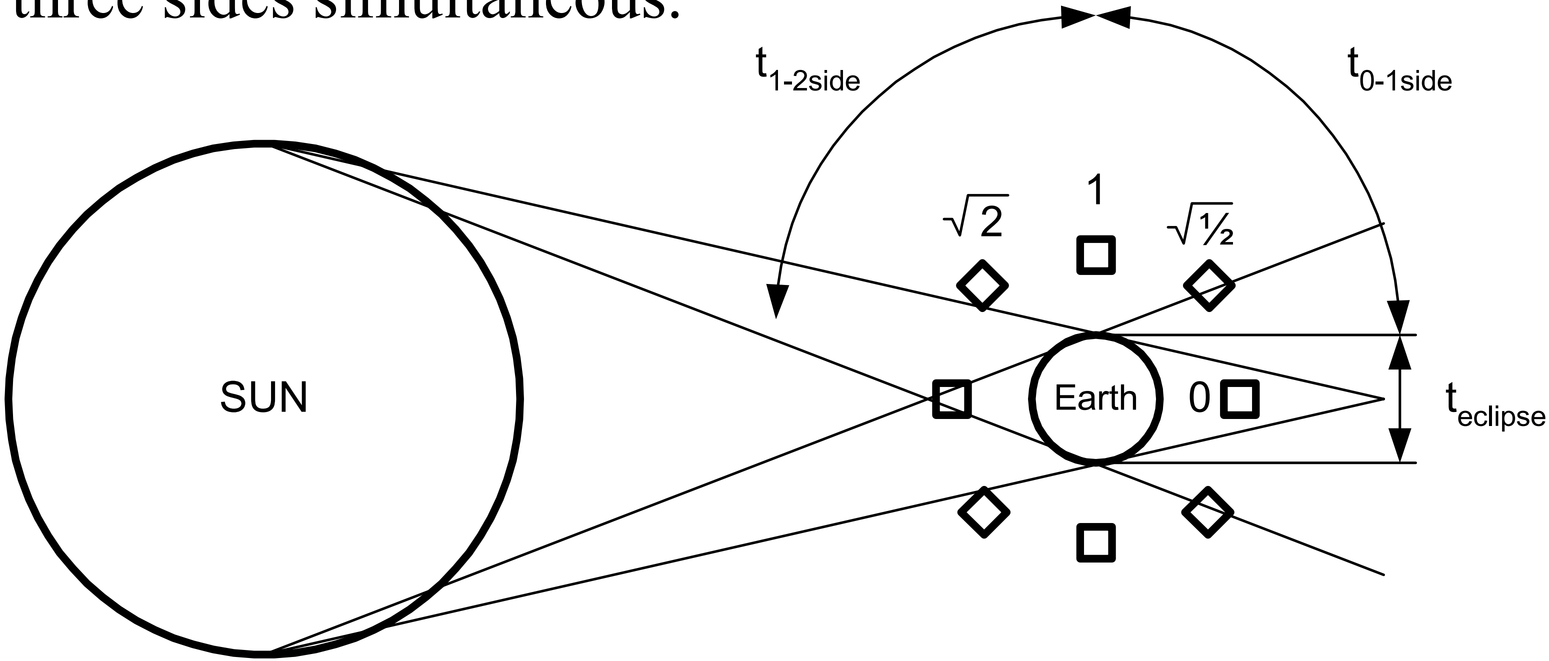
The Cubesat is illuminated on either zero, one, two or three sides simultaneous.



In the figure is goes like: 0, 1, 1, 2, 1, 2, 1, 1, 0 because the side with the antenna is pointing toward the Earth

Power Budget

$$t_{eclipse} = \frac{2 \cdot \operatorname{asin}\left(\frac{r_{Earth}}{r_{Cubesat}}\right)}{\omega_{Cubesat}}$$

$$t_{0-1side} = \frac{t_{orbit}}{2} - \frac{2 \cdot \operatorname{asin}\left(\frac{r_{Earth}}{r_{Cubesat}}\right)}{\omega_{Cubesat}}$$

$$t_{1-2side} = \frac{t_{orbit}}{2}$$

$$S_{eclipse} = 0$$

$$S_{0-1side} = \left|\sin\left(\omega_{Cubesat} \cdot t\right)\right|$$

$$S_{1-2side} = \left|\sin\left(\omega_{Cubesat} \cdot t\right)\right| + \left|\cos\left(\omega_{Cubesat} \cdot t\right)\right|$$

Power Budget

The load power is distributed amongst

- On Board Computer (OBC)
- Attitude Control System (ACS)
- Communication System (COM)
- Payload (CAM)

The OBC is running during the entire orbit. The Payload runs only a few seconds during each orbit. The on-time for the ACS depends on the payload and power system. The COM is running when the Cubesat is visible from the ground-station.

$$t_{COM} = \frac{\pi - 2\cdot\theta_{GS} - 2\cdot a\sin\left(\frac{r_{Earth}}{r_{Cubesat}}\cdot\cos(\theta_{GS})\right)}{\omega_{Cubesat}}$$

Power Budget

The Cubesat is situated in a Low Earth Orbit (LEO) approximately 700 km above the Earth' surface.

The radius of the Earth equals 6366 km and the mass equals 5.972 10^{24} kg.

The dimension of the Cubesat is 0.1 m * 0.1 m * 0.1 m with a mass of maximum 1 kg.

The PV cells on one side equal 0.0057 m^2 with an efficiency of 26%.

The incoming irradiation amounts to 1353 W/m^2

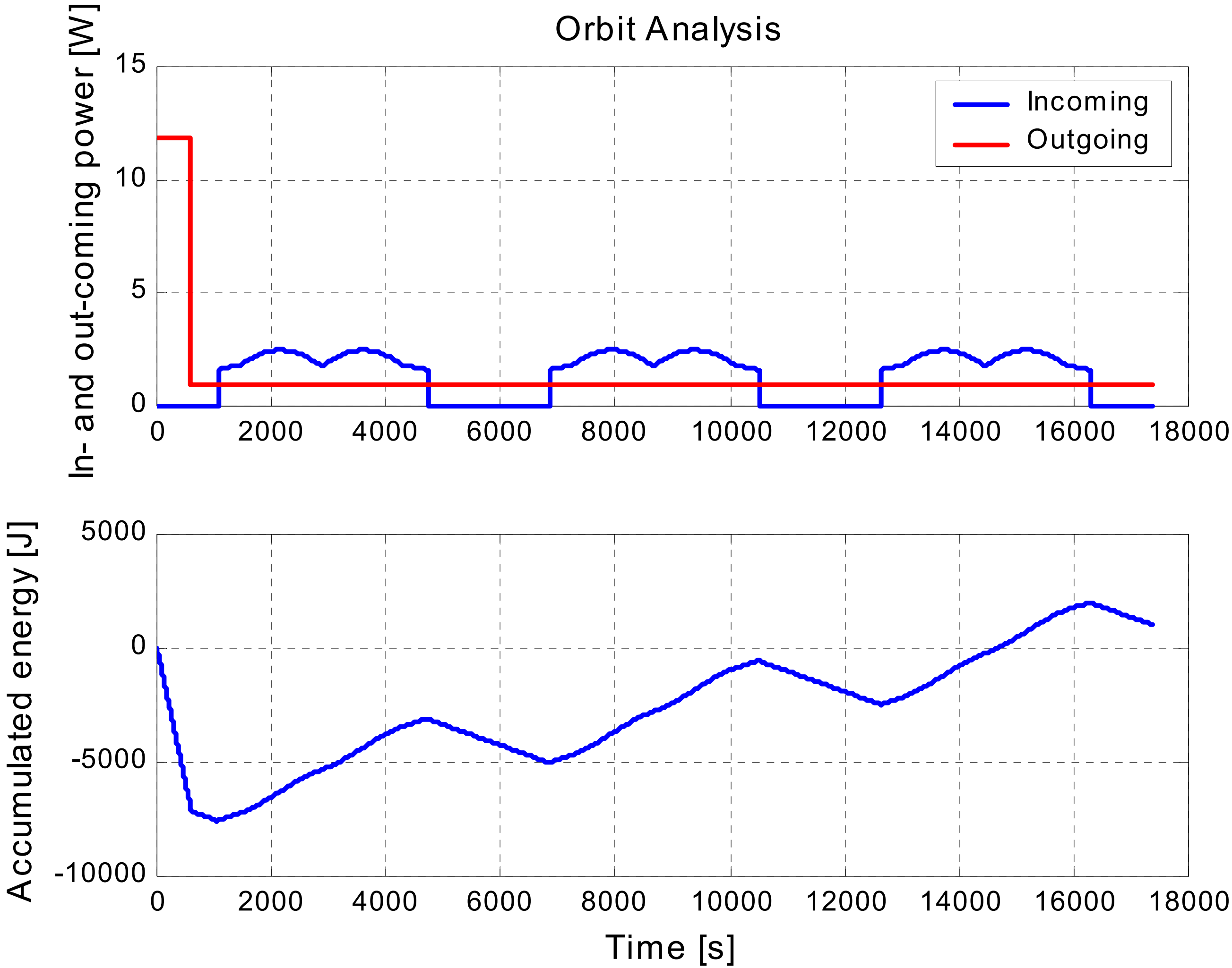
Power Budget

The satellite consists of six sides. Five sides with PV cells and one with antenna etc. The available power then equals

$$P = A \cdot S \cdot \eta \cdot k(t)$$

Where A is the area of the PV cells for one side, S is the irradiation, k(t) is determined by the number of sides illuminated and η is the PV cells efficiency.

Power Budget



Power Budget

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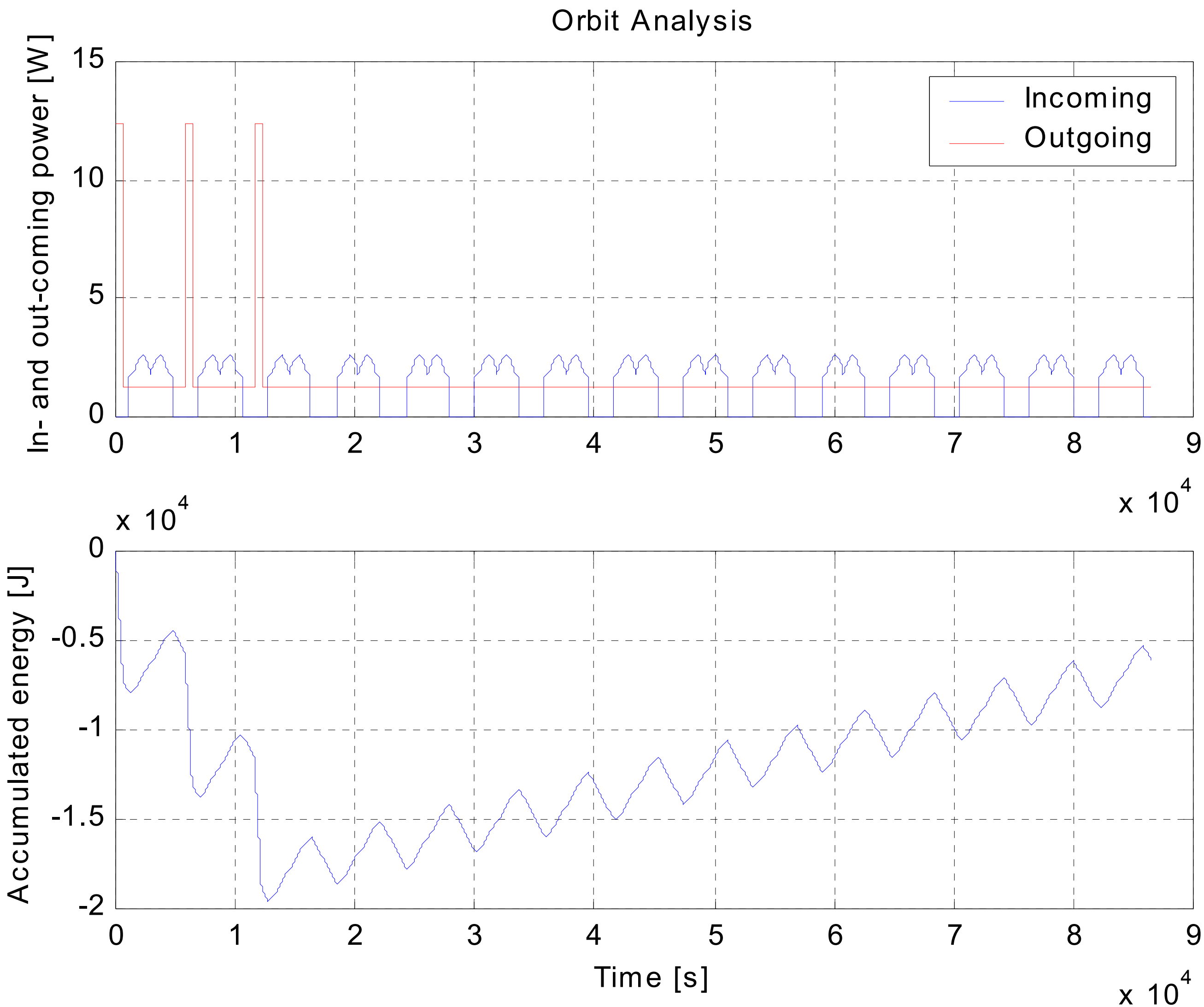
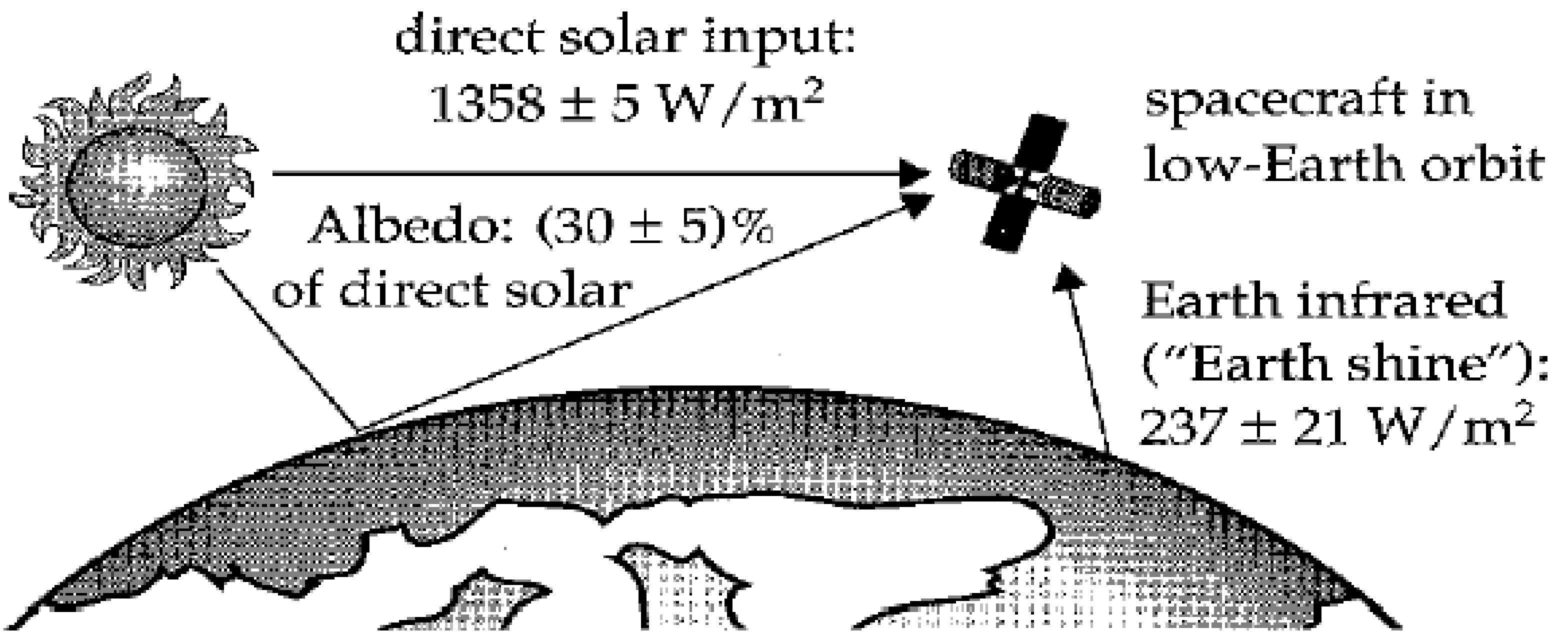


Power Budget

- Albedo from the Earth: app. 410 W/m^2
- Infrared from the Earth: app. 240 W/m^2



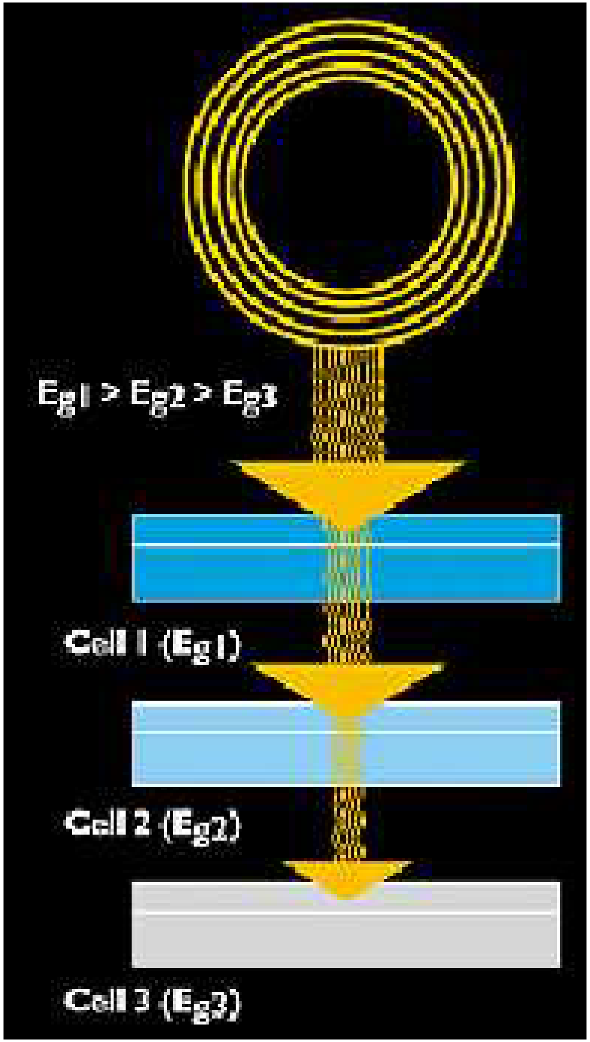
Power Budget

- In the first example we investigated the Cubesat orbit in a situation where the 'antenna-side' was pointing toward the Earth all the time. The average input power during one orbit amounts to 7760 J / 5780 s = 1.34 W.

- Because the orbit of the Cubesat is near sun-synchronous a power-input close to the worst (shown above) case can be experienced for extended periods of time each year depending on how much the satellite orbit deviates from that of an sun-synchronous orbit.

- The best case is when the orbit is such that the satellite is always illuminated by the sun and its attitude is such that three sides are pointed towards the sun during the complete orbit. The average power then equals: 17 550 J / 5780 s = 3.03 W.

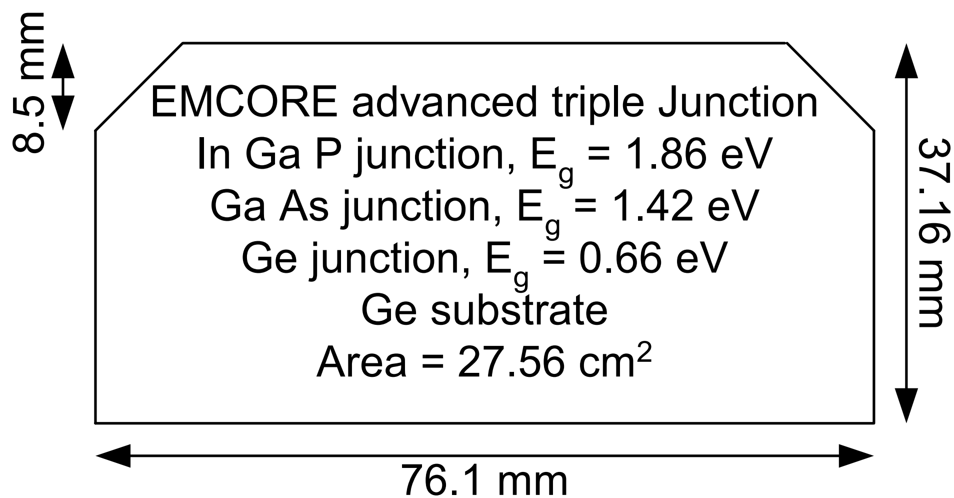
Photovoltaic Cell



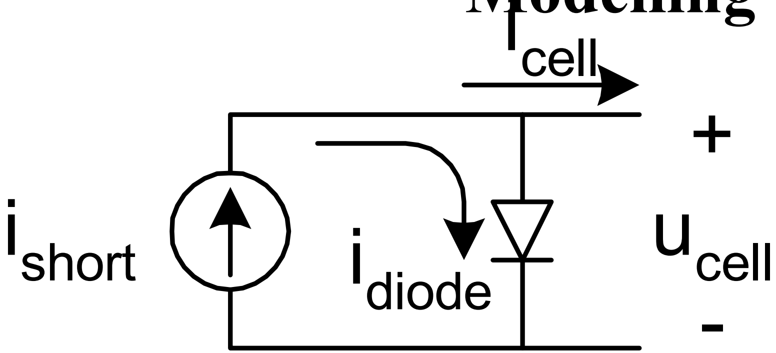
EMCORE advanced triple junction cell

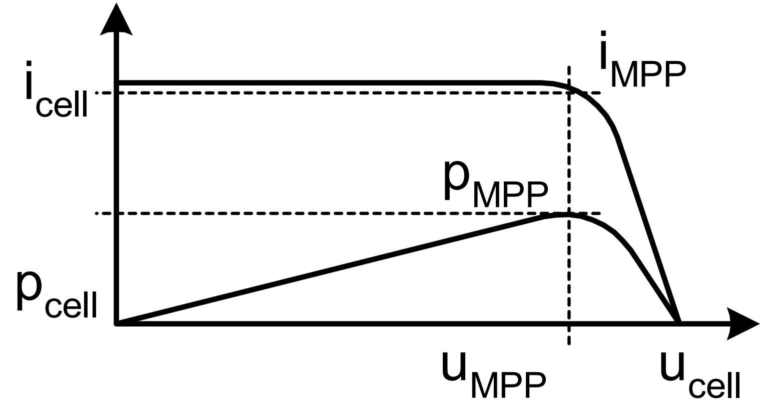
Efficiency = 24.5% to 28.0%

Open circuit voltage:	*2.57 V*
Short circuit current:	*446 mA*
MPP voltage:	*2.28 V*
MPP current:	*427 mA*
MPP power:	*0.97 W*



Modelling the PV Cells





i_{short} : Short circuit current

i_{diode} : Diode current

i_{cell} : Output current from the cell

u_{cell} : Voltage across the cell

i_{MPP} : Maximum power point current

u_{MPP} : Maximum power point voltage

p_{MPP} : Maximum power

Photovoltaic Cell

$$i_{Cell} = i_{short} - i_{diode}$$

$$i_{short} = \left(i_{short,STC} + k_{temp} \cdot \left(T_{Cell} - T_{STC}\right)\right) \cdot \frac{S}{S_{STC}}$$

$I_{short,STC}$: Short circuit current at STC (446.5 mA)
k_{temp} : Temperature coefficient (0.27 mA/K)
T_{Cell} : Actual temperature [K] (-106 °C to 2 °C)
S: Irradiation [W/m^2] (0 – 1353 W/m^2)
STC: 1353 W/ m^2 @ 28 °C

Note: All temperatures must be in Kelvin

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$$i_{diode} = i_{sat} \cdot \left(\exp\left(\frac{q \cdot u_{Cell}}{k \cdot T_{Cell} \cdot A} \right) - 1 \right)$$

$$i_{sat} = i_{sat,STC} \cdot \left(\frac{T_{Cell}}{T_{STC}} \right)^3 \cdot \exp\left(\frac{E_g}{k \cdot A} \cdot \left(\frac{1}{T_{STC}} - \frac{1}{T_{Cell}} \right) \right)$$

$$p_{Cell} = u_{Cell} \cdot i_{Cell} = u_{Cell} \cdot \left(i_{short} - i_{diode} \right)$$

i_{sat} : Reverse saturation current

$i_{sat,STC}$: Reference RSC

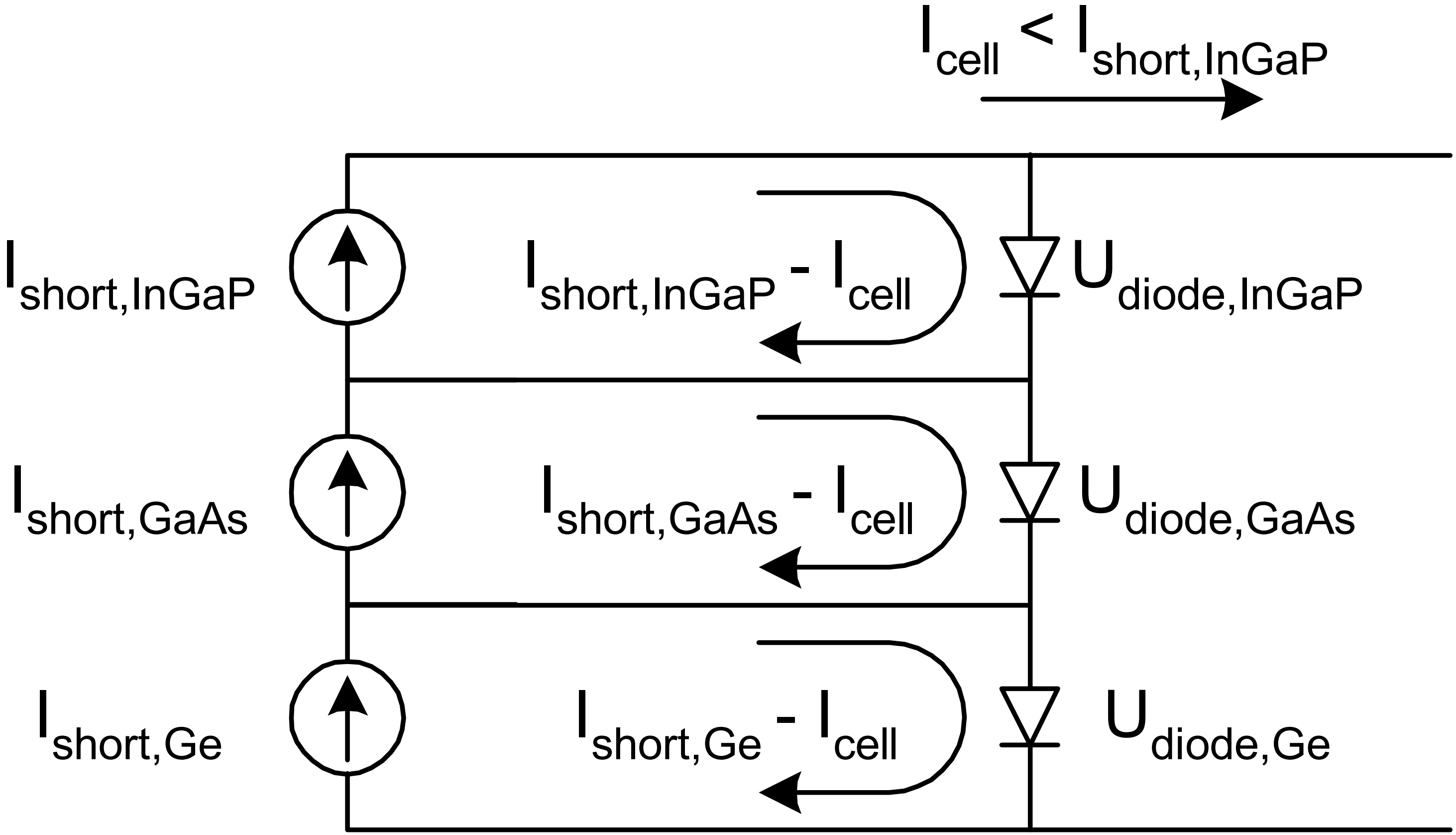
q : Electron charge ($160.2 \cdot 10^{-21}$ C)

k: Boltzmann's constant ($13.81 \cdot 10^{-24}$ J/K)

A: Quality factor

E_g : Band gap energy

Photovoltaic Cell



The cell current is lower than the InGaP sub-cell short circuit current, because this sub-cell has the lowest short circuit current. (Principle of the weakest link)

Photovoltaic Cell

	U_{open}	I_{short}	A	Eg	$I_{sat,STC}$
InGaP	1.377V	0.452A	2.5	1.86	276pA
GaAs	0.955V	0.539A	2.0	1.42	5.54nA
Ge	0.218V	1.043A	1.4	0.66	2.6mA

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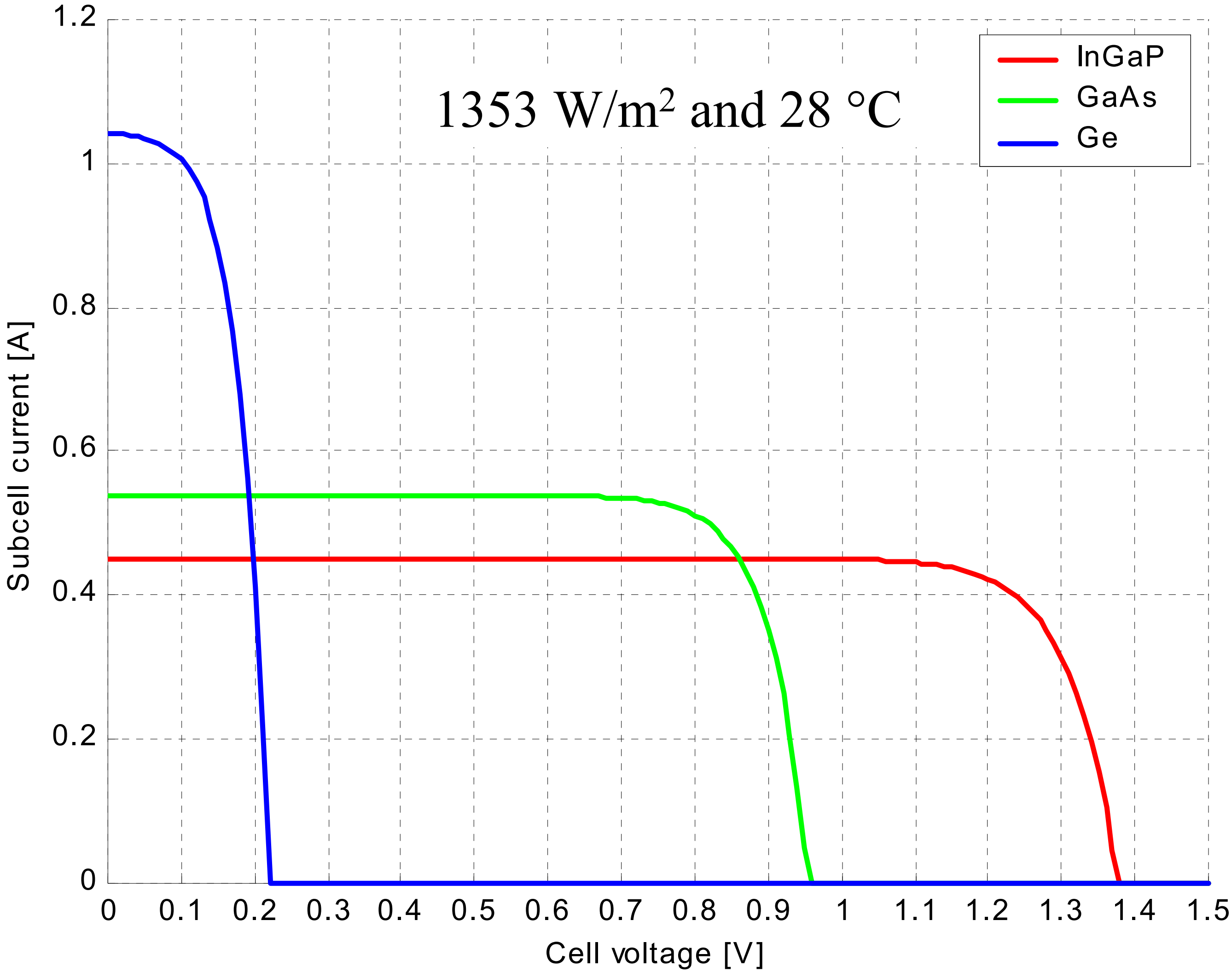
Light curves for InGaP, GaAs and Ge subcells.



Photovoltaic Cell

Thermal range for the PV Cells

The PV Cell temperature must somehow be determined. This is easiest done be using the 'thermal equilibrium' approach where the absorbed power equals the radiated power.

$$P_{in,thermal} = S \cdot \alpha \cdot A_{in} \cdot \left(1 - \eta_{Cell}\right)$$

$$P_{ou,thermal} = \varepsilon \cdot \sigma \cdot A_{out} \cdot \left(T^4 - T_0{}^4\right) \approx \varepsilon \cdot \sigma \cdot A_{out} \cdot T^4$$

$$P_{in,thermal} = P_{out,thermal}$$

α is the absorbitivity of the sides, A_{in} is the area receiving the power, η_{cell} is the PV Cell efficiency, ε is the emmissivity of the sides, σ is Stephan-Boltzmann constant ($56.7 \cdot 10^{-9}$ W/m^{2}K^4) ,A_{out} is the area radiating the power and, T_0 is the cosmic background temperature (2.7 K) and T is the temperature.

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Some common values for α and ε are

	PV cells	**Carbon**	**Aluminium (CAM)**
α	0.75	0.96	0.55
ε	0.83	0.90	0.30
Coverage of sides	57%	43%	100%

Photovoltaic Cell

Thus, the equilibrium temperature is given as

$$T = \sqrt[4]{\frac{A_{in} \cdot S \cdot (1 - \eta_{Cell}) \cdot \overline{\alpha}}{A_{out} \cdot \sigma \cdot \overline{\varepsilon}}}$$

where the ‘ - ‘ means average values. For one, two and three PV sides pointing toward the sun, the temperature equals

$$T_1 = \sqrt[4]{\frac{0.01m^2 \cdot 1353 \,{}^{W}\!/\!{}_{m^2} \cdot (1 - 24.5\%) \cdot (57\% \cdot 0.75 + 43\% \cdot 0.96)}{0.01m^2 \cdot \sigma \cdot \{5 \cdot (57\% \cdot 0.83 + 43\% \cdot 0.90) + 0.30\}}} = 240K$$

$$T_2 = \sqrt[4]{T_1^{\ 4} \cdot \sqrt{2}} = 261K$$

$$T_3 = \sqrt[4]{T_1^{\ 4} \cdot \sqrt{3}} = 275K$$

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And in case of eclipse for one, two and three PV sides pointing toward the Earth (Infrared only):

$$T_1 = \sqrt[4]{\frac{0.01m^2 \cdot 240 \, {}^{W}\!/_{m^2} \cdot (1-0\%) \cdot (57\% \cdot 0.75 + 43\% \cdot 0.96)}{0.01m^2 \cdot \sigma \cdot \{5 \cdot (57\% \cdot 0.83 + 43\% \cdot 0.90) + 0.30\}}} = 167K$$

$$T_2 = \sqrt[4]{T_1^{\,4} \cdot \sqrt{2}} = 182K \qquad T_3 = \sqrt[4]{T_1^{\,4} \cdot \sqrt{3}} = 191K$$

The equilibrium temperature is however an average value for the entire Cubesat, and not only the PV cells!!!

Another approach is to calculate the temperature for one side, assuming a total insulation between the PV cell and the Cubesat-structure.

The actual temperature is then between these two boundaries.

Photovoltaic Cell

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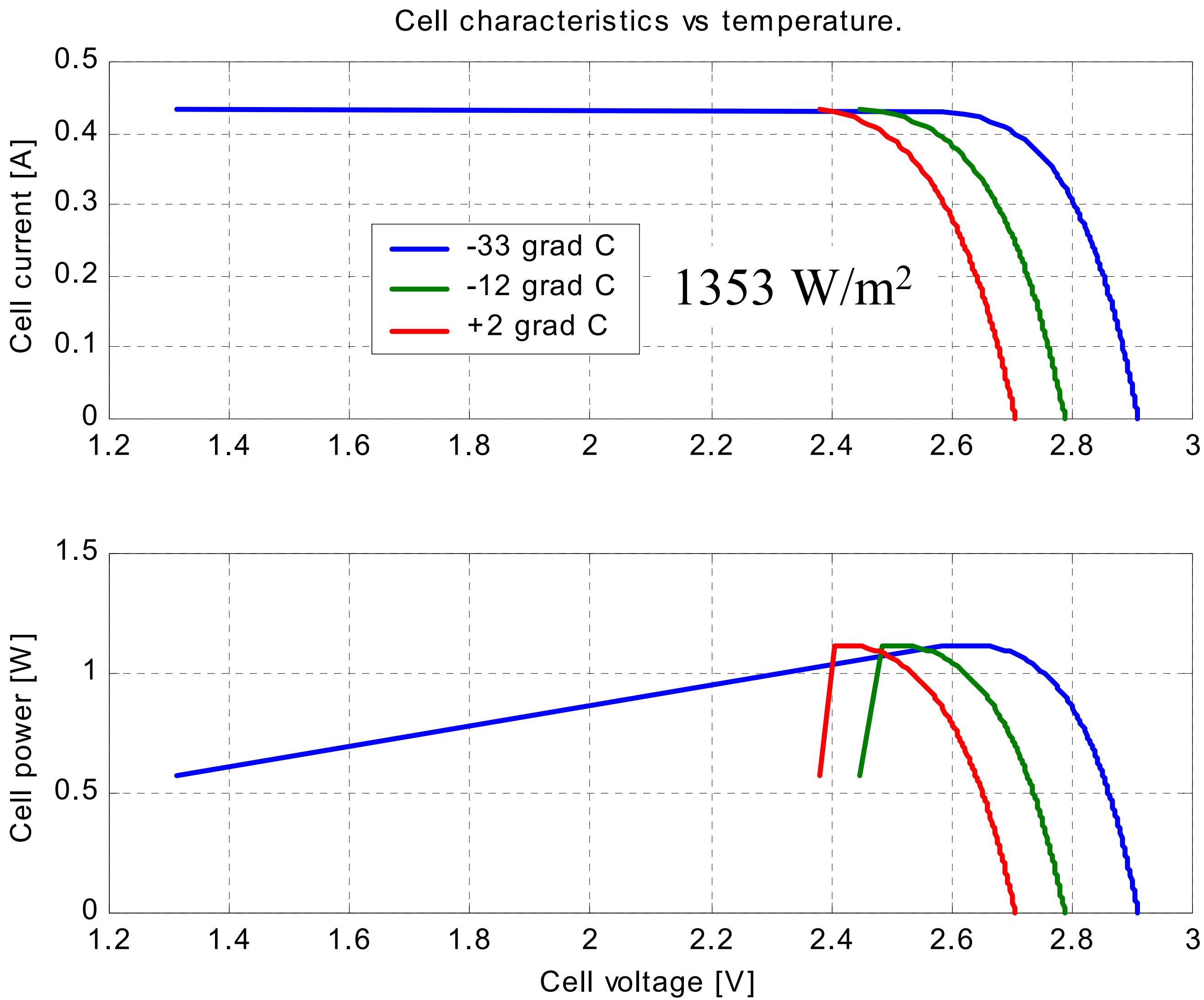

Photovoltaic Cell

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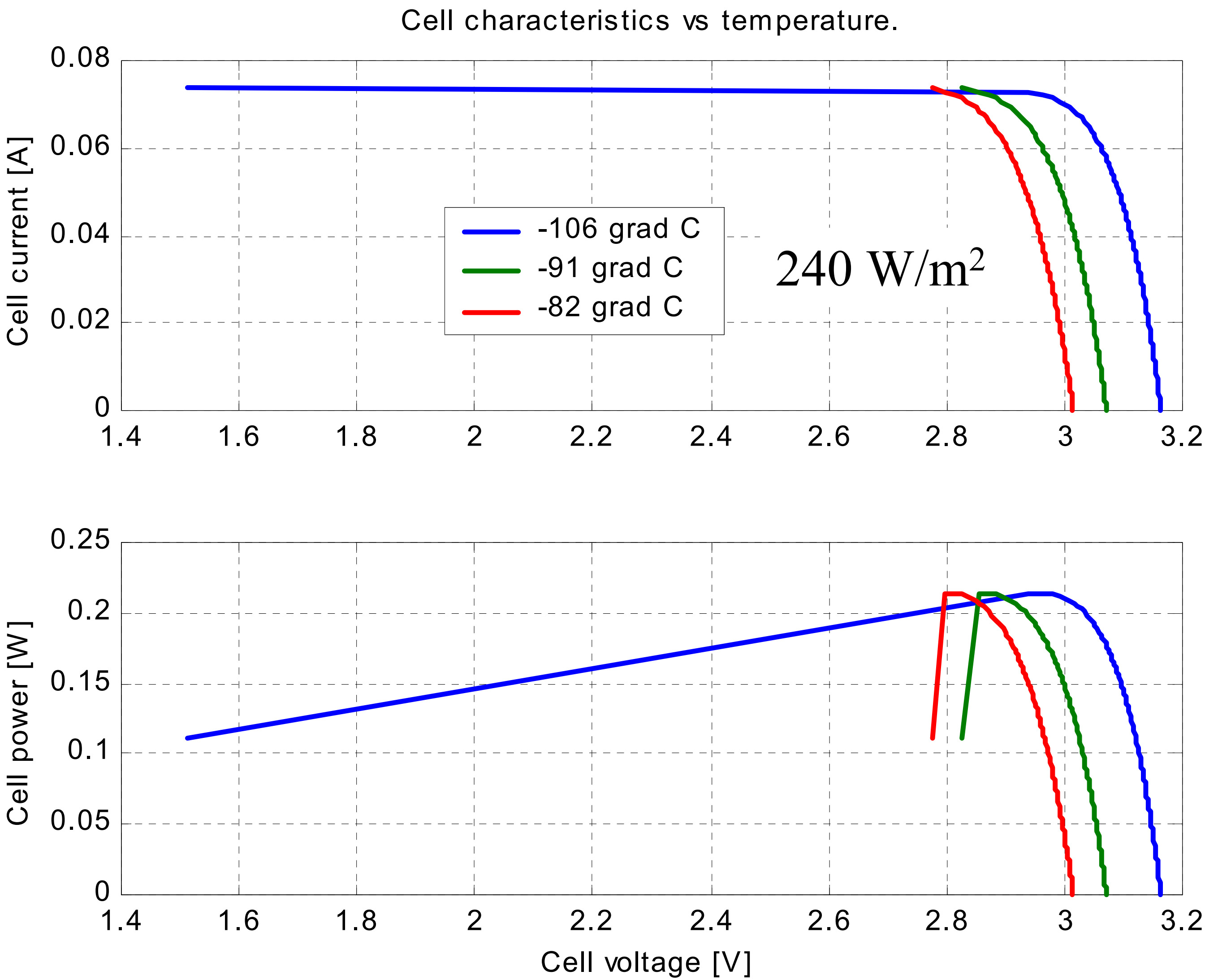
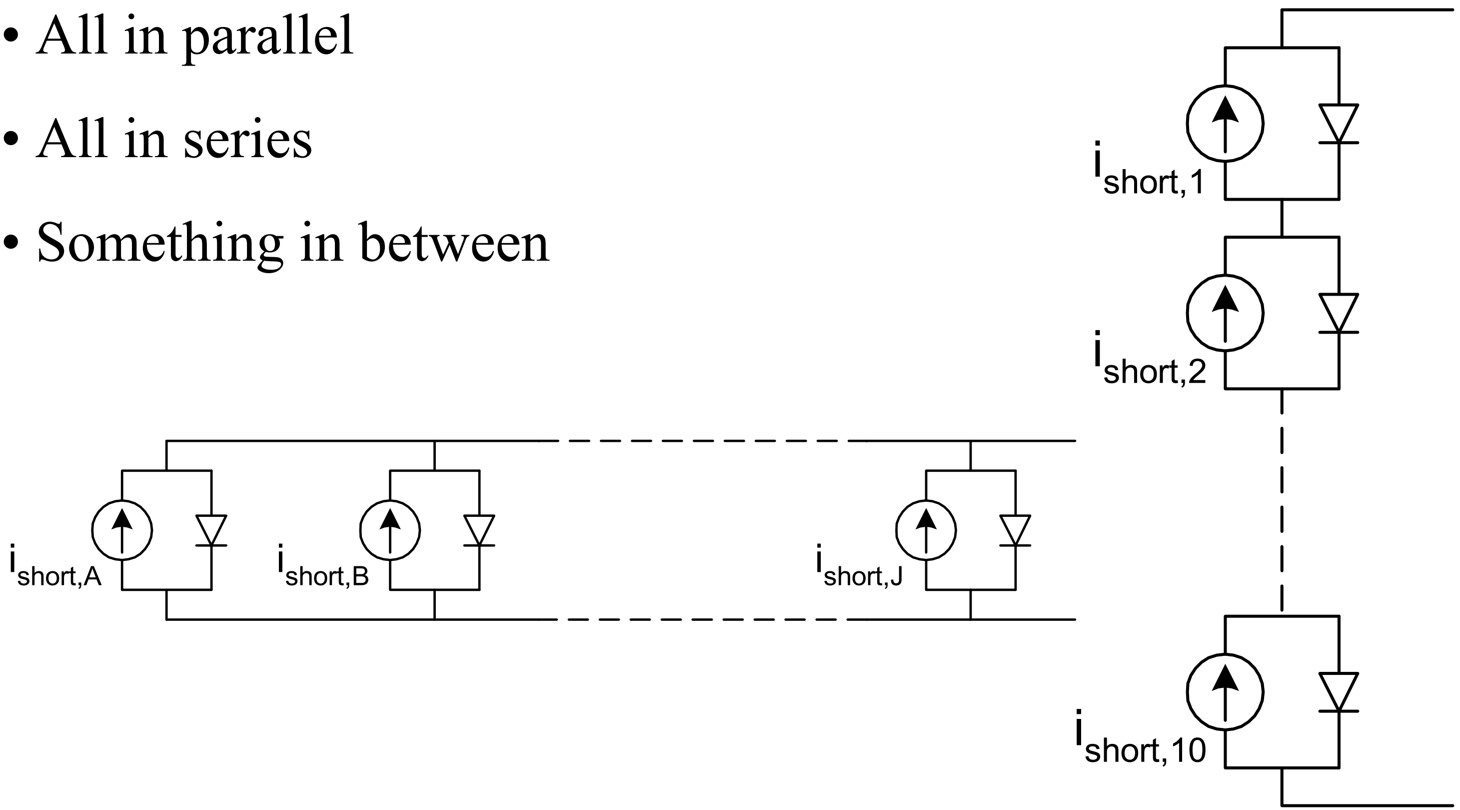


Photovoltaic Cell

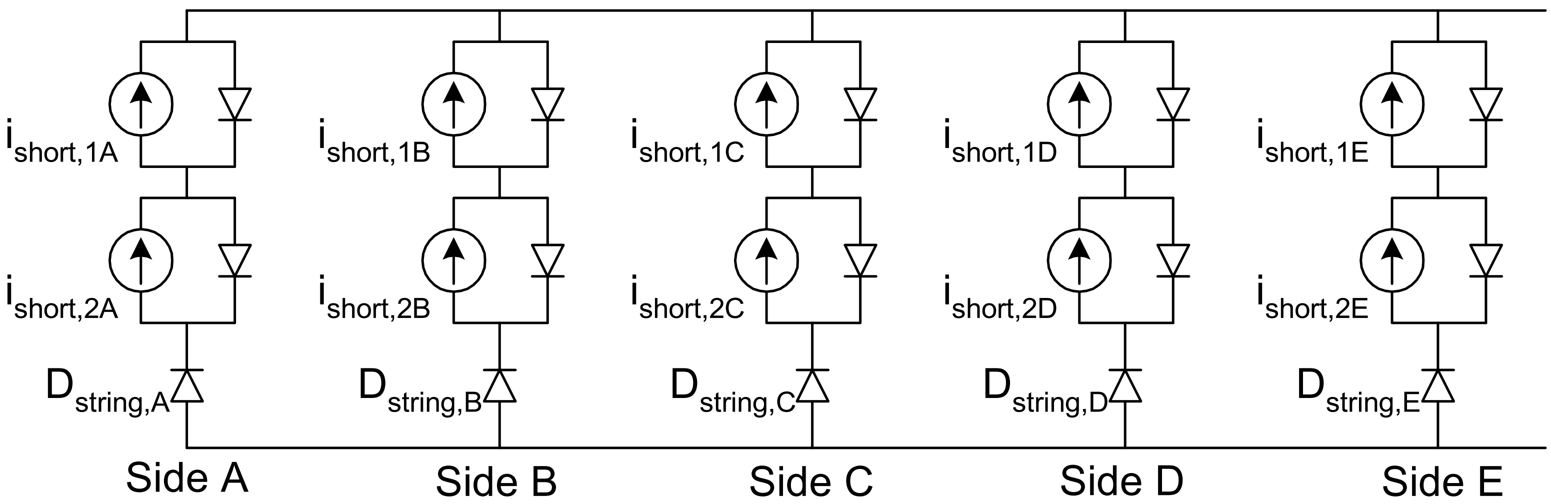
There is place for two cells on each side and five sides in all. Hence, 10 Cells forms the PV generator, but how to connect them?

- All in parallel
- All in series
- Something in between



Photovoltaic Cell

- The parallel connection suffers from a low voltage.
- The series connection suffers from the 'weakest link'.
- Something in between seem to be the optimum!!!



Photovoltaic Cell

The ‘optimum’ connection scheme:

• Two cells on a side is connected in series with a string-diode.

• Five strings are connected in parallel.

• The string-diode is included in order to prevent reverse current through the cells when they are in shadow.

• The string-diode must be selected in order to lower the loss associated with it.

$$P_{string,X} = P_{Cell,1X} + P_{Cell,2X} - P_{stringdiode,X}$$

$$P_{string,X} = \left(U_{MPP,1X} + U_{MPP,2X} - U_{stringdiode,X}\right)\cdot I_{MPP,X}$$

• Schottkey diodes has a forward voltage drop of approximate 0.3 V. Normal diodes has a corresponding drop of 0.7 V to 1.0 V. It is also possible to use a controlled MOSFET.

Photovoltaic Cell

The cells on each side must be matched, so their current capabilities fits together. If not, a lower power generation will be the consequence due to the ’weakest link’.

Cell	Uoc [V]	Isc [mA]	Umpp [V]	Impp [mA]	
1	2,63	435	2,31	421	Nc
2	2,60	456	2,27	429	III
3	2,58	463	2,22	442	V
4	2,58	455	2,25	431	IV
5	2,62	462	2,29	425	I
6	2,61	460	2,30	425	I
7	2,61	462	2,31	423	Nc
8	2,61	467	2,26	434	V
9	2,60	464	2,28	425	II
10	2,59	465	2,26	430	IV
11	2,62	464	2,31	423	Nc
12	2,62	438	2,27	427	Nc
13	2,62	439	2,30	428	II
14	2,62	439	2,28	430	III

MPPT

As seen before, the power generated by the PV cells depends on their point of operation. The design must therefore include a Maximum Power Point Tracker

Before carrying on, information about the PV voltage range and the voltage of the following power-bus must be gained.

•U_{MPP} = 4.5 V to 4.9 V (hot) or 5.3 V to 5.7 V (cold)

•U_{DC} = 3.0 V to 4.2 V (for a battery pack of one battery in 'series')

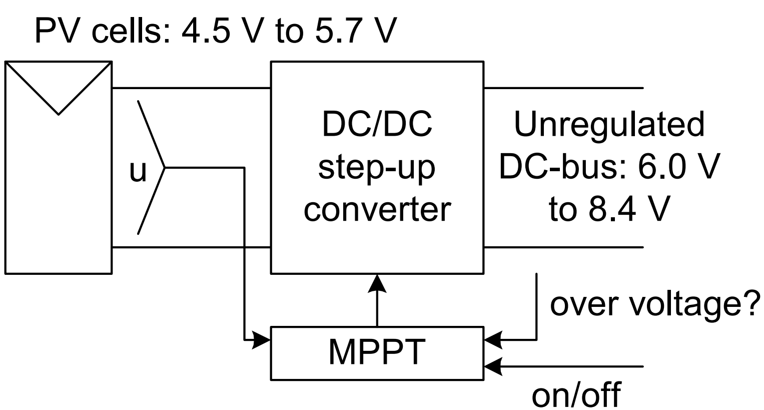
•U_{DC} = 6.0 V to 8.4 V (for a battery pack of two battery in series)

It seems that the approach with two batteries in series is the optimum while it only requires to step-up the PV voltage. In case of only one battery in 'series' a step up/down DC/DC converter is needed.

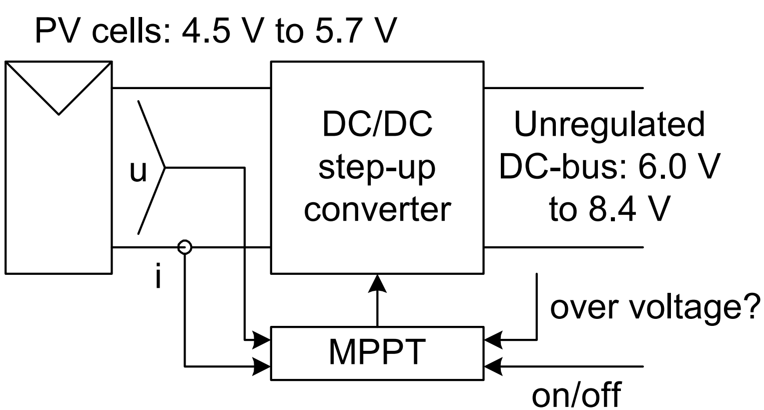
MPPT

The MPPT may be done in one of two ways.

- With a fixed PV voltage reference according to the PV model presented before.
- With a search algorithm, which alters the PV voltage reference, measures the corresponding power and makes a decision about the direction of the MPP.



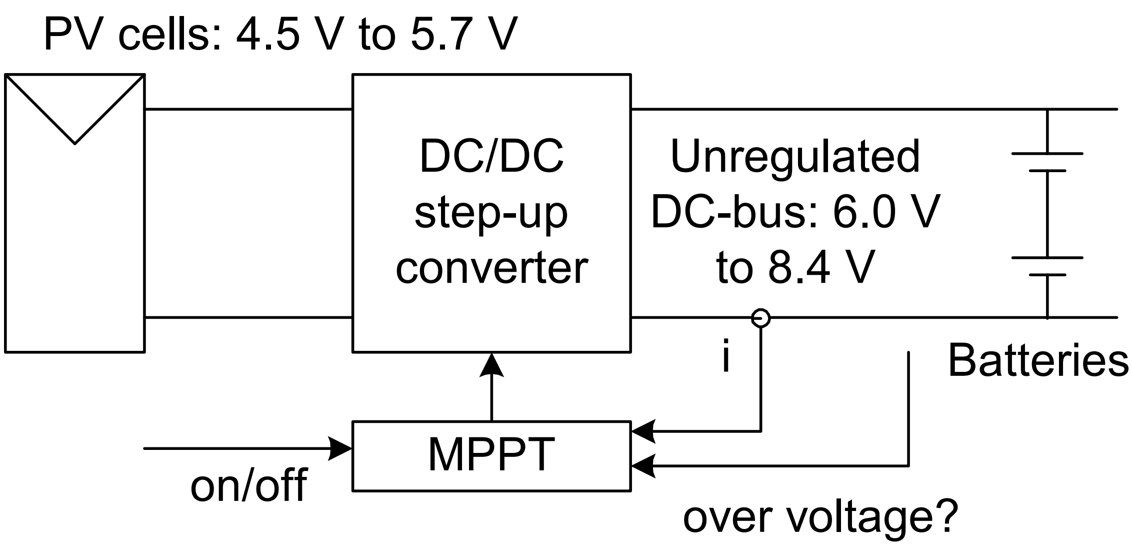
Fixed PV voltage reference (u_{ref} = 4.5... 5.7 V)



Searching algorithm

MPPT

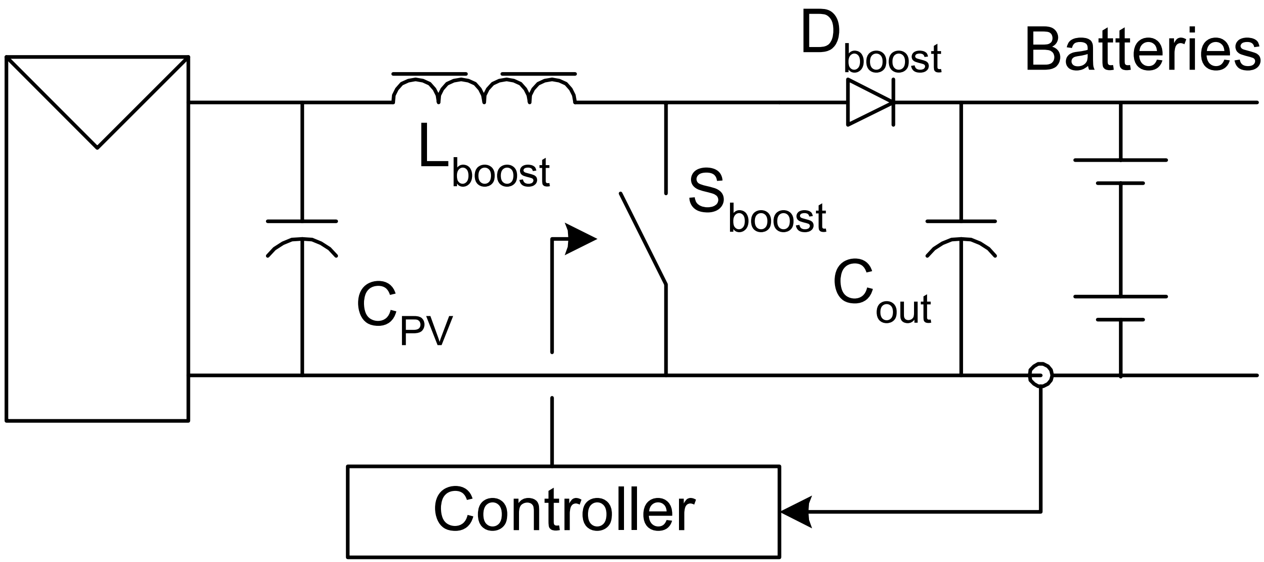
A variant of the searching approach exist. The batteries forms a large capacitor. Hence, the DC-bus voltage do not change instantaneous within a minute. Therefore it becomes sufficient to maximise the current from the DC/DC converter!



Modified searching algorithm

$$C_{eq} = Q \cdot \frac{U_0 + U_1}{U_0^2 - U_1^2} = 700mAh \cdot \frac{4.2V + 3.0V}{(4.2V)^2 - (3.0V)^2} = 2.1kF$$

MPPT

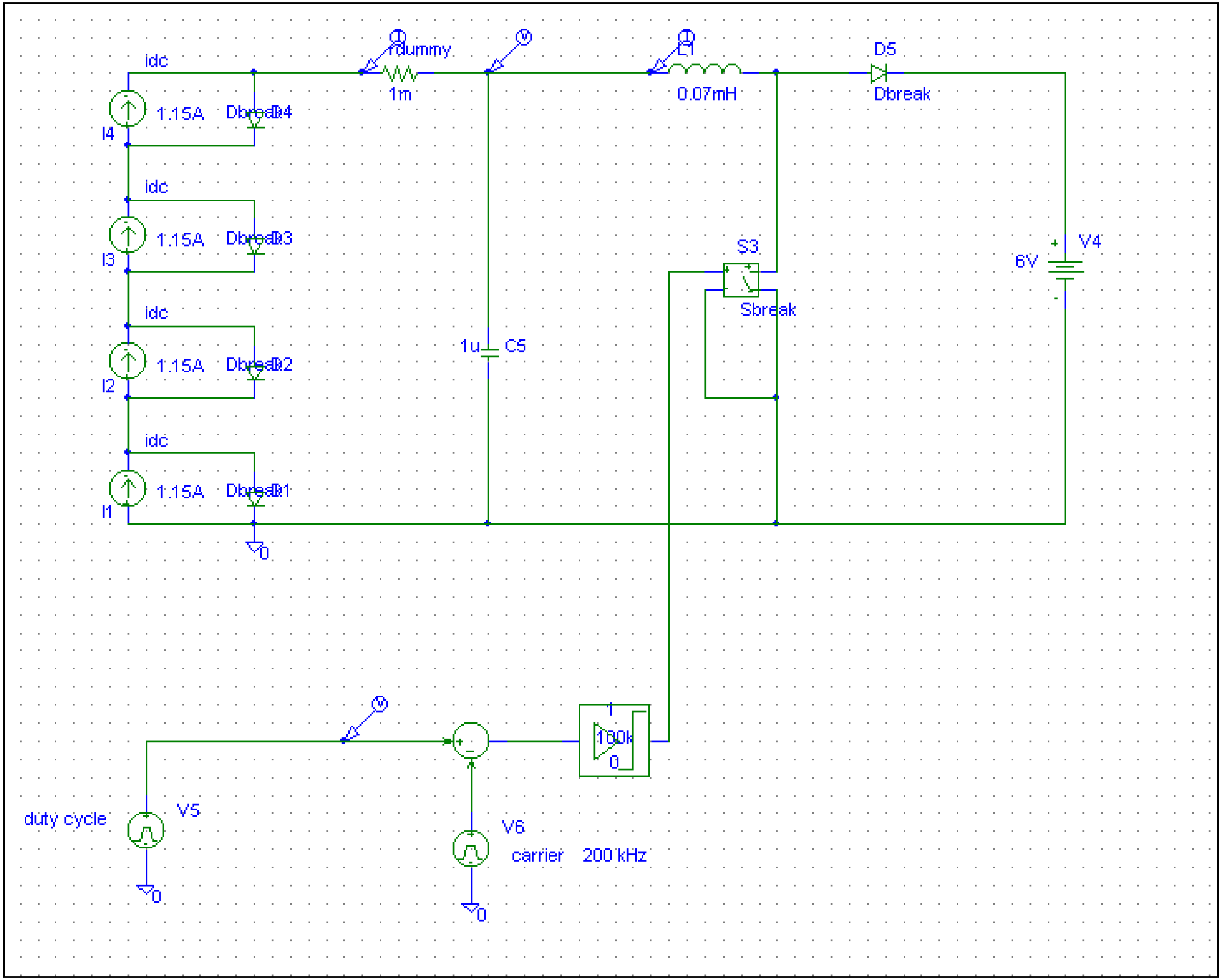


The relationship between the in- and out-put voltages is given as

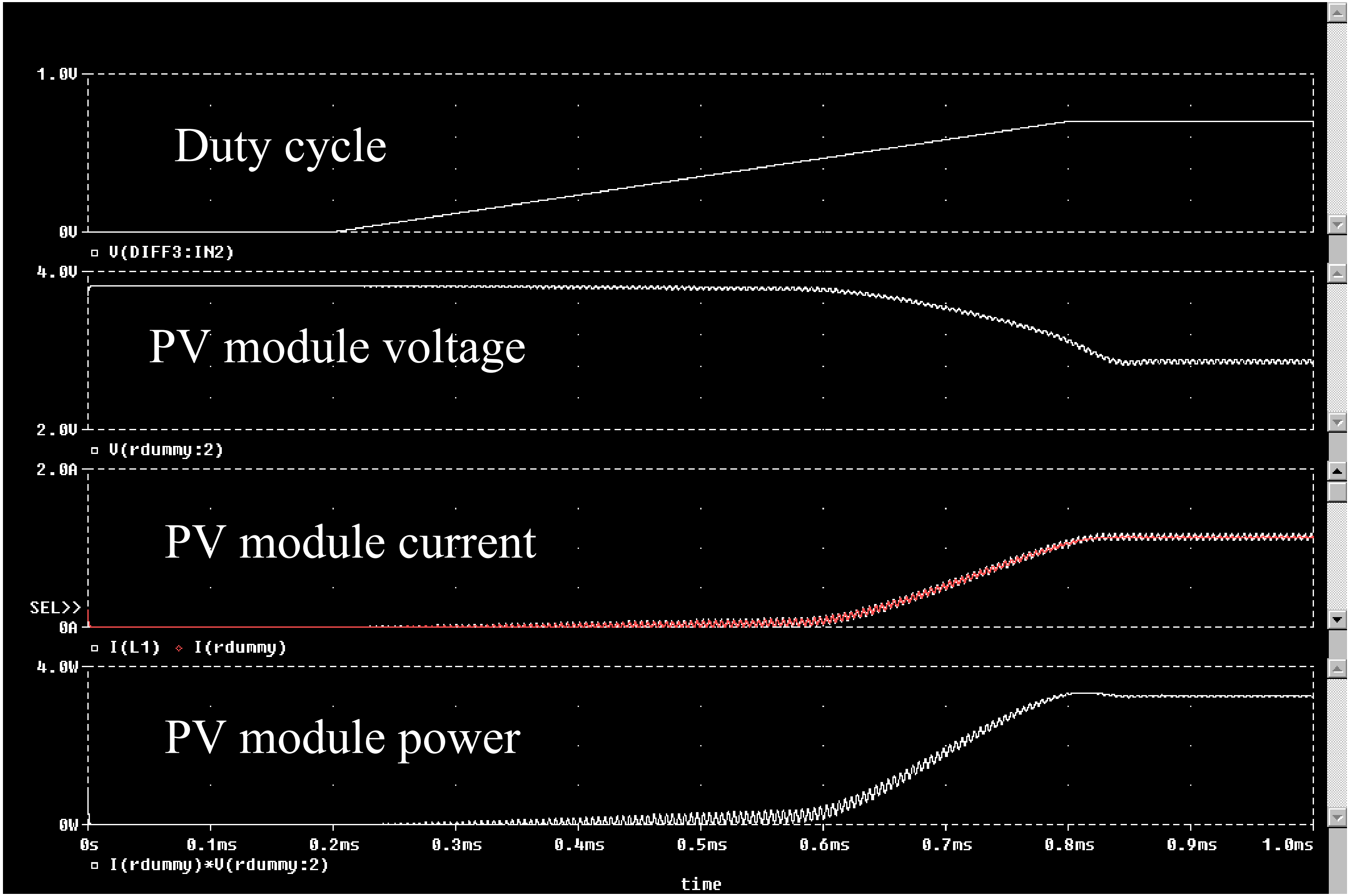
$$\frac{U_{DCbus}}{U_{PV}} = \frac{1}{1-D},\ D \in [0;1]$$

If the current through the boost-inductor is continuous.

MPPT

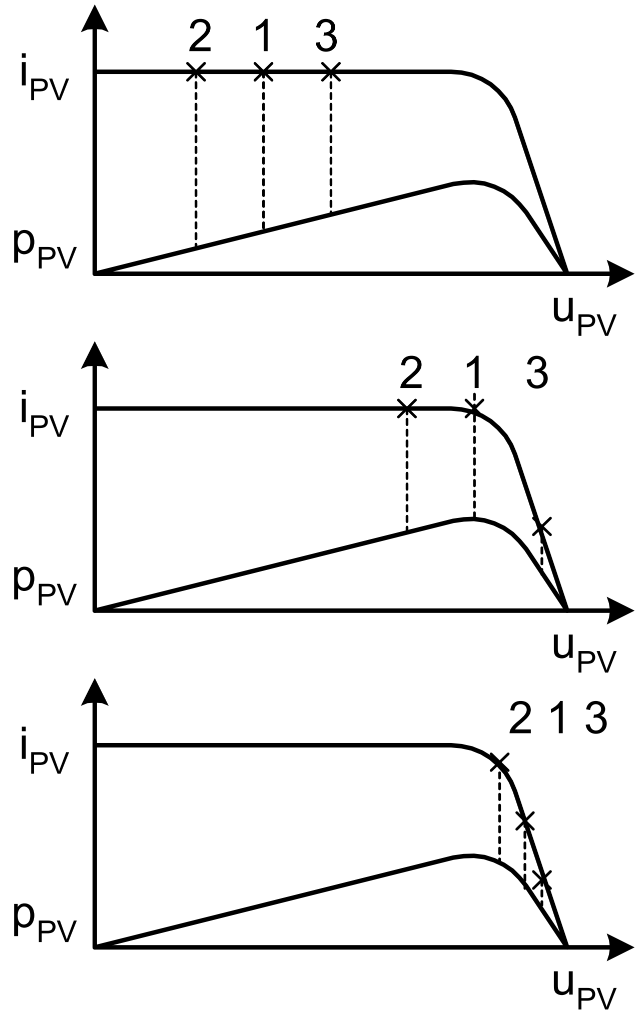

Rdummy
1m
L1
0.07mH
D5
Dbreak
idc
1.15A
Dbreak
D4
I4
idc
1.15A
Dbreak
D3
I3
idc
1.15A
Dbreak
D2
I2
idc
1.15A
Dbreak
D1
I1
0
1u
C5
S3
Sbreak
6V
V4
duty cycle
V5
0
V6
carrier
200 kHz
0
100k
0

MPPT


1.0V
0V
Duty cycle
V(DIFF3:IN2)
4.0V
2.0V
PV module voltage
V(rdummy:2)
2.0A
SEL>>
0A
PV module current
I(L1) I(rdummy)
4.0W
0W
PV module power
0s
0.1ms
0.2ms
0.3ms
0.4ms
0.5ms
0.6ms
0.7ms
0.8ms
0.9ms
1.0ms
I(rdummy)*V(rdummy:2)
time

MPPT


```
D = 0;
d = small compared to D;
While (1)
{
        I1 = Sample Iout;
        D =  D+d (Lowers the PV voltage);
        I2 = Sample Iout;
        D =  D-2*d (Increases the PV voltage);
        I3 = Sample Iout;
        if (I3<I1)&(I2<I1)
                {I1 was the MPP, so D = D+d;}
        elseif (I3<I1)&(I2>I1)
                {I2 was in the direction of
                the MPP, so D = D+2*d;}
        else
                {I3 was in the direction of
                the MPP, so D = D;}
}
```



Li Ion Batteries

Søren Bækhøj Kjær

The voltage range for the Lithium Ion batteries is between 3.0 V to 4.2 V. The capacity equal 700 mAh (Danionics DLP 443573). The charge current must never exceed the capacity, hence 700 mA. The discharge current must never exceed two times the capacity.

In the worst case: no power from the PV cells and transmitting in three subsequent orbits. The COM module from One Step Satellite Solution (OSSS) requires approximate 10 W. The maximum load power then amounts to app. 12 W. The maximum available power from one series-connection of batteries is

$$P_{bat,max} = (6.0V \ldots 8.4V) \cdot 2 \cdot 0.7A = 8.4W \ldots 11.8W$$

It seems like one series-connection of batteries is sufficient if they are fully charged. This can also be seen by consider the energy

$$E_{COM} = 12W \cdot 600s = 7200J < E_{bat} = \frac{8.4V + 6.0V}{2} \cdot 0.7Ah = 18144J$$

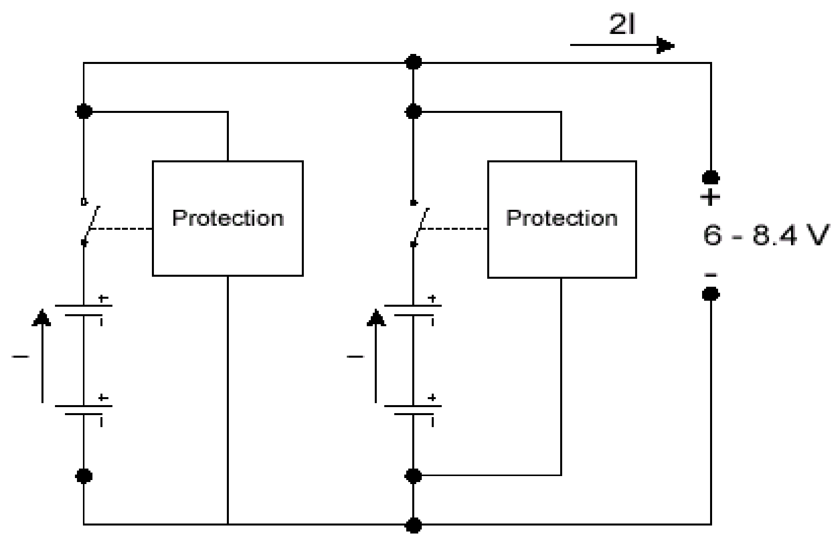
Li Ion Batteries

Søren Bækhøj Kjær

But they cannot stay fully charged after 3 orbit with transmission. The discharge current would exceed the limit of two times the capacity which would lower the batteries lifetime. And what more important is, the batteries can only withstand 400 cycles of total charge - discharge operation, which would be the result if one series-connection of batteries is used.

Hence, to obtain a sound design two series-connected batteries should be put in parallel!!!

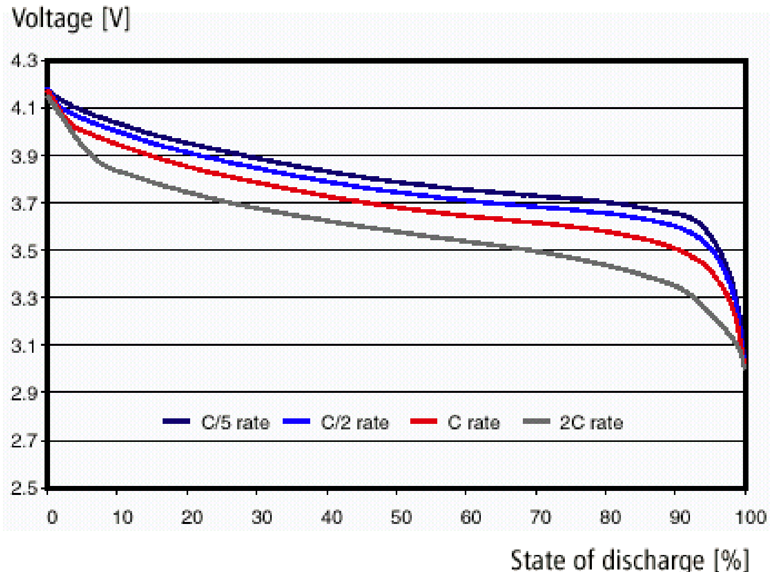
With a suitable protection-circuit (E.g.: UCC3911, TI). The protection is included in order to prevent over-charging (over-voltage) and over-discharging (under-voltage).



Li Ion Batteries

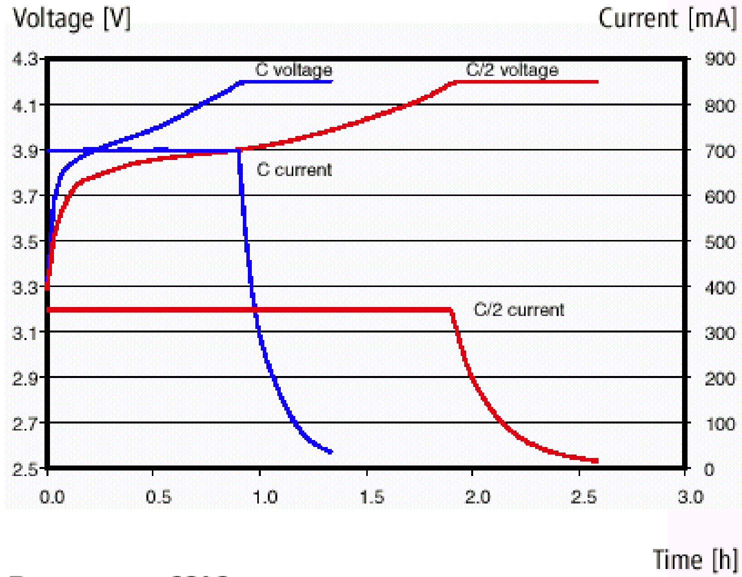
Søren Bækhøj Kjær

Discharge characteristics



Discharge: C rate
Charge method and rate CC-CV (4.2V): C/2 rate at 23°C

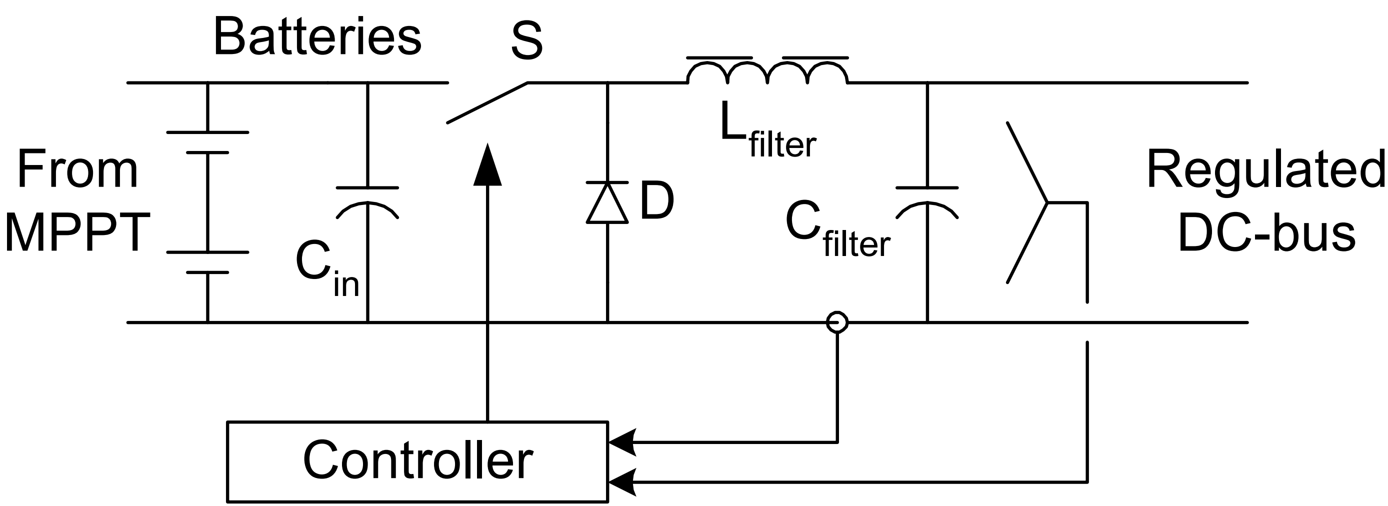
Charge characteristics



Temperature: 23°C

Power Conditioner

The unregulated DC-bus, fed by the PV cells and batteries, supplies the loads with 6.0 V to 8.4 V. However, the loads requires 5.0 V with a small amount of ripple (E.g. 2% = 0.1 V peak2peak). To overcome this demand, a step-down (Buck) converter must be utilised. It is also possible to apply a Linear Voltage Regulator (LVR) like the LM7805. However, the efficiency for the LVR is rather low (60% to 85%) whereas for the Buck it exceeds 90%.



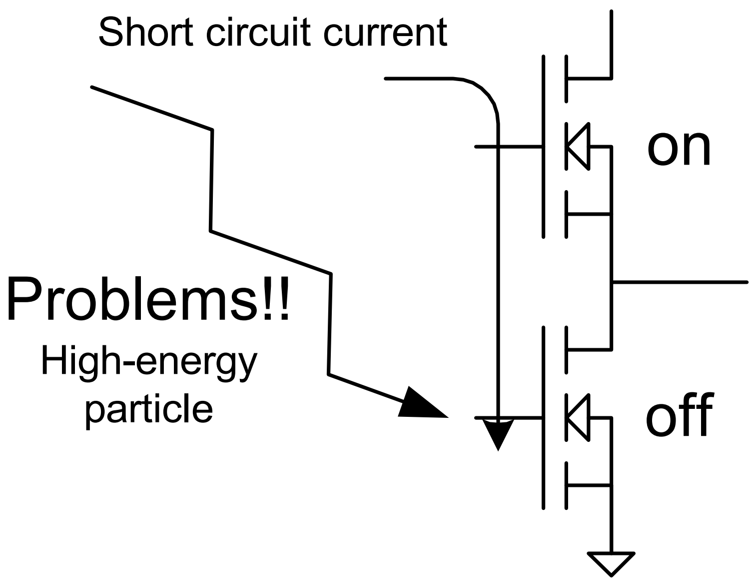
Power Conditioner

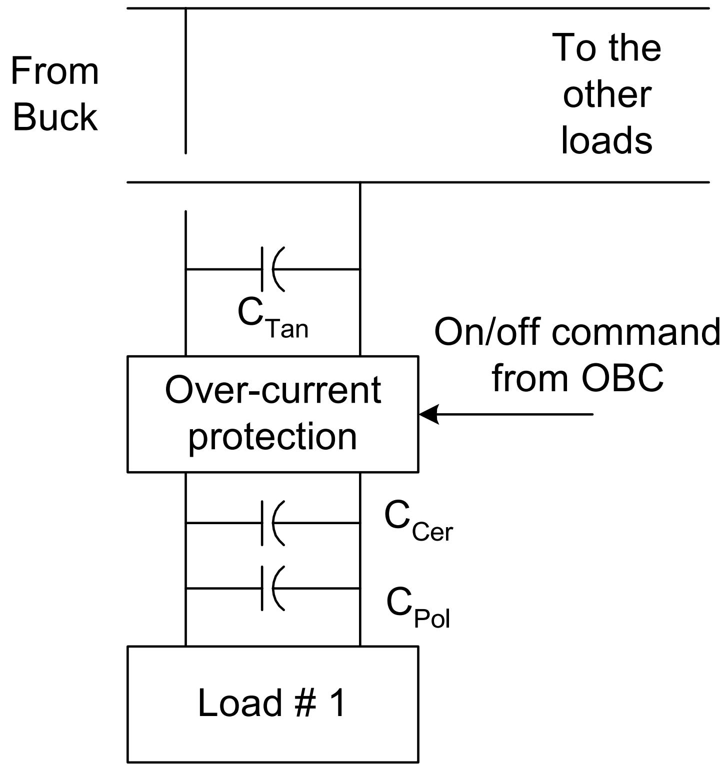
The regulated DC-bus must be low-impedance, so transients from one load do not impose noise to other loads. This is done by including a capacitor-bank at the input to each load. A de-coupling capacitor (polystyrene) must also be applied for each IC. Approximate 470 pF to 1 nF for digital IC' and 1 nF to 50 nF for analogue IC'.

- Tantalum electrolytic: dc - 1 kHz
- Ceramic: 1 kHz - 100 kHz
- Polystyrene: 10 kHz - 1000 MHz

Power Conditioner

The power conditioner must be able to turn on/off a load by command from the OBC. What more important is, the PC must also protect the loads from over-currents, due to incoming high-energy particles.





Power Conditioner

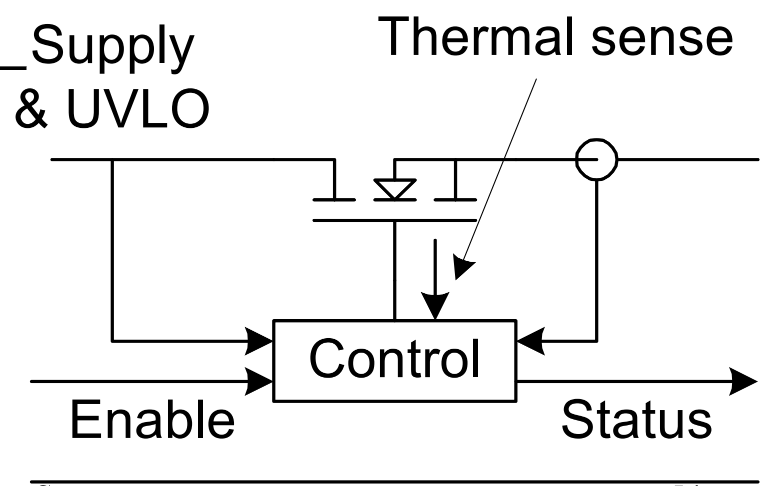
Søren Bækhøj Kjær

However, the protection for the OBC must NEVER turn off the OBC (how should it command the PC to turn itself on again??, just asking). Two solutions exists:

- Limit the current
- Turn off the OBC, and then back on again!!!

The TPS203XD circuit does the job:

Device	**Max. load current/ Current limit**
TPS2030D	0.2 A / 0.3 A
TPS2031D	0.6 A / 0.9 A
TPS2032D	1.0 A / 1.5 A
TPS2033D	1.5 A / 2.2 A
TPS2034D	2.0 A / 3.0 A



Killswitch

A ‘Remove-Before-Flight’ pin is included in the design. The killswitch(es) are active when the Cubesat is situated inside the launching vehicle. Hence, the RBF pin can be removed without turning on the Cubesat.

When the Cubesat is released from the vehicle, the killswitch is also released, hence power is provided to the Cubesat. However, CalPoly demands a delay of min. 0.3 sec's between release and power up. This is either done mechanically or electronically. The latter is to prefer, because the switch then does not have to carry the entire load current (It is low reliable).

Killswitch

The p-type MOSFET is off when zero volts is applied between gate-source. It starts to conduct then the gate-source voltage decreases below the threshold voltage (negative for a p-type and positive for a n-type).

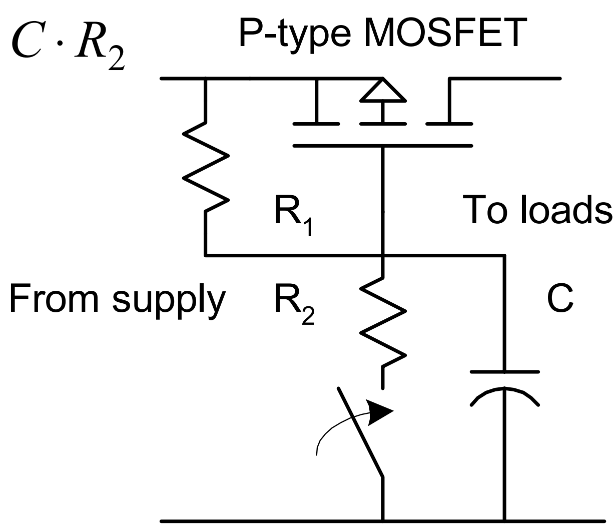
The capacitor C is charged up to the input voltage by means of the resistor R_1 (E.g. 100 kΩ). C is discharged by means of R_2, when the killswitch is released. Hence, the gate-source voltage is decreasing.

$$u_{gs} = -u_{supply} \cdot \left(1 - \exp\left(\frac{-t}{\tau}\right)\right),\ \tau = C \cdot R_2$$

$$\tau = \frac{-t_{delay}}{\ln\left(\frac{u_{supply} + u_{gs(th)}}{u_{supply}}\right)}$$

$$t_{delay} = 0.3s,\ u_{supply} = 8.0V,$$

$$u_{gs(th)} = -2.0V \Rightarrow \tau = 1.05s$$

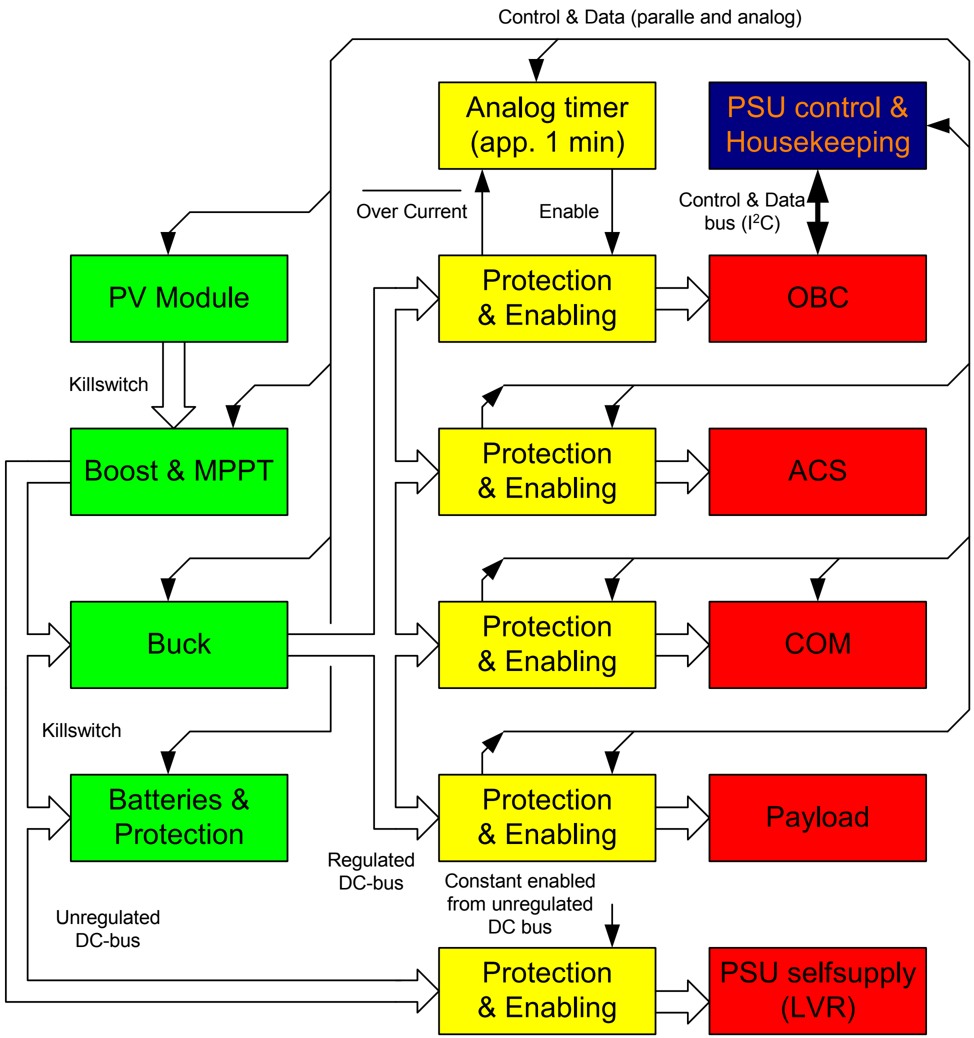


Cubesat Power System

Søren Bækhøj Kjær

Overview:

- Main power circuit
- Protection
- Control
- Loads

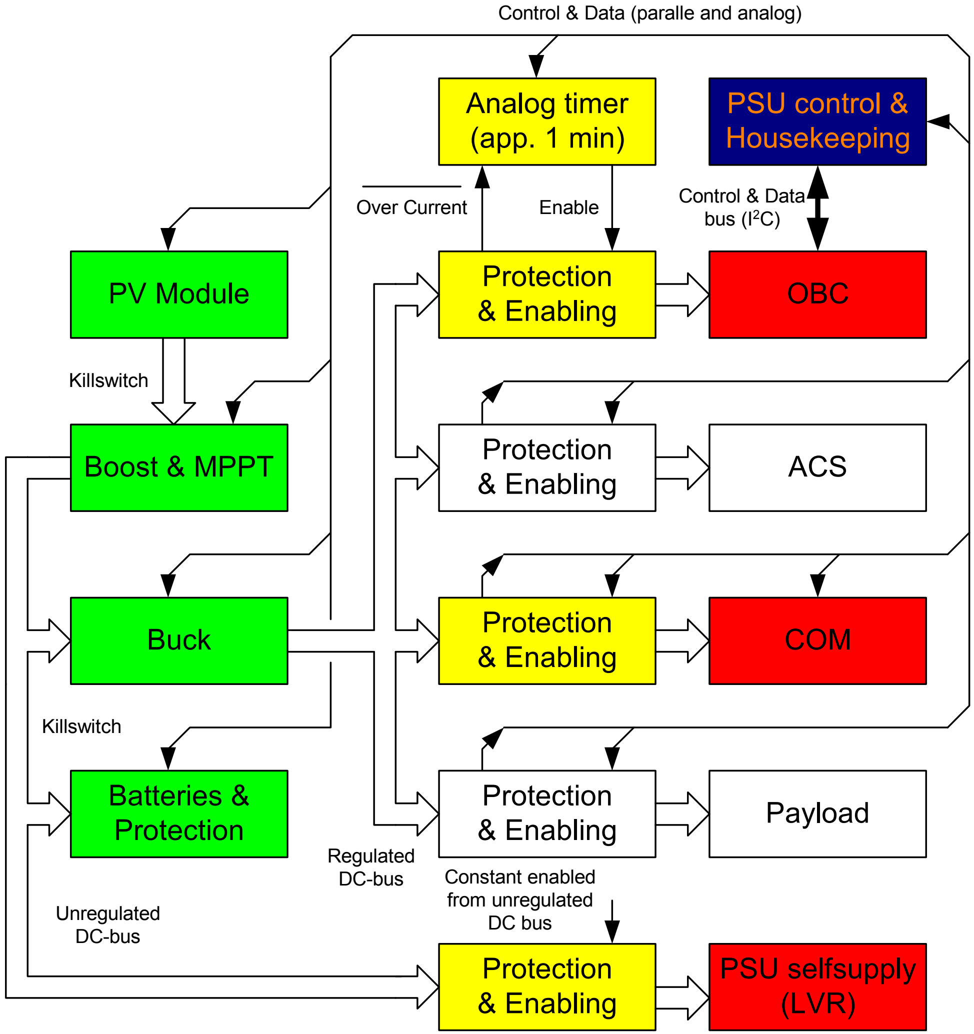


Cubesat Power System

Søren Bækhøj Kjær

The PSU controller has several tasks when the Cubesat is released from the launching vehicle:

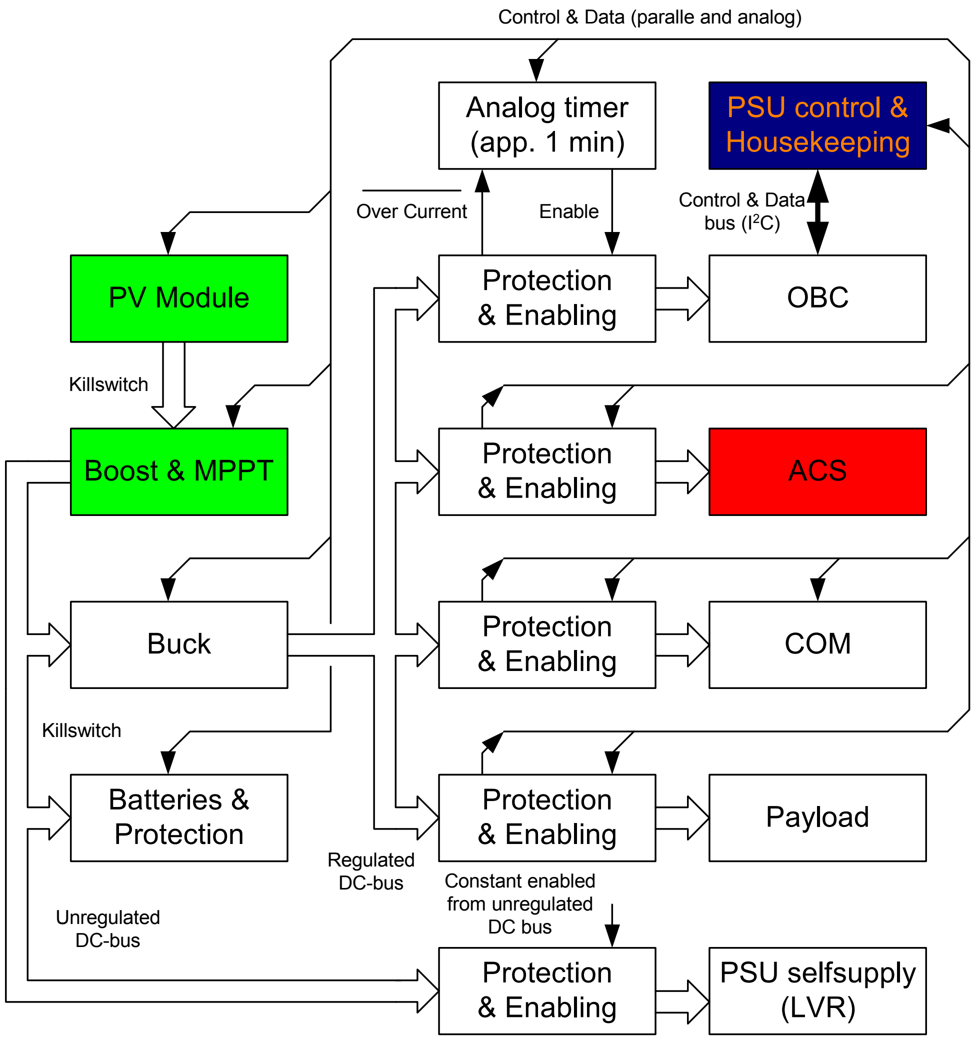
- Wait for several minutes (30).
- Enable the MPPT, OBC and COM.
- Deploy the antenna.
- Activate the Push-to-talk pin on the COM, in order to transmit a 'basic beacon' signal (E.g. Morse-code).



Cubesat Power System

Søren Bækhøj Kjær

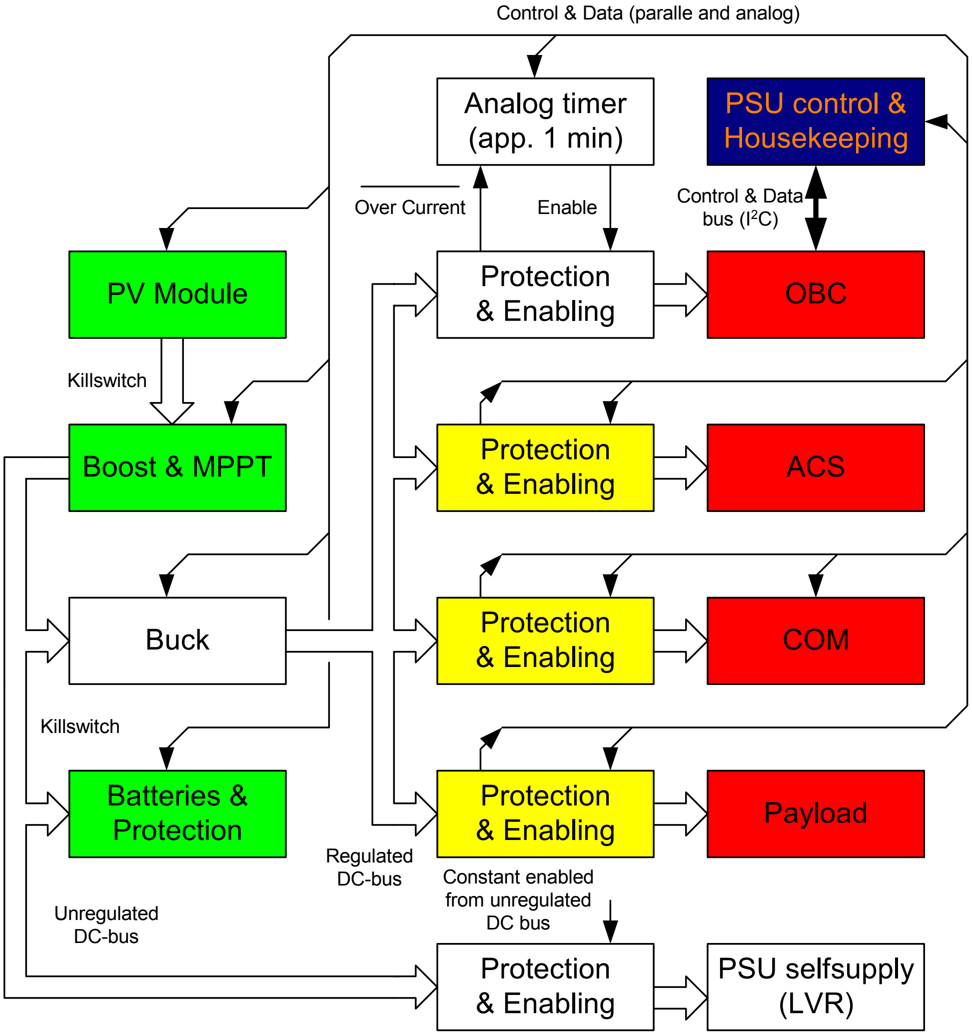
The PSU controller contains the MPPT algorithm. The PSU controller should notify the ACS, by means of the OBC, to turn three sides into sunlight whenever possible.



Cubesat Power System

Søren Bækhøj Kjær

The PSU controller monitors the batteries state of charge. If it becomes too low a warning must be send to the OBC, indicating that power is soon to be turned off to some of the loads (Not the OBC). If it becomes to high a warning should be transmitted to the MPPT, to slow down the power generation.

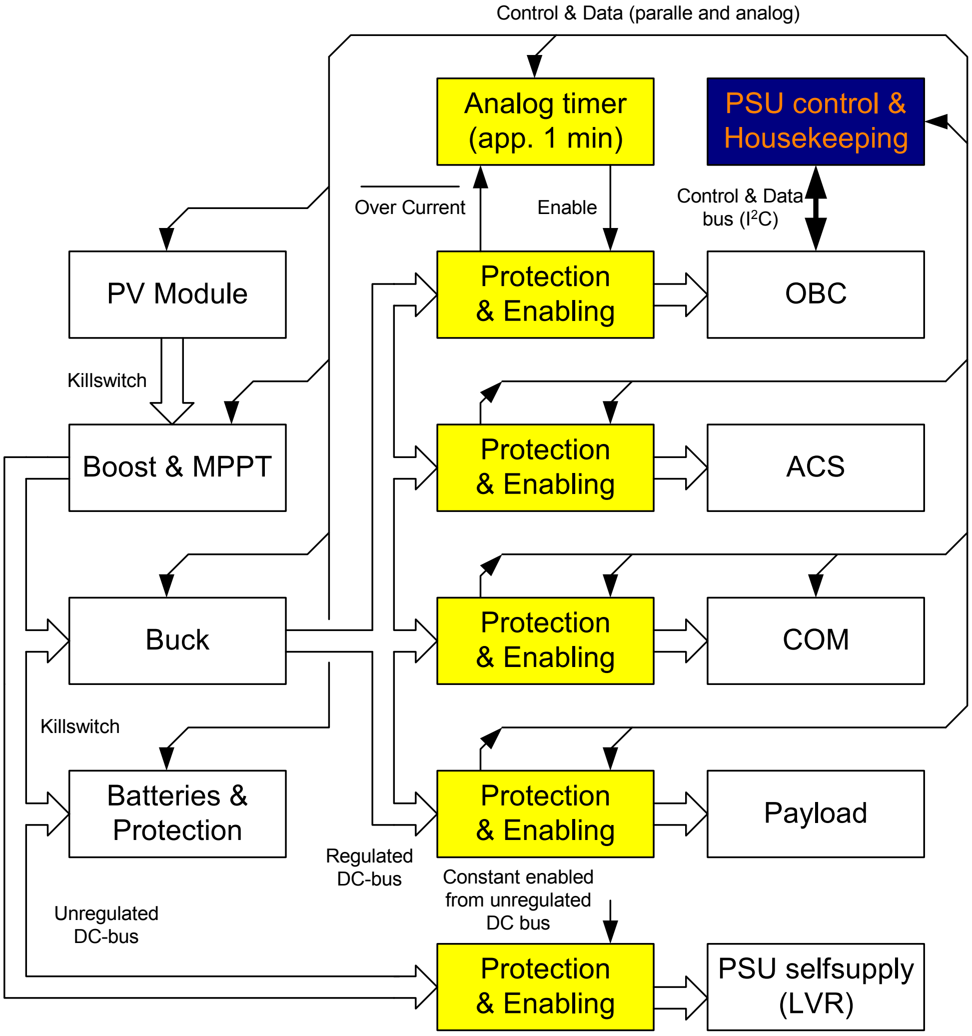


Cubesat Power System

Søren Bækhøj Kjær

Three types of protection and enabling circuits is required.

- The protection for the OBC should be autonomous. Hence, if an over-current situation happens, the OBC must be shut-down for a moment (app. 1 min), after which it must be turned on again.
- The enabling for the ACS, COM and payload is controlled by the OBC. However, the over-current protection is still done by the power conditioner.
- The PSU self-supply is only protected against over-current.

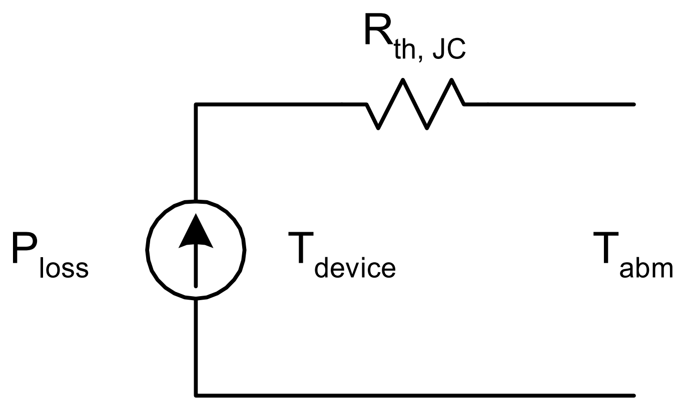


Thermal design

The thermal conditions inside the Cubesat is of great importance. Use a simulator (E.g. PSPICE) to simulate the temperatures.

- Represent loss with a current source
- Represent thermal resistance with a resistor
- Represent ambient temperature with a voltage source
- All temperatures then correspond to voltages!!

$$T_{device} = P_{loss} \cdot R_{th,JC} + T_{abm}$$



As much copper as possible should stay on the PVB for two reasons:

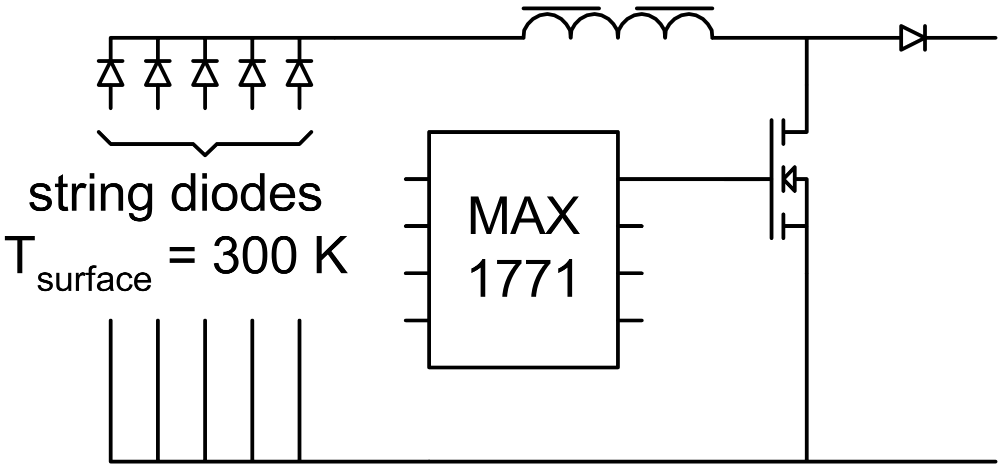
- To obtain a good ground-plane for EMC consideration
- To conduct away the heat

Thermal design

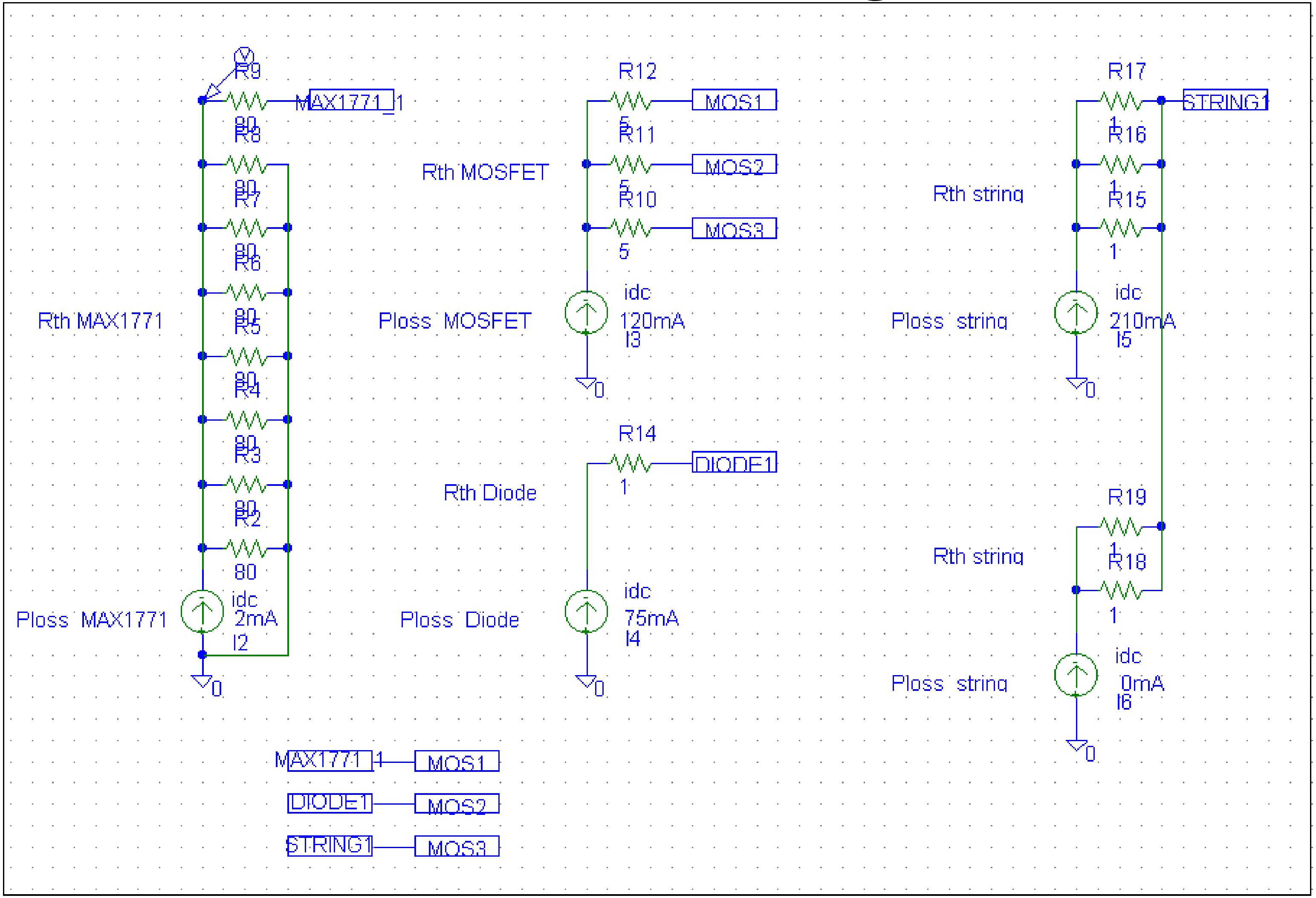
Søren Bækhøj Kjær

- MAX1771: 2 mW, 10 K/W, 8 legs
- MOSFET: 120 mW, 1.7 K/W, 3 legs
- Diode: 75 mW, 0.5 K/W, 2 legs
- String diodes: 3 * 70 mW, 0.5 K/W, 2 legs

- MAX1771: 5 K
- MOSFET: 39 K
- Diode: 40 K
- String diodes: 40 K



Thermal design



Components

The following consideration should be made when selecting the components.

• Accessibility, how easy can You get the component.
• The components must be based on a proofed technology.
• For MOSFETs, either use radiation-hardened devices, VERY EXPENSIVE (k$), or select a device with at a break-down voltage at least twice as large as it will ever be used for.
• Never use aluminium electrolytic capacitors. The fluid inside them is evaporating in vacuum. Use tantalum ones instead.
• Use low-power Integrated-Circuits (IC) in order to save power.
• Run the micro-controller with a low clock frequency.
• Use Read-Only-Memory (ROM) for storing the software. They are not so easily altered by incoming high energy particles.
• Use military rated IC'.

Components

• Boost converter:	MAX1771
• Battery charger:	ADP3810
• Battery protection:	UCC3911
• Buck converter:	MAX1744
• Power distribution:	TPS203xD
• Current measuring:	MAX4372
• Temperature sensor:	LM19
• PSU self supply:	LM78L05
• N-type MOSFET (boost):	MTD20N03HDL
• P-type MOSFET: (Buck):	NTD456P
• PSU controller:	PIC16C774

- 8-bit
- 4 kB ROM for program and 32 B RAM for data
- 10 analogue inputs (A/D converter) for MPPT and housekeeping.
- I2C bus for communicating with the OBC
- 5 digital input/output ports (3 * 8 bit + 1 * 6 bit + 1 * 3 bit)
- Pulse Width Modulator (PWM), e.g. for MPPT
- Watchdog timer, e.g. for rebooting the OBC

Redundancy

Redundancy is extremely important when speaking about satellite systems! Remember, You cannot perform any hardware service on the satellite when first is in orbit!! How to increase the redundancy:

- The Cubesat Power System should be capable of operating without the micro controller (at least for a short period).
  - The default MPPT should be the one implemented in the micro controller. However, if the micro controller halts, the constant reference should be used.
  - Use a watchdog-timer to detect if the micro controller halts, and if it halts: reboot the micro controller.
- Never use power topologies with two switches in series, like the half bridge converter. A high energy particle may cause a short circuit through the switches.
- For critical components (e.g. the mechanical parts of the kill-switch or MOSFET' within the Buck and Boost converters), use two or more in parallel.
- When making decisions within the SW, always make a cross-check before an action is carried out.

Appendix

- MATLAB script for PV cell, one and triple junction [homepage]
- MATLAB script for orbit analysis [homepage]
- EMCORE PV cell specification
- DANIONICS battery specification
- Papers:
  - Cycling and low temperature performance of Li ion cells.
  - Lithium-ion cells for aerospace applications.
  - Low temperature operation of a boost converter.
  - New very low power, high efficiency DC/DC power supply for LEO satellite constellation.
  - System analysis
  - Three generations of DC power systems for experimental small satellites.
  - Triple-junction GaInP/GaAs/Ge solar cells - production status, qualification results and operational benefits.
  - Tsinghua-1 Micro-satellite power system architecture and design.

Appendix

- www.iet.auc.dk/~sbk
- www.cubesat.auc.dk
- www.maxim-ic.com/powersupplies.cfm
- www.national.com/appinfo/power
- www.danionics.dk
- www.emcore.com
- www.calpoly.edu
- www.buchmann.ca/Article5-Page1.asp

Exercises

1) Calculate the incoming power during one orbit, attitude = 750 km (both when in eclipse and in sun). Take the PV-cell temperature into consideration

• Hints: Assume an initial PV efficiency of 26% and a total isolation between the structure and the PV cells. The side with the antenna (camera) points towards the Earth during the entire orbit and maximum two sides containing PV cells are illuminated.

2) Estimate the input power to the boost-converter (remember the Shottkey diodes??). How would You obtain a high efficiency for the boost converter when in shadow??

• Hint: The boost converter inters burst-mode-operation when the PV power decreases below 0.4 W. The boost efficiency equals 90% at min. power and 95% at max. power (linear dependency).

Exercises

3) Calculate the load power. The COM consumes 11 W when transmitting, the OBC, payload and ACS power amounts to 1.4 W. Assume a ground station view angle, θ_{gs}, of 10°.

4) Calculate the power into the Buck converter. The efficiency equals 90% at min. power and 95% at max. power (linear dependency).

5) Calculate the energy stored in the batteries.

6) Design the boost and buck converters
• Hint: Use some of the given web-references

Are You ready to design Your own Cubesat Power System??