Unmanned Solar Powered Airship Concept Evaluation

Preliminary Design Report

Power Subsystem

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Acronyms

APR Array Power Regulator

COTS Commercial Of-The-Shelf

DM Development Model

ECSS European Cooperation for Space Standardization

EMI Electromagnetic Interference

EPS Electrical Power Subsystem

FM Flight Model

GaAs Gallium Arsenide

IC Integrated Circuit

MEA Main Error Amplifier

MPP Maximum Power Point

MPPT Maximum Power Point Tracking

MPPTU Maximum Power Point Tracking Unit

OpAmp Operational Amplifier

PCB Printed Circuit Board

PWM Pulse Width Modulated

SAR Solar Array Regulator

SA Solar Array

TBD To Be Decided

TV Thermal Vacuum

List of Figures

List of Tables

Contents

1 Introduction

The Electrical Power Subsystem (EPS) will provide power to the motors, communication system and payloads. Power is generated from a solar panel and stored in a battery. DC-DC regulators are used to provide regulated voltages to payloads and onboard computers.

2 Functional and Technical Requirements

2.1 Functional Requirements

Below are listed the primary functional requirements for the EPS:

- Provide adequate power to motors and payload
- Proof that flying on solar energy is possible i.e more power produced than consumed

Additional desired requirements are:

- Scalability to higher power levels
- Flexible and robust design, allowing flight in more extreme conditions (altitude, weather etc.)
- Optimal design and high performance to increase power capability and minimize system mass

2.2 Technical Requirements

The EPS technical requirements are listed in table 1.

Table 1 – *Technical requirements for the EPS*

Minimum power output	$8\,W$
Maximum mass	$750\,g$(including solar arrays)
Maximum cost	$2500\,SEK$
Maximum internal power dissipation	$< 500\,mW$
Output voltages	$3.3\,V$(un-regulated), $5\,V$(regulated)
Regulator phase margin	$60\,deg$
Regulator gain margin	$10\,dB$
Control loop bandwidth	$> 10\,kHz$
Operational temperature	$-20°C\,to + 25°C$
Battery capacity	$> 5\,Wh$ ($> 30\,min$ of battery powered flight)

2.3 Mission and Environmental Constraints

This section discusses some of the challenges opposed by the mission and the parameters of operation environment and how these will influence the EPS design constraints.

Solar Array Temperature

Temperature variation of the solar panels, significantly changes the solar panels characteristics. In [1], the temperature coefficients of the open-circuit voltage, of a proposed solar cell, is listed as $-0.36\,\%/K$. When going from $-20°C$ to $+25°C$, V_{oc} drops by 16.2%. The short-circuit current, I_{sc}, is only increased by less than $3\,\%$, hence in overall the power output from the solar cell drops. The IV-curve for the solar cell is reproduced in figure 1. To ensure that the solar cell can supply enough current to support the cell output voltage, the voltage operating point must always stay a bit to the left of the IV-curve. For an unregulated architecture, when the actual array temperature is lower (down to $-20°C$), an efficiency drop in the order of $15-20\,\%$ can be expected, due to the non-optimal voltage operating point.

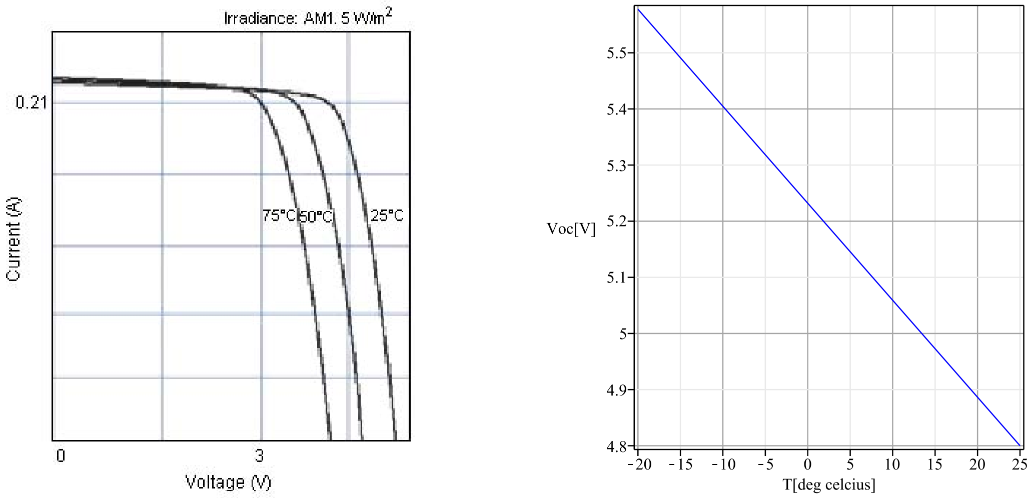

Figure 1 – *Temperature dependence on solar cell IV-characteristics*

Solar Incidence Angle

The launch site of U-SPACE is near Kiruna at 67.5° northern latitude. In summer solstice, at midday, the solar incidence angle, from local horizontal, is:

$$\begin{aligned} \alpha_{sun} &= 90° - 67.5° + 23,5° = \\ \alpha_{sun} &= 46° \end{aligned} \tag{1}$$

The solar cell output current drops with the Kelly cosine function, shown in figure 2. To minimize power losses, due to inclined solar incidence, the optimal mounting position and angle of the solar panels must be considered.

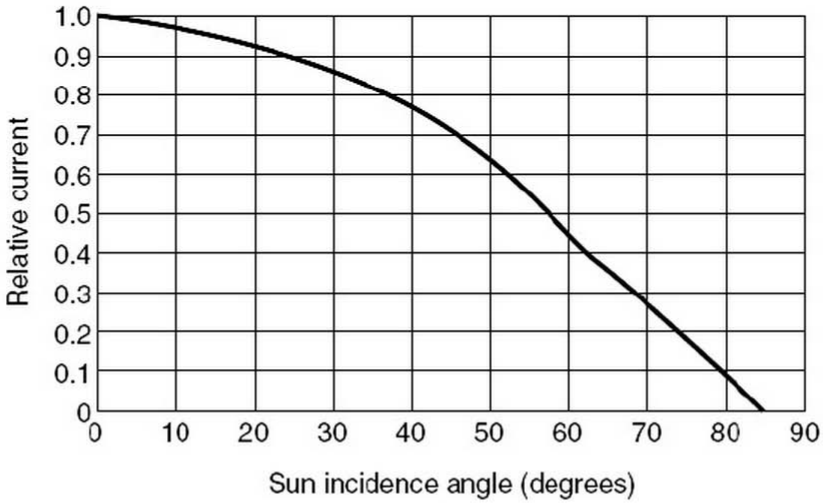

Figure 1.22 Kelly cosine curve for PV cell at sun angles form 0 to 90°.(Ref:3)

Figure 2 – *Kelly cosine function showing how solar cell photo current depends on sun incidence angle*

Solar Array Shading

Shading on the solar panels, for example caused by airship stabilizer structures or objects in the landscape, can cause a significant drop in the cell output voltage, as described in [2, p. 165]. Bypass diodes can be used to partly mitigate this issue as well as using a Maximum Power Point Tracking (MPPT) regulator. Otherwise it could be necessary to ensure that the airship structure cannot cast shadows on the panels and that the airship only fly above or away from landscape objects.

2.4 Expected Performance

Table 2 – *Expected performance of the EPS*

Power conversion efficiency(overall)	$80 - 90\%$
Power production(overall)	$9\,W < P_{avg} < 12.5\,W$
Battery capacity	$10.44\,Wh$
Mass	$\sim 500 - 750\,g$ [a]

[a]Depends on the chosen regulator design and system scaling

3 Preliminary Design

3.1 Solar Array Design

Section 2.3 discussed the importance of the sun incidence angle on the solar panels. It is first considered having the solar array divided into two identical panels on each side of the airship. Considering that the sun incidence is directly falling on one of the sides of the airship, the "back-side" solar panel on the airship may still produce power, if the incidence angle is not too large. Considering the Kelly cosine function from figure 2, the maximum total output current (power), from each solar panel, is around 71%, when both solar panels are at 90° angles (completely flat on top of the airship). In practical, having complete flat panels on top of the airship is hard to realize and a compromise must be made. Hence, the panels should be angled as small as possible, to maximize the total power output.

The same issue goes for the changing sun incidence angle due to the flight attitude around the vertical axis. Again, ideally the solar panels should be flat on the top of the airship. In practical, it is more realistic to place four identical solar panels on top of the airship, with as small an angle as possible with respect to vertical. The proposed layout of the four solar panels is illustrated in figure 3.

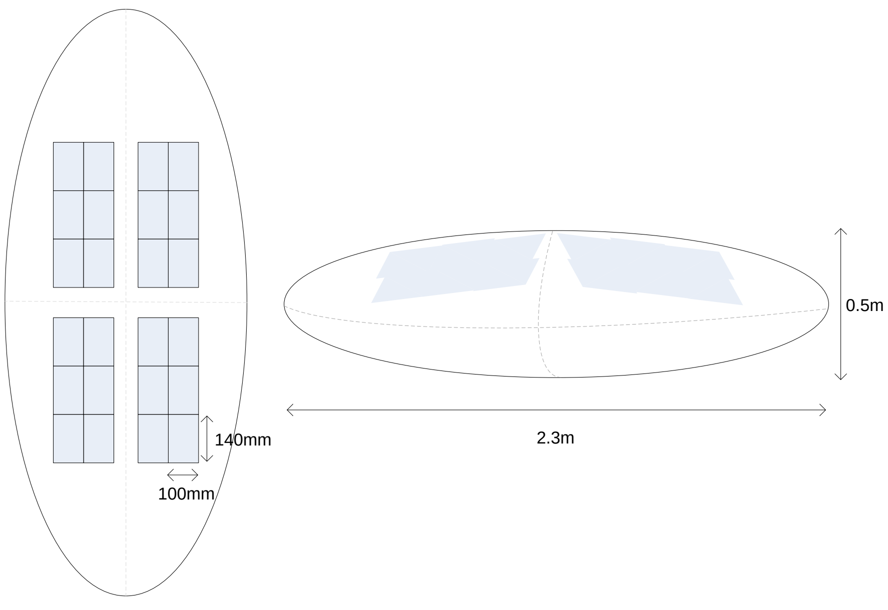

Figure 3 – *Mounting of the solar panels*

The proposed solar cell, [1], has the following current and voltages at the Maximum Power Point (MPP):

$$V_{cell,MPP} = 3.85\,V$$
$$I_{cell,MPP} = 210\,mA \qquad (2)$$

Each of the four panels will consist of six solar cells giving a maximum power output of:

$$
\begin{aligned}
P_{panel,MPP} &= 6 \cdot V_{cell,MPP} \cdot I_{cell,MPP} \\
P_{panel,MPP} &= 4.85\,W
\end{aligned}
\tag{3}
$$

It is considered having two series-connected cells and three in parallel, thus having an output voltage of:

$$V_{panel,out} = 7.7\,V \tag{4}$$

3.2 Regulator Design

An important trade-off analysis is the selection of the Solar Array Regulator (SAR). Table 3 shows the comparison between three possible regulators. These three are shortly described below:

Zener Diode Regulator

The most simple design is to use a Zener-diode regulator, as shown in figure 4. The circuit comprises a Zener-diode with a reverse break-down voltage equal to the desired output voltage. Excessive current from the solar arrays runs through the Zener-diode, thus keeping the load current and output voltage constant. The resistor is included to limit the current drawn by the Zener-diode to protect it from over-currents. Since a series resistor is inserted, significant power losses are experienced and therefore this circuit is only useful in low power applications.

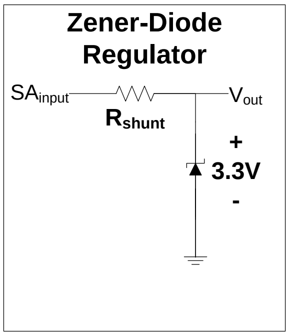

Figure 4 – *Simple Zener-diode regulator*

Shunt Regulator

The shunt regulator concept also uses a shunt resistor, but the Zener-diode is replaced by a transistor. When the transistor is closed, the solar array current is shorted to ground through the shunt resistor. A feedback line measures the output voltage, compares it to a reference voltage and generates a control signal. This signal is fed to a Pulse Width Modulated (PWM) driver for the transistor gate. This way, the current supplied to the load can be controlled and the output voltage kept constant. The solar array will operate at the same voltage as the output voltage. By manually changing the reference voltage, the output voltage could be changed, thus adding some degree of flexibility for operating conditions of the solar array. The shunt-regulator concept is shown in figure 5.

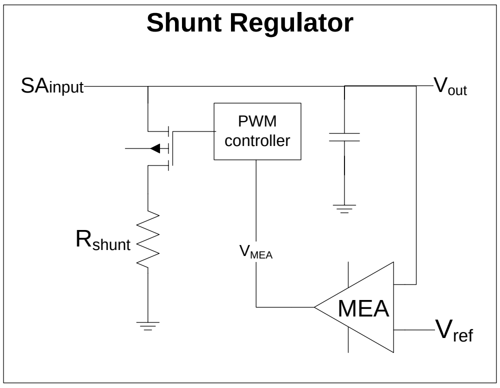

Figure 5 – *Shunt regulator diagram*

Maximum Power Point Tracking Regulator

The most advanced and robust solution is to use an MPPT regulator as shown in figure 6. A standard DC-DC converter topology (buck or boost) is used, comprising a transistor, free-wheel diode, inductor and output capacitor. Like in the shunt-regulator, the output voltage is measured and compared to a reference voltage, to generate a PWM control signal, to drive the transistor. By varying the duty cycle of the PWM signal, the input voltage (solar array operating voltage) can be controlled. Additionally an MPPT circuit is added. The solar array current and voltage are measured and fed to the circuit which then calculates the power output of the solar array. By making small steps in the solar array operating voltage, the characteristic IV-curve of the solar array can be generated and the MPP can be tracked, thus always operating the solar array at is optimal operating point. When using an MPPT regulator, three operating modes will be possible:

- Battery discharge MPPT - when the solar array input power is insufficient to cover the load power demand, the battery is slowly discharged in order to maintain the output voltage.
- Battery charge MPPT - when the solar array input is greater than the load power, the excessive power is used to recharge the battery.
- Input power limitation - when the battery is fully charged, the regulator will operate the solar array at a non-optimal voltage, thus limiting the input power to keep the output voltage constant. The extra potential input power is dissipated as heat externally on the solar arrays.

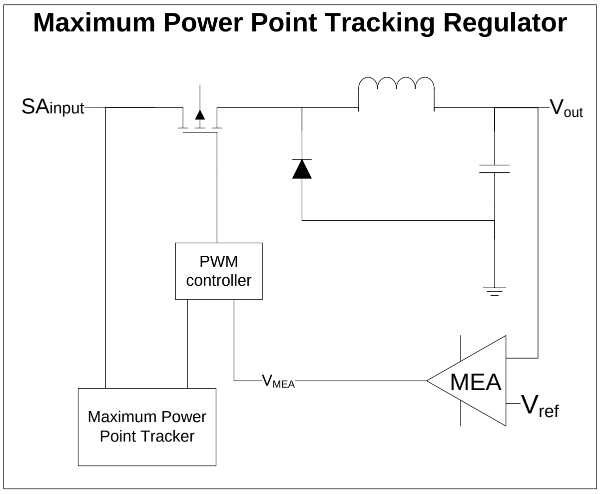

Figure 6 – *MPPT regulator diagram*

Table 3 – *Trade off analysis*

SA Regulator Concepts:	**MPPT**	**Shunt-Regulator**	**Zener-diode Regulation**
Costs	Medium(some ICs required)	Medium(some ICs required)	Low(simple components)
Regulator efficiency	High($90-95\%$)	Medium($70-95\%$)	Low($40-70\%$[a])
Size/mass	$\sim 140-240g$[b]	$\sim 50g$	$\sim 45g$
Output voltage stability	Good	Average	Poor
Scalability	Very good	Average	Poor
Internal heat dissipation	Low	Medium	High
Complexity	High	Medium	Low
Flexible to variations(temperature, shading, degradation)	Very good	poor (only manually)	none
Implementation time	$\sim 1-2\,months$	$\sim 3-4\,weeks$	$< 1\,week$

[a] Efficiency drops significantly at high current loads, due to the shunt resistor
[b] up to four identical circuits are needed, one for each solar panel, hence the larger mass

3.3 Battery Design

A trade-off analysis between different battery chemistry has been conducted and the results are listed in table 4.

Table 4 – *Trade off analysis*

Battery type	Advantages	Disadvantages
NiCd	?	Has memory effect and toxic Cadmium
NiH2	More robust to over-charge/discharge	Low energy density, high self-discharge rate and the pressurized cell is more dangerous to handle
NiMH	No internal pressure, higher energy density and less sensitive to temperature	Cannot deliver high peak power, high self-discharge rate, sensitive to high temperatures and is damaged by over-charging
Li-ion	Highest energy density, high charge efficiency and supports high charge/discharge rates due to low internal impedance	Expensive, damaged by over-charging/discharging, sensitive to low temperatures and increased internal impedance at low temperatures
AgZn	High specific energy, stable cell voltage during dis-charge	Short life time

It is proposed to use a Panasonic PA-LN19 Li-ion battery [3]. The battery has the following important specifications:

Table 5 – *Specification of proposed battery*

Battery chemistry	Li-ion
Battery voltage	$3.6\,V$
Battery capacity	$2.9\,Ah$ / $10.44\,Wh$
Weight	$49\,g$

3.4 Argumentation for Chosen Concept(s)

It is proposed to use the MPPT concept, since this provides the most efficient and robust design and easy scales up to a larger system if/when required. It also mitigate design challenges occurring due to varying environment conditions, i.e. temperature, weather etc.

For the battery, Li-ion technology offers the most compact design ensuring low weight and relative high energy capacity.

The complete EPS diagram is shown in figure 7. For providing the $5\,V$ regulated voltage to the payloads, Commercial Of-The-Shelf (COTS) DC-DC regulator(s) are used. The battery charging/discharging is controlled by the SAR.

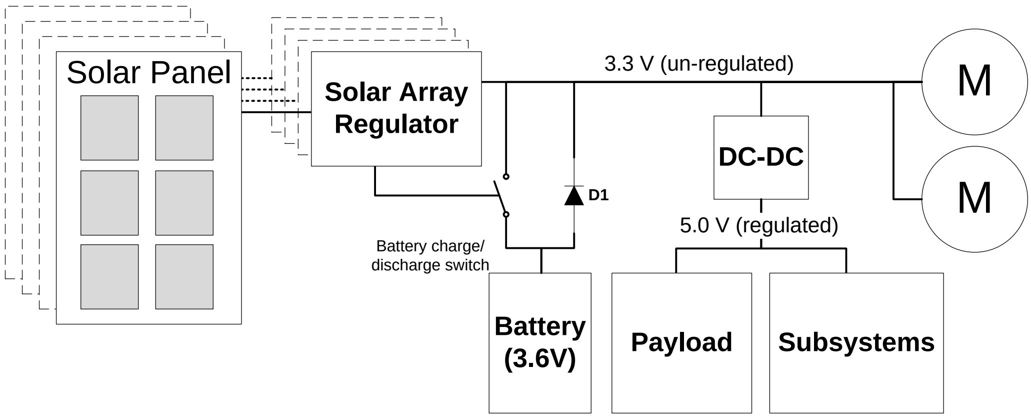

Figure 7 – *EPS system diagram*

3.5 Feasibility Study and Risk Analysis

MPPT Regulator

The MPPT regulator is a relative large and complicated circuit requiring significant amount of man-hours to design, build and test. The responsible team has previous practical experience with both SARs and MPPTs which is believed to drastically reduce the implementation time. With the MPPT regulator, it is proposed first to build the DC-DC converter with output voltage control(feedback) thus resembling the shunt-regulator in functionality only with a few percent higher losses due to the DC-DC converter. This design allows one regulator to operate all four solar panels, since the MPPT circuit is not yet included. Using this approach, it will be faster to build a first-prototype regulator, working as a backup plan, should the full MPPT regulator prove to complicated to implement within the given project constraints. As a third backup, the extremely simple, but crude Zener-diode regulator can be implemented within very shot time, to provide a minimum amount of power.

Li-ion Battery

Li-ion battery technology is widely spread used technology for modern computers and electronics. However, the technology requires more sophisticated protection circuitry against over-charge/discharge conditions, which can lead to a major system failure and potentially pose a safety risk. Extensive testing and use of application procedures should be applied.

Solar Arrays

The solar arrays are the major contribution to the EPS cost and mass budget. The proposed solar cells, [1], list very promising specifications, however the credibility remains to be verified. If cheap and light-weight solar cells are not available, it will be a critical roadblock for realizing the project.

3.6 Telemetry and Telecommands

The required/recommended telemetry and telecommands, EPS , are listed in table 6.

Table 6 – *Telemetry and telecommands*

Telemetry	Data rate/frequency	Data size
Battery voltage	Every 30 sec	1 byte
Solar array temperature	Every 30 sec	1 byte
Solar array voltage	Every 1 sec(MPPT performance)	2 bytes
Solar array current	Every 1 sec(MPPT performance)	2 bytes

3.7 External Interfaces

The interfaces of the EPS external are listed in table 7.

Table 7 – *External interfaces*

External interface	Implementation
Solar array mounting to rigid ballon structure	Screws and bolts
DC-DC regulators	Mounted on PCB which sits in system housing. Thermal contact points should be included, to remove internal heat dissipation.
Voltage/current sensor telemetry	Analog signals to Microcontroller
Payload supply voltages	$3.3\,V$(unregulated) and $5.0\,V$(regulated)

4 Test and Verification of Design

4.1 Design Models and Verification Methods

PSpice Simulations

PSpice transient and average simulation models of the SAR will be created. These will help in the design and testing of the regulator performance and system stability during transient loading.

Development Model

A Development Model (DM) will be build using self-made "mini-mount" pads and mainly surface-mount components, to minimize parasitic effects. System stability will be tested using a Network Analyzer and MPPT performance will be tested in a Thermal Vacuum (TV) chamber cycling the solar array temperature.

Flight Model

If time allows, a dedicated Flight Model (FM) will be build, using a custom designed Printed Circuit Board (PCB) schematic layout. An optimized PCB layout will minimize the system mass and size while maximizing the efficiency and system robustness.

5 Resources and Scheduling

5.1 Main Tasks

The main tasks, to implement the proposed EPS design, are listed in table 8.

Table 8 – *Main EPS design and implementation tasks*

No.	Task	Duration [days][a]	Dependence (finish to start)
1	Design DC-DC regulator	3	-
2	PSpice regulator simulation	5	1
3	Order components and produce mini-mount patches[b]	1	1, 2
4	Assemble solar cells	3	1, 3
5	Design battery regulation and protection circuits	3	1
6	Build and test battery circuits	2	3, 5
7	Build prototype regulator (without MPPT)	3	1, 3
8	Test prototype regulator (without MPPT)	3	1, 2, 7
9	Design and build MPPT	5	7
10	Test MPPT	2	9
11	Design custom PCB layout	2	1, 5, 9
12	Manufacture PCB and mount components	3	11

[a] 1 day = 8 effective working hours
[b] small pieces of PCB, with sticky bottom, very suitable for high frequency circuit prototyping

5.2 Parts List and Costs

The preliminary parts list for the EPS is listed in table 9.

Table 9 – *Main EPS design and implementation tasks*

Part	Part No.	Cost[SEK][a]	Reference
Solar cells	MC-SP0.8-NF-GCS	61 kr	www.farnell.com
Battery	PA-LN19	326 kr	www.farnell.com
PWM controller	To Be Decided (TBD)	-	-
Power MOSFET	TBD	-	-
Power diode	TBD	-	-
MOSFET gate driver (high side)	TBD	-	-
OpAmps (feedback regulators)	LT1498	92 kr	www.farnell.com
Main bus capacitors	CKG45NX7R1H335M	38 kr	www.farnell.com
COTS DC-DC converter	IK1205SA	39 kr	www.farnell.com
Inductor core(s)	TBD	-	-
Current sensor	TBD	-	-
PCB	TBD	-	-

[a]cost per piece, hence total cost may be significant higher, depending on required quantity

5.3 Electronics Ground Support Equipment (EGSE)

- Laboratory equipment, i.e. Network Analyzer, Digital Oscilloscope, power supplies, multi-meters
- TV chamber

5.4 Mechanical Ground Support Equipment (MGSE)

- PCB manufacturing facilities, i.e. UV light source, etching facility, punch-through hole machine, photo-resist

References

[1] Multicomp. *MC-SP0.8-NF-GCS*. Tech. rep. www.farnell.com, 2010.

[2] *Spacecraft Power Systems*. CRC Press, 2005.

[3] Panasonic. *PA-LN19.K02.R001*. Tech. rep. http://www.farnell.com/datasheets/1441772.pdf, 2011.