Power Supply Monitoring for Wireless Sensor Platforms

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ABSTRACT

Most of the portable electronic devices use a battery as a primary power source. Nowadays, when the applications are becoming smaller and smaller and more power efficient, the designer needs to concentrate more on reducing power consumption, using secondary power sources and introducing power storage devices. Multiple power source availability and a power storage device on the board will make the applications much more useful and efficient in everyday use.

This thesis proposes a power supply unit (PSU) for wireless sensor platforms which is capable of supplying a sensor node with energy from multiple sources, as well as status information from the PSU.

Present power storage devices, like electric double-layer capacitors (EDLCs) and batteries, have become more and more common as their characteristics have developed. The EDLCs are popular due to their ability to charge and discharge efficiently and quickly at high currents. In addition, there are no limits for the number of charge and discharge cycles. The advantage of batteries is their ability to store a larger amount of energy (with longer charging period) and their decreasing size. In this design, both battery and EDLCs are used. Batteries will be used only in critical conditions. Otherwise, the system will be powered by renewable solar energy which will charge the EDLCs at the same time.

The device’s architecture contains a context- and power-aware task manager, which controls the node’s low-power modes and decides when they are activated. Its main responsibility is to schedule the moments when the energy consuming task can be dispatched. Depending on task priority and system configuration, the task can be dispatched, discarded or delayed.

Key words: power consumption, power supply unit (PSU), super capacitors
TIIVISTELMÄ


Laitteen arkkitehtuurin käsittää konteksti- ja tehoksiestoisten toimintojen hallintajärjestelmän, joka kontrolloi ja päätää, milloin pienoitehohiset moodit ovat aktivoituina. Sen päätavuud on ajoittaa energiankulutustoiminto. Toiminto voidaan joko suorittaa, hylätä tai viivästää riippuen toiminnon prioriteeta ja systeemin asetuksista.

Avainsanat: tehonkulutus, teholahdeyksikkö, superkondensaattori
# TABLE OF CONTENTS

ABSTRACT
TIIVISTELMÄ
TABLE OF CONTENTS
PREFACE
SYMBOLS AND ABBREVIATIONS
1. INTRODUCTION.......................................................................................................10
2. POWER SOURCES IN PORTABLE APPLICATIONS ...........................................12
  2.1 Overview of battery technologies .................................................................12
    2.1.1 The Nickel Cadmium (NiCd) Battery ........................................................12
      2.1.1.1 NiCd principles of operation .........................................................12
      2.1.1.2 NiCd chemical equations ............................................................13
    2.1.2 Nickel Metal Hydride (NiMH) ...............................................................13
      2.1.2.1 NiMH principles of operation .......................................................13
      2.1.2.2 NiMH chemical equations ..........................................................14
    2.1.3 Lithium Ion (Li-ion) ...............................................................................14
      2.1.3.1 Li-ion principles of operation .......................................................14
      2.1.3.2 Li-ion chemical equations ............................................................15
    2.1.4 Lithium-Polymer (LiPo) .......................................................................15
      2.1.4.1 LiPo principles of operation ..........................................................16
      2.1.4.2 LiPo chemical equations ..............................................................16
    2.1.5 Battery Comparison ...............................................................................17
  2.2 Electric Double Layer Capacitor (EDLC).............................................................17
    2.2.1 History of EDLC ..................................................................................17
    2.2.2 Principle of EDLC ................................................................................17
    2.2.3 Advantages and disadvantages ............................................................18
    2.2.4 Examples of application .......................................................................19
    2.2.5 Comparison between battery, double layer capacitor and electrolytic capacitor .................................................................19
  2.3 Photovoltaic Cell ..............................................................................................20
    2.3.1 Principle of photovoltaic ......................................................................20
    2.3.2 I-U Curve of Solar Cells ......................................................................21
    2.3.3 Solar energy scenarios .........................................................................21
  2.4 Discussion .............................................................................................................22
3. MULLE – THE WIRELESS SENSOR NETWORKING PLATFORM....................23
4. POWER SUPPLY UNIT IN EISLAB PLATFORM..................................................24
  4.1 Overview of PSU ............................................................................................24
  4.2 Block diagram and short presentation how this system works in practice .......24
  4.3 Hardware ...........................................................................................................26
    4.3.1 Battery .................................................................................................27
    4.3.2 Photovoltaic cell ...................................................................................27
    4.3.3 Super capacitors ...................................................................................28
    4.3.4 Supervisory circuit with switchover ......................................................28
    4.3.5 Boost-converter ....................................................................................29
    4.3.6 Comparator ...........................................................................................30
    4.3.7 Stand-alone fuel gauge IC .....................................................................30
    4.3.8 Analog digital converter .......................................................................30
    4.3.9 Port expander .......................................................................................31
PREFACE

This Master thesis is part of the Embedded Internet System Platform development project carried out with EISLAB researchers of Luleå University of Technology.

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I would like to thank my family, friends and Mallaspollo for their background support. Especially, I am grateful to my fiancée Satu Hoikkala, who helped me very much during the period of writing this thesis.

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Mikko Auno
SYMBOLS AND ABBREVIATIONS

c      Speed of Light  
E       Energy  
$E_G$   Band Gap Energy  
h      Planck’s Constant (6.6260693*10^{-34} Js)  
I      Current  
$I_{sc}$ Short-Circuit Current  
N      Resolution  
P      Power  
t      Time  
U      Voltage  
$U_{batt}$ Voltage from Battery  
$U_{cc}$ Voltage from Solar Cell  
$U_{DD}$ Logic ‘1’ Voltage Level  
$U_{EDLC}$ Voltage from EDLC  
$U_{in}$ Input Voltage  
$U_{oe}$ Open-Circuit Voltage  
$U_{out}$ Voltage Out from the Component/System  
$U_{sc}$ Voltage from Solar Cell  
$U_{ss}$ Ground Pin in DS2782  
$U_{TH}$ Threshold Voltage  

€      Euro  
Ω      Ohm  
μ      Micro (10^{-6})  
%     Percent  
λ     Wavelength  
A     Ampere  
Ah     Ampere-Hour  
As     Ampere Second  
d     Day  
F     Farad  
h     Hour  
H     Henry  
Js     Joule-Second  
k     Kilo (10^3)  
kB     Kilobit  
Kg     Kilogram  
ksps    Kilo Samples per Second  
L     Inductance  
LSB     Least Significant Bit  
m     Milli (10^{-3})  
min     Minute  
mm     Millimetre  
n     Nano (10^{-9})  
Q     Charge  
V     Volt
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wh</td>
<td>Watt-hour</td>
</tr>
<tr>
<td>C</td>
<td>Carbon, Capacitance</td>
</tr>
<tr>
<td>Cd</td>
<td>Cadmium</td>
</tr>
<tr>
<td>Cd(OH)$_2$</td>
<td>Cadmium Hydroxide</td>
</tr>
<tr>
<td>e$^-$</td>
<td>Electron</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>Water</td>
</tr>
<tr>
<td>KOH</td>
<td>Potassium Hydroxide</td>
</tr>
<tr>
<td>Li</td>
<td>Lithium</td>
</tr>
<tr>
<td>Li$^+$</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td>LiC</td>
<td>Lithium Cobaltite</td>
</tr>
<tr>
<td>LiCoO$_2$</td>
<td>Lithium Cobalt Oxide</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium Ion</td>
</tr>
<tr>
<td>LiMn$_2$O$_4$</td>
<td>Lithium Manganese Oxide</td>
</tr>
<tr>
<td>LiNiO$_2$</td>
<td>Lithium Nickel Oxide</td>
</tr>
<tr>
<td>LiPo</td>
<td>Lithium Polymer</td>
</tr>
<tr>
<td>M</td>
<td>Metal Alloy</td>
</tr>
<tr>
<td>MH</td>
<td>Metal Hydride</td>
</tr>
<tr>
<td>Ni</td>
<td>Nickel</td>
</tr>
<tr>
<td>NiCd</td>
<td>Nickel Cadmium</td>
</tr>
<tr>
<td>NiMH</td>
<td>Nickel Metal Hydride</td>
</tr>
<tr>
<td>Ni(OH)$_2$</td>
<td>Nickel Hydroxide</td>
</tr>
<tr>
<td>NiOOH</td>
<td>Nickel Oxyhydroxide</td>
</tr>
<tr>
<td>OH$^-$</td>
<td>Hydroxide</td>
</tr>
<tr>
<td>Pb</td>
<td>Lead</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>Titanium Dioxide</td>
</tr>
</tbody>
</table>

- a.k.a: Also known as
- AD: Analog Digital
- ADC: Analog-to-Digital Converter
- AIN: Input Pin for Analog Signal
- Batt: Battery
- CD: Compact Disc
- CMOS: Complementary Metal Oxide Semiconductor
- CPU: Central Processing Unit
- DC: Direct Current
- DSSC: Dye Sensitized Solar Cell
- e.g.: For Example
- EDLC: Electric Double Layer Capacitor
- EEPROM: Electronically Erasable Programmable Read-Only Memory
- EIS: Embedded Internet System
- EISLAB: Embedded Internet System Laboratory
- ESD: Electrostatic Discharge
- ESR: Equivalent Series Resistance
- etc.: Et Cetera (and the rest of such things)
- GND: Ground
- FET: Field Effect Transistor
- FGIC: Fuel Gauge Integrated Circuit
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRAM</td>
<td>Ferroelectric Random Access Memory</td>
</tr>
<tr>
<td>h⁺</td>
<td>Hole</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/Output</td>
</tr>
<tr>
<td>I-U</td>
<td>Current-Voltage</td>
</tr>
<tr>
<td>I²C</td>
<td>Inter-Integrated Circuit</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>LED</td>
<td>Light-Emitting Diode</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>MP</td>
<td>Mallaspallo</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PE</td>
<td>Port Expander</td>
</tr>
<tr>
<td>pMOSFET</td>
<td>P-Channel Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>PN</td>
<td>P-type and N-type Semiconductors Together</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>Rₚ</td>
<td>Pull-Up Resistor</td>
</tr>
<tr>
<td>RTC</td>
<td>Real Time Clock</td>
</tr>
<tr>
<td>SCL</td>
<td>Serial Clock</td>
</tr>
<tr>
<td>SDA</td>
<td>Serial Data</td>
</tr>
<tr>
<td>SNS</td>
<td>Sense Pin in DS2782</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

Sensors and actuators are widely used devices in various system implementations. Devices, which are intelligent and accessible to the Internet, can open new possibilities for system fault detection, control, maintenance and support. EISLAB at Luleå University of Technology has approached this challenge by developing an Embedded Internet System (EIS) architecture for small mobile devices. This architecture comprises three major components: first, light-weighted sensor/actuator devices with embedded communication capability, second, the mobile connection of such devices to the global Internet in a simple and cheap way, third, ad-hoc Internet networking of such devices. The evolution towards such an EIS has been underway for a number of years. The most recent result has been named MULLE; a minimal light-weighted EIS sensor platform with processing and communication capability where power consumption is minimized during actions. With the low power consumption the MULLE can transact several duties in a row without frequent discharge of the battery.

Different kinds of power supplies have various characteristics. Some of them can transform mechanical energy to electricity while some of them can transform heat energy to electricity and so on. Therefore, commonly known names for the power supplies are electrical or mechanical power supplies. The big issue is how much power they can supply, how good is their capability to produce stable output voltage and output current or how long the power supply can generate energy without recharging or refuelling.

This thesis develops a suitable power supply unit for the MULLE embedded system with the target of designing a practical power management system with switchover between the battery and a photovoltaic cell. The work was started by searching different kinds of power supply unit solutions from the internet, books and databases. Good ideas were collected and the advantages and drawbacks were identified from each solution. While examining power supply units for the MULLE, priority factors were low power consumption, adequate prize and small size.

The MULLE has one power source at a time and it has a simple mechanism to measure the voltage on its battery. In most cases, one power source and just measuring the voltage are enough but in some cases where system life time is utterly important a more advanced solution is required. Also, one of the major targets was to prolong a battery’s lifetime. This was achieved by using photovoltaic cells (a.k.a. solar cell) and EDLC (a.k.a. super capacitor) as a power source whenever it was possible. EDLCs help to generate power into the load under deep darkness after initial charge. The solution allows the end-user to know the condition and capacity of the battery all the time and the battery will last longer.

Chapter 2 of this thesis briefly discusses power sources. Commonly used battery types, principles of photovoltaic cells and EDLCs are introduced. Differences between NiCd, NiMH, Li-ion and Lipo batteries are discussed and those characteristics are depicted in table form. Reviewing the facts of photovoltaic cells and the facts of EDLCs will be given at the end of the chapter.

Chapter 3 is an overview of the MULLE platform. The MULLE’s construction and basic characteristics are introduced. Chapter 4 is reserved to specifications of final power supply unit hardware. There is an overview, a block diagram and a small introduction how this PSU works. This chapter concentrates on different segments which were used in this study and gives detailed information of items used. Chapter 5
discusses and shows different tests which were made during the writing of this thesis. Chapter 6 gives a short description of the software solution used and presents the MULLE and PSU interface. Chapter 7 includes examples of practical use. Chapter 8 depicts thoughts and a discussion about future developments and the last two chapters are reserved for references and appendixes. The appendixes include e.g. schematic, layout and digital pictures of the PSU board.
2. POWER SOURCES IN PORTABLE APPLICATIONS

2.1 Overview of battery technologies

During the last few decades, only moderate improvements concerning rechargeable batteries have been made in terms of higher capacity and smaller size. Compared with the vast advancement in areas such as microelectronics, the lack of progress in battery technology is apparent. Consider a computer memory core of the sixties and compare it with a modern microchip of the same byte count. What once measured a cubic foot now sits on a tiny chip.

Research has brought about a variety of battery chemistries, each offering distinct advantages, but none providing a fully satisfactory solution. With today’s increased selection, however, better choices can be applied to suit specific user applications. The consumer market, for example, demands high energy densities and small sizes. This has to be done to maintain adequate runtime of portable devices that are becoming increasingly more powerful and power hungry. Relentless downsizing of the portable equipment has pressured manufacturers to invent smaller batteries [2] [12].

This chapter addresses the most commonly used consumer and industrial batteries, which are NiCd, NiMH, Li-ion and LiPo. It introduces the battery’s principles of operation, concerning chemical reactions and main applications. This chapter also includes the principle of EDLC.

2.1.1 The Nickel Cadmium (NiCd) Battery

This is mature technology, and it has been successfully used for several decades to develop rechargeable batteries for portable electronic devices. Nickel-Cadmium cells are characterised by long life, relatively high rates of discharging and charging and the ability to operate at low temperatures [2].

While NiCd technology has been losing ground in recent years, owing to its low energy density and bulky size, it is still used in low cost applications like portable radios, CD/tape players, etc. [4]. Health risks associated with the manipulation of cadmium may also affect future developments of this system.

2.1.1.1 NiCd principles of operation

In the charged state, the positive electrode of a nickel-cadmium cell is nickel oxyhydroxide, and the negative electrode is cadmium. In the discharged state, nickel hydroxide is the active material of the positive electrode, and cadmium hydroxide that of the negative. Which electrolyte is used depends on the temperature. “Generally used is an aqueous solution of potassium hydroxide. For low temperature applications, more concentrated KOH solutions are used and at high temperatures aqueous sodium hydroxide is sometimes used as electrolyte” [8].

The operation of the sealed cell is based on the use of a negative electrode having a higher effective capacity than the positive. During the charging, the positive electrode reaches full charge level before the negative and begins to evolve oxygen. Since the negative electrode has not reached full charge it will not give hydrogen off. A separator
permeable to oxygen is used so that oxygen can pass through the separator to the
negative electrode. After the positive electrode is overcharged, gas is consumed at the
negative electrode. This will protect the electrode from overcharging and keeps the cell
in equilibrium. The average operating voltage of the cell under normal discharge
conditions is about 1.2 volts [3].

2.1.1.2 NiCd chemical equations

During charging, nickel hydroxide, Ni(OH)$_2$, is converted to a higher-valence oxide,

$$\text{Ni(OH)}_2 + \text{OH}^- \rightarrow \text{NiOOH} + \text{H}_2\text{O} + e^-.$$ 

At the negative electrode, cadmium hydroxide, Cd(OH)$_2$, is reduced to cadmium,

$$\text{Cd(OH)}_2 + 2e^- \rightarrow \text{Cd} + 2\text{OH}^-.$$ 

The overall reaction is (charging and discharging)

$$\text{Cd} + 2\text{NiOOH} + 2\text{H}_2\text{O} \leftrightarrow \text{Cd(OH)}_2 + 2\text{Ni(OH)}_2.$$ 

2.1.2 Nickel Metal Hydride (NiMH)

Nickel metal hydride battery is a new and sophisticated technology which uses similar
characteristics as a nickel-cadmium battery. The principal difference is that the nickel
cadmium battery uses cadmium for the active negative material whereas the nickel
metal hydride uses hydrogen, absorbed in a metal alloy [7].

These batteries have been in widespread use in recent years for powering laptop
computers and mobile phones because they have approximately twice the energy
density of NiCd batteries. Today, nickel-hydrogen batteries are mainly used for satellite
applications. Recently many manufacturers and end-users tend to think that NiMH is a
better choice for their applications because it is free of cadmium and that’s why it is
more environmentally friendly than a NiCd battery. However, the nickel metal-hydride
battery has a shorter cycle life, is more expensive, and is inefficient at high rates of
discharge, compared to the nickel cadmium battery [4] [7].

2.1.2.1 NiMH principles of operation

The positive active metal in the charged state, is nickel oxyhydroxide. The active
material of the negative electrode, in the charged state, is hydrogen in the form of a
metal hydride. This metal alloy is capable of undergoing a reversible hydrogen
absorbing-desorbing reaction as the battery is charged and discharged. The electrolyte is
an aqueous solution of potassium hydroxide.

The principle after which NiMH cells operate is based on their ability to absorb,
release, and transport hydrogen between the electrodes within the cell. When charging a
NiMH cell, the positive electrode releases hydrogen, and that hydrogen, in turn is
absorbed in the negative electrode. After a combination between hydroxide (OH\(^-\)) from the electrolyte and nickel hydroxide (Ni(OH)\(_2\)) from the positive electrode happens, the reaction begins. This reaction produces nickel oxyhydroxide (NiOOH) within the positive electrode, water (H\(_2\)O) in the electrolyte, and an electron (e\(^-\)). The metal alloy (M) in the negative electrode, water (H\(_2\)O) from the electrolyte, and one free electron (e\(^-\)) react to produce a metal hydride (MH) in the negative electrode and hydroxide (OH\(^-\)) in the electrolyte. When a NiMH cell is discharged, the chemical reactions are the reverse of what happens when it is charged.

The success of the NiMH battery technology comes from the hydrogen absorbing alloys used in the negative electrode. These metal alloys contribute to the high energy density of the NiMH negative electrode that results in an increase in the volume available for the positive electrode. This is the primary reason for the higher capacity and longer service life of NiMH batteries over other competing battery technologies [3].

### 2.1.2.2 NiMH chemical equations

During charging, nickel hydroxide is oxidized to nickel oxyhydroxide,

\[
\text{Ni(OH)}_2 + \text{OH}^- \rightarrow \text{NiOOH} + \text{H}_2\text{O} + \text{e}^-. 
\]

At the negative electrode, metal alloy (M) is converted to metal hydride (MH),

\[
\text{M} + \text{H}_2\text{O} + \text{e}^- \rightarrow \text{MH} + \text{OH}^-.
\]

The overall reaction is (charging and discharging),

\[
\text{Ni(OH)}_2 + \text{M} \leftrightarrow \text{NiOOH} + \text{MH}.
\]

The process is reversed during discharging.

### 2.1.3 Lithium Ion (Li-ion)

Lithium is the lightest of all metals and Lithium-ion is the fastest growing battery technology. It has great energy density, high cell voltage (up to about 4V per cell), and long charge retention or shelf life. Because of these advantages the Lithium-ion battery has become very useful in modern technology, especially in portable applications, where it is the most popular battery choice [4] [2].

The Lithium battery was discovered as early as in 1912, but the first commercial version was not available until the 1970s. The first rechargeable lithium batteries were developed in 1980s, but those attempts failed due to safety problems. After researchers started to use lithium ions instead of lithium metal, the lithium battery became safe when used properly [4] [2] [7].
2.1.3.1 Li-ion principles of operation

There is a relatively wide choice of materials that can be selected for the positive and the negative electrodes of lithium batteries. Typically, the positive electrode is lithium cobalt oxide (LiCoO$_2$), or lithium manganese oxide (LiMn$_2$O$_4$). The negative electrode is typically a graphitic carbon. The choice of electrolyte in lithium-ion batteries is also important. The electrolyte should consist of certain characteristics that are desired to be in equilibrium with lithium. Propylene carbonate and ethylene carbonate are the most common electrolyte solvents due to their low reactivity with lithium. During the charge and discharge processes, lithium ions are inserted or extracted from interstitial space between atomic layers within the material of the battery [3].

2.1.3.2 Li-ion chemical equations

Here the charge/discharge chemical reactions are shown. XX is one of the various combining elements including e.g. cobalt and manganese [3].

Positive electrode (charge/discharge):

\[
\text{LiXXO}_2 \leftrightarrow \text{Li}_{1-x}\text{XXO}_2 + \text{Li}^+ + x\text{e}^-.
\]

Negative electrode (charge/discharge):

\[
\text{C} + x\text{Li}^+ + x\text{e}^- \leftrightarrow \text{Li}_x\text{C}.
\]

Overall equation (charge/discharge):

\[
\text{LiXXO}_2 + \text{C} \leftrightarrow \text{Li}_x\text{C} + \text{Li}_{1-x}\text{XXO}_2.
\]

2.1.4 Lithium-Polymer (LiPo)

The Lithium-polymer battery system was discovered in the 1970s and its electrolyte has not been changed since that day. The LiPo battery uses a dry solid electrolyte. Therefore, this technology enables ultra thin batteries (less than 1mm thickness), and simpler packaging style. It is expected to fulfil the needs of lightweight, next-generation portable computing and communication devices. Often, lithium-polymer batteries, which are a lower cost version of lithium-ion batteries, are used in mobile phones.

Unlike Li-ion, LiPo batteries can sustain a significant amount of abuse. For example, a fully charged Lithium Polymer battery can be punctured with a nail without explosion or fire. On the other hand, overcharging the lithium-polymer batteries is strictly prohibited because of their ability to vent with a flame if the cell is overcharged. Therefore, a protective circuit is used to prevent overcharge and overdischarge [2].
2.1.4.1 LiPo principles of operation

A lithium-polymer battery is technically a lithium-ion polymer battery. It is very similar to the lithium-ion battery, but without some of the drawbacks. Lithium-polymer electrochemistry currently covers a wide range of active materials such as LiCoO₂, LiNiO₂, and its Co-doped derivatives.

A lithium-polymer battery includes a cathode, an anode and a porous separator disposed between the cathode and the anode. The first polymeric electrolyte is positioned on a first surface of the separator in contact with the cathode. A second polymeric electrolyte is positioned on a second surface of the separator layer in contact with the anode. The electrolyte is usually dry and solid.

2.1.4.2 LiPo chemical equations

Here is one example of charging lithium-polymer cells. When the cells are firstly charged, lithium ions are transferred from the layers of lithium cobaltite to the carbon material that forms the anode.

Initial charge:

\[ \text{LiCoO}_2 + \text{Li}_x\text{C} \rightarrow \text{Li}_{1-x}\text{CoO}_2 + \text{Li}_x\text{C}_6. \]

Subsequent charge and discharge reactions are based on the motion of lithium ions between anode and cathode.

Charge/discharge:

\[ \text{Li}_{1-x}\text{CoO}_2 + \text{Li}_x\text{C} \leftrightarrow \text{Li}_{1-x+d}\text{CoO}_2 + \text{Li}_{x-d}\text{C}. \]

During charge/discharge, Li⁺ ions are transported back and forth between two insertion electrodes [2].
2.1.5 Battery Comparison

Different characteristics of NiCd, NiMH, Li-ion and LiPo batteries are shown in Table 1. Values in the table are typical values and can vary with different manufacturers.

Table 1. Battery characteristics

<table>
<thead>
<tr>
<th>Battery type</th>
<th>NiCd</th>
<th>NiMH</th>
<th>Li-ion</th>
<th>Li-polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric Energy Density [Wh/kg]</td>
<td>45-80</td>
<td>60-120</td>
<td>110-160</td>
<td>100-130</td>
</tr>
<tr>
<td>Cycle Life [to 80% of initial capacity]</td>
<td>1500</td>
<td>500 to 800</td>
<td>500 to 1000</td>
<td>300 to 500</td>
</tr>
<tr>
<td>Overcharge Tolerance</td>
<td>moderate</td>
<td>low</td>
<td>very low</td>
<td>low</td>
</tr>
<tr>
<td>Self-discharge/Month [at 20° of Celsius]</td>
<td>20 %</td>
<td>30 %</td>
<td>10 %</td>
<td>~10 %</td>
</tr>
<tr>
<td>Cell Voltage [V, nominal]</td>
<td>1.25</td>
<td>1.25</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Load Current [As]</td>
<td>1</td>
<td>0.5 or lower</td>
<td>1 or lower</td>
<td>1 or lower</td>
</tr>
<tr>
<td>Maintenance Requirement [d]</td>
<td>30 to 60</td>
<td>60 to 90</td>
<td>not required</td>
<td>not required</td>
</tr>
<tr>
<td>Cost per Cycle [€]</td>
<td>0.03</td>
<td>0.09</td>
<td>0.11</td>
<td>0.22</td>
</tr>
<tr>
<td>In commercial use since</td>
<td>1950</td>
<td>1990</td>
<td>1991</td>
<td>1999</td>
</tr>
</tbody>
</table>

NiCd’s cycle life is based on regular control and maintenance. On the contrary, NiMH, Li-ion and Li-polymer are developed technology and there is no need for such an accurate maintenance [9] [10].

2.2 Electric Double Layer Capacitor (EDLC)

2.2.1 History of EDLC

During the past years, a pollution-free high performance electric energy storage device has been demanded. One of the best solutions is the electric or electrochemical double layer capacitor (EDLC), also known as the super capacitor or the ultra capacitor.

Professor Pieter van Musschenbroek invented the first capacitor in 1745 by accident. Later, in the middle of the 19th century, the German physicist Herman Ludvig Ferdinand von Hemholtz formulated the principle of an electrochemical double layer capacitor. It took almost a century before some scientists started to develop Hemholtz’s idea, and in the beginning of 1980, the Japanese were the first to succeed in the technical realization, and a bulky sized capacitor with a capacitance of 10 Farads came onto the market. After that, scientists and manufacturers have invested time for this technology field, which has become very widespread in the whole electric world.

2.2.2 Principle of EDLC

A basic capacitor consists of conductive foils and a dry separator. There are three types of electrode materials adequate for the EDLC. One of the most common is the high surface area activated carbon. It is also the cheapest to manufacture. The two other electrode materials are metal oxide and conducting polymers, but these last two are not as commonly used as the activated carbon.
EDLC is a charge storage device, which utilizes a double layer formed on a large surface area of micro porous material such as activated carbon. The structure of the double layer is shown in Figure 1.

Figure 1. Principle of electric double layer capacitor [11].

EDLC stores the energy in the double layer formed near the carbon electrode surface. There are two layers; one layer of electrolyte molecules and a second layer of diffusion. In the first layer, the electrons can not move at all and in the second layer the electrons can move around a little [11].

2.2.3 Advantages and disadvantages

The EDLC is a widely broadening component in the whole power electronic field especially nowadays when simple and workable methods are highly recognized. The EDLC has many good features. Charge, electric discharge and virtually unlimited cycle life are the best of these. The EDLC can be charged to full in seconds and it can be cycled millions of time. The EDLC has a simple charging method; there is no need to build any protection circuits. Overcharging or overdischarging does not have a negative effect on the lifespan, as it does with batteries. After full charge, it stops accepting charge. EDLCs do not cause harm for nature because they do not contain pollution like some batteries. Ni-Cd batteries include cadmium (Cd) and lead-acid batteries include lead (Pb). EDLCs are very environmental friendly.

The electric double layer capacitor is not an ideal component. There are some limitations which are good to highlight. The cells have low voltage, and if there is a need for a higher voltage, serial connection is needed. If there are more than three capacitors in series, voltage balancing is required. It will extend the board space radically, especially in portable applications and that could be crucial for the whole system. EDLCs have a high self-discharge rate. After one month, the charge of the capacitor decreases from full to 50 percent. On the other hand, the EDLC is a long-lasting capacitor; it deteriorates to 80 percent after one decade in normal use. Also, one
of the disadvantages is its low energy density. EDLCs usually hold one-fifth to one-tenth of the energy of an electrochemical battery [12].

2.2.4 Examples of application

Applications of double layer capacitors have grown enormously during the last years and manufacturers are currently developing them to get optimal features in reasonable packages. Electrical double layer capacitors are used in applications, such as the following [11][13]:

- Memory backup for programs, timers, etc…
- Backup power sources for portable application in power failure.
- Power sources for equipment that uses photovoltaic cells.
- Uninterruptible power supply (UPS). It supplies e.g. emergency generators.
- Starter for small motors.
- Underground networks (subway systems) support.

2.2.5 Comparison between battery, double layer capacitor and electrolytic capacitor

Comparing battery, double layer capacitor and electrolytic capacitor gives information of the difference between these energy storage devices. One of the most important characteristic for any energy storage device is energy density, or storable energy amount per volume or weight.

EDLCs are devices with energy storage density and power density intermediate between electrolytic capacitors and batteries. The capacity of a super capacitor can be measured in farads (F). While normal capacitors are rated in microfarads (µF), nano-farads (nF) or pico-farads (pF). Comparison between the capacitors and battery characteristics is shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Battery</th>
<th>Double Layer Capacitor</th>
<th>Electrolytic Capacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Discharge Time</td>
<td>0.3 to 3 h</td>
<td>1 to 30 s</td>
<td>$10^{-6}$ to $10^{-3}$ s</td>
</tr>
<tr>
<td>Energy Density Wh/kg</td>
<td>20 to 100</td>
<td>1 to 10</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Power Density W/kg</td>
<td>50-200</td>
<td>1000-2000</td>
<td>&gt;10 000</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>500 to 2000</td>
<td>&gt;100 000</td>
<td>Infinite</td>
</tr>
</tbody>
</table>
2.3 Photovoltaic Cell

2.3.1 Principle of photovoltaic

Photovoltaics (PV) or solar cells (the name for the individual PV element) are semiconductor devices that generate direct current (DC) electrical power measured in watts (W). As long as light is shining on the solar cell, it generates electrical power.

Semiconductor solar cells are quite simple devices. They have the capacity to absorb light and to deliver a portion of the energy of the absorbed photons to carriers of electrical current. A semiconductor diode separates and collects the carriers and conducts the generated electrical current preferentially in a specific direction. A simple conventional solar cell structure is depicted in Figure 2. Sunlight comes from the top on the front of the solar cell. A metallic grid forms one of the electrical contacts of the diode and allows light to fall on the semiconductor between the grid lines and thus be absorbed and converted into electrical energy. An antireflective layer between the grid lines increases the amount of light transmitted to the semiconductor.

All electromagnetic radiation, including sunlight, is composed of particles called photons, which carry specific amount of energy determined by the spectral properties of their source. Photons also exhibit a wave-like character with the wavelength, $\lambda$, being related to the photon energy, $E_{\lambda}$, by $E_{\lambda} = hc/\lambda$, where $h$ is Planck’s constant ($6.6260693 \times 10^{-34}$ Js) and $c$ is the speed of light. Only photons with sufficient energy to create an electron – hole pair, that is, those with energy greater than the semiconductor band gap ($E_G$), will contribute to the energy conversion process [5].

![Figure 2. Basic solar cell structure [5].](image-url)
2.3.2 I-U Curve of Solar Cells

Current-voltage (I-U) relationships that measure the electrical characteristics of PV devices are called I-U curves. On an I-U plot, the y-axis refers to current and the x-axis refers to voltage. The actual I-U curve typically passes through two significant points. The short-circuit current ($I_{sc}$) is the current produced when the positive and negative terminals of the solar cell are short-circuited, and the voltage between the terminals is zero. The open-circuit voltage ($U_{oc}$) is the voltage across the positive and negative terminals under open-circuit conditions, and the current is zero.

The cell may operate over a wide range of voltages and currents. By varying the load resistance from zero (a short circuit) to infinity (an open circuit), it is possible to determine the highest efficiency as the point where the cell delivers maximum power. The maximum-power point (MPP) occurs where the production of current multiplied by voltage is at its highest. No power is produced at the short-circuit current with no voltage, or at open-circuit voltage with no current. The maximum power is found somewhere between these two points, and it is generated at only one place on the I-U curve. This point represents the maximum efficiency of the solar device in converting sunlight into electricity. Maximum power point (MPP) in the I-U curve is depicted in Figure 3.

![Figure 3. I-U curve from solar cell [5].](image)

2.3.3 Solar energy scenarios

Solar energy is one of the most developing energies in the world at the moment. Photovoltaic cells improve all the time. Their size is getting smaller and smaller while the output power is increasing. Therefore, they will become more and more common for the portable devices.

One of the ultimate targets is to reduce the cost of solar cells below that of fossil fuel-generated electricity. At present, the big drawback is the cost of photovoltaic cells, but in the near future, cell prices will come down since different inventions are coming onto the market. Also, manufacturers are concentrating on reducing or
completely getting lead and other heavy metals out of the system. This will further reduce the photovoltaic cell prizes. Astro-technology is a forerunner of using solar energy and makes the most of the latest solar cells technology. When developing more and more cars, houses and portable devices, solar energy is a number one energy source. Some expert has said that in ten years, mobile phones’ and laptops’ battery chargers will be small solar energy systems. There is no question that solar energy is the energy of the future [14] [15].

2.4 Discussion

Choosing the right power source for the portable application is not an easy task. Therefore, every application has different characteristics for using electric power. Some of them store energy into different kind of energy storage devices and some of them use energy directly to the action. Almost every portable application carries a battery with them as a primary power source.

NiCd and NiMH batteries are going off the markets, little by little, because their energy density is too small and their cell voltage is too low. That’s why they need more cells to be competitive with present days Lithium batteries. More cells means bigger case size. The Lithium polymer battery develops rapidly all the time; its size is getting smaller and smaller and the present cells are much thinner while their electrical characteristics will last.

EDLCs are one solution for using a secondary energy storage device in the system. The benefits for using EDLCs are their ability to charge and discharge efficiently and quickly at high currents. There are no limits for the number of charge and discharge cycles. EDLCs have also a wide operating temperature and EDLCs do not contain heavy metals or toxic materials like Ni, Cd or Pb. Therefore, EDLCs are safer to use in daily life.

To use a battery and EDLCs together as an energy storage device will increase the functionality and the operation time of the system. In addition, supplying the load at the photovoltaic cell is a really good choice and will become common in the near future.
3. MULLE – THE WIRELESS SENSOR NETWORKING PLATFORM

EISLAB at Luleå University of Technology has developed the MULLE platform for wireless sensor networking (see Figure 4). The system is based on a Renesas M16C microprocessor. The bare die microprocessor chip is bonded to a six-layer two-sided circuit board, which also hosts a Bluetooth module on the opposite side. The platform is battery powered and designed for low-power consumption. The size of the MULLE platform is only 25 x 23 x 5 mm.

The MULLE platform is a complete standalone system aimed at ad-hoc sensor networking and ambient intelligence systems. The platform has analog and digital interfaces, signal processing capabilities, an integrated web server, as well as integrated wireless communication capability.

One important issue that EISLAB focused during the MULLE project was to minimize the power consumption using efficient power down mode. The conclusion was that large power savings can be implemented when a sensor application does not require a continuous high bandwidth data stream. A few strategies were used to reduce power consumption. One was to send data in a batch mode (data aggregation) storing data in the memory in the Real Time Clock (RTC). Another power saving strategy was to not store and communicate all measured data unless data meeting for the application certain or critical values were obtained from sensor.

The MULLE have five different power modes and those are introduced below.

- **Stop mode; 2.3 mA.** All internal clock nets and external interfaces in the M16 are stopped, and the CPU core is disabled. The Bluetooth chipset is set to deep sleep mode. The M16 can be woken up by external interrupt only, e.g. from a timer on the RTC or external reset. Stop mode is useful for longer periods of inactivity, as the response time can be up to a few seconds.
- **Wait mode; 14 mA.** Clock nets and external interfaces are functional, but the CPU core is disabled. The Bluetooth chipset is set to deep sleep mode. The M16 can be woken up by internal as well as external interrupts.
- **High frequency mode; 24 mA.** The M16 is fully functional, with activity every clock cycle. The Bluetooth chipset is set to deep sleep mode.
- **Bluetooth mode; 35 mA.** Bluetooth and M16 are active. Various tasks are performed by the M16, with periods of wait state in between. The amount of data handled by the M16 and transferred over Bluetooth is in the order of 1 kB per second.
- **Full system mode; 51 mA.** The same setup as for Bluetooth mode above, but includes also current consumption for some internal sensors [1].

Figure 4. MULLE platform.
4. POWER SUPPLY UNIT IN EISLAB PLATFORM

4.1 Overview of PSU

A power supply unit or PSU is a device or system that supplies electrical or other types of energy to an output load. In this application the PSU is a complete system with various characteristics. It supplies electrical energy from two different power sources. One should be a battery but another can be anything which has output voltage between 1 and 6 volts. Therefore, there are two power sources, the PSU should make a decision which one is powering the load. An automatic switch can choose the higher voltage and connect that to the load.

A power supply unit will do more tasks than to just supply to load. For example, it can collect measured voltages from different nodes of the PSU and store those values into the on-chip memory. Controlling the whole board is essential to achieve comprehensive low power consumption and to get accurate information from the power sources.

This chapter introduces a block diagram (see Figure 6) of the PSU and a short presentation of how this system works in practice. The components used in this application are introduced separately in their own sections. At the end of the chapter is an I2C-interface represented and how that is used to connect PSU to the MULLE.

4.2 Block diagram and short presentation of how this system works in practice

The system configuration and operation are shown in Figure 5. A photovoltaic array (PV), a DC-DC converter (DC-DC), a switchover IC (Switch) and a load (Load) are connected in series. Electric double layer-capacitors (EDLCs) are connected to the outputs of DC-DC. A Lithium Polymer battery (Batt) is connected to the switchover IC’s input. In the system a DC-DC converter conditions the power. On clear days, the power for charging the EDLCs and the power to the load are supplied from PV array. At night and on cloudy days, the EDLCs discharge to supply to the load. If cloudy weather conditions persist, the Lithium Polymer battery supplies to the load. When the battery is fully discharged it should disconnected and charged back to full manually.
Figure 5. Configuration and operation of the system.

The power supply unit’s block diagram is depicted in Figure 6. It contains eight integrated circuits and some external components like resistors, capacitors, leds and MOSFETs. Figure 6 is not an exact copy of the used schematic because this section gives only a general description of how the system should work.

Fuel gauge IC (FGIC) measures battery characteristics and it does not have any affect on the rest of the board. The FGIC is a completely separate net and it is powered by a Lithium polymer battery (Batt). An analog digital converter (ADC) measures the voltage from the solar cell and from EDLC. MOSFETs (3) and (4) act like a switch and connect the desired net to the ADC’s input after the port expander (PE) has provided a command to the MOSFET’s gate. The port expander also provides a state from the comparator’s shutdown pin and the switch’s batt on pin to the host. In addition, it controls the OR gate’s state as well. All commands from the port expander come from the host so the port expander just provides commands in the different areas of the PSU.

Values from FGIC and the conversion result from ADC are stored into the FRAM memories. The data from memories is read and delivered in bigger blocks rather than byte by byte. The MULLE will constantly check the stored data from FRAM memory through I²C-bus. All ICs have I²C interface and they will communicate with the host through that interface.
4.3 Hardware

The PSU hardware consists of six different ICs, two electric double layer capacitors, a couple of power MOSFETs, two led and many discrete components like resistors, capacitors, inductors, and diodes.

The heart of the PSU is an Analog Devices ADM691A switchover circuit that selects which energy source to use. ADM691A includes an automatic switch with a threshold voltage and it chooses the power source between a battery and electric double layer capacitors which are charged by solar cell. The battery which is used in this application is Lishen SP0425AB Li-Ion Polymer battery [20] and the photovoltaic cell which is used is either silicon or dye sensitized cells. Between the solar cell and the capacitors is high-efficiency Maxim MAX866 boost converter. MAX866 is controlled via Maxim MAX921 low power comparator which monitors the voltage from the solar cell and shut down the boost converter if the voltage from the solar cell is too low. The start-up voltage for MAX866 is as low as 0.8 V and it will ramp the voltage as high as 5.0 V. The EDLCs are charged by the output voltage of the boost converter. EDLCs can hold a substantial amount of energy and that’s why they are good to run while the solar cells do not source enough energy to the MULLE all the time.

The hardware includes Maxim MAX1237 ADC that measures voltages from the solar cell and EDLCs but it is not used in this design because the an inadequate I²C address. There is also a Dallas Semiconductor DS2782 stand-alone fuel gauge IC which monitors battery voltage, current, and temperature. DS2782 is a high precision battery measurement system that can give an absolute and relative capacity estimated from coulomb count, discharge rate, temperature and battery cell characteristics.

Power MOSFETs are used as analog switches which are controlled by a Maxim MAX7315 port expander. This port expander communicates with the host via I²C interface as well as ADC and fuel gauge IC. PSU hardware needs one port expanders.
to expand I/O ports on the system. 10 I/O-port expander is enough to cover to needs of this application. Two LEDs from the port expander make easier to follow which power source is in use, battery or solar cell with EDLCs [17].

4.3.1 Battery

Lishen SP0405AB is a Lithium Polymer battery (see Figure 7) and it is really small (Size is 4x20x25 mm), it has 140 mAh capacity and its weight is about 3g. Therefore, it is a good battery for this application. Lishen SP0405AB’s output power is 1 W so that is good enough to power up the MULLE [20].

![Figure 7. Lishen SP0405AB, Lithium polymer battery.](image)

4.3.2 Photovoltaic cell

Dye sensitized solar cells (DSSCs) [16] are currently being studied by numerous groups around the world as a low cost alternative to silicon photovoltaic cells. In low light applications, DSSCs outperform silicon solar cells and have been seen to match or outperform silicon in large scale outdoor applications. As a result DSSCs are expected to find a market as an inexpensive portable power source for low powered devices such as sensor networks.

The DSSCs used were made at Monash University. The components used were P25 (Degussa) (TiO₂), tech 16 FTO glass (Hartford), N719 dye ((nBu₄N)₂[Ru(Hdcbpy)₂(NCS)₂]) where dcbpy is 4,4-dicarboxylate-2,2-bipyridine and the electrolyte consisted of; 0.6 M tetrabutylammonium iodide (Aldrich), 0.5 M Lil (Lancaster), 0.04 M I₂ (Lancaster) and 0.05 M 4-tert-butylpyridine (Aldrich) in acetonitrile.

The advantage of the DSSC is that the components are cheap. Instead of having a single crystal of silicon, a DSSC typically consists of nanoparticles of TiO₂, a readily available material, already used in many applications. Currently the weakness of the DSSC is the electrolyte used in the regeneration of the dye. The volatile and corrosive nature of this substance makes the sealing of cells difficult and greatly reduces the lifetime of the cell [18].
4.3.3 Super capacitors

For this design, two capacitors of 1.0 F are used to add more flexibility to the system. In similar conditions when a boost converter is off, the capacitors will run the MULLE. These capacitors can hold a significant amount of energy, are insensitive for over and under charge, and can be recharged virtually an unlimited number of times. The capacitors do however suffer from a high leakage current, i.e. they can be drained in less than 24 hours without any load. With a low current load super the capacitors are discharged in less than 12 hours. This high discharge rate requires that capacitors are recharged on a daily basis by solar panels. The used super capacitor is, ELNA DB-5R5D105 (see Figure 8), a backup-capacitor 1 F/5.5 V [13].

![Figure 8. ELNA, 1 F capacitor (21.5 x 8.0 mm).](image)

4.3.4 Supervisory circuit with switchover

ADM691A is 16-pin, low power, microprocessor supervisory circuit which includes automatic backup-battery switchover. \( U_{cc} \) or \( U_{bat} \) is internally switched to \( U_{out} \) depending on which is at the highest potential.

Batt_on pin is a logic output which is used for communication with the host. Via that information the host will know which power source is in use and determines functions which are possible to start and which are strictly prohibited. Batt_on pin is low if \( U_{cc} \) is internally connected to \( U_{out} \) and high if \( U_{bat} \) is internally switched to \( U_{out} \). During a normal operation \( U_{cc} \) is switched to \( U_{out} \) via external power pMOSFET. It can supply a more continuous current than a switch can, and power pMOSFET is much faster than the internal switch is inside of ADM691A. Hence, there is no possibility that output voltage will drop under 3.3 V during the state changes.

ADM691A has 4.65 V threshold voltage but when a voltage detector and another power pMOSFET is connected in parallel with \( U_{cc} \) pin, the threshold voltage of whole switch system will change. Voltage detectors will now define the threshold voltage. Connection is depicted in Figure 9 which is a separate part of the block diagram.
Figure 9. ADM691A switch connection, part of the block diagram.

$V_{\text{TH}}$ is 3.4 V and the voltage detector’s output will control pMOSFET’s (1) gate. Since $U_{\text{cc}}$ is under 3.4 V gate is in low potential and the battery will be connected to the $U_{\text{out}}$. Since $U_{\text{cc}}$ is over 3.4 V the gate is high and the battery is disconnected. $U_{\text{cc}}$ is switched to the $U_{\text{out}}$. In Table 3 a truth table for the switch functions is shown. OR-gate between voltage detector and pMOSFET (1) is added so that MULLE can disconnect the battery when ever it wants.

Table 3. ADM691A’s truth table [22]

<table>
<thead>
<tr>
<th>$U_{\text{CC}} &gt; U_{\text{batt}}$</th>
<th>$U_{\text{CC}} &gt; U_{\text{TH}}$</th>
<th>$U_{\text{OUT}}$</th>
<th>Batt on</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>$U_{\text{CC}}$</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>$U_{\text{CC}}$</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>$U_{\text{CC}}$</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>$U_{\text{batt}}$</td>
<td>1</td>
</tr>
</tbody>
</table>

4.3.5 Boost-converter

MAX866 is high-efficiency, step-up, DC-DC switching regulator for low power consumption applications. MAX866 boost converters input can range as low as 0.8 V to $U_{\text{OUT}}$. Its task is to produce a fixed 5.0 V to output and also act as a buffer; to make sure that the solar panels operate at a good bias point. After it has ramped up the voltage to 5.0 V boost converter will charge two capacitors 1 F each.

IC includes an internal N-channel power MOSFET, so called “sense-FET” for best efficiency. That MOSFET has a very low gate threshold voltage to ensure start-up with low voltages.

This small MAX866 IC also has a shutdown input. When shutdown input is in low state, the entire circuit is off and the supply current is as low as 1 μA. The shutdown is connected to a low-power comparator output which monitors to output voltage from the cells, and when the level is higher than the minimum start-up voltage, shutdown input is in high state and the boost converter is activated. The low-power comparator is introduced more closely in the next chapter [23].
4.3.6 Comparator

A low-power comparator, MAX921, is used as a monitoring circuit for the solar cells. It monitors the voltage from the cells and determines if the boost converter is activated or not. The comparators’ output gives at the same time a wake-up signal to the boost converter and a logic signal to the MULLE. In the same way, the MULLE knows the state of the solar cells. In low state there is not enough power available from solar cells. In that case the MULLE is powered by the battery.

The voltage divider from the REF-pin to IN−pin is made to get the comparators threshold voltage in the correct level (in this case 0.81 V, minimum start-up voltage for the boost converter). When the voltage from the solar cells is over than 0.81 V comparators output rises to 3.3 V and a boost converter is activated. If the voltage is lower than 0.81 V the comparators output is 0 V and the rest of the circuit is disconnected [23].

4.3.7 Stand-alone fuel gauge IC

Stand-alone fuel gauge IC a.k.a. Dallas Semiconductor DS2782 is used to monitor battery conditions like voltage, current and temperature, and it estimates the available capacity for lithium-ion and lithium polymer batteries. The capacity estimation reported in mAh remaining and percentage of full. DS2782 has on-chip EEPROM where is stored cell characteristics and all calculations. It communicates with the host through I2C interface.

20 mΩ sense resistor is connected between pins Uss and SNS to measuring current flow into and out of the battery, continually. The result is stored in a 15-bit current register which is updated every 3,515 second. Current resolution (1 LSB) is 78.13 μA while using a 20 mΩ sense resistor.

The battery voltage is measured at the Vin input with a resolution of 4.88 mV. The results are stored in a 10-bit voltage register and the register is updated every 440 ms.

The DS2782 uses an integrated temperature sensor to measure the battery temperature. Therefore, the battery should be placed very close to DS2782 to get the best results. Also the temperature register is a 10-bit register with a resolution 0.125 C and it is updated every 440 ms.

DS2782 is an extremely low current consumption fuel gauge, which will take only 1 µA from the battery in sleep mode. While in active mode it will draw about 70 µA from the battery [23].

4.3.8 Analog digital converter

Maxim, MAX1237 is 12-bit and eight pin analog-digital converter with four analog input ports. This ADC has very low power consumption which depends on the sampling rate. In 94.4 ksps sampling rate it will draw 670 μA, 40 ksps (230 μA), 10 ksps (10 μA), 1 ksps (6 μA), and in a power-down mode MAX1237 will consume only 0.5 μA.

An analog digital converter traces a voltage both from the solar panel and from EDLCs. The voltages are measured at the AIN input with respect to GND over a range of 0 V to 2.048 V, with a resolution of 0.50 mV. There are voltage dividers
made to get a correct input voltage into the ADC input channels. Calculated equations (1 and 2) are shown below. \(X\) is AD conversion result (12-bit binary), \(N\) is MAX1237’s resolution (12). \(R_1, R_2, R_6\) and \(R_7\) are resistors in voltage dividers \((R_1=220\,k, R_2=220\,k, R_6=220\,k\) and \(R_7=220\,k)\). The place of voltage dividers is shown in appendix 3.

\[
U_{sc} = \frac{X \times 2.048V \times (R_1 + R_2)}{(2^N - 1) \times R_2} \tag{1}
\]

\[
U_{EDLC} = \frac{X \times 2.048V \times (R_6 + R_7)}{(2^N - 1) \times R_7} \tag{2}
\]

Solar cell voltage measuring is controlled by two power pMOSFETs. While the MOSFET (5) disconnects the whole load, simultaneously another MOSFET (3) connects the solar cells to the voltage divider and the current will flow through that divider to the AIN0 port and a conversion is made. Voltage from EDLCs is measured in a same way but only using one MOSFET (4). Picture 10 in chapter 4.3.12 shows how these MOSFETs are connected. All MOSFETs are controlled directly from the host through MAX7315 port expander [23].

The current design does not contain ADC, MAX1237, because it has the same \(I^2C\) address than fuel gauge IC, DS2782, has. To switch this ADC for a different one which has a different \(I^2C\) address will be one solution to dispose of this problem. During tests the MULLE’s AD-converter was used.

### 4.3.9 Port expander

Maxim, MAX7315 is 16-pin port expander IC which includes 8 I/O-pins, a ninth port can be used for transition detection interrupt or as a general purpose output, \(I^2C\)-interface, and three address inputs (AD0, AD1 and AD2). AD0 to AD2 sets devices slave address. MAX7315 has open drain outputs so it can only sink current. Therefore, pull-up resistors are needed in ports which are set to be an output.

The port expander is used to reduce wiring to the MULLE. It is easy to connect via \(I^2C\)-interface and it is essential IC to link all digital signals from the PSU to the MULLE. MAX7315 controls p-channel MOSFETs to do their duties and also supply batt_on- and DCDC_enable-pins state to the MULLE. The OR-gate is also controlled via the port expander. That is the way how the MULLE can control the whole circuit only using two wire interface, \(I^2C\). There are two more analog I/O ports to go for later use. In this experiment we used two of those ports for the LEDs. The green led is on and the red led is off if we are using EDLCs as a power source and vice versa if we are using a battery as a power source [23].
4.3.10 Serial FRAM memory

Ramtron, FM24CL64 includes an I2C-interface and a 64-kilobit memory employing an advanced ferroelectric process. A ferroelectric random access memory (FRAM) is non-volatile and performs reads and writes like a RAM and its functional operations are similar to serial EEPROM. The major difference between the FM24CL64 and serial EEPROM with the same pin-out relates to its superior write performance. FRAM provides reliable data retention for 10 years while eliminating the complexities, overhead, and system level reliability problems caused by EEPROM and other non-volatile memories.

FM24CL64 FRAM is used in this PSU to get more memory and speed to the system and there is no need to utilize the load internal memory of MULLE anymore. Using an external memory chip on the board will reduce the power consumption. Since, FRAM memory needs much lower power during writes than EEPROM does [24].

4.3.11 Voltage detector

Voltage detector, MAX6378, is an ultra low power detector in surface mount SOT-23 package. It consumes only 0.5 μA in active mode and can be used comfortably in any portable applications. Its output goes zero whenever the Ucc supply voltage falls below a preset threshold. Otherwise, the output has the same voltage as the input. The MAX6378 voltage detector family contains threshold voltages between 2.20 V to 4.60 V in 100 mV increments and it is possible to choose an active-low, active-high, push-pull or open-drain output.

3.4 V threshold voltage, active-low and push-pull output is chosen for this application. The voltage detector is used to control pMOSFET between the battery and ADM691A switch (see Figure 9 in chapter 4.3.4) [23].

4.3.12 Other components on the board

Five pMOSFETs are soldered on the board. Three of them are, IRLML6401PBF, a very powerful p-channel power MOSFETs and the other two are, SI4435DYPBF, p-channel power MOSFETs. Two IRLML6401PBF, (3) and (4) is used as a switch to control on-chip measurements from the solar cell and EDLC. The third IRLML6401PBF (5) disconnects the solar cell from the entire board. The MOSFET (5) is used if we want to measure the solar cells’ momentary voltage. At that time the MOSFET (5) is off and the MOSFET (3) is on and the measurement is taken by ADC. When measuring a voltage from EDLC’s the MOSFET (4) is on and the value is converted by ADC. See Figure 10.
Meanwhile, the SI4435DYPBF (1) connects/disconnects the battery and ADM691A switchover IC and the second MOSFET (2) drives higher current to the load if necessary. This situation is depicted in Figure 9. in chapter 4.3.4. All these power MOSFETs have a fast switching time, they are small and their on-resistance is very low. Therefore, the voltage drops over the MOSFETs are near zero volts.

NC7S32M5 is a single 2-input high performance CMOS OR-gate. Advanced Silicon Gate CMOS fabrication assures high speed and low power circuit operation. When another input or both inputs are high the output is high, otherwise low. NC7S32M5 is connected between the EDLCs and the MOSFET’s gate where the MOSFET is connecting/disconnecting the battery from ADM691A. The OR-gates first input is connected to the EDLCs and second input to the MULLE. This way the MULLE can control the battery if it is either connected or disconnected to the switch. It will reduce power consumption from the battery if the track between the battery and ADM961A in disconnected completely by using a MOSFET.

The coil is Drossel LPC4045 and an inductor value of 330 μH works well in this application. Absolute maximum DC current through the coil is 150 mA and it is not good to go over that limit.

LEDs, HSMC-C120 and HSME-C120, are surface mounted and their size is only 1.6 x 1.0 x 0.6 mm. This makes them very suitable for portable and indication application where space is a constraint.

The diode is normal 1N4148, the resistors and capacitors which are used are surface mounted components. The resistors’ value varies from 20 mΩ to 220 kΩ and capacitors’ value varies from 0.1 nF to 47 μF.

**4.4 I²C Interface**

Philips designed a simple bidirectional 2-wire bus almost 20 years ago. This bus called the Inter IC or I²C-bus. The I²C-bus’ main two advantages are the bus architecture and the 2-wire communication. The advantage of having true bus architecture is less wiring needed since each device connected to the bus is software addressable by a unique address and simple master/slave relationships exist at all times. Masters can operate as master-transmitters or as master-receivers. Only two bus lines are required; a serial data line (SDA) and a serial clock line (SCL), instead of having separate wires to every slave device. It also allows for several masters to be connected to the same bus. The principle of I²C-bus and connected master/slave devices is specified in Figure 11.
The master tries to detect the slaves, and backs off as soon as the other master seems to be accessing the bus. This normally means that the master unit that tries to use the bus first, will take the right to use it until it releases the bus into an idle state. When the bus is idle, the SDA wire carries a logic ‘1’. Electrically this means that all units connected to the wire have set their output buffers in a high impedance state. The voltage level of the line is then pulled up by a pull-up resistance \( R_P \) connected to \( U_{DD} \). The logic ‘0’ is accomplished by connecting the output buffer to ground. This means that any connected unit can force a logic ‘0’ on to the bus, while the logic ‘1’ is accomplished only when the outputs of all units are in a high impedance mode [21] [25].

4.5 Discussion about PSU hardware

This hardware was designed knowing that the MULLE has an \( \text{I}^2\text{C} \) interface ready and power consumption is an essential feature for this board. That is why \( \text{I}^2\text{C} \) was the best choice for this application. All \( \text{I}^2\text{C} \)-bus compatible devices on the board incorporate an on-chip interface which allows them to communicate directly with the host via the \( \text{I}^2\text{C} \)-bus. These devices include special features which are particularly attractive for portable equipment and battery-backed systems. All \( \text{I}^2\text{C} \) compatible components can be powered down, in sleep mode, by writing efficient software. It will reduce power consumption since the component which is not necessary to use is in sleep mode and only the used components are in running mode.

The size of the PSU board is interesting because the smaller the board is the better it fits for every day use. The EDLC’s size is crucial. The more farads you want on the board the bigger your board will be. On the other hand, a 2 F capacitor will supply the load for a longer time than a smaller one. There are several possibilities you can choose from and speculation between different properties is one of the biggest issues to get the best result for your self-designed application. The most interesting properties to concentrate on are: size, prize, power consumption, the ease of use and the ease of integration of the MULLE platform.

As it was shortly discussed in the previous paragraph the size of the designed PSU board is rather big compared with the size of the MULLE but the size will decrease at least to one fourth of the original size if the board is going to be made in professional manufacture. The prize is not the problem in this application. All the components were bought from general distributors or ordered from manufacturers.

The PSU takes 180 \( \mu \text{A} \) from the solar panels in normal use while the battery is not
used. So, the power consumption is low and EDLC’s charge will last several hours. The battery’s discharge is essential for evaluating the life-time. In sleep mode it takes only 1 uA from the battery and if the weather is good the battery will drain very slowly, and after this it needs manual recharging.
5. TESTING

The test chapter includes all the experiments what were made. The list below shows the measurements.

- Super capacitor’s charge time.
- Super capacitor’s discharge time.
- Power consumption of the PSU and each component.
- ADM691A’s switching time.
- Operational principle of PSU.

5.1 Super capacitor test

One important test in this thesis was to evaluate the super capacitor’s charge and discharge time, and this way to estimate how efficient the designed power supply unit is, or more precisely how efficient, the MAX866, DC-DC-converter actually is.

5.1.1 Theory of the experiments

The super capacitor’s energy, E, is calculated by using equation (3). Where C is the capacitors capacitance and U is the voltage which is charged to the capacitor. In this case U is 5V; it is an output voltage from, MAX866, DC-DC-converter.

\[ E = \frac{1}{2} * C U^2 \]  
(3)

\[ P = \frac{E}{t} \]  
(4)

As it is shown in equation (4), power (P) is energy (E) divided by time (t). The equation (5) by charging/discharging the capacitors with a constant current is depicted below.

\[ U = \frac{I}{C} * t \]  
(5)

\[ t = \frac{C * (U_{max}^2 - U_{min}^2)}{I * (U_{max} + U_{min})} \]  
(6)

Equation (6) is the same as equation (5) if the charging is started in zero volts (\( U_{min} = 0 \)). It is possible to calculate theoretical charge/discharge time from any volts to any volts by using an equation (6) [26].

There are three different developments performed in the graphic representation section. The first one depicts a discharge curve with and without ADM691A switchover IC system. The second one depicts a desired solar panel’s characteristic.
the output power of which is 36 mW (3.6 V/10 mA). In addition, this graph includes also outputs like 20 mW (2.0 V/10 mA) and 18 mW (1.8 V/10 mA). The third one represents a small solar panel which will give out 10 mW (2 V/5 mA) or 9 mW (1.8 V/5 mA).

The ideal charging experiment is realized by connecting two 1 farad capacitors in parallel. The source meter acts like a solar cell in this experiment. Its output is set to give 5 V and variable output current (2 mA, 5 mA, 10 mA, 15 mA and 20 mA). A mobile phone timer was used to count the consumed time. In the beginning the measurements were taken every 30 seconds to get a good looking curve but while approaching the end also the gap increases between two consecutive measurements. The ideal charge time was also evaluated by using one farad capacitor instead of two. Otherwise, the settings were the same. A DC voltage from the capacitors was measured by using a multimeter.

Also the discharge time from the super capacitors was evaluated. The first measurement was made without any load and after that a discharge test was measured with switchover IC, a voltage detector and p-channel MOSFET.

The last experiment was to measure the charging time by using a complete PSU board. Making this experiment gives a real estimation of how long it will take to fully charge the capacitors with the PSU board. A complete PSU board was used. Keithley 2400 SourceMeter was connected to input of the board which will charge the super capacitors through DC-DC-converter. The Mascot power source acts like power from the MULLE and it supplies a comparator, both FRAM memories, ADC and a port expander. The battery is connected to its own place and it powers fuel gauge IC but does not have any effects on the super capacitor’s charge or charging time.

### 5.1.2 Test environment

The equipment used in this experiment was Keithley 2400 SourceMeter, Mascot power source, Fluke 75 multimeter, Sony Ericsson K518i mobile phone, ELNA back-up capacitor (1 F/5.5 V) and complete PSU board. All measurements were made in high ESD protected laboratory in EISLAB, Luleå University of Technology.
5.1.3 Test results

This chapter introduces the feedback of the super capacitor’s test results and graphic representation. Two extra graphs are introduced as an appendix at the end of the thesis.

Table 4 below depicts the super capacitor’s charge time in different circumstances. The theoretical value was calculated by using equation (5). The ideal charge and charge with PSU board techniques was introduced in chapter 5.1.1.

Table 4. EDLC’s charge time with two different capacitor (1 F and 2 F)

<table>
<thead>
<tr>
<th>Capacitance</th>
<th>2 mA</th>
<th>5 mA</th>
<th>10 mA</th>
<th>15 mA</th>
<th>20 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical (equation 5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 F</td>
<td>42 min</td>
<td>17 min</td>
<td>8 min</td>
<td>6 min</td>
<td>4 min</td>
</tr>
<tr>
<td>2 F</td>
<td>1 h 23 min</td>
<td>33 min</td>
<td>17 min</td>
<td>11 min</td>
<td>8 min</td>
</tr>
<tr>
<td>Ideal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 F</td>
<td>36 min</td>
<td>13 min</td>
<td>6 min</td>
<td>4 min</td>
<td>3 min</td>
</tr>
<tr>
<td>2 F</td>
<td>1 h 13 min</td>
<td>28 min</td>
<td>13 min</td>
<td>8 min</td>
<td>6 min</td>
</tr>
<tr>
<td>With PSU board (2.0 V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 F</td>
<td>3 h 52 min</td>
<td>1 h 5 min</td>
<td>28 min</td>
<td>18 min</td>
<td>13 min</td>
</tr>
<tr>
<td>2 F</td>
<td>6 h 53 min</td>
<td>2 h 5 min</td>
<td>54 min</td>
<td>35 min</td>
<td>25 min</td>
</tr>
</tbody>
</table>
5.1.3.1 Graphic representation

All super capacitor’s charge measurements can be shown in graph form. Figure 12 represents a discharge without load and with PSU board. The time scale in X-axis is one day (24 hours).

![Figure 12. Ideal discharge and discharge with Switchover IC.](image)

The ideal discharge lines (black and red) show that EDLCs will drain slowly after they were charged to full and left floating. Connecting the ADM691A switchover IC after EDLCs the discharge time will decrease but is still over 20 hours with a 2 F capacitor on the board. The discharge time with a 1 F capacitor is half of the 2 farad capacitor’s time.

According to the datasheet and the test results ADM691A draws 70 µA from EDLCs and supplying the external load e.g. the MULLE the discharge rate is even more. Hence, so high discharge rate requires that EDLCs are recharged on a daily basis by the solar panels.

Figure 13 represent a charge without PSU board and a charge with PSU board at three different input voltages (1.8 V, 2.0 V and 3.6 V). The input current in this test was limited to 10 mA. The time scale in the X-axis is slightly over one hour starting at 00.00. 36 mW was the most interesting test value when writing this thesis because the solar panel which was going to be used has the output voltage of 3.6 V and the output current of 10 mA.
Figure 13. Charging table with 10 mA charge current.

The Red line (1 F capacitor) and the black line (2 F capacitor) represent an ideal charge while the capacitors were charged to 5 V with a constant current (10 mA). The charging time in the 1 F case is around 6 minutes and with the 2 F case it is around 13 minutes. It is possible to calculate the theoretical charging time by using equation (5) from chapter 5.1.1. In this experiment the charging time was metered until the voltage reached 5 V. Therefore, there was a difference between the measured and the theoretical value.

\[ t = \frac{5V \times 1F}{10mA} = 500s \approx 8\text{ min} \]

\[ t = \frac{5V \times 2F}{10mA} = 1000s \approx 17\text{ min} \]

The DC-DC-converter limits the output current and that is why the charging time with the PSU board is practically the same at varying input voltages. The used input voltages in this experiment were 1.8 V, 2.0 V and 3.6 V and the input current was 10 mA. These test conditions represent a real life situation where a smaller solar panel is used or solar cells are used in poor daylight conditions. The reason for the same charging time is the electrical properties of the DC-DC-converter. Therefore, the input current (power) for the DC-DC-converter is sufficient the DC-DC-converter will be running at full blast. While charging the EDLCs with PSU board (1 F and 28 min / 2 F and 55 min) it takes 4.8 times longer time than charging EDLCs directly, without the PSU board (6 min / 13 min).
Figure 14 represents a charge without a PSU board and a charge with PSU board at two different input voltages (1.8 V and 2.0 V). The input current in this test was limited to 5 mA. As we can see 5 mA input current into the DC-DC-converter is high enough to work well. Therefore, there is no difference if the input voltage is 1.8 V or 2.0 V.

![Figure 14. Charging table with 5 mA charge current.](image)

5.2 PSU test

The power consumption test was made in this section. In addition, the switching time of ADM691A’s switch and the operational principle of the complete PSU in use were also measured. The operational principle introduces a method of how the PSU works in practice and the power consumption experiments will give an overlook of consumed current in each component separately.

5.2.1 Theory of the experiments

It is essential to know the current consumption of the whole board for the evaluation of the lifetime and to decide a useful environment for this board. The tests were made individually with each IC. The switch current consumption was measured in both cases; The EDLCs connect to out and the battery connects to out. The power supply block is measured separately from the rest of the board. See Figure 15 where the power supply block is defined from the entire board. Moreover, the fuel gauge IC’s supply current was also tested at the same time.
The test was made by connecting Keithley’s SourceMeter 2400 to the input of DC-DC converter without an output load. The source meter displays how much current the net will draw. After that the comparator was connected to the DC-DC-converter and the current consumption was read again from the display. Same measurement was measured after switch was connected with DC-DC-converter and comparator. Figure 14 shows the current consumption results from the power supply block.

The switch current consumption was measured by using a Fluke 75 multimeter. The multimeter was connected in series between EDLCs and ADM691A $U_{cc}$-pin (pin3). The measurements were made without EDLCs and with EDLCs. In the same way the current consumption for fuel gauge IC was metered. Now the Multimeter was connected in series between the batteries’s positive terminal and the ADM691A $U_{batt}$-pin (pin1).

Figure 16 depicts a data acquisition block of the PSU. A port expander IC which supplies commands from the host is also included. This part of the board gets power from the MULLE and these components are really low power ICs. The measurement was executed in same way as before, each component separately. A Mascot power source was used, Fluke 75 multimeter and PSU board with jumpers. Only one jumper was used at the time and the current was measured by using a multimeter. After one component was measured the jumper was removed and the next component was connected with the jumper etc.
It is important to know the ADM691A’s switching time and it should be fast enough to prevent re-booting of the MULLE every time the switch changes its state. The test was executed in the laboratory with Tektronix TDS7254 Digital Phosphor Oscilloscope, Keithley 2400 SourceMeter, a Mascot power source and a PSU board. The test was made for three different output loads. First, without load, second, a load which draws 10 mA from the EDLCs, third, where the load draws 20 mA from the EDLCs. By using these three different load values we can compare how the switching speed changes. Figures 18 to 20 shows the results in the test result chapter. Figures 21 and 22 are the pictures from the oscilloscope screen. During this experiment the whole system was working and the oscilloscope’s four channels were connected to the PSU. The first channel measures the EDLCs voltage. The second channel is reserved for the battery voltage. The third channel is used for output voltage and the fourth channel is a digital output from the batt_on pin. This test will give you an overall overview how this switch system works with both power sources connected.

5.2.2 Test environment

The equipment used in this experiment were Tektronix TDS7254 Digital Phosphor Oscilloscope with Windows98 operating system, Keithley 2400 SourceMeter, Mascot power source, Keithely 6485 Picoammeter and Fluke 75 multimeter. PSU board version was used with 330 $\mu$F capacitors instead of 2 F EDLCs to allow measurements with higher accuracy. All measurements were made in high ESD protected laboratory in EISLAB, Luleå University of Technology.

5.2.3 Test results

As it is shown in Figure 17 the DC-DC-converter’s start-up voltage is around 1,0 V and it will draw about 50 uA in active mode since the input voltage is 3,6 V. Running step-up converter with comparator the ramp up voltage is higher (about 1,34 V) because there is a voltage divider in front of the IN+-pin of the comparator. The voltage divider is made with two resistors, $R_3=56$ k and $R_4=470$ k (see appendix 3). It will set the output to high and it allows the DC-DC-converter to start since the IN+-pin is higher than the comparators internal reference (1.182 V). When $U_{in}$ is 1.34 V the voltage in IN+-pin is a little less than 1.2 V. See equation (7). DC-DC-converter together with comparator draws in its entirety 70 uA. There is no big difference if we are using only the DC-DC-converter or both the DC-DC-converter and the comparator.

$$U_{IN+} = \frac{R_4}{R_4+R_3} * U_{in} = \frac{470k\Omega}{470k\Omega + 56k\Omega} * 1.34V = 1.20V \quad (7)$$
The current consumption is 180 μA since the switch is connected to the DC-DC converter and the comparator while EDLCs are fully charged. The ADM691A switch itself draws about 70 μA when the EDLCs are full and they are connected to the out. That is the same as with the datasheet. Of course the leakage from EDLCs will have small affects to the whole power consumption in the system.

DS2782 Fuel gauge IC draws 70 μA in active mode but in sleep mode it takes only 1 uA. While in active mode, the DS2782 is fully functional with measurements and capacity estimation continuously updated. In sleep mode, the DS2782 conserves power by disabling measurement and capacity estimation functions, but preserves the register contents.

Figure 13 shows how much current the comparator and both FRAM memories will draw from the MULLE. ADC current consumption depends on the speed of the conversion. If ADC is running at 94.4 ksps it will draw 670 μA, 40 ksps and 220 μA, 10 ksps and 60 μA or 1 ksps and 6 μA. In power-down mode ADC will consume only 500 nA.

The port expander has four different running modes and each of those modes consumes a different amount of current. MAX7315 takes about 2 μA in sleep mode (Interface is idle and PWM is disabled) and while the interface is idle and PWM is enable it takes more or less 10μA. In active mode (the interface is running and PWM is enabled) the port expander takes little bit more than 50 μA and while the interface is running and PWM is disabled it consumes around 40 μA.

Figures 18, 19 and 20 depict the switching time for the ADM691A switchover IC. In all three figures the system is running first for the battery and switches its state in the middle of the figure. There is no load in Figure 18, where the switching time is 300 ns.
In Figure 19 the load draws 10 mA from the EDLC at that time the switch changes its state in 400 ns. The switch is 25% slower than it is in no load situation.

In Figure 20 the load after the switch is bigger and draws about 20 mA from EDLC. At the time switching time is around 420 ns and will not rise so rapidly anymore. We can see that the switching time is little bit over 400 ns in normal use.
Figure 20. ADM691A switch with load which draws 20 mA.

The next two figures (21 and 22) are taken from Tektronix TDS7254 Digital Phosphor Oscilloscope. This EDLC’s charging figure (Figure 21) shows how the ADM691A switchover IC works in normal use. The green line is $U_{out}$ and it follows the battery voltage (Blue line) so long as the EDLCs have charged (Red line) over 3.4 V. At that point the EDLCs are connected to the $U_{out}$ and $U_{out}$ follows EDLC’s voltage. The purple line is batt_on -pins state. At the beginning the batt_on is high and goes low since the switch connects the EDLCs to the $U_{out}$.

Figure 21. System’s configuration during EDLC’s charge.

Figure 22 is a discharging figure and it shows how the switch acts during the EDLCs’ discharge. When the EDLCs’ charge goes lower than the voltage detectors threshold voltage, 3.4 V, the switch connects the battery to out. At the same time batt_on goes high and the EDLCs’ continue to discharge until the sun is shining.
again. Also in this figure the blue line is the battery voltage, the red line is the EDLCs’ voltage, the green line is $U_{out}$ and the purple line is the `batt_on` –pin.

Figure 22. System’s configuration during EDLC’s discharge.

5.3 Summary of performance

The switch that was used has good features as well as bad characteristics. It chooses the power source automatically and its switching time is fast enough, so that the MULLE will not boot up if the switch changes the state. The setback is the internal resistance which will cause the voltage drop over the switch and size. Another setback is that the ADM691A includes many I/O ports that were not used in this application.

The MULLE takes 35 mA during active mode. It means that Bluetooth and M16 are running. The PSU consumes a little less than 200 $\mu$A while running from solar cells. Comparing these current consumptions; the PSU takes under one percent of the whole system’s current. This is an important piece of information. Therefore, the PSU is a good solution for powering the MULLE.

If the solar cell is running the system on day time and the EDLCs during the night, that means that we do not need to use a battery at all. 140 mAh battery will be dead theoretically after 15 years. Therefore, the battery’s power consumption is 1 $\mu$A but in real life the deep discharge time would be less. The EDLCs are charged under sunlight so that they can be used at night if some tasks are needed to be carried out. Therefore, the EDLC’s charge is enough to keep the system in standby all the time.
6. SOFTWARE FOR PSU

The software for this power supply unit is from another project. The updates are made so that the PSU and, the software are fitted together. Below is a description and the principle of the software used.

The software supports a number of low-power modes, as well as monitoring the PSU hardware. The Task manager, check Figure 20 below, receives information from the power supply unit; e.g. the battery levels and the status of the energy harvesting system. It also receives requests from energy demanding tasks, such as turning on a sensor or making a data transmission. Depending on the priority of the task and the available energy levels, the task can be dispatched, delayed or discarded. The estimated energy required for each task must be given at a compile time and it is obtained and is obtained by characterization techniques [19]. The Task manager also has a configuration which is given at compile time, which sets e.g. the priority levels (i.e. which level is allowed to use the battery), and what kind of actions that are to be performed when the task request is received. The Task manager acts as a context- and energy-aware task scheduler, controlling the energy consuming tasks when they are allowed to be dispatched [18].

![Figure 20. Power management architecture [18].](image-url)
7. PSU BOARD IN GENERAL USE

Stand-alone photovoltaic power systems are potential power sources for portable equipment installed in rural areas. Extending the lifetime and optimizing the charging method of backup power storage devices are the keys to increasing the system lifetime and efficiency. This chapter discusses the PSU’s usability in different sunlight circumstances.

7.1 Low sunlight region

One interesting area is the geographic region of the Arctic Circle and its surroundings like the northern parts of Scandinavia. At midsummer, the sun does not set, on the other hand, at midwinter, there is period of darkness when the sun does not rise over the horizon. Of course, in summer the sunbeams will not meet perpendicularly the solar panel’s interface on these latitudes but the EDLCs are charging all the time since the sunlight is available throughout the night. Momentary output power from the solar cells is smaller but non-stop power will equalize the split.

In this side of the Earth you have to pay attention to the maintenance more than near the equator. Especially, in winter snow will cover the solar panels really easily and the sunlight will not reach the interface of the panel. Keeping the panel clear and clean guarantees good conversion from radiation to electricity. Cold weather could also be problem. Since, some components on the board have a frosty limit about -40 degrees.

Because of the long winter time the PSU board is not so efficient so far up north. For example on the Arctic Circle the sun is seen an average of three hours per day in midwinter which is not enough to charge the EDLCs completely. So, absolutely the better choice for the PSU is to use it in summer, but it will work fine also in winter.

7.2 High sunlight region

High sunlight regions include e.g. the Tropical and Mediterranean areas. The tropics are in the geographic region of the Earth centred on the equator and limited in latitude by the Tropic of Cancer in the northern hemisphere and the Tropic of Capricorn in the southern hemisphere. This area includes all the areas of the Earth where the sun reaches a point directly overhead at least once during the solar year. In addition, nights and days are almost the same length all the time and sunlight is available all around the year.

In this area solar panels are commonly used because so much sunlight and thereupon solar energy is available. Using the MULLE here with a PSU will be success. The most of the time the sun is shining towards the cells and the angle where the beams meet the interface is small enough. Therefore, the EDLCs can be charged on a daily basis and the MULLE can be run only on solar energy.

One application for the system could be to measure some nature factors, like the temperature, wind power, precipitation or moisture. For example, one measurement will be made in every hour. In day time the connection will occur by using a Bluetooth and information is sent right after the values are stored. During the night
the measurement will be metered every hour, as well, but the values are just stored in
the memories and will be sent to the end-user after sunrise in the morning. That is
made because of the high power consumption of Bluetooth. After every transfer the
EDLCs will be charged back to full since the all transfers are made in daylight.
8. FUTURE DEVELOPMENT

In this chapter, a few proposals for future developments will be discussed. It is evident that solar energy is the future’s energy source. Solar panels and methods will develop rapidly during the next decades and more and more power will be degenerated from the solar cells.

8.1 Reducing energy lost

The EDLCs are driving the load when the voltage is over 3.4 V. After the voltage decreases under the 3.4 V the battery is driving the load. Inside the EDLCs there is over 11 joules unused energy from 0 V to 3.4 V. This amount of energy is completely useless in the present design and needs to be mobilized some way. To add a second DC-DC converter after the EDLCs and ramp up the voltage again to 5 V will decrease the switch system’s threshold voltage in a major way. In two DC-DC converters’ system the threshold voltage is the latter DC-DC converter’s start up voltage (1.34 V). Now, the battery is driving the load until the EDLCs charge has dropped under 1.34 V. Therefore, more energy is at the MULLE’s disposal. These upgrades will bring out some drawbacks, as well. The size of the board will increase a little and the power consumption is higher than before.

ADM691A has now 4.65 V threshold voltage which is really high for this application. Another too high value which the ADM691A switch includes is internal resistance when the battery is connected to the U_{out}. In that case the internal resistance is over 10 \Omega which means that there is 0.4 V voltage drop when running the host from the battery. To find a new and more sophisticated switchover IC will reduce components on the board and extend the battery’s life. Besides, there is no need to consider another DC-DC converter.

Small hardware changes will improve the PSU’s efficiency. Placing the components in a better way will give small improvements but replacing the whole component to a different one will be a better choice in some cases.

There are many possibilities for the DC-DC converter’s external components. Forthcoming sentences will depict a few of these. Inductor values are not critical but they will change some features. In general, smaller inductor values supply more output current while larger values start with a lower input voltage. In addition, higher efficiency and output current are achieved with lower inductor resistance, but unfortunately this is inversely related to physical size. Some of the smallest coils have resistances over 10 \Omega and will not provide the same output power or efficiency as the 1 \Omega coil. At light loads, however (below 5 mA), the efficiency differences between low- and high-resistance coils may be only a percent or two.

The equivalent series resistance (ESR) of both bypasses and filter capacitors affects efficiency and output ripple. Use low-ESR capacitors for best performance, or connect two or more filter capacitors in parallel.

For optimum performance, a switching Schottky diode (such as the 1N5817 or MBR0520LTI) is recommended but for low output power applications a PN-junction switching diode (such as the 1N4148) will also work fine. Although, the greater forward voltage drop will reduce efficiency and raise the start-up voltage.
**8.2 Reducing power consumption**

The more external components there are on the board the more they will draw current. Therefore, after minimizing extra components, the current consumption will decrease as well. Two biggest current spenders at the moment are the ADM691A switchover IC and the MAX7315 port expander. The port expander has many external resistors around it because it has open drain outputs and those outputs can only sink current. Therefore, pull-up resistors are needed on the board to draw extra current from the source. Change the MAX7315 port expander for a different one e.g. a PCA9534 port expander which is pin and software compatible with a Maxim circuit. The PCA9534 has CMOS output ports which can source current, and therefore does not need any pull-up resistors. Another choice is a PCA9535 that is a 24-pin port expander which could be a better choice for future design, since it contains more I/O-ports. The more I/O-ports are available the more information can be collected from the board. That will help us to predict how long the stored energy will last. Of course, it is impossible to know exactly, but more accurate estimations can be made if we know every detail of the present design. That is the direction where we should take this application in the future.

**8.3 Charging the battery**

A Lithium polymer battery is the best choice for the back-up power. The battery is small, its shape can be modified, and moreover it can be charged at the same time as the solar cell is supplying the load. This would be an excellent solution, because the charging circuit in front of the battery can enter the current into the battery. Therefore, more energy is stored and more lifetime for the system is provided. The battery can store a lot more energy than the EDLCs, and moreover, the EDLCs can be erased on the board, which will shrink the board size dramatically.
9. CONCLUSION

The aim of this thesis was to develop a power supply unit for MULLE, a wireless sensor platform, which needed to be ultra low power and small in size. One vital requirement was to design a system that chooses the power source between the battery and one renewable power source; in this case the one renewable power source was the solar cells. In addition, the host needs to know e.g. the state of charge of the EDLC, the battery and voltage from the solar cell, whenever it is necessary.

The proposed design is a stand-alone photovoltaic power system that uses electric double layer-capacitors (EDLCs) as a power storage device and a Lithium polymer battery as a back-up power source. DS2782, the fuel gauge IC, was found to be the best data acquisition system which has low power consumption and measures all the interesting characteristics like voltage, current, state of charge, temperature, etc. from the Lithium polymer battery.

The energy storage system in this application was chosen between the EDLCs, batteries and normal capacitors. The normal capacitors are too weak and too small for this device. Therefore, energy is needed for a long time. The best solution is both the battery and the EDLCs together. These two were connected to the input of the ADM691A switchover IC in parallel which makes automatically the decision which one of these is driving the load.

The solar panels output power is still too low for charging modern batteries or otherwise modern batteries are not so sophisticated that they can be charged with little current. Thereby, the EDLCs were the only energy storage device on the board. Small charging current will have affects also to EDLC’s charging time which is long if the charging is started at zero volts. This problem can be easily relieved by pre-charging the EDLCs before the system starts to operate.

The data acquisition system is developed around the I²C-bus. The I²C interface was found to be the most practical solution for connecting the PSU and the MULLE together. All components which collect information from the PSU have an I²C-interface or the MULLE can control them through the I²C-bus. The port expander provides commands from the host and reduces greatly the number of wires between the PSU and MULLE. Therefore, it is the major IC for the system. Other I²C components are an analog digital converter, the already mentioned fuel gauge IC and two FRAM memories.

The PSU board was a self-made double-sided PCB which is about 70x50 mm. Using a commercial PCB manufacturer and making a four-layer board should probably shrink the size at least by 50 percent.
10. REFERENCES


11. APPENDIX

Appendix 1  Charge with 2 mA, Charge with 15 mA and Charge with 20 mA
Appendix 2  Bill of Materials
Appendix 3  Schematic of PSU
Appendix 4  Layout and digital pictures of PSU
Appendix 1  Charge with 2 mA, Charge with 15 mA and Charge with 20 mA (1/2)

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**Ideal Charge (2 mA) / Charge with PSU (2.0 V, 2 mA)**

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Appendix 1  Charge with 2 mA, Charge with 15 mA and Charge with 20 mA (2/2)

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Diagram: Ideal Charge (20 mA) / Charge with PSU (2.0 V, 20 mA)
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Appendix 4  Layout and digital pictures of PSU