Solar Powering of Distributed Embedded Systems

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Abstract

The high level of energy consumption that the industrialised countries have reached and the pollution that this brings has long been a cause for analysis and debate, development and usage of so called renewable energy sources is therefore more important than ever. The energy in the electromagnetic radiation from the sun is an interesting alternative. One way of harvesting this energy is by using solar cells, devices that generate DC current when exposed to electromagnetic radiation.

The goal of this master's thesis was to design a solar powered power supply to Syntronic AB’s Midrange platform. The envisioned application is a stand-alone distributed embedded system, for example a node-based temperature monitoring system. Creating a tool for design of solar powered systems and identifying important factors needed to be taken into consideration was the objective. One of the set requirements was that the system had to be able to operate in Sweden with a maximum of 5% down-time, using the daily solar irradiance of 2009 as a reference.

The final results are two different hardware-based solutions, both using a solar module with a maximum power of 1 W, a 52 F ultracapacitor as energy storage and a circuit to both control the operation of the solar module and to provide the Midrange platform with a 3 V supply voltage. The systems were implemented to evaluate their performance. With the approximated performance together with daily irradiance for three different locations in Sweden, the result was that both solutions met the requirement of 5% down-time for the solar irradiance in Stockholm and Malmö, for Luleå however neither solution met the requirement.
Sammanfattning

Industriländernas omfattande energi- och resursförbrukning har länge varit ett hett debattämne och utvecklingen och användandet av så kallade förnyelsebara energikällor är idag viktigare än någonsin förr. Energiinnehållet i den elektromagnetiska strålningen från solen kan utnyttjas på en rad olika sätt, ett av dessa är att använda solceller, en teknologi där celler genererar likström då de utsätts för elektromagnetisk strålning.

Syftet med examensarbetet var att konstruera en solcellsdriven energiförsörjning till Syntronic AB's Midrangeplattform. Det tänkta användningsområdet är fristående distribuerade inbyggda system som exempelvis nodbaserade temperaturövervakningssystem. Att skapa ett verktyg för konstruktion och dimensionering av ett solcellsdrivet system och identifikation av viktiga aspekter som måste tas hänsyn till var målet. Ett av de ställda kraven var att det skulle kunna användas i Sverige med ett årligt maximum av 5 % av dagarna i stillastående med den dagliga solinstrålningen under 2009 som referens.

Examensarbetet resulterade i två olika hårdvarubaserade lösningar innehållande en solcell med maxeffekt 1 W, en 52 F ultrakondensator som energilagring och en effektövervakningskrets som reglerar solcellens arbetspunkt och som förser Midrangeplattformen med en 3 V matningsspänning. Systemen implementerades för att utvärdera prestandan. Resultaten sammanställdes sedan med den dagliga energiinstrålningen för tre olika platser under 2009, resultatet var att båda lösningarna klarade kravet på max 5 % av dagarna i stillastående för solinstrålningen i Stockholm och Malmö, lösningarna klarade dock inte kravet med solinstrålningen i Luleå.
Acknowledgements

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Also, thank you Marika Edoff at Uppsala University for guidance in the solar cell field and for providing the project with a solar module and Fredrik Carlsen at OEM Electronics for help with ultracapacitor choice and sponsoring. Finally, many thanks go to Mats Blomqvist at Triab AB for sponsoring the project with PCB mounting when no other solution was within reach.
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1. Introduction

1.1. Background
The high level of energy consumption that the industrialised countries have reached and the pollution that this brings has long been a cause for analysis and debate, development and usage of so called renewable energy sources is therefore more important than ever. Also, reaching a high efficient way of generating and storing energy is of importance since the sources of energy that dominate the global energy production are finite.

Some of the solutions that have emerged derive the energy encapsulated in different natural phenomena on the globe such as wind, waves, waterfalls, osmosis and solar radiation. The energy in the electromagnetic radiation from the sun is an interesting alternative. One way of harvesting this energy is by using solar cells.

Syntronic AB have developed a platform based on an ARM Cortex-M3 32-bit microcontroller called the Midrange platform that is intended to be used in future projects. They wanted to investigate the possibility to develop applications based on the platform that are solar powered with a temporary energy buffer. The envisioned application is a stand-alone distributed embedded system, for example a node-based temperature monitoring system. As a part of this it was of interest to optimise the operation of the solar module, the usage of the energy that it produces and the charging of the energy storage.

1.2. The objective
The goal of this master’s thesis was to design a solar powered power supply to Syntronic AB’s Midrange platform. Creating a tool for design of solar powered systems and identifying important factors needed to be taken into consideration was the objective. The focus was to optimise the charging and power flows in the system from a low energy consuming point of view, meaning that losses should be minimised while maintaining the stability of the power supply and not renouncing the energy storage life length. Some of the main questions that were investigated were:

- What power demands were there, including possible transients? Could these be minimised?
- How is the dimensioning of the solar cells and energy storage for a certain load and available solar energy at the chosen operating location made?
- What were the main losses in the system? How could these be minimised?
1.3. Requirements and delimitations

One of the demands was that the system should be based on Syntronic’s Midrange platform. The microcontroller of the platform could be used as a part of the power supply. Apart from this smaller changes were allowed to be done on the platform to increase the efficiency of the system as a total.

It was not of importance to take the final system's operating environment, such as moisture, into account when designing the system, except for the incoming solar irradiance. Furthermore the system had to be able to run during the entire year and should be dimensioned for the solar irradiance available in Sweden. Finally a complete system with hardware, eventual software and belonging documentation should be delivered.

1.4. Method

The master’s thesis corresponds to 30 credits and was carried out in project form with the V-model, see Figure 1, as basis for the methodology. Initially the requirements for the system were set from a functional point of view and a macroscopic system design was made. A literature study was then performed to deepen the knowledge about the Midrange platform, the solar irradiance conditions in Sweden and solar cell technology. After this the design process was initialised and different possible solutions were derived using simulation tools. The final solutions that were the most attractive from a low energy consuming point of view were then implemented. After this unit testing and final testing was made and the results were analysed.

Figure 1. The V-model was the basis for the working methodology.
### 1.5. Terminology

The terminology that was set for the project is listed in Table 1.

Table 1. List of terminology for the project.

<table>
<thead>
<tr>
<th>Variable/Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c )</td>
<td>Speed of light in vacuum</td>
</tr>
<tr>
<td>( E )</td>
<td>Energy</td>
</tr>
<tr>
<td>( E_{\text{cap consumed}} )</td>
<td>Consumed energy from ultracapacitor over an elapsed time</td>
</tr>
<tr>
<td>( E_g )</td>
<td>Band gap energy</td>
</tr>
<tr>
<td>( E_{\text{load, 24h}} )</td>
<td>Energy that the load consumes during 24 h</td>
</tr>
<tr>
<td>( FF )</td>
<td>Fill factor, determines quality of a solar module</td>
</tr>
<tr>
<td>( h )</td>
<td>Planck’s constant</td>
</tr>
<tr>
<td>( I_{\text{cap}} )</td>
<td>Ultracapacitor current</td>
</tr>
<tr>
<td>( I_{\text{load}} )</td>
<td>Output current, supply current to Midrange platform</td>
</tr>
<tr>
<td>( I_{\text{MPP}} )</td>
<td>Solar module current at maximum power point</td>
</tr>
<tr>
<td>( I_{\text{PV}} )</td>
<td>Solar module current</td>
</tr>
<tr>
<td>( I_{\text{SC}} )</td>
<td>Solar module short circuit current</td>
</tr>
<tr>
<td>Load</td>
<td>The Midrange platform</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point, best operation point of solar module</td>
</tr>
<tr>
<td>( P_{\text{average consumed}} )</td>
<td>Average power consumed from ultracapacitor over an elapsed time</td>
</tr>
<tr>
<td>( P_{\text{cap}} )</td>
<td>Power provided by ultracapacitor</td>
</tr>
<tr>
<td>( P_{\text{cap loss}} )</td>
<td>Internal losses in the ultracapacitor</td>
</tr>
<tr>
<td>( P_{\text{load}} )</td>
<td>Output power consumed by Midrange platform</td>
</tr>
<tr>
<td>( P_{\text{loss}} )</td>
<td>All losses except for internal losses in ultracapacitor</td>
</tr>
<tr>
<td>( P_{\text{MPP}} )</td>
<td>Solar module power at maximum power point</td>
</tr>
<tr>
<td>Power supply</td>
<td>The energy harvesting source, the energy storage and any parts controlling these</td>
</tr>
<tr>
<td>( P_{\text{PV}} )</td>
<td>Solar module power</td>
</tr>
<tr>
<td>PV cell</td>
<td>A single photovoltaic cell, also called solar cell</td>
</tr>
<tr>
<td>PV module</td>
<td>Several interconnected solar cells working as one module</td>
</tr>
<tr>
<td>System</td>
<td>The system as a total including the energy harvesting source, the energy storage, any parts controlling these and the Midrange platform</td>
</tr>
<tr>
<td>Unit</td>
<td>A part of the system</td>
</tr>
<tr>
<td>( V_{\text{cap}} )</td>
<td>Ultracapacitor voltage</td>
</tr>
<tr>
<td>( V_{\text{load}} )</td>
<td>Output voltage, supply voltage to Midrange platform</td>
</tr>
<tr>
<td>( V_{\text{MPP}} )</td>
<td>Solar module voltage at maximum power point</td>
</tr>
<tr>
<td>( V_{\text{DC}} )</td>
<td>Solar module open circuit voltage</td>
</tr>
<tr>
<td>( V_{\text{PV}} )</td>
<td>Solar module voltage</td>
</tr>
<tr>
<td>( \eta )</td>
<td>Efficiency</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Wavelength</td>
</tr>
</tbody>
</table>
2. **System requirements and macroscopic layout**

2.1. **Set requirements**

The following requirements were set from a functional point of view for the final system.

- The power supply shall ensure that the load, the Midrange platform, is provided with a stable input power to be able to work properly.
- The supply voltage for the load shall at steady state operation be 3 V.
- Down-time is defined as periods when the supply voltage is below 2 V.
- The load shall be able to operate during the whole year and should be dimensioned for the solar irradiance available in Sweden. A maximum of 5% down-time is allowed with solar irradiance conditions during 2009 as reference.
- The energy storage shall not be overcharged.
- The system shall be designed in such a way that the system could start up by itself, even if the energy storage is empty.

2.2. **Excluded functionalities**

The following functionalities or aspects were excluded.

- Notification of malfunction to the user. This would however be an important feature for these kinds of systems.
- Tuning of the wanted voltage level by the user.
- The climate, excluding the solar irradiance, where the system will be used.
- The casing of the system.

2.3. **Identification of system components**

Initially the main system units were identified. First of all the system was divided into two main parts; the power supply and the load. The load side contains the dimensioning units and in this case it consists of the Midrange platform, hence it defines the power and energy demand that the power supply need to deliver. The power supply consists of an energy harvesting unit, an energy storage unit and a controlling unit. The energy harvesting unit is the PV module, the solar module, and the energy storage works as a buffer for operation at times with no solar irradiance. The controlling unit, called the power supervisor, controls the operation of the PV module,
charges the energy storage and supplies the load with correct voltage. Figure 2 gives an overview of how these units are interconnected and the terminology.

**Figure 2.** *The macroscopic system layout and definition of system units.*

Note that the microprocessor on the Midrange platform was allowed to be used as a part of the power supervising unit. To be able to choose suitable PV module and energy storage and to design the power supervising unit, further knowledge concerning the Midrange platform, available solar irradiance in Sweden and PV cell technologies had to be retrieved.
3. The Midrange Platform

The Midrange Platform is Syntronic’s latest development platform. It is based on ARM Cortex-M3 32-bit microcontroller and is equipped with peripheral units for the interfaces below, where the number in parentheses denotes how many of each peripheral units that are present on the platform.

- RS232 (2)
- A/D (8)
- D/A (2)
- USB (1)
- SD-card reader (1)
- CAN (1)
- GPIO:s
- RS485 (1)
- Ethernet (1)
- I2C (1)
- SPI (1)
- Display
- CAN (1)

The used microcontroller is the STM32F103VC. The core is an ARM Cortex M3 32-bit that has a maximum frequency of 72 MHz. It has the low power modes Sleep, Stop and Standby and a supply voltage range of 2.0-3.6 V [1]. Figure 3 shows a picture of the Midrange platform.

![Figure 3. The Midrange platform.](image)

3.1. Power consumption

The power consumption of the microcontroller depends on several factors. One of the most central factors is the clock frequency, the power consumption decreases with decreasing frequency. For instance the STM32F103xC, STM32F103xD and STM32F103xE microcontrollers’ current consumption in run mode when using internal clock, with all peripherals enabled and code running from Flash is 45 mA at 64 MHz, 6.6 mA at 8 MHz and 0.7 mA at 125 kHz, this is with a 3.3 V input voltage, [1] Table 18. Due to this it is of importance to choose a clock frequency that is sufficient for the needed performance of an application when low consumption is needed. Another way of lowering the power consumption is to make sure that different
peripherals are disabled when not used. The STM32F103xC, STM32F103xD and STM32F103xE microcontrollers’ current consumption in run mode when using internal clock, with all peripherals disabled and code running from Flash is 27 mA at 64 MHz, 4.4 mA at 8 MHz and 0.6 mA at 125 kHz, this is with a 3.3 V input voltage, [1] Table 18. Also peripheral clocks could be lowered to decrease power consumption and by using lower supply voltage the current consumption decreases marginally. The current consumption increases with increasing temperature why measures should be taken to cool the microcontroller to lower power consumption. Figure 4 shows how the current consumption depends on the surrounding temperature and the supply voltage level.

![Figure 4. Current consumption in standby mode versus the surrounding temperature for different supply voltage levels. [1]](image)

The low power modes are built in features of the microcontroller to reach low power consumption. With correct software design the average current consumption could be lowered substantially by using these low power modes. The STM32F103xC, STM32F103xD and STM32F103xE microcontrollers’ current consumption in sleep mode when using internal clock, with all peripherals enabled and code running from Flash is 25.6 mA at 64 MHz, 3.3 mA at 8 MHz and 0.6 mA at 125 kHz, this is with a 3.3 V input voltage, [1] Table 19. In stop mode the current consumption is typically 25-35 µA with 3.3 V input voltage and standby mode gives a current consumption of typically 2.1-3.8 µA with 3.3 V input voltage, these values depend on the configuration of the chosen mode, [1] Table 17.

Depending on what peripheral units on the microprocessor and on the platform that are used, the power consumption will increase. For the thought usage field of a stand-alone solar powered Midrange platform it was thought that a fairly low average current consumption could be reached.
4. Solar irradiance in Sweden

Irradiance is a term used to describe the power of electromagnetic radiation per unit of area, W/m². The sun emits electromagnetic radiation that hits the outer limits of earth’s atmosphere with an average of 1366 W/m² [2], this is often called the solar constant. The distance between the sun and earth varies with ±1.5 % [2] but the variations in irradiance over a year depend upon the earth’s axis angle to the orbit around the sun. The irradiance at a horizontal plane on the earth’s surface consists of direct and diffuse irradiance. The latter is any irradiance that is scattered by the atmosphere and the former is the amount of irradiance coming directly from the sun. The sum of these two is called global irradiance and it is this value that is of interest when calculating the amount of energy that is available for energy generation using PV cells [2].

For a plane that is not horizontal, another factor is present, the reflected irradiance, which is irradiance that has been reflected by the ground. Figure 5 shows the yearly sum of the global irradiation in Sweden, derived by the European Commission during the PVGIS project [3]. The charts show the value for a surface at optimum inclination angle and facing south and for a surface with horizontal orientation. A chart over the yearly sum of global irradiation at a surface at optimum angle for Europe could be found in Appendix 1 [3].

Figure 5. The yearly sum of the global irradiation in Sweden for optimum angle and horizontal plane. [3]
It could be seen in the two charts in Figure 5 that there is an increase in the magnitude of 20% in the incoming energy at optimum angle in comparison to the horizontal plane. This increase is due to the fact that a larger amount of the direct irradiance and some reflected irradiance will hit a surface at the optimum angle. The optimum angle for a certain location does however also depend on surrounding terrain, such as mountains, that might shade the surface for some part of the day. For some locations in Sweden a horizontal orientation has been shown to reach highest yield. The optimum inclination angle in Sweden has been calculated to be between 37°-47° depending on the location, the average angle in Sweden is about 43°. [3]

4.1. SMHI’s model system STRÅNG

SMHI (Sveriges Meteorologiska och Hydrologiska Institut) has developed a model system called STRÅNG [4], that calculates different types of irradiate data for the Scandinavian region based on data from scientific models. From this model, data could be extracted from 1999 and forward. The data could be in hourly, daily, monthly or yearly basis and values, fields or charts could be extracted for

- UV irradiation, 15 % maximum error
- Global irradiation, 15 % maximum error
- Direct irradiation (at angle normal to incoming irradiation), 30 % maximum error
- Sunshine duration, 30 % maximum error
- Photosynthetic photon density, no available maximum error

Figure 6 show two extracted charts over the global irradiation in Wh/m² for a horizontal plane in 2009-01-01 and 2009-07-01 respectively.

Figure 6. The daily global irradiation for horizontal plane in 2009-01-01 and 2009-07-01. [4]
5. Photovoltaic technology

This chapter gives an overview of photovoltaic cell technology and the main characteristics of photovoltaic cells.

5.1. Background

A photovoltaic cell, often called PV cell, is a device that generates electrical energy when exposed to electromagnetic radiation in the gap between UV-IR without any material consumption. It applies the photovoltaic effect; the ability of some materials to convert electromagnetic radiation into electricity on the atomic level. The material will absorb photons and excite electrons. A single PV cell produces DC current at a fairly low voltage, typically around 0.5 V [5], why it is often series connected into a PV module to reach a useful voltage. It was Edmond Becquerel who discovered the phenomenon in 1839 and in 1905 Albert Einstein described the physics of the photoelectric effect, which later earned him the Nobel Prize in physics [6]. Still, it was only when the semiconducting material silicon was introduced in the late 1950's that the first generation PV cells became available and initially it was mainly used in calculators and satellites. With the start-up of the climate debate in the early 1970’s the PV cell as an alternative energy generating resource became a big field of research. [7]

One main characteristic of a PV cell is its efficiency, the amount of power that the PV cell is exposed to that is converted into electrical power. Today a commercial PV module typically has an efficiency level around 5-15 % [8] and recently a 22 % PV module has been introduced by SunPower [9]. Tests in laboratory environment have however reached efficiencies above 40 % [10]. The efficiency and price are today said to be the main properties that need to reach a certain level for the PV cell to become a true alternative energy generating source meaning that performance per manufacturing cost should be high [11]. Also the pay-back time for the PV cell is of great importance, which is the time that it takes for the PV cell to generate the same amount of energy that was used when producing it [12].

Today more than 95 % of all produced commercial PV cells are silicon based [13]. With silicon being the second most abundant element in the earth's crust, the availability is not the foremost problem, however there has been a shortage of silicon suppliers to the PV industry. Through the years, other types of PV cells using different types of semiconducting materials have emerged with potential of lowering cost and reaching higher efficiency levels. Amongst these, new technologies applying nanotechnique go beyond the traditional PV cell structure; the energy absorption takes place in a dye instead of in a semiconductor [11].
The PV cell technologies are today often divided into three groups [14]:

First generation: Based on crystalline silicon, both monocrystalline and polycrystalline silicon.

Second generation: Based on amorphous silicon or other types of semiconductors, thin-film cells, CIGS, tandem cells.

Third generation: Nanocells, also called Grätzel cells or Dye-synthesised Solar Cells (DSC).

5.2. Underlying physics

The band gap energy

Semiconductors are materials that are neither conductors nor isolators. A silicon atom has four valence electrons meaning that the atom could share electrons with four other atoms, building a crystalline structure. This structure has semiconducting properties since the electrons are locked in the crystalline structure, but can be excited.

For a semiconductor there is an energy gap between the highest filled energy band, called the valence band, and the first empty band, called the conduction band. This gap is called the band gap energy, $E_g$. By applying energy corresponding to the band gap, electrons could be excited from the valence band to the conduction band. When this happens there will be a vacant position in the valence band, an electron hole. The electrons in the conducting band and the electrons holes, which will act as a positive charge, are the charge carriers in a semiconductor, both can move within the semiconductor and are often called an electron-hole pair. When these are present the semiconductor could conduct electricity. [8]

The band gap of crystalline silicon is 1.1 eV which corresponds to electromagnetic radiation of wavelength 1100 nm, denoted as infrared light. Photons with the energy level $E < E_g$ will not excite an electron, while photons with the energy level $E \geq E_g$ will excite an electron to the conduction band. The eventual residual energy will rapidly be lost as heat, if the energy of the photon has twice the band gap the residual energy could though excite one more electron. [7]

The electromagnetic radiation

The main electromagnetic radiation from the sun that hits the earth’s surface lies between the wavelengths, $\lambda$, 300 nm and approximately 2500 nm, from UV radiation to IR radiation [2]. The photon energy, $E$, of the radiation increase with increasing frequency, $\nu$, i.e. decreasing wavelength, $\lambda$, according to Planck’s quantum formula, also called Planck’s law,
\[ E = h \nu = \frac{hc}{\lambda} \]  

(1)

where 

\[ h \approx 6.626 \times 10^{-34} \text{Js}, \text{Planck's constant, and} \]

\[ c \approx 2.998 \times 10^8 \text{m/s}, \text{the speed of light in vacuum}. \]

With the relation that

\[ 1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} \]

the energy level in eV of the photons could be calculated. The photon energy levels available at the earth’s surface lie in between 0.50 eV (at 2500 nm) and 4.1 eV (at 300 nm). The total power that hit a surface, the irradiance, however also depends on the intensity. Figure 7 describes a typical spectral irradiance at sea level, which shows that the highest irradiance per wavelength roughly lies in between 400 nm and 700 nm, i.e. the gap of visible light. Here the available photon energy levels are between 1.8 eV (at 700 nm) to 3.0 eV (at 400 nm).

![Figure 7. The spectral irradiance from the sun at sea level. [2]](image)

### 5.3. Photovoltaic cell characteristics

#### The IV-curve

A PV cell has a typical current-voltage characteristic shown in the upper graph in Figure 8. For a module consisting of many cells the curve will have the same appearance. The IV-curve shows that the voltage over the PV cell decreases with increasing current consumption. The produced power will therefore vary with the load, which could also be seen in Figure 8. There is a maximum power point, MPP, where the PV cell should be operating to achieve highest efficiency, and the current and the voltage at this point are often denoted as \( I_{MPP} \) and \( V_{MPP} \) respectively. The power produced at MPP is often denoted as \( P_{MPP} \). The short circuit current, \( I_{SC} \), and the open
circuit voltage, $V_{OC}$, are typical parameters when characterising a PV cell, these are also shown in Figure 8.

Another characteristic of a PV module that is often used is the fill factor, $FF$, which is defined as

$$FF = \frac{V_{MPP}I_{MPP}}{V_{OC}I_{SC}} = \frac{P_{MPP}}{V_{OC}I_{SC}}. \quad (2)$$

It is basically a figure saying something about the “squareness” of the IV-curve. The closer the value is to 1, the better is the performance of the PV cell since the $P_{MPP}$ would be larger. The look of the IV-curve depends of the PV cell characteristics such as the equivalent shunt resistance, $R_{SH}$, and the equivalent series resistance, $R_s$. The equivalent circuit of a non-ideal PV cell is shown in Figure 9 where the shunt and series resistances are shown. For an ideal PV cell $R_s$ would be infinitely small and $R_{SH}$ would be infinitely big. This would result in an entirely square IV-curve and $FF$ would be 1.

Figure 8. Typical IV-curve of a PV cell. The power dependence is shown in the lower graph with the maximum power point marked out.

Figure 9. Equivalent circuit of a non-ideal PV cell.

Figure 10 shows the IV-curve for a commercial PV module and how it depends of the irradiance and the temperature. The current is directly proportional to the irradiance and gets lower with
lower irradiance, with a slightly lowered voltage. The voltage is however dependent on the temperature, higher temperature gives a lower voltage.

![Typical IV-curve for a PV module from SunPower with shown irradiance and temperature dependence.][1]

**Figure 10.** Typical IV-curve for a PV module from SunPower with shown irradiance and temperature dependence. [15]

**Theoretical limit of efficiency**

There is an actual theoretic limit of the efficiency of a PV cell. The efficiency, $\eta$, is defined as the overall energy conversion as

$$\eta = \frac{P_{MPP}}{P_{in}} = \frac{I_{MPP}V_{MPP}}{P_{in}}$$

where

- $P_{MPP}$ is the power at MPP.
- $P_{in}$ is the irradiate power incident on the PV cell under standard test conditions; 1000 W/m$^2$ irradiance, temperature 25 °C and AM 1.5 reference spectrum. [16]

The generated energy from a PV cell is directly dependent on the flux of photons with energy $E \geq E_g$, and therefore depends on the band gap of the material in the PV cell. As said before the photons with lower energy level $E < E_g$ will not excite electrons, nor will most of the residual energy $E > E_g$, most of this energy is lost as heat. This means that a great amount of the incoming energy is lost, hence the theoretical efficiency limit. PV cells are therefore suited for a specific spectral range, depending on the material that is consists of, and the possible amount of energy converted into electricity is limited. However, the second and third generation of PV cells are often able to cover a larger spectral range by combining materials with different band gaps, resulting in a potentially higher efficiency.

Why not choose a material with a really low band gap? The current will increase with decreasing band gap, but at the same time the net energy transferred to each electron-hole pair decreases,
as it is equal to $E_g$. This means that the band gap determines the voltage over the PV cell. Therefore there exists an optimal band gap for which a maximum of energy could be generated, where roughly half of the electromagnetic radiation energy will contribute to an electron-hole pair with a first generation PV cell [7]. The optimum band gap for single-junction PV cells, first generation PV cells, has been calculated to 1.14 eV [17].

Other types of losses that contribute to the theoretical efficiency limit are optical losses and conduction losses. The optical losses that could occur are a result of the shadowing of the PV cell surface made by the contact grid placed on the top of the cell, but also because of the fact that some of the radiation will be reflected by the surface. Conduction losses are due to electrical resistance in the semiconductor, the conductors and the connectors, these are increased with increased current. Also defects in the structure of the materials should be considered. [13]

Figure 11 shows the best research efficiencies that have been achieved for different types of PV cell technologies.

![Best Research-Cell Efficiencies](image)

Figure 11. Best research efficiencies for different PV cell technologies. [18]

5.4. Three generations of photovoltaic cells

First generation PV cells

The first generation PV cells are based on either monocrystalline or polycrystalline silicon. Monocrystalline silicon PV cells have been shown to reach higher efficiencies out of these two
but polycrystalline silicon PV cells are cheaper to manufacture. These PV cells have also shown to have excellent stability and reliability over several decades, even under outdoor conditions [7]. Tests has shown that the lifetime exceeds 20 years for these types of PV cells, under the criteria that maximum power should not decrease more than 8% of the initial maximum power. This has been confirmed by the first installed PV systems that have lasted for 20 years plus [19]. These factors make the first generation PV cells the dominating produced PV cells and also the fast growth in manufacturing of PV cells has meant large investments in existing production techniques since new higher performing PV cells production techniques are not yet verified [11].

As said before crystalline silicon has a band gap of 1.1 eV, which corresponds to photons with wavelength 1100 nm. This is not in the visible electromagnetic spectrum, but in the infrared spectrum. The theoretical efficiency limit has been calculated to 33%, with the main losses in heat losses [20]. Commercial PV modules have in general an efficiency of about 11-13% [11], SunPower recently released a commercial module with 22% efficiency [9].

The first PV cells consisted of two layers of crystalline silicon that are n- and p-doped respectively. Doping means that impurities intentionally are introduced in the material to create charge carriers and giving the material higher conducting properties. In this case the impurities are atoms with one electron too much, called n-doping, or one electron too little, p-doping. This means that the n-doped silicon will have electrons that are weakly bounded to its original atom in the valence band, the material will be electrically negative. The p-doped silicon will have a lack of electrons, electron holes, and will be electrically positive. Usually phosphorous atoms are used for n-doping and boron atoms are used for p-doping. Figure 12 shows how the crystalline silicon structure looks for non-doped, n-doped and p-doped silicon, note that it in reality is a 3-dimensional structure.

![Figure 12. 2-dimensional picture of the silicon structure. a) is pure crystalline silicon, b) is n-doped silicon with phosphorus atoms and c) is p-doped silicon with boron atoms.](image)

When putting the n-doped and p-doped silicon together a p-n-junction occurs in the boundary between the layers. Initially a diffusion of electrons from the n-doped side to the p-doped side will take place and the electrons fill the electron holes. This is a transient however since an
electric field occurs and it becomes harder and harder for the electrons to diffuse. After a while equilibrium is reached and no free electrons can fill the holes, an electric field has been formed acting as a diode only allowing electrons diffuse from the bottom p-doped silicon to the top n-doped silicon. A PV cell has been produced. Figure 13 shows the basic layout of a PV cell. The bottom could be completely covered with conducting material and the top often has a grid of conducting material so that as little as possible of the top area is covered. [8]

![Figure 13. The first generation PV cell and its main parts.](image)

When photons hit the PV cell, electron-hole pairs will occur. The electric field will repel the electrons to the top side of the PV cell, the n-doped silicon, and the holes will be attracted by the p-doped silicon and pass through the p-n-junction. Now, there is an electric potential over the PV cell. If a load is connected in between the top and the bottom side, a current will occur, with the bottom side acting as the positive pole and the top side acting as the negative pole. [7]

![Figure 14. PV cell generating DC current.](image)

**Second generation PV cells**

This group of PV cells is characterised by the motivation of lowering the cost per produced kWh. This is not made by reaching higher efficiency levels as for the first generation PV cells, but by lowering usage of expensive materials and developing cost effective production strategies [21]. There has been a wide range of research concerning this type of PV cells which are often called thin-film solar cells, which are often referred to as those who use active semiconducting material thickness of about 10 µm or less [8]. Some of the most common types are amorphous silicon cells, tandem cells, and CIGS cells. Amorphous silicon PV cells were the first thin-film cell type to reach the stage of large scale production. Its low efficiency values have although been its major handicap, commercial modules have efficiencies between 4 and 8 %. [7]
Tandem cells, or multi-junction cells, are PV cells consisting of several semiconductors with different band gaps, leading to the potential of absorbing a larger amount of the incoming photons. Basically the cell has several pn-junctions in series and by making each layer thin enough the light will be able to pass through semiconductors with a too high band gap. The different semiconducting materials are chosen with care to tune the absorbed photon wavelength and reach higher efficiency. This design has though been shown to be expensive and the reached efficiencies has been lower than for the commercial first generation PV modules and consequently the PV cell type does not have a commercial potential in the nearest future. [11][20]

The photon absorbing material in a CIGS cell is Cu(In,Ga)Se$_2$, hence the name. It has a typical band gap between 1.1 to 1.2 eV depending of the composition [7]. It has reached the commercialisation stage and is thought to be a competitive solution for future large scale energy harvesting. This because of its relatively effective material usage, cost effective production strategies and high efficiency, NREL (National Renewable Energy Laboratory, Golden, Colorado) has reached 19.2 % in test environments and Ångström Solar Center in Uppsala has reached 16.6 % efficiency for a commercial module [11]. The CIGS cell is a single-junction cell and is built up by several layers, see Figure 15, were the CIGS layer (Cu(In,Ga)Se$_2$) is of p-type and zinc oxide layer (ZnO) is of n-type. Between these a very thin buffer layer of cadmium sulphide (CdS) is present, which has been shown to play a very important role in the PV cell performance. The back contact consists of molybdenum (Mb) and the front contact consists of a transparent layer of aluminium doped zinc oxide (ZnO:Al). This construction lays on a glass substrate. [21][22]

![Figure 15. Schematic figure of the different layers in a CIGS cell.](image)

**The third generation PV cells**

The third generation PV cell has emerged as an important step in the right direction. It differs from the first and second generation since it implements a different approach when harvesting the photon energy. The photon absorption takes place in a dye instead of in a semiconductor and the reaction is often compared to photosynthesis. The third generation PV cells are often called Dye-sensitised Solar Cell (DSC), nanocell or Grätzel cell, and acts on a molecular level, giving it the potential to have other physical properties than previous generations of PV cells. It was
Michael Grätzel and his co-workers who realized the first DSC in the early 1990’s and in June 2010 Michael Grätzel was awarded with the Millennium Technology Prize for his discoveries. [23]

A DSC cell consists of four main components which are a photosensitive dye, an electrolyte, a nanostructured electrode and a counter electrode. The nanostructured electrode, called the working electrode, often consists of titanium dioxide (TiO$_2$) particles deposited on a transparent conducting substrate, for example tin oxide (SnO$_2$) coated glass, giving it a much larger actual TiO$_2$ area than the macroscopic area. The dye is adsorbed to the nanostructured electrode, the TiO$_2$ particles have been dye-sensitised. Between this electrode and a counter electrode, typically platinum (Pt) coated glass, an electrolyte is present. The electron-hole pairs occur in the dye. The working electrode, the counter electrode and the electrolyte acts as charge carriers in the PV cell, the working electrode will act as the negative pole and the counter electrode will act as the negative pole. [8][20]

Depending of the choice of materials, for example plastic substrates, this kind of PV cells could be made transparent, lightweight and flexible, giving it many new attractive fields of usage, for example energy harvesting windows. It has also been shown that the voltage does not drop at lower irradiance, giving it good potential of indoor operation. As for the second generation PV cells its foremost advantage is not the efficiency but potential low price and simple energy-efficient production, in general it has a lower efficiency than the previous generations (11 % has been reached in laboratory environment [21]). However there are still question marks regarding life time and efficiency for commercial modules.
6. **System design**

6.1. **Initial considerations**

One important aspect when designing these types of systems is whether the focus should lay on minimising the cost or optimising the performance. It was decided that the aim was to optimise the performance but to still choose the needed components with care. In this case optimising the performance meant to minimise the energy losses between the consumers and the PV module, and also to maximise produced power from the PV module while active. It was important to have in mind that high complexity often means more components and also more consumers. This meant that the win in maximising the produced power could be lost in additional consumers.

It was early decided that an ultracapacitor would be used as energy storage due to the fact that the technology is emerging as an interesting alternative to batteries for, amongst others, these kinds of applications. Furthermore ultracapacitors do not have the same poor aging and temperature characteristics as batteries, supervision of the charging is not needed and in general a higher current could be maintained from an ultracapacitor if needed. The ultracapacitors’ foremost disadvantage is its self-discharging rate due to leakage current, which closely had to be considered during the dimensioning, and its low power volume and energy volume relationship in comparison to batteries.

The Midrange platform has potential to use a large amount of power with all peripherals activated and running. This would however not be the case for the thought field of usage in this case, such as stand-alone systems monitoring the environment in some way. The software of the microcontroller could be implemented with a low power point of view by using different built in features, such as lowering the system clocks and by using the sleep or standby modes and other measures mentioned in the previous chapter. The power demand had also been lowered with the initial requirement that it should be supplied with a 3 V supply voltage instead of 3.3 V, which is the typical input voltage of the microcontroller. The actual software implementation to reach low consumption was not investigated further.

The Midrange platform has a 5 V input and a low-dropout (LDO) regulator that supplies the microcontroller with 3.3 V. The input to the Midrange platform was however decided to be modified to suit the power supply requirements, the stored energy needed to be used as efficient as possible. The microprocessor will be fed directly from the power supply.
6.2. Further work on the system layout

The macroscopic view of the system, see Figure 2, was initially considered and reworked with the knowledge that had been achieved during the pre-study. The power supervisor was set to have the following main functions.

- To keep the PV module at its maximum power point or as close to it as possible while active.
- To block energy from being consumed by the PV module while not active.
- To charge the energy storage when the PV module is active.
- To make sure that the load is provided with a stable voltage of 3 V when sufficient energy is available from the energy storage and/or PV module.

This ended up in a new system layout where the power supervisor is divided into two blocks; a charging circuit and a voltage leveller, see Figure 16. The voltage leveller was considered separately from the charging circuit when looking at possible solutions. The dimensioning of the energy storage and PV module and the design of the power supervisor was made with this system layout as base.

![System layout after pre-study.](image)

6.3. Power and energy calculations

**Definition of power directions**

The different power flows that were identified and the definition of their set directions are shown in Figure 17. $P_{PV}$ is the net power that the PV module produces. $P_{cap}$ is the power that the ultracapacitor delivers to the power supervisor. $P_{loss}$ include the additional consumers such as needed components in the power supervisor and internal losses in the power supervisor and through the PV module. The leakage current of the ultracapacitor and the resistive losses due to the equivalent series resistance, ESR, when charging and discharging the ultracapacitor are denoted as $P_{cap \ loss}$. $P_{load}$ is the power that the Midrange platform consumes. Note that the losses of the PV module due to its overall efficiency are not considered.
Consumers

Initially an estimation of the power demands of the system had to be done. The Midrange platform was set to be allowed to consume an average of 1 mA at input voltage 3 V. The losses were hard to estimate at this point since the individual components were not chosen yet. Instead the power demand of the Midrange platform solely was used as guideline for an initial system design for later revision with losses included. The power demand of the Midrange platform, $P_{load}$ was calculated to

$$P_{load} = V_{load}I_{load} = 3\, \text{V} \times 1\, \text{mA} = 3\, \text{mW}. \quad (4)$$

This means that the energy consumption during 24 hours, $E_{load,24h}$ would be

$$E_{load,24h} = P_{load} \times 60 \times 60 \times 24 = 3 \times 10^{-3} \times 60 \times 60 \times 24 \approx 259\, \text{Ws}. \quad (5)$$

This corresponds to 0.0720 Wh per day.

Available solar irradiance

To be able to choose suitable PV module and energy storage, information from SMHI’s model system STRÅNG [4] was extracted for three different locations in Sweden with fairly different irradiance levels, Luleå (65°N, 022°E), Stockholm (59°N, 018°E) and Malmö (55°N, 013°E). The incoming energy, in Wh/m², for the global irradiance for each day during 2009 was extracted. This data was then compiled into graphs showing the incoming energy variation during 2009. Figure 18 shows the data for Stockholm and data for all three locations could be found in Appendix 2. It could be seen that there are large variations in incoming energy from day to day and also that the available solar energy is multiple times higher during the summer time in comparison to the winter time.
Figure 18. Daily incoming global irradiance in Wh/m² in Stockholm, data extracted from STRÅNG [4].

The further design of the system was from this point a compromise between the size of the energy storage and the energy that the PV module produces with the known available solar irradiance. By organising the extracted data from STRÅNG in an Excel document with different inputs such as PV module area and $P_{MPP}$ and later on energy storage specifications, a tool for verification of the requirement of 5% down-time was created.

6.4. Choice of PV module

To start with, the choice of a suitable PV module, see Figure 19, was made.

Figure 19. The system layout with shown PV module.

The initial approach was to use a PV module with a $P_{MPP}$ of about 1 W. Uppsala University was able to provide a CIGS module for the project and the specifications are listed in Table 2. These values are measured under the standard test conditions mentioned in the photovoltaic technology chapter.
Table 2. Specifications of CIGS module provided by Uppsala University.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_SC</td>
<td>0.1297 A</td>
</tr>
<tr>
<td>I_MPP</td>
<td>0.1135 A</td>
</tr>
<tr>
<td>V_OC</td>
<td>9.944 V</td>
</tr>
<tr>
<td>V_MPP</td>
<td>7.582 V</td>
</tr>
<tr>
<td>P_MPP</td>
<td>0.8606 W</td>
</tr>
<tr>
<td>FF</td>
<td>0.67</td>
</tr>
<tr>
<td>Module efficiency</td>
<td>9.562 %</td>
</tr>
<tr>
<td>Module area</td>
<td>90 cm$^2$</td>
</tr>
<tr>
<td>Series resistance</td>
<td>542.00 mΩ/cell</td>
</tr>
<tr>
<td>Cells serial</td>
<td>18</td>
</tr>
</tbody>
</table>

The module was decided to be used since it has a high efficiency in its category giving it a compact size of about $10 \times 10$ cm$^2$. It was also of interest to use a second generation PV module since it is thought to be one of the main emerging PV technologies that are on the verge to successfully be commercialised.

6.5. Choice of energy storage

Next step was to decide the needed size of the energy storage, see Figure 20.

![Figure 20. The system layout with shown energy storage.](image)

The energy stored in a capacitor, $E_{cap}$, could be calculated with the following relationship

$$E_{cap} = \frac{CV_{cap}^2}{2}$$

where $C$ is the capacitance and $V_{cap}$ is the capacitor voltage. Since the Midrange platform could be supplied with voltage down to 2 V, the energy in the ultracapacitor could only be used down to this threshold voltage. The energy that would be able to be used from the ultracapacitor could be calculated with the following equation,
\[ E_{\text{cap}} = \frac{C(V_{\text{cap,max}}^2 - V_{\text{cap,min}}^2)}{2}. \]  

(7)

The statement in Equation 7 above shows that an increase of the maximum voltage would have a larger impact on the energy that could be stored than an increase of the capacitance. With the initial assumption that about three times of the daily energy consumption should be able to be stored, the losses were at this point discarded, and with a maximum voltage set to be the same as the PV module maximum voltage, 9.944 V, and a minimum voltage of 2 V, the capacitance of the ultracapacitor would need to be

\[ C = \frac{2 * 3 * E_{\text{load,24h}}}{(V_{\text{cap,max}}^2 - V_{\text{cap,min}}^2)} = \frac{2 * 3 * 259}{(9.944^2 - 2^2)} \approx 16.4 \text{ F}. \]  

(8)

This was the guideline that was used when looking at possible ultracapacitors. It should be mentioned that the maximum and minimum voltage of ultracapacitor were recognised as parameters that would have to be revised when the system had been designed taking eventual voltage drops into consideration.

The leakage current and equivalent series resistance, ESR, of the ultracapacitor were identified as important factors when choosing ultracapacitor, thus these had to be minimised when choosing ultracapacitor. Possibilities of series connecting different sizes to reach the needed working voltage, 10 V, were considered and some of the possible combinations are listed in Table 3.

**Table 3.** Possible ultracapacitors with specified ESR and leakage current. V is the rated voltage and N denotes the number of capacitors in series to reach a working voltage of minimum 10 V. Leakage current occurs at rated voltage. The values have been taken from each ultracapacitor’s manufacturer datasheet.

<table>
<thead>
<tr>
<th>Fabricator and name</th>
<th>V</th>
<th>C</th>
<th>N</th>
<th>V</th>
<th>C</th>
<th>ESR</th>
<th>Leakage current</th>
<th>Volume total</th>
<th>Weight total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxwell BCAP0100P270T07</td>
<td>2.7 V</td>
<td>100 F</td>
<td>4</td>
<td>10.8 V</td>
<td>25 F</td>
<td>60 mΩ</td>
<td>1.04 mA</td>
<td>0.396 l</td>
<td>100 g</td>
</tr>
<tr>
<td>VIMA SuperCapR100-2.5</td>
<td>2.5 V</td>
<td>100 F</td>
<td>4</td>
<td>10 V</td>
<td>25 F</td>
<td>48 mΩ</td>
<td>-</td>
<td>0.112 l</td>
<td>160 g</td>
</tr>
<tr>
<td>Maxwell BPAK0052P015B01</td>
<td>15 V</td>
<td>52 F</td>
<td>1</td>
<td>15 V</td>
<td>52 F</td>
<td>0.8 mΩ</td>
<td>1 mA</td>
<td>0.566 l</td>
<td>500 g</td>
</tr>
<tr>
<td>Power Burst PBD-58/16.2K</td>
<td>16.2 V</td>
<td>58 F</td>
<td>1</td>
<td>16.2 V</td>
<td>58 F</td>
<td>22.4 mΩ</td>
<td>1 mA</td>
<td>0.592 l</td>
<td>514 g</td>
</tr>
<tr>
<td>Maxwell BPAK0058E015B01</td>
<td>15 V</td>
<td>58 F</td>
<td>1</td>
<td>15 V</td>
<td>58 F</td>
<td>19 mΩ</td>
<td>1 mA</td>
<td>0.566 l</td>
<td>560 g</td>
</tr>
<tr>
<td>Maxwell BCAP0310P270T10</td>
<td>2.7 V</td>
<td>310 F</td>
<td>4</td>
<td>10.8 V</td>
<td>77.5 F</td>
<td>8.8 mΩ</td>
<td>1.8 mA</td>
<td>0.212 l</td>
<td>248 g</td>
</tr>
<tr>
<td>VIMA SuperCapMR100-14</td>
<td>14 V</td>
<td>100 F</td>
<td>1</td>
<td>14 V</td>
<td>100 F</td>
<td>18 mΩ</td>
<td>-</td>
<td>0.93 l</td>
<td>1100 g</td>
</tr>
<tr>
<td>VIMA SuperCapMC110-14</td>
<td>14 V</td>
<td>110 F</td>
<td>1</td>
<td>14 V</td>
<td>110 F</td>
<td>7 mΩ</td>
<td>-</td>
<td>1.5 l</td>
<td>1700 g</td>
</tr>
</tbody>
</table>

Note that the leakage current is at rated voltage, the value is measured at steady state and could be higher initially and at lower voltages the leakage current decreases substantially. In some experiments the leakage current has been shown to decrease exponentially with the voltage.
[24]. Maxwell has however commented on this statement and said that there is no such rule. According to Maxwell the leakage current depends on not only the voltage but also the stress history and temperature of the ultracapacitor. With cycling of the ultracapacitor voltage the leakage current will decrease. A higher temperature will increase the leakage current.

The top two candidates in Table 3 would have a total capacitance of 25 F. Because of a leakage current of about 1 mA and the fact that the guideline capacitance, 16.4 F, does not include losses and eventual voltage drop, this capacitance would not be sufficient. At least the double guideline capacitance was thought to be needed since the leakage current is about the same as the supply current to the load. Maxwell’s BPAK0052 P015 B01 ultracapacitor with capacitance 52 F has the lowest ESR in comparison to the other candidates and the leakage current is about the same as for the other ultracapacitors. It was therefore decided to use this ultracapacitor as energy storage, the datasheet could be found in Appendix 3. This meant that the total amount of energy that could be stored is

$$E_{cap} = \frac{C(V_{cap, \text{max}}^2 - V_{cap, \text{min}}^2)}{2} = \frac{52 \times (9.944^2 - 2^2)}{2} \text{Ws} \approx 2470 \text{Ws.} \quad (9)$$

This is 9.5 times the daily energy demand of the Midrange platform only, but was thought to be needed to compensate for the leakage current and the other losses in the system. Note that BPAK0052 P015 B01 has inbuilt active balancing. An ultracapacitor often consists of several interconnected ultracapacitor cells. To ensure that no individual cell is overcharged balancing is needed. [25]
7. HW-design and modelling

The design process of the power supervisor, see Figure 21, was initiated by using LTspice, which is a simulation tool for hardware design. When the design was tested in the simulation environment, the following step was to implement the preferred solution for later unit testing and final testing of the complete system.

![Figure 21. The system layout with shown power supervisor.](image)

7.1. Creating a model of the PV module

First of all a LTspice model of the PV module had to be created to be able to verify that the final hardware design works properly. The PV module model was created by first of all creating a subsystem of an individual PV cell according to the equivalent circuit for a non-ideal PV cell, see Figure 22. The series resistance for each PV cell was given in the PV module specifications, 0.542 Ω/cell. The shunt resistance however was not known and had to be decided experimentally to get and IV-curve as similar to the IV-curve of the chosen PV module as possible, it was approximated to 60 Ω/cell. Also the so called model card, seen in the bottom in Figure 22, for the non-ideal diode in the model had to be adjusted to suit the PV cell. The current source, I1 in the model, was set to the short circuit current, 0.1297 A. MyD, Iph, Rsh and Rs are local parameters in the simulation.

![Figure 22. The LTspice model of an individual non-ideal PV cell and the created symbol.](image)
Note that since the PV module consists of 18 PV cells connected in series the following relationships had to be fulfilled for one individual PV cell:

\[
V_\text{OC,cell} = \frac{V_\text{OC}}{18} = \frac{9.944}{18} V = 0.5524 V
\]

\[
V_\text{MPP,cell} = \frac{V_\text{MPP}}{18} = \frac{7.582}{18} V = 0.4212 V
\]

\[
I_\text{SC,cell} = I_\text{SC} = 0.1297 A
\]

\[
I_\text{MPP,cell} = I_\text{MPP} = 0.1135 A
\]

\[
P_{\text{MPP,cell}} = \frac{P_{\text{MPP}}}{18} = \frac{0.8606}{18} W = 0.04781 W.
\]

The resulting model of the PV cell had an IV- and power-curve shown in Figure 23.

![Figure 23. The final IV- and power-curve of the final model of the individual PV cell.](image)

When the individual PV cell was verified to have the right properties, the PV module model was built up. 18 PV cells were interconnected in series as could be seen in Figure 24.

![Figure 24. 18 PV cells connected in series to create the model of the PV module and the created symbol of the PV module.](image)

The resulting model of the PV module had an IV- and power-curve shown in Figure 25.
Figure 25. The IV- and power-curve of the final model of the PV module.

This model could now be used during the modelling of the solution for the power supervisor.

7.2. Charging circuit strategy

With the designed PV module model the design process of the charging circuit, see Figure 26, could be initialised. It was first needed to decide a strategy for the operation of the charging circuit.

Figure 26. The system layout with shown charging circuit.

The tasks of the charging circuit had been said to be the following:

- To keep the PV module at its MPP or as close as possible while active.
- To block energy from being consumed by the PV module while not active.
- To charge the energy storage when the PV module is active.

There are commercial Maximum Power Point Tracking systems on the market (often called MPPT) implementing different algorithms to track the MPP, these systems differ widely in amongst other things accuracy, cost, efficiency and complexity. It was however of interest to
design a application and power demand specific charging circuit to get knowledge about the
difficulties in the field. These systems will therefore not be further investigated. For further
reading concerning the MPPT algorithms the reader is recommended to read [26].

To keep the PV module at MPP the current flow from the PV module had to be controlled. Due to
the PV cell characteristics the voltage over the PV module, $V_{PV}$, decreases when the current, $I_{PV}$,
increases. This means that the PV module could not be directly connected to the ultracapacitor
since the ultracapacitor will occur as a short circuit when empty and when being charged $V_{PV}$
would be the same as $V_{cap}$. This would mean a quick increase of $I_{PV}$ and $V_{PV}$ would decrease
leading to a power close to zero. To limit $I_{PV}$ an actively controlled transistor was decided to be
used. By controlling the state of the transistor the PV current could be controlled. This could for
example be implemented by using a PWM signal of which the duty cycle is changed.

One other difficulty was that $V_{MPP}$ is not always constant, it decreases slightly with decreasing
irradiance and with increasing temperature. Two main categories of solutions of different
complexity were defined.

1. Active tracking of MPP for any irradiance and temperature. Both $I_{PV}$ and $V_{PV}$ needed to be
   supervised to be able to derive the present $V_{MPP}$.

2. Passive tracking with a compromise of a fix $V_{PV}$ that is close enough to $V_{MPP}$. Only $V_{PV}$
   needed to be supervised.

These two categories were further analysed in the following chapters.

**Active tracking**

The active MPP tracking category was thought to lead to the most complex system, but also had
potential to reach a high efficiency of the PV module for any irradiance and temperature. This
category requires that both $I_{PV}$ and $V_{PV}$ are supervised to be able to decide whether to increase or
decrease $I_{PV}$ to reach $V_{MPP}$. To be able to implement this some calculations need to be made to
make an active decision and a PWM signal preferably need to be used to switch the transistor.
The duty cycle would be increased or decreased to change $I_{PV}$. This means that some type of
microcontroller would be needed. In this case it could either be the microcontroller of the
Midrange platform or a separate power supply specific microcontroller. However, the solution
requires that the microcontroller is in some kind of state where the PWM signal could be
maintained and that $I_{PV}$ and $V_{PV}$ are sampled at a certain rate followed by calculations. Once
again, the complexity might end up in a substantially higher consumption and might require
more power than the win in always having a good operating point. However, one important
advantage in using this kind of system would be the flexibility that it brings since the software
could always be tuned for better performance. Figure 27 gives an overview of how the active MPP tracking by using the microcontroller of the Midrange platform was thought to look like.

**Passive tracking**

The passive MPP tracking category could be implemented by choosing an operating voltage, $V_{PV^*}$, that is close enough to $V_{MPP}$ at the times when it is profitable to harvest the irradiated energy. This gives the possibility to design a simple system that only need to supervise $V_{PV}$ and increase or decrease $I_{PV}$ by using a transistor so that $V_{PV}$ goes towards $V_{PV^*}$. This could of course also be implemented by using a microcontroller and setting the duty cycle of a PWM signal controlling the transistor. But it could also be implemented by using hardware only. The basic working algorithm for a non PMW solution would be as shown in Figure 28. Note that a hysteresis was thought to be needed to avoid constant switching when the measured value is very close to the wanted value.

This kind of solution was thought to have better potential to reaching low power consumption in comparison to the active tracking category and was also thought to be more flexible since it is not specific to the Midrange platform. However the design would be specifically for this PV module and its $V_{MPP}$. The wanted operating point, $V_{PV^*}$, would be defined in the hardware which leads to low flexibility in usage of PV modules with another $V_{MPP}$. Still, low power consumption was the foremost aim for the system why it was decided that the passive MPP tracking strategy

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**Figure 27.** The system layout for possible solution of active MPP tracking.

**Figure 28.** Working algorithm for a hardware based solution.
would be further investigated. 7 V was thought to be a good compromise of $V_{pv^*}$ for the chosen PV module. At standard test conditions $V_{MPP}$ of the PV module is 7.582, this meant a decrease of 2.3 % of $P_{MPP}$. The total decrease at lower irradiance was not known, a factor of 10 % lowered efficiency was used when verifying the set requirement of maximum 5 % down-time.

### 7.3. Initial system draft

The different known parts of the system were initially interconnected in a circuit, see Figure 29, which was the starting point. The diode’s, D1, purpose was to prevent the stored energy in the ultracapacitor from being consumed by the PV module due the PV module characteristics. The main criteria were low reverse current and low forward voltage drop. A schottky diode was chosen, Vishay 30BQ060. It is specified for a maximum reverse voltage of 60 V and a forward current of 3 A. The forward voltage drop decreases with decreasing forward current and is 0.32 V at 25°C and 0.1 A forward current. The reverse current is about 1.5 µA at 10 V reverse voltage.

![Figure 29. HW design draft.](image)

An input capacitor, C1, was then placed in parallel with the MPP tracker, this to increase the source current when the switch is conducting. Two smaller capacitors, small in comparison to the ultracapacitor’s capacitance, were also placed in parallel with the ultracapacitor, C2 and C3, to buffer energy during the switching. Figure 30 shows the HW design with the capacitors placed out.

![Figure 30. HW design draft with buffering capacitors.](image)
The voltage leveller
The voltage leveller could either be implemented by using a switching buck regulator, also called a step-down regulator, or a low-dropout voltage regulator, LDO. The LDO will consume more power at higher voltages. However, the switching buck regulator has a certain efficiency, for some types it is as low as 65%. Due to the fact that it was foremost at lower ultracapacitor voltages that the consumption needed to be low, and since the LDO makes it possible to have a much lower input voltage in comparison to the one needed with a switching buck regulator to reach a certain output voltage, the LDO was thought to be the best alternative. This leads to a low voltage drop when the ultracapacitor voltage is close to the threshold voltage of 2 V. This means that a larger amount of energy from the ultracapacitor could be used at lower ultracapacitor voltages. Also, the quiescent current was found to be lower for LDO’s in comparison to switching buck regulators.

The criteria for the LDO were that it should have as low quiescent current and voltage dropout as possible. Linear Technology’s LT1521-3 was decided to be used. It has a dropout voltage of 0.5 V, quiescent current of 12 µA and an output voltage of 3 V. The maximum output current is 300 mA. Figure 31 shows the HW design with the chosen LDO implemented according to its datasheet.

Figure 31. HW design with chosen voltage leveller type.

7.4. Two final solutions
Two different solutions of the MPP tracker were derived with the given criteria. The first one implement a comparator to monitor the PV module voltage and the second implement a switching buck regulator with a feedback of the input voltage instead of the output voltage. These are explained in the following chapters.

Comparator power supply
The final design of the comparator power supply is shown in Figure 32. The basic thought of the solution is that a comparator is used to monitor the PV module voltage. A comparator works in such a way that when the positive input goes below the negative input, the output is high, and
vice versa. The chosen comparator is Linear Technology’s high speed comparator LTC1440. It has a low quiescent current, 2.1 µA, but a sufficient propagation delay of 8 µs. The chosen comparator has a built in programmable hysteresis and a reference voltage of 1.18 V.

Figure 32. The comparator power supply.

The reference voltage of the comparator was in this case used as positive input. The negative input should be 1.18 V when the PV module voltage is 7 V. This was created with a voltage divider, note that the forward voltage drop over the input diode, D1, had to be taken into account. The chosen values of the resistances (R1, R2, R3 and R9) for the voltage divider could be seen in Figure 32.

The comparator hysteresis input is the one beneath the positive input and below the hysteresis the reference is found, see Figure 32. R5, R6 and C6 were chosen according to the comparator datasheet. R4 define the hysteresis.

A pMOS transistor was used to control the current flow, M1 in Figure 32. It needed to have low static drain-to-source on-resistance and manage a drain-to-source voltage of at least 15 V. International Rectifier’s IRF7425 was used. The drain-to-source on-resistance is dependent on the drain-current and is typically 8.2 mΩ at 13 A. Most importantly it has a low drain-to-source leakage current of 1.0 µA.

One concern was that even if the switch would be turned on for a short period of time, the ultracapacitor’s low ESR would lead to a large but short current rush. An inductor, L1, could be used as damping of the current, it would store energy in a magnetic field when the switch is conducting and release the stored energy to the ultracapacitor when the switch is not conducting. A configuration similar to the one of the basic switching buck regulator was therefore implemented, L1 and D2 in Figure 32.
By simulating the solution it was found that a very large inductance was needed to reach acceptable amplitude of the ripple on the PV module voltage, this due to the comparator propagation delay. After looking at available inductors Noratel TI-53115 with inductance 1.6 mH was chosen. The used diode, D2, is the same as the input schottky diode, Vishay 30BQ060, due to its low forward voltage drop, low reverse current, typically 1.5 µA at reverse voltage 10 V, and high forward current rating, 3 A. Also it was of importance that it was specified for usage in high frequency applications. Vishay 30BQ060's typical applications are amongst others converters and switching power supplies.

100 µF was thought to be a feasible value of C1 and C2. C3 was set to 1 µF. The criteria for the larger capacitors was once again low leakage current but also that they should manage a fairly high ripple current. Epcos B41142A4107M000 was chosen due to its low leakage current, maximum 35 µA at rated voltage, and high ripple current resistance.

**Buck power supply**

This solution implements a switching buck regulator with the feedback on the input voltage instead of the output voltage. The chosen buck regulator, Linear Technology's LT3971, has a built in transistor and the inductor and diode could be chosen freely to suit the wanted solution. It has a quiescent current of 2.8 µA and a wide input voltage range of up to 38 V. Also the frequency of which the buck circuit is working could be adjusted by choosing a resistor between the Rf pin and ground. The final design of the buck power supervisor is shown in Figure 33.

![Figure 33. The buck power supply.](image-url)

The feedback pin, FB, of the buck regulator is regulated to 1.19 V. When the buck regulator is implemented according to its thought operation, as a step-down regulator, the FB pin is connected to the output voltage. The circuit changes the duty cycle of a signal controlling a transistor, if the output voltage is too low the duty cycle is increased and vice versa. But in this case the duty cycle had to be decreased if the PV module voltage is too low. Still, it had to
maintain the set duty cycle if FB is 1.19 V. This meant that the PV module voltage not only had to 
be down sized so that 7 V corresponds to an FB input voltage of 1.19 V, but also that the signal 
needed to be inverted so that an increase of the PV module voltage corresponds to decrease of 
the FB input voltage. To achieve this an operational amplifier, LT1077, was used, the connection 
could be seen in Figure 33.

The operational amplifier is connected as an inverting amplifier. The positive input of the 
operational amplifier is a voltage reference of 1.19 V and the negative input is the PV module 
voltage down sized so that PV module voltage 7 V corresponds to 1.19 V by using a voltage 
divider, R4 and R5. To create the voltage reference of 1.19 V a shunt voltage reference, LT1389 
(D3 in Figure 33), of 1.25 V was used followed by a voltage divider, R2 and R3.

The resistor defining the frequency of the buck circuit, R7, was set to 120 kΩ which leads to a 
frequency of 400 kHz. The frequency should not be set too high since this lowers the efficiency 
due to higher switching losses. There is a strict relationship between the frequency and needed 
inductance, with lower frequency the inductor need to bee a bit bigger though. The needed 
inductance was calculated according to the buck regulator's datasheet to be 30 µH, Cooper 
Bussman DR127-330-R was chosen for this purpose. The same schottky diode as in the 
comparator circuit was used, Vishay 30BQ060. The same capacitor values of C1, C2 and C3 as in 
the comparator power supply were used.

7.5. Evaluation of solutions
The simulation result of the two solutions could be found in Figure 34 and Figure 35 
respectively, note that the scale of the current is not the same for the two circuits. Due to 
limitations in LTspice the simulation time was too long to be able to make any approximations of 
the time until the ultracapacitor is fully charged when the simulation was made with the actual 
ultracapacitor size, 52 F. The simulations were however used to verify that the circuits had the 
wanted behaviour and could keep the PV module at an operation point of 7 V. The simulations 
were therefore made for a lower ultracapacitor value of 0.52 F and a current source was put in 
parallel with the ultracapacitor to "quick charge" the ultracapacitor in steps to get an 
approximation of the current ripple and the average current at different voltage levels of the 
ultracapacitor. Unknown errors occurred at higher ultracapacitor voltages when simulating the 
buck power supply leading to terminated simulation.
Figure 34. LTspice simulation of the comparator power supply with lower ultracapacitor value, 0.52 F, and with quick charging in two steps.

Figure 35. LTspice simulation of the buck power supply with lower ultracapacitor value, 0.52 F, and with quick charging in five steps. Due to limitations in the simulation program it was not possible to simulate the circuit until the ultracapacitor value reached 7 V.
The simulation of the two circuits showed that the initial current into the ultracapacitor was higher for the buck power supervisor than for the comparator power supervisor. For the buck power supervisor the RMS peak current was 1.85 A, the comparator power supervisor had a RMS peak current of 785 mA.

It was also found that the PV module operating voltage was not exactly 7 V, at steady state the buck power supervisor kept the PV module at RMS operating voltage 6.95 V whilst the comparator power supervisor kept the PV module at RMS operating voltage 7.07 V. This was however expected, the resistance values were set according to available resistors from hardware dealers, leading to a compromise to reach a operation voltage as close to 7 V as possible.

It was decided that both solutions should be implemented for later testing with the PV module and the ultracapacitor and evaluation of the overall efficiency of the power supply for each solution.

7.6. PCB-design

To implement the solutions a PCB was designed for each circuit, CADint was used for this purpose. The PCBs have two layers. The bottom layer consist of the ground layer only and the components are mounted on the top layer. It was of importance that the path of the relatively high current from the PV module, though the switch/the buck regulator and into the ultracapacitor was made as short as possible. Instead of drawing thick traces along this high current path, larger areas were poured were it was possible, this to decrease the resistive losses. Free areas were poured and connected to the ground layer with vias. Figure 36 and Figure 37 shows the two final circuit boards with mounted components. The CADint schematic and PCB layout for the comparator power supervisor could be found in Appendix 4 and Appendix 5, and for the buck power supervisor in Appendix 7 and Appendix 8. Complete component lists for both of the solutions could be found in Appendix 6 and Appendix 9. All of the components that were chosen meet the RoHS directives. Also note that the input schottky diode was not a part of the initial design, why it could not be seen in Figure 36 and Figure 37. It was before the final testing soldered to the PV module positive wire. It is however placed in the final schematics, PCB designs and component lists.
Figure 36. The final comparator power supervisor.

Figure 37. The final buck power supervisor.
8. Testing and analysis

8.1. The final system

Figure 38 gives an overview of the final system and shows how the different parts are interconnected and the power flow through the system. Note that the final power supply is not specific to the Midrange platform, but could be used for any load with average power consumption 3 mW.

![Figure 38. Overview of the final solution.](image)

8.2. Unit testing

The PV module

To be able to test the system a source of light was needed, an overhead projector was used for this purpose. The distance from the projector head where approximately standard test condition intensity of 1000 W/m² was retrieved was measured. At this distance the used PV module should deliver 120 mA at operating voltage 7 V. The distance was approximated to be about 20 cm. It was also found that after a while under exposure the generated power decreased since the PV module temperature increased which accord with the presented theory. It should be said that the overhead projector deliver at slightly unstable intensity at a certain distance from the projector head.

The power supply circuits

Both power supply circuits were tested to verify that the components had been mounted correctly. The PV module input was fed with 7 V from a voltage source. This showed that the
supply voltage was 3 V as wanted. Also the voltage levels at some crucial points of the two circuits were measured to verify that they had the desired levels.

8.3. Final testing and verification

The different units of the final system were interconnected for final testing of the system. First of all the power supervisor solutions were tested so that they managed to regulate the PV module voltage at 7 V. The aim of the subsequent tests was to approximate:

- the overall efficiency of the system during charging at standard test conditions.
- the average total power consumption of the system at different ultracapacitor voltage levels.
- the losses in the power supervisor with no power provided from the PV module.
- if the 3 V output is stable and at which ultracapacitor level the output voltage goes below 2 V, leading to down-time.
- the down-time with irradiance of 2009 as reference.

At this stage the Midrange platform was not used, instead a 3 kΩ resistor simulating an average 3 mW power consumption was connected to the power supply output.

**Charging sequence with comparator power supply**

To approximate the overall efficiency of the system when the PV module is generating power, a charging sequence was made to approximate how the power varies with the ultracapacitor voltage. The system with the comparator power supervisor was tested with an ultracapacitor voltage close to 0 V and the overhead projector was used as source of electromagnetic radiation. The PV module distance to the overhead projector head was moved so that approximately 120 mA was generated. An oscilloscope was used to measure the PV module voltage, the ultracapacitor voltage and the output voltage. The PV module current and the ultracapacitor current were supervised by using amperemeters in series with the positive poles. During the charging sequence the oscilloscope view was saved for different ultracapacitor voltage levels and the measured current of the PV module and the ultracapacitor were noted. Figure 39 shows the voltage of the PV module, the ultracapacitor and the output voltage at four different ultracapacitor voltage levels; 1.56 V, 3.50 V, 6.47 V and 7.33 V. By using the measured values of the PV module current and the ultracapacitor current an approximation of the efficiency of the entire system during charging was made. The efficiency is defined as

$$\eta = \frac{P_{load} - P_{cap}}{P_{pv}}.$$
Figure 39. The yellow line (1) show the PV module voltage, the green line (2) show the ultracapacitor voltage and the purple line (3) show the output voltage. The RMS values of all three voltage levels could be seen in the lower margin of each oscilloscope view. The scale of the x- and y-axis could be seen in the upper margin of each oscilloscope view.

Table 4 shows the measured voltages and currents and the resulting power and efficiency at different ultracapacitor voltage levels.

Table 4. Charging sequence values for comparator power supervisor.

<table>
<thead>
<tr>
<th>Vpv [V]</th>
<th>Ipv [mA]</th>
<th>Ppv [mW]</th>
<th>Vcap [V]</th>
<th>Icap [mA]</th>
<th>Pcap [mW]</th>
<th>Vload [V]</th>
<th>Iload [mA]</th>
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The comparator power supervisor manages to keep the RMS PV module voltage fairly stable, initially it is closer to 7.07 V and when the ultracapacitor voltage reaches about 3 V the PV module voltage is kept at about 7.12 V. Somewhere between an ultracapacitor voltage of 6.47 V and 7.01 V the PV module voltage increases as expected and is about 0.3 V higher than the ultracapacitor voltage.

The switching frequency is about 20.0 kHz when the ultracapacitor voltage is around 1 V, at this point the RMS PV module voltage is 7.09 and the ripple varies between 6.95 V and 7.20 V, which is about ±0.13 V. The amplitude of the ripple decreases with increasing ultracapacitor voltage, this could also be seen in Figure 39. At ultracapacitor voltage 3.50 V the switching frequency has reached its maximum of about 34.5 kHz, the RMS PV module voltage is 7.12 V and the ripple varies between 7.07 V and 7.17 V, which is ±0.050 V. Both the switching frequency and the ripple amplitude decrease after this stage and the switching becomes fairly irregular after ultracapacitor voltage 4.5 V. At ultracapacitor voltage 7.01 the switch is constantly closed. The 3 V output is fairly stable and no mentionable transients due to the switching are transferred to the output. The output voltage reaches the threshold voltage 2 V, which is the lowest voltage at which the Midrange platform could operate, at an ultracapacitor voltage of slightly below 2.07 V.

The calculated efficiency increases with increasing ultracapacitor voltage and with decreasing ultracapacitor current, the losses are in other words higher when the ultracapacitor voltage is low. As said before the time between the switching increases with increasing ultracapacitor voltage. One of the reasons to why the losses are higher initially is that the current is higher which will lead to higher resistive losses. Losses also occur during the switching, high frequent switching lead to higher losses. Other losses are due to the fact that some of the components are not passive and therefore have a quiescent current as mentioned before, also the ultracapacitor leakage current is a source of losses. The overall efficiency of the comparator power supervisor was used to verify that the system could operate with a maximum of 5 % down-time with the extracted irradiance values from 2009.

**Charging sequence with buck power supply**

The system was tested in the same way with the buck power supply and Figure 40 shows the voltage of the PV module, the ultracapacitor and the output voltage for the ultracapacitor voltage levels; 1.52 V, 3.50 V, 6.02 V and 7.51 V. The efficiency is defined in the same way as for the comparator power supply, see Equation 15.
Figure 40. The yellow line (1) show the PV module voltage, the green line (2) show the ultracapacitor voltage and the purple line (3) show the output voltage. The RMS values of all three voltage levels could be seen in the lower margin of each oscilloscope view. The scale of the x- and y-axis could be seen in the upper margin of each oscilloscope view.

Table 5 shows the measured voltages and currents and the resulting power and efficiency at different ultracapacitor voltage levels.

Table 5. Charging sequence values for buck power supervisor.

<table>
<thead>
<tr>
<th>Vpv [V]</th>
<th>Ipv [mA]</th>
<th>Ppv [mW]</th>
<th>Vcap [V]</th>
<th>Icap [mA]</th>
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<td>0.83</td>
<td>2.06</td>
<td>0.765</td>
</tr>
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<td>7.00</td>
<td>116</td>
<td>812</td>
<td>2.99</td>
<td>-210</td>
<td>-628</td>
<td>2.89</td>
<td>0.98</td>
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<td>7.01</td>
<td>121</td>
<td>848</td>
<td>3.50</td>
<td>-190</td>
<td>-665</td>
<td>2.99</td>
<td>1.01</td>
<td>3.02</td>
<td>0.788</td>
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<tr>
<td>7.00</td>
<td>118</td>
<td>826</td>
<td>4.29</td>
<td>-157</td>
<td>-674</td>
<td>2.99</td>
<td>1.01</td>
<td>3.02</td>
<td>0.819</td>
</tr>
<tr>
<td>7.00</td>
<td>121</td>
<td>847</td>
<td>4.50</td>
<td>-160</td>
<td>-719</td>
<td>3.00</td>
<td>1.01</td>
<td>3.03</td>
<td>0.853</td>
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<tr>
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<td>123</td>
<td>862</td>
<td>5.06</td>
<td>-147</td>
<td>-744</td>
<td>2.99</td>
<td>1.01</td>
<td>3.02</td>
<td>0.866</td>
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<tr>
<td>7.00</td>
<td>124</td>
<td>868</td>
<td>5.51</td>
<td>-129</td>
<td>-711</td>
<td>2.99</td>
<td>1.01</td>
<td>3.02</td>
<td>0.823</td>
</tr>
<tr>
<td>7.00</td>
<td>120</td>
<td>840</td>
<td>6.02</td>
<td>-112</td>
<td>-674</td>
<td>2.99</td>
<td>1.01</td>
<td>3.02</td>
<td>0.807</td>
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<tr>
<td>7.74</td>
<td>113</td>
<td>874</td>
<td>6.51</td>
<td>-105</td>
<td>-683</td>
<td>2.99</td>
<td>1.01</td>
<td>3.02</td>
<td>0.785</td>
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<td>7.98</td>
<td>48</td>
<td>383</td>
<td>6.87</td>
<td>-34</td>
<td>-233</td>
<td>3.00</td>
<td>1.01</td>
<td>3.03</td>
<td>0.617</td>
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<td>8.20</td>
<td>84</td>
<td>689</td>
<td>7.00</td>
<td>-70</td>
<td>-490</td>
<td>2.99</td>
<td>1.01</td>
<td>3.02</td>
<td>0.716</td>
</tr>
</tbody>
</table>
Also the buck power supervisor manages to keep the RMS PV module voltage fairly stable, it is kept around 7.00 V ± 0.01 V until the ultracapacitor reaches a voltage somewhere between 6.02 V and 6.51 V. This is a lower PV module voltage deviation than was reached with the comparator power supervisor, and also closer to the wanted PV module voltage 7 V. After this ultracapacitor voltage level the PV module voltage increases as expected, but with a higher difference between the PV module voltage and the ultracapacitor voltage, about 1.2 V which could be compared to the comparator power supervisor voltage difference of about 0.3 V.

The buck power supervisor has a higher switching frequency than the comparator power supervisor, the buck regulator had been configured to have an operating frequency of 400 kHz. As could be seen in the first oscilloscope caption in Figure 40 the waveform of the PV module voltage is fairly unstable at a low ultracapacitor voltage, the frequency is 400 kHz but the duty cycle changes from one switching cycle to another. The duty cycle is fairly low at lower ultracapacitor values, which correspond with the fact that the PV module voltage should decrease faster at lower ultracapacitor voltages since the current is higher. For higher ultracapacitor voltage, somewhere in between 2.5 V and 3.0 V, the waveform of the PV module voltage reaches a more harmonic state and the frequency 400 kHz and duty cycle of about 50 % could be seen clearly, see Figure 40. The duty cycle increases with increasing ultracapacitor voltages and at ultracapacitor voltage 6.5 V the PV module voltage has no increase or decrease between the switching. It could however be seen that the switching continues, instead of the switch being constantly closed meaning duty cycle 100 %, which would be the optimum behaviour. The maximum duty cycle of the chosen buck regulator depends on the output load and the set frequency, it increases with increasing frequency and decreasing output load.

Just as for the comparator power supervisor, the amplitude of the ripple of the PV module voltage decreases with increasing ultracapacitor voltage. It could be seen in Figure 40 that the switching give rise to transients trough the circuit. If these are disregarded the amplitude of the ripple is lower that the one of the comparator power supervisor. At ultracapacitor voltage 3.5 V the ripple is about ±0.035 V for the buck power supervisor in comparison to ±0.050 V for the comparator power supervisor.

The transients due to the switching however affect the 3 V output of the power supervisor. At lower ultracapacitor voltages the transient amplitude is the highest throughout the charging sequence, the maximum is ±100 mV. It gets slightly lower at higher ultracapacitor voltages and is not noticeable at maximum duty cycle, when the ultracapacitor voltage is about 7.0 V. These transients must probably be eliminated for the Midrange platform to operate properly, which could be realized by tuning the capacitor values. The output voltage reached the threshold voltage 2 V at an ultracapacitor voltage of about 2.04 V.
Table 5 shows that the buck power supervisor has its highest efficiency around ultracapacitor voltage 5 V. At higher voltage the efficiency decreases. The reason to why the efficiency is low at low ultracapacitor voltages is thought to be the same as for the comparator power supervisor, the resistive losses are higher. The switching losses are though present throughout the charging sequence since the buck regulator is constantly switching with a frequency of 400 kHz. Other losses occur due to the components’ quiescent current and the ultracapacitor leakage current. The overall efficiency of the buck power supervisor was used to verify that the system could operate with a maximum of 5 % down-time with the extracted irradiance values from 2009.

Discharging sequence for comparator and buck power supply

The discharging sequence of the power supplies was made to approximate the losses in the system, that is the ultracapacitor internal losses due to leakage current and ESR, $P_{\text{cap loss}}$, and the power supervisor losses, $P_{\text{loss}}$, see Figure 17. This to get usable values of the energy consumption when approximating the down-time with the irradiance values for 2009.

As said before the leakage current of the ultracapacitor is strongly dependent of the voltage level. $P_{\text{cap loss}}$ will consist of mainly this factor. The cycling of the ultracapacitor and the time at a certain level affects the leakage current. The method presented here will therefore only show the trend and not give any exact values of leakage current.

The losses in the power supervisor only, should be more or less linearly dependent of the ultracapacitor voltage since an LDO is used to regulate the 3 V output level.

The discharge sequence was initiated by charging the ultracapacitor to a voltage slightly above the maximum PV module voltage 9.944 V, up to 10 V. After some minutes held at 10 V, when the leakage current in the ultracapacitor has balanced a bit, the ultracapacitor was connected to the power supervisor. The PV module was also connected to the power supervisor but the active side was blocked so that it could not generate any power. The same 3 kΩ resistor on the 3 V output to simulate a consumer of 3 mW. With some hours interval, except for during the night time, the voltage and the current of the ultracapacitor and the output voltage was noted. Figure 41 shows the discharge curve of the comparator and buck power supply respectively.
**Figure 41.** The ultracapacitor voltage versus progressed time for the comparator and the buck power supply.

The discharge curve shows that the comparator power supervisor has lower losses initially in comparison to the buck power supervisor. The ultracapacitor voltage of the buck power supply decreases quickly during the first 3 hours until the voltage reaches slightly above 7 V. The comparator power supply manages to stay above the threshold output voltage 2 V for almost 74 hours whilst the buck power supply output voltage goes below 2 V after about 59 hours.

The average power consumption, $P_{\text{average consumed}}$, of the entire system between two voltage measurements, $V_0$ and $V_1$, with the progressed time, $t = t_1 - t_0$, was calculated using the two following equations.

\[
E_{\text{cap consumed}} = \frac{C(V_1^2 - V_0^2)}{2} \quad (17) \\
P_{\text{average consumed}} = \frac{E_{\text{cap consumed}}}{t} \quad (18)
\]

The momentary net power provided from the ultracapacitor to the system, $P_{\text{cap}}$, is calculated with

\[
P_{\text{cap}} = V_{\text{cap}} I_{\text{cap}} \quad (19)
\]

The average net power provided by the ultracapacitor, $P_{\text{cap average}}$, between $t_0$ and $t_1$, was together with the average power consumption used to approximate the internal losses, $P_{\text{cap loss}}$, of the ultracapacitor,

\[
P_{\text{cap loss}} = P_{\text{average consumed}} - P_{\text{cap average}} \quad (20)
\]

The momentary losses of the power supervisor only were defined as

\[
P_{\text{loss}} = P_{\text{cap}} - P_{\text{load}} \quad (21)
\]
where $P_{\text{load}}$ is defined as

$$P_{\text{load}} = \frac{V_{\text{load}}^2}{R}. \quad (22)$$

The resistance, $R$, is the 3 kΩ resistor used to simulate the average 3 kW load that the Midrange platform would consume. Figure 42 and Figure 43 shows the resulting losses as a function of the average ultracapacitor voltage for the comparator power supply and the buck power supply.

**Figure 42.** The total losses, ultracapacitor internal losses, power supervisor losses and Midrange platform consumption versus the ultracapacitor voltage for the comparator power supply.

**Figure 43.** The total losses, ultracapacitor internal losses, power supervisor losses and Midrange platform consumption versus the ultracapacitor voltage the buck power supply.
There are big differences between the two discharge sequences in the capacitor internal losses and the power supervisor losses. The total losses of the comparator power supply is initially about 54 mW of which the internal losses in the ultracapacitor is the larger part of the total losses, whilst the total losses of the buck power supply is up to 126 mW initially of which the losses in the power supervisor is the larger part of the total losses.

The ultracapacitor internal losses, $P_{\text{cap loss}}$, of the two solutions could be seen in Figure 44, which shows that the losses initially is almost five times higher for the comparator power supply and decreases until it reaches a level where the two have about the same decrease. The internal losses mainly consist of the leakage current, which does not depend of the two power supervisor. This leads to the result that the high initial losses for the comparator power supply is a consequence of possibly temperature, previous cycling or that the ultracapacitor was charged fairly quickly before the test started. This means that the high initial total losses of the comparator power supervisor, seen in Figure 42, would be lower in a real implementation where charging of the ultracapacitor is made over a longer time. The dependence of the internal losses for the buck power supply is therefore a better indicator when verifying the solutions versus the irradiance data from 2009.

![Figure 44. Comparison of the ultracapacitor internal losses for the comparator power supply and for the buck power supply versus the ultracapacitor voltage.](image)

The calculated losses of the power supervisors, $P_{\text{loss}}$, should however be fairly the same regardless of previous usage. Figure 45 shows the dependence of the power supervisor losses versus the ultracapacitor voltage for both solutions. It could be seen that the comparator power supervisor losses are linearly dependent of the ultracapacitor voltage as expected. The buck power supervisor losses however are quite high initially and decreases down to the same level as the comparator power losses at about ultracapacitor voltage 7.2 V, after this a linear dependence could be seen. The initial high losses in the buck power supervisor are thought to occur in the buck regulator. When the ultracapacitor voltage is higher than 7 V, which is the level
that the circuit regulates the PV module to, the buck regulator tries to lower the voltage by increasing the duty cycle to maximum duty cycle. A current loop occurs, from the ultracapacitor into the buck circuit, though the switch and back to the ultracapacitor, which give rise to losses. Higher duty cycle also leads to slightly higher quiescent current of the buck circuit because of the base current of the switch.

![Figure 45. Comparison of the power supervisor losses in the comparator power supply and for the buck power supply versus the ultracapacitor voltage.](image)

**8.4. Sufficient performance for irradiance in 2009?**

The approximated voltage dependence of the charging efficiency, ultracapacitor internal losses and power supervisor losses were used together with the extracted irradiance data from 2009 in Stockholm, Luleä and Malmö to get an approximation of the down-time. The input parameters that are used are listed in Table 6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value comparator</th>
<th>Value buck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily global irradiance</td>
<td>Extracted data from Strång</td>
<td>Extracted data from Strång</td>
</tr>
<tr>
<td>Average charging efficiency</td>
<td>78 %</td>
<td>73 %</td>
</tr>
<tr>
<td>Approximate average PV module efficiency decrease because of passive tracking</td>
<td>10 %</td>
<td>10 %</td>
</tr>
<tr>
<td>Starting voltage</td>
<td>10 V</td>
<td>10 V</td>
</tr>
<tr>
<td>Maximum voltage level of ultracapacitor (max PV voltage 9.944 V minus diode voltage drop 0.3 V)</td>
<td>9.644 V</td>
<td>9.644 V</td>
</tr>
<tr>
<td>Minimum voltage level of ultracapacitor (threshold voltage leading to output voltage 2 V)</td>
<td>2.04 V</td>
<td>2.04 V</td>
</tr>
<tr>
<td>Increase in incoming irradiance by tilting PV module to optimum angle (could be 20 %)</td>
<td>0 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

The voltage dependence of $P_{\text{load}}$, $P_{\text{cap\ loss}}$ and $P_{\text{loss}}$ was implemented as well. Since the irradiance is given in Wh/day, a dependence of the previous day's voltage was approximated and verified with the measured voltage drop after 24 h from the discharging sequence tests.
Table 7 shows the resulting down-time for the two solutions and for three different locations.

**Table 7. Resulting performance with irradiance data from 2009.**

<table>
<thead>
<tr>
<th>Comparator power supply</th>
<th>Buck power supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days of down-time</td>
<td>Percentage</td>
</tr>
<tr>
<td>Stockholm</td>
<td>3</td>
</tr>
<tr>
<td>Luleå</td>
<td>47</td>
</tr>
<tr>
<td>Malmö</td>
<td>1</td>
</tr>
</tbody>
</table>

This means that both the comparator and the buck power supplies did meet the requirement of maximum 5 % down-time for irradiance in Stockholm and Malmö, in Luleå the down-time was too large. The variations of the ultracapacitor voltage for the two solutions could be seen for irradiance in Stockholm in Figure 46 and Figure 47. The difference between the two graphs is small and it is only during the last two months of 2009 that the system has down-time. The graphs for Stockholm, Luleå and Malmö for each solution could be seen in Appendix 10.

**Figure 46.** Ultracapacitor voltage level variations with irradiance in Stockholm during 2009 for comparator power supply.

**Figure 47.** Ultracapacitor voltage level variations with irradiance in Stockholm during 2009 for buck power supply.
9. Conclusion

Both of the solutions have been shown to regulate the PV module at the wanted operating point 7 V. Both the comparator and the buck power supply managed to meet the set requirements of a maximum of 5% down-time with 2009 irradiance for Stockholm and Malmö. With the irradiance in Luleå the performance of neither the comparator nor the buck power supply did meet the requirement.

The comparator power supply produces a stable 3 V output, higher charging efficiency and lower losses in the power supervisor, whilst the buck power supply 3 V output contained unwanted transients due to the buck regulator characteristics and high losses in the power supervisor at higher ultracapacitor voltage. The buck power supervisor's foremost advantage is however its compact size in comparison to the comparator power supervisor. It should be kept in mind that the buck regulator is designed for another purpose. This makes it hard to have full control over the operation of the circuit as a total, in this case this lead to high unexpected power losses at higher voltages.

One way of increasing the charging efficiency of the comparator power supervisor is to use a lower resistance on the pMOS gate, which leads to higher gate current and shorter delay between the non-conducting and the conducting state meaning lower losses. This was tested in the LTspice model, the 100 Ω resistor was changed to a 15 Ω resistor which lead to higher RMS current into the ultracapacitor. This was however not implemented in the final hardware.

The chosen ultracapacitor has a fairly high leakage current loss, even if it was the candidate with potential of having lowest internal losses. Still, since this had been taken into account early in the design process it did not have large impact on the overall performance of the two power supply solutions. The results also showed that during testing the ultracapacitor should be charged up to the wanted starting voltage and kept there for a longer period for the leakage current to settle before the tests are initiated.

Both solutions are flexible since they are not specific to the Midrange platform. Any 3 V application could be used with an average current consumption around 1 mA, higher transient current consumption should not be a problem due to the ultracapacitor capacity of delivering high power and the LDO has a maximum output current of 300 mA.
10. Discussion

The report describes the working process when dimensioning and designing a PV module based power supply to a thought low power application, but even for high power applications the design process would be more or less the same. Necessary tools and aspects needed to be taken into account have been presented for future projects where solar energy harvesting is of interest.

10.1. Accuracy

The method presented to verify that the design produces sufficient energy is based on data from a computer model over irradiance in Sweden during 2009. It should be mentioned that the STRÅNG model is not free from errors, the presented method does however give a good indication. Possibly data from several years could be used to get a better mean value of the annual variations of irradiance for a certain location. Also it should be considered whether the conditions during 2009 were extraordinary in some kind of way, this would lead to incorrect performance values.

A 10 % decrease of the PV module efficiency was used when estimating the down-time because of the passive tracking strategy. This figure is probably lower in reality which means that the system might have less down-time than the approximated figure. The used PV module would need to be tested in laboratory environment to see what the actual decrease is with a 7 V PV module voltage at different irradiances and temperatures.

It should also be said that throughout all of the tests, the instruments used to measure voltage and current levels are not ideal and will not give exact figures. Also the noted time of when the measurements were made is not precise, a small change in the measurement time gives a quite high impact on the subsequent approximated values. The voltage dependence of the consumers and the load is therefore not entirely accurate but gives a sufficient approximation of the down-time.

10.2. Further work

Further work that could be made on the designed power supply solutions is to test the system outdoors with actual solar irradiance and with the Midrange platform as load. Temperature and other aspects of outdoor conditions have not been taken into account during the design process, this was not a part of the project, meaning that an investigation of this is necessary before final implementation of the system. It would also be of interest to investigate tilting of the PV module...
to optimum angle facing south to see if this leads to up to 20 % more irradiance hitting the module surface as the pre study indicate.

Another factor that needs to be investigated is the surroundings objects of a thought placement for the final system, there might be shadowing of the system which would reduce the produced energy. It could also be of interest to investigate an active MPP tracking power supervisor solution implementing a low power microprocessor, especially if a first or second generation PV module is used. It should be said that the designed power supervisor solutions should give better overall performance for a system with a third generation PV module since its voltage does not decrease with decreasing irradiance. The fact that the inventor of the third generation PV cells was awarded with the 2010 Millennium Technology Prize for his discoveries is an indication that the technology is a true competitor in the alternative energy generation field.

To increase the performance of the buck power supply a larger capacitor could be used to filter the transients on the 3 V output. Also the losses at higher ultracapacitor voltages could be reduced by using a diode on the buck regulator output to make sure that it does not continue switching at full duty cycle when the PV module is not generating power and the ultracapacitor is at higher voltage than 7 V. Possibly looking at other buck regulators that could reach 100 % duty cycle could be way of increasing the efficiency. Also lowering the frequency of the buck regulator might lead to better performance.

For this kind of power supply systems to be a true alternative to battery driven solutions for distributed low power embedded systems, the life time of the used components need to be monitored closely during the design process. Even if the first generation PV cell technologies has been shown to reach up to 20 years of life time the other parts of the system need to work properly during this time. Especially the performance degradation of the ultracapacitor need to be investigated thoroughly for the system life time to be sufficient.

10.3. Solar cells for energy harvesting in Sweden

Energy harvesting using PV modules is not a common sight in Sweden. For a long time the price of PV systems has been too high relative to the available irradiance. The cost of PV cell manufacturing is however thought to decrease with new PV technologies and production methods. With this in mind PV cells might be a future green energy generating source with potential to successful applications with available irradiance in Sweden, applications such as PV cell coated buildings, PV cell powering for remote houses and node based embedded systems. Still, not only new technology and applications are needed to expand the usage of PV cells but also political initiatives are needed to stimulate the future expansion of solar power in Sweden.
11. References


Appendix 1. Yearly sum of global irradiance in Europe

Photovoltaic Solar Electricity Potential in European Countries
Appendix 2. Incoming irradiance during 2009

Wh/m² per day during 2009 in Malmö

Wh/m² per day during 2009 in Stockholm

Wh/m² per day during 2009 in Luleå
## Appendix 3. Datasheet ultracapacitor

**DATASHEET**

**15V POWER AND ENERGY SERIES ULTRACAPACITOR PACKS**

### FEATURES AND BENEFITS
- 15V working voltage
- Individually balanced cells
- Rugged, fully enclosed system
- Screw terminals
- Module-to-module balance cable included
- UL Recognized

### APPLICATIONS
- Automotive subsystems
- Consumer electronics
- Portable power tools
- Renewable energy systems
- Short term UPS and telecom

### PRODUCT SPECIFICATIONS

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<thead>
<tr>
<th>CAPACITANCE</th>
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<th>BPAK0052 B02</th>
<th>BPAK0058 B01</th>
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<td>52 F</td>
<td>58 F</td>
<td>58 F</td>
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<td>Tolerance capacitance</td>
<td>±20%</td>
<td>±20%</td>
<td>±20%</td>
<td>±20%</td>
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</table>

**VOLTAGE**

- Rated voltage 15 V
- Surge voltage 15 V
- Maximum operating voltage 50 V
- Isolation voltage 1,100 V

**RESISTANCE**

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<tr>
<th>ESR, DC</th>
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<th>BPAK0052 B02</th>
<th>BPAK0058 B01</th>
<th>BPAK0058 B02</th>
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<tbody>
<tr>
<td>0.8 mΩ</td>
<td>0.8 mΩ</td>
<td>0.58 mΩ</td>
<td>19 mΩ</td>
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<td>Resistance tolerance</td>
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<td>±25%</td>
<td>±25%</td>
<td>±25%</td>
</tr>
<tr>
<td>Thermal resistance (Rth)</td>
<td>6.5°C/W</td>
<td>5.3°C/W</td>
<td>1.8°C/W</td>
<td>1.8°C/W</td>
</tr>
</tbody>
</table>

**TEMPERATURE**

- Operating temperature range -40°C to +65°C
- Storage temperature range -40°C to +70°C

**Temperature characteristics**

- Capacitance change
  - Within ±5% of initial measured value at 25°C (at -40°C)
- Internal resistance change
  - Within 150% of initial measured value at 25°C (at -40°C)

**POWER**

<table>
<thead>
<tr>
<th>Power</th>
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<th>BPAK0058 B01</th>
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<tr>
<td>Pd</td>
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<td>3,000 W/kg</td>
<td>3,000 W/kg</td>
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<td>Pmax</td>
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<td>11,200 W/kg</td>
<td>11,200 W/kg</td>
<td>11,200 W/kg</td>
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**ENERGY**

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<tr>
<td>3.63 Wh/kg</td>
<td>3.63 Wh/kg</td>
<td>3.63 Wh/kg</td>
<td>3.63 Wh/kg</td>
<td></td>
</tr>
</tbody>
</table>

**LIFESPAN**

- Endurance
  - After 1,000 hours application of rated voltage at 65°C.
    - Capacitance change
      - Within 20% of initial specified value
    - Internal resistance change
      - Within 25% of initial specified value
- Life test
  - After 10 years at rated voltage and 25°C.
    - Capacitance change
      - Within 20% of initial specified value
    - Internal resistance change
      - Within 100% of initial specified value
## DATASHEET
### 15V POWER AND ENERGY SERIES ULTRACAPACITOR PACKS

**BPAK0052 P015 B01**  
**BPAK0052 P015 B02**  
**BPAK0058 E015 B01**  
**BPAK0058 E015 B02**

### PRODUCT SPECIFICATIONS (cont.)

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<th>BPAK0052 B01</th>
<th>BPAK0052 B02</th>
<th>BPAK0058 B01</th>
<th>BPAK0058 B02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance change</td>
<td>Within 20% of initial specified value</td>
<td>Within 20% of initial specified value</td>
<td>Within 100% of initial specified value</td>
<td>Within 100% of initial specified value</td>
</tr>
<tr>
<td>Internal resistance</td>
<td>Within 20% of initial specified value</td>
<td>Within 100% of initial specified value</td>
<td>Within 100% of initial specified value</td>
<td>Within 100% of initial specified value</td>
</tr>
<tr>
<td><strong>CURRENT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leakage current</td>
<td>1 mA</td>
<td>55 mA</td>
<td>1 mA</td>
<td>55 mA</td>
</tr>
<tr>
<td>After 72 hours at 25°C. Initial leakage current can be higher.</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short circuit current (Isc)</td>
<td>1,500 A</td>
<td>1,500 A</td>
<td>1,500 A</td>
<td>1,500 A</td>
</tr>
<tr>
<td><strong>CAUTION:</strong> Current possible with short circuit from URL. Do not use as an operating current</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Maximum continuous current</td>
<td>20 A</td>
<td>20 A</td>
<td>20 A</td>
<td>20 A</td>
</tr>
<tr>
<td>Maximum peak current, 1 sec</td>
<td>80 A</td>
<td>80 A</td>
<td>80 A</td>
<td>80 A</td>
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<tr>
<td><strong>CONNECTION</strong></td>
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<tr>
<td>Terminal</td>
<td></td>
<td></td>
<td></td>
<td>Screw</td>
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<td><strong>MONITORING (IN-BUILT)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balancing</td>
<td>Active</td>
<td>Passive</td>
<td>Active</td>
<td>Passive</td>
</tr>
<tr>
<td>Thermal monitoring</td>
<td></td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>SIZE</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Dimensions</td>
<td></td>
<td></td>
<td></td>
<td>See drawing.</td>
</tr>
<tr>
<td>Mass</td>
<td>500g</td>
<td>500g</td>
<td>560g</td>
<td>560g</td>
</tr>
<tr>
<td>Volume</td>
<td>0.566 L</td>
<td>0.566 L</td>
<td>0.566 L</td>
<td>0.566 L</td>
</tr>
<tr>
<td><strong>RATINGS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Vibration resistance</td>
<td></td>
<td></td>
<td></td>
<td>IEC 61373</td>
</tr>
</tbody>
</table>
## DATASHEET
### 15V POWER AND ENERGY SERIES ULTRACAPACITOR PACKS

<table>
<thead>
<tr>
<th>Part number</th>
<th>L</th>
<th>W</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPAK0052 P015 B01</td>
<td>216</td>
<td>69</td>
<td>38</td>
</tr>
<tr>
<td>BPAK0052 P015 B02</td>
<td>216</td>
<td>69</td>
<td>38</td>
</tr>
<tr>
<td>BPAK0058 E015 B01</td>
<td>216</td>
<td>69</td>
<td>38</td>
</tr>
<tr>
<td>BPAK0058 E015 B02</td>
<td>216</td>
<td>69</td>
<td>38</td>
</tr>
</tbody>
</table>

Product dimensions are for reference only unless otherwise identified. Product dimensions and specifications may change without notice. Please contact Maxwell Technologies directly for any technical specifications critical to application.

### MOUNTING RECOMMENDATIONS
Units may be mounted and operated in any orientation. The pack should be shock mounted within a protective enclosure. Care should be taken to prevent motion between the pack and the enclosure. This motion can wear through the shrink-wrap covering over time and expose electrically conductive surfaces. **Do not reverse polarize module.**

### MARKINGS
Modules are marked with the following information: Rated capacitance, rated voltage, product number, name of manufacturer, positive and negative terminal, warning marking, serial number.
Appendix 4. Comparator circuit CADint schematic
Appendix 5. Comparator circuit CADint PCB layout
## Appendix 6. List of components comparator power supply

Component list comparator power supervisor card, part number according to CADint schematic.

<table>
<thead>
<tr>
<th>Part</th>
<th>Description</th>
<th>Size</th>
<th>Manufacturer and part number</th>
<th>Casing</th>
<th>RoHS</th>
<th>Distributor</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Capacitor</td>
<td>1 µF</td>
<td>Kemet C0805C10524VAC C-7800</td>
<td>0805</td>
<td>x</td>
<td>ELFA 65-809-97</td>
</tr>
<tr>
<td>C2</td>
<td>Capacitor</td>
<td>0,1 µF</td>
<td>Kemet C0805C104K5RAC C-7025</td>
<td>0805</td>
<td>x</td>
<td>ELFA 65-766-31</td>
</tr>
<tr>
<td>C3</td>
<td>Capacitor</td>
<td>1 µF</td>
<td>Kemet C0805C10524VAC C-7800</td>
<td>0805</td>
<td>x</td>
<td>ELFA 65-809-97</td>
</tr>
<tr>
<td>C4</td>
<td>Capacitor</td>
<td>1,5 µF</td>
<td>Kemet C1206C155K4RAC C-7025</td>
<td>1206</td>
<td>x</td>
<td>ELFA 65-833-71</td>
</tr>
<tr>
<td>C5</td>
<td>Input capacitor</td>
<td>100 µF</td>
<td>Epcos B41142A4107M000</td>
<td>-</td>
<td>x</td>
<td>Farnell 1735328</td>
</tr>
<tr>
<td>C6</td>
<td>Output capacitor</td>
<td>1 µF</td>
<td>Kemet C0805C10524VAC C-7800</td>
<td>0805</td>
<td>x</td>
<td>ELFA 65-809-97</td>
</tr>
<tr>
<td>C7</td>
<td>Output capacitor</td>
<td>100 µF</td>
<td>Epcos B41142A4107M000</td>
<td>-</td>
<td>x</td>
<td>Farnell 1735328</td>
</tr>
<tr>
<td>C8</td>
<td>Output capacitor</td>
<td>N.M.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>Schottky diode</td>
<td>-</td>
<td>Vishay 30BQ060</td>
<td>SMC</td>
<td>x</td>
<td>ELFA 70-229-65</td>
</tr>
<tr>
<td>D2</td>
<td>Schottky diode</td>
<td>-</td>
<td>Vishay 30BQ060</td>
<td>SMC</td>
<td>x</td>
<td>ELFA 70-229-65</td>
</tr>
<tr>
<td>L1</td>
<td>Inductor</td>
<td>1,6 mH</td>
<td>Noratel TI-5311S</td>
<td>-</td>
<td>x</td>
<td>ELFA 58-702-58</td>
</tr>
<tr>
<td>L1</td>
<td>Mounting detail inductor</td>
<td>60 mm</td>
<td>Noratel ISOLERSKIVA60MM,EPDM60-81</td>
<td>-</td>
<td>x</td>
<td>ELFA 58-708-78</td>
</tr>
<tr>
<td>R1</td>
<td>Resistor</td>
<td>1000 kΩ</td>
<td>KOA RK73H2ATTD1004F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-182-12</td>
</tr>
<tr>
<td>R2</td>
<td>Resistor</td>
<td>5600 kΩ</td>
<td>KOA RK73H2ATTD5604F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-183-94</td>
</tr>
<tr>
<td>R3</td>
<td>Resistor</td>
<td>1 kΩ</td>
<td>KOA RK73H2ATTD1001F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-174-95</td>
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<tr>
<td>R4</td>
<td>Resistor</td>
<td>2400 kΩ</td>
<td>KOA RK73H2ATTD2404F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-183-03</td>
</tr>
<tr>
<td>R5</td>
<td>Resistor</td>
<td>430 Ω</td>
<td>KOA RK73H2ATTD4300F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-174-04</td>
</tr>
<tr>
<td>R6</td>
<td>Resistor</td>
<td>1 Ω</td>
<td>KOA RK73H2TTD1R00F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-167-52</td>
</tr>
<tr>
<td>R7</td>
<td>Resistor</td>
<td>100 Ω</td>
<td>KOA RK73H2ATTD1000F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-172-55</td>
</tr>
<tr>
<td>R8</td>
<td>Resistor</td>
<td>1 Ω</td>
<td>KOA RK73H2TTD1R00F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-167-52</td>
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<tr>
<td>R9</td>
<td>Resistor</td>
<td>180 kΩ</td>
<td>KOA RK73H2ATTD1803F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-180-30</td>
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<tr>
<td>T1</td>
<td>pMOS transistor</td>
<td>15 A</td>
<td>IR IRF7425PBF</td>
<td>SO8</td>
<td>x</td>
<td>ELFA 71-383-81</td>
</tr>
<tr>
<td>U1</td>
<td>Comparator</td>
<td>-</td>
<td>Linear LTC1440IS8#PBF</td>
<td>SO8</td>
<td>x</td>
<td>Farnell 1663623</td>
</tr>
<tr>
<td>U2</td>
<td>LDO</td>
<td>3 V</td>
<td>Linear LT1521CS8-3#PBF</td>
<td>SO8</td>
<td>x</td>
<td>Farnell 1273581</td>
</tr>
<tr>
<td>Xx1</td>
<td>PV-module input</td>
<td>2-pole</td>
<td>Phoenix MKDS 1/2-3,81</td>
<td>-</td>
<td>x</td>
<td>ELFA 48-383-14</td>
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<tr>
<td>Xx2</td>
<td>Ultracapacitor input</td>
<td>2-pole</td>
<td>Phoenix MKDS 1/2-3,82</td>
<td>-</td>
<td>x</td>
<td>ELFA 48-383-15</td>
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<tr>
<td>Xx3</td>
<td>3 V output</td>
<td>2-pole</td>
<td>Molex Rak 6410-02A / 2227-2021</td>
<td>-</td>
<td>x</td>
<td>ELFA 43-808-61</td>
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</table>
Appendix 7. Buck circuit CADint schematic
Appendix 8. Buck circuit CADint PCB layout
### Appendix 9. List of components buck power supply

Component list buck power supervisor card, part number according to CADint schematic.

<table>
<thead>
<tr>
<th>Part</th>
<th>Description</th>
<th>Size</th>
<th>Manufacturer and part number</th>
<th>Casing</th>
<th>RoHS</th>
<th>Distributor</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Capacitor</td>
<td>0,47 µF</td>
<td>Kemet C0805C474K5RACTU</td>
<td>0805</td>
<td>x</td>
<td>Farnell 1650878</td>
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<td>C2</td>
<td>Capacitor</td>
<td>4,7 µF</td>
<td>Taiyo Yuden EMK212BJ475KG-T</td>
<td>0805</td>
<td>x</td>
<td>Farnell 1650925</td>
</tr>
<tr>
<td>C3</td>
<td>Capacitor</td>
<td>1 µF</td>
<td>Kemet C0805C105Z4VAC C-7800</td>
<td>0805</td>
<td>x</td>
<td>ELFA 65-809-97</td>
</tr>
<tr>
<td>C4</td>
<td>Capacitor</td>
<td>1,5 µF</td>
<td>Kemet C1206C155K4RAC C-7025</td>
<td>1206</td>
<td>x</td>
<td>ELFA 65-833-71</td>
</tr>
<tr>
<td>C5</td>
<td>Input capacitor</td>
<td>100 µF</td>
<td>Epcos B41142A4107M000</td>
<td>-</td>
<td>x</td>
<td>Farnell 1735328</td>
</tr>
<tr>
<td>C6</td>
<td>Output capacitor</td>
<td>1 µF</td>
<td>Kemet C0805C105Z4VAC C-7800</td>
<td>0805</td>
<td>x</td>
<td>ELFA 65-809-97</td>
</tr>
<tr>
<td>C7</td>
<td>Output capacitor</td>
<td>100 µF</td>
<td>Epcos B41142A4107M000</td>
<td>-</td>
<td>x</td>
<td>Farnell 1735328</td>
</tr>
<tr>
<td>C8</td>
<td>Output capacitor</td>
<td>N.M.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D1</td>
<td>Schottky diode</td>
<td>-</td>
<td>Vishay 30BQ060</td>
<td>SMC</td>
<td>x</td>
<td>ELFA 70-229-65</td>
</tr>
<tr>
<td>D2</td>
<td>Schottky diode</td>
<td>-</td>
<td>Vishay 30BQ060</td>
<td>SMC</td>
<td>x</td>
<td>ELFA 70-229-65</td>
</tr>
<tr>
<td>L1</td>
<td>Inductor</td>
<td>33 µH</td>
<td>Cooper DR127-330-R</td>
<td>DR127</td>
<td>x</td>
<td>ELFA 58-101-14</td>
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<tr>
<td>R1</td>
<td>Resistor</td>
<td>1000 kΩ</td>
<td>KOA RK73H2ATTD1004F</td>
<td>0805</td>
<td>x</td>
<td>ELFA 60-182-12</td>
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<tr>
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<td>KOA RK73H2ATTD4704F</td>
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<td>x</td>
<td>ELFA 60-183-78</td>
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<td>3300 kΩ</td>
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<td>x</td>
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<td>Resistor</td>
<td>715 kΩ</td>
<td>Welwyn PCF0805R-715KBT1</td>
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<td>x</td>
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<tr>
<td>R6</td>
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<td>KOA RK73H2ATTD5603F</td>
<td>0805</td>
<td>x</td>
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<tr>
<td>R7</td>
<td>Resistor</td>
<td>120 kΩ</td>
<td>KOA RK73H2ATTD1203F</td>
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<td>x</td>
<td>ELFA 60-179-90</td>
</tr>
<tr>
<td>U1</td>
<td>Voltage reference</td>
<td>1,25 V</td>
<td>Linear LT1389BCS8-1.25#PBF</td>
<td>SO8</td>
<td>x</td>
<td>Farnell 1273436</td>
</tr>
<tr>
<td>U2</td>
<td>LDO</td>
<td>3 V</td>
<td>Linear LT1521CS8-3#PBF</td>
<td>SO8</td>
<td>x</td>
<td>Farnell 1273581</td>
</tr>
<tr>
<td>U3</td>
<td>Switching buck regulator</td>
<td>-</td>
<td>Linear LT3971EMSE#PBF</td>
<td>MSE</td>
<td>x</td>
<td>Farnell 1786835</td>
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<tr>
<td>U4</td>
<td>OP amplifier</td>
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<td>SO8</td>
<td>x</td>
<td>Farnell 9559671</td>
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<tr>
<td>Xx1</td>
<td>PV-module input</td>
<td>2-pol</td>
<td>Phoenix MKDS 1/2-3.81</td>
<td>-</td>
<td>x</td>
<td>ELFA 48-383-14</td>
</tr>
<tr>
<td>Xx2</td>
<td>Ultracapacitor input</td>
<td>2-pol</td>
<td>Phoenix MKDS 1/2-3.82</td>
<td>-</td>
<td>x</td>
<td>ELFA 48-383-15</td>
</tr>
<tr>
<td>Xx3</td>
<td>3 V output</td>
<td>2-pol</td>
<td>Molex Rak 6410-02A / 2227-2021</td>
<td>-</td>
<td>x</td>
<td>ELFA 43-808-61</td>
</tr>
</tbody>
</table>
Appendix 10. Resulting voltage variation during 2009

Comparitor power supply ultracapacitor voltage with irradiance in Malmö during 2009

Comparitor power supply ultracapacitor voltage with irradiance in Stockholm during 2009

Comparitor power supply ultracapacitor voltage with irradiance in Luleå during 2009