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Multicell Battery monitoring and balancing with AVR

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Problem Description

Make a system to monitor and balance cells in 7-10 series Lithium phosphate or Lithium Manganese Spinel batteries targeted for power tools. Lithium Phosphate and Lithium Manganese batteries are inherently safer than the standard Lithium Cobalt batteries, and don't require as much protection. Thus, a battery pack can be made by using a standard TinyAVR or megaAVR MCU and using resistor dividers to scale down the voltage of the cells to a range that can be measured by the MCU. To enable a long lifetime of the battery pack, cell balancing becomes important. Gas gauge is also required. A voltage based gas gauge is deemed sufficient.

Assignment given: 16. January 2009
Supervisor: Trond Ytterdal, IET

Abstract

Today Lithium Ion batteries are extensively used in all kinds of electronic equipment due to its superior properties. However, Lithium Ion batteries need to have all the individual cells monitored to ensure the safety and long life time. This master thesis' objective is to design a managing system for a ten cell Lithium Ion battery with an Atmel AVR microcontroller.

The main challenge was to scale down the high voltage level a 10 cell battery has and still maintain accuracy when reading this voltage with the AVR. This was solved by using current sense monitors which can handle large common mode voltages. Hardware was made to show proof of concept. It was found that the scaling circuitry had an accuracy of $46mV$.

In competition with other single chip devices, some other methods have to be found. The design in this thesis is physically too large and too expensive to be of any commercial use. However some other methods worth looking into have been proposed in the last chapter.

Preface

Writing this thesis has been both enjoyable and challenging. I have got a very good picture of how a state of the art battery system is working. A little bit frustration over the fact that some of the good ideas came very late in the process and only ended up in the future work section. Even though the system that was designed cannot compete commercially, ideas that emerged during the process might. It has been fun to actually make the hardware and see it working.

I want to thank Atmel for giving me this challenge and for letting me use all the equipment I needed, the guys at the department of Engineering Cybernetics for letting me use their equipment for prototyping, my supervisors Håvard Nygård and Trond Ytterdal and my friend Marius Lind Volstad for helping me out with coding and correction reading.

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Ole Johnny Borgersen

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List of Abbreviations

I^2C	A multi master serial bus
ADC	Analog to Digital Converter
Battery	One or more cells in parallell, series or both
CC-CV	Constant Current - Constant Voltage
Cell	A single voltage source device often part of a battery with multiple cells
Li-Ion	Lithium Ion - A battery technology
Li-Po	Lithium Polymer - A battery technology
MCU	MicroController Unit
SB200	Smart Battery development platform for SB20x reference designs
SB201	Evaluation and development kit for the Atmel Smart Battery device ATmega16HVA
SBS	Smart Battery System - An open standard
SMBus	A two wire interface derived from I^2C
SoC	State of Charge
STK600	A complete starter kit and development system for the AVR and AVR32 flash microcontrollers from Atmel
TWI	Two Wire Interface - Compatible with I^2C
UART	Universal Asynchronous Receiver/Transmitter - A simple serial protocol identical to RS-232, but operates on different voltage levels

Chapter 1

Introduction

This thesis will present a system for monitoring, balancing and protecting a multi cell lithium ion battery pack. The main unit for controlling this system will be a standard AVR microcontroller. The target product for this application is mainly power tools which nowadays often run on relatively high voltages. The main challenge with this application is that one has to deal with large voltages compared to what a regular microcontroller is able to handle.

The design will be built and tested to give a proof of concept.

1.1 Specification

There has only been given a few guidelines for design in this assignment. The author has therefore made some assumptions and made a list of specifications that makes sense in an application like this.

1.1.1 Control Unit

The controlling unit is specified in the problem description to be an AVR microcontroller of some sort. Exactly which one will be decided based on the needs for communications, I/O pins, etc.

1.1.2 Battery Size

This is also specified in the problem description to be 7 to 10 cells. This thesis will therefore focus on a design with 10 cells. It is generally easier to scale down the circuitry to fewer cells than to scale it up to more cells. This is because of the requirement for certain components to handle larger voltages.

1.1.3 Cell Types

As the voltage level of most Lithium Ion cells is more or less within the same range, the actual cells that is used in the design is not critical. The principles and functions of the circuitry will be the same with only minor or no hardware and software modifications. It has therefore been made a choice to use TrustFire cells in this specific design. This is because these are the cells that come with Atmel's Smart Battery demonstration kit SB200 and they are cost-effective.

1.1.4 Physical Size

It is desirable to get the physical size down to a minimum, since the circuit will actually be inside a battery pack. However in this thesis, the main focus is not to shrink the physical size, but to get a working prototype. Package types will be chosen to be of a size that can be soldered by hand without too much trouble. Most standard components as resistors, capacitors, transistors etc exists in very small packages. It is likely that a design will be scalable down to an acceptable size with good layout and substitution with smaller packages.

1.1.5 Power Source and Power Usage

The circuit will be powered by the battery itself. It is an aim to minimize the power usage.

1.1.6 Communication

Visual

It is desirable to have LEDs to indicate the state of charge of the battery to quickly give an indication to the user. The leds will not always be on, because this will contribute to a higher power usage. Instead the lights will be turned on for a few seconds when the user pushes a button.

Non visual

The battery must have some way to communicate with the host[1] and the charger. Especially important is communication with the charger because of the danger involved of overcharging a Lithium Ion battery[15]. An important function like cell balancing is also in use when charging.

The Smart Battery standard is a standard that describes a communication protocol for a battery system[2]. This protocol lies on top of the SMBus Standard [12]. It is desirable that the system in this thesis is compatible with the Smart Battery standard as long as it is practical. However, there is no point in implementing functions that never will be used. As a consequence of following the SBS, the AVR unit has to be able to communicate with a two wire interface.

1.1.7 Gas gauging

As stated in the problem description, gas gauging based on voltage only is sufficient. A table or graph that describes voltage as a function of state of charge for the specific cell type is needed.

1.1.8 Temperature Sensor

Some AVRs have internal temperature sensors. However external thermistors can be connected to an ADC channel if there is one free. Temperature sensing will be a useful function, but it will not be prioritized in this design.

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[1] In this case, the power tool

[2] A Smart Battery system consists of a battery, a host and a charger

1.1.9 Current monitoring for Safety

As the problem description does not say anything about this, it will only be implemented if the chosen AVR has enough available I/O pins for this.

1.1.10 Authentication

Authentication can be useful to ensure that only batteries from certain manufacturers can be used. With usage of the Smart Battery standard, an authentication method is purely a software issue. As it is relatively easy to implement at a later point, authentication will not be a part of this specific design.

1.1.11 Cost

As with physical size, cost is not the main focus. In electronics, cost is highly dependent on volume. The time spent on the design will be used on getting a working system and not searching for the cheapest component. However, since this is a product that eventually can be commercialized the cost will be kept in mind. With a working design, it is likely that the cost can be reduced on a future stage by replacing components. It is the principle of the design that is important.

Chapter 2

Background Information and Theory

2.1 Lithium Ion Battery Technology

Lithium Ion and Lithium Polymer batteries are now used in a lot of electronic equipment because of the superior properties compared to traditional batteries. They have among others very high energy density and low self discharge rate[15][4].

Due to the chemistry of these batteries, they require voltage monitoring for protection. Excessive discharge of a cell may lead to shift of polarization and permanent damage. Overcharge may lead to overheating and in worst case ignition and explosion. And so it is critical to have some kind of protection circuitry that can shut down the charging and discharging process.

In batteries with multiple cells connected in series one need to monitor each single cell to make sure that the voltage is within a safe range. Even though the battery pack voltage is normal, single cells may be outside normal limits due to cell imbalances. Electronics used in Lithium Ion batteries also often integrate some kind of balancing mechanism in addition to voltage monitoring. In traditional batteries, cell balancing is done by so called controlled overcharging [1][10]. The excess energy of full cells is released by gassing.

In laptops, digital cameras, cell phones etc. it is required to have some kind of gas gauge to give the user an estimated runtime of the application. This often requires complex electronics. Since the voltage versus state of charge curve of a Lithium Ion battery is relatively flat in the middle, a voltage based gas gauge is often not good enough. In addition a coulomb counter is also a part of these kinds of batteries. This combination of monitoring often gives a very accurate reading of state of charge.

2.1.1 Charging Li-Ion Batteries

Today, short charging time is often a requirement for portable equipment. An often used charging profile is the Constant Current - Constant voltage method, referred to as CC-CV. With this method the charger is generating the required voltage to create a constant charging current. When the voltage reaches a threshold, it holds it there until the current is below a specified value. The CC-CV charging profile can be seen in figure 2.1

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[1] Continued charging until all cells are full

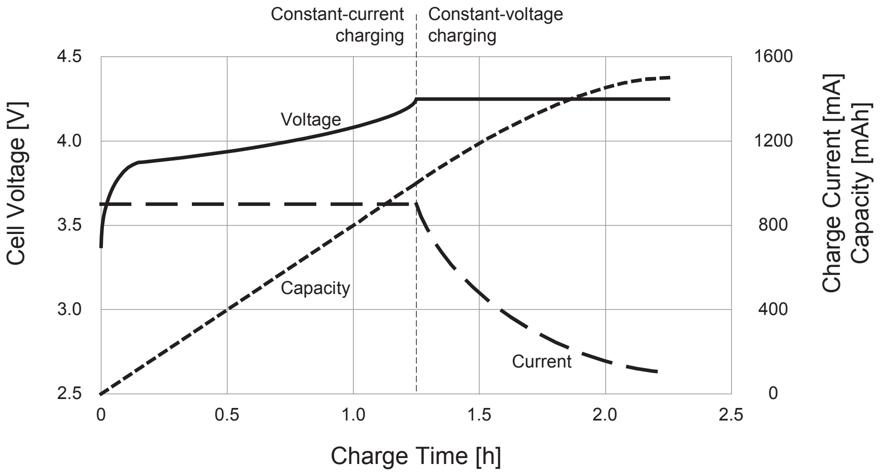

Figure 2.1: Constant Current Constant Voltage charging profile. (Image taken from [4])

It is essential that voltages and currents are within limits set by the manufacturer of the cells. Overheating and other damages might happen to the cells.

2.1.2 Discharging Li-Ion Batteries

It is important that discharge is terminated when the lower voltage limit of the battery is reached. Continued discharge after this limit is reached will cause permanent damage to the cell. To maximize the capacity of a cell without damaging it, an accurate ADC to monitor the voltage is desirable.

The current drawn from the battery must not exceed what is specified by the manufacturer. Doing so can cause overheating and rupture of the cell. Protection against shorting and over current can easily be implemented in systems where there is a coulomb counter present.

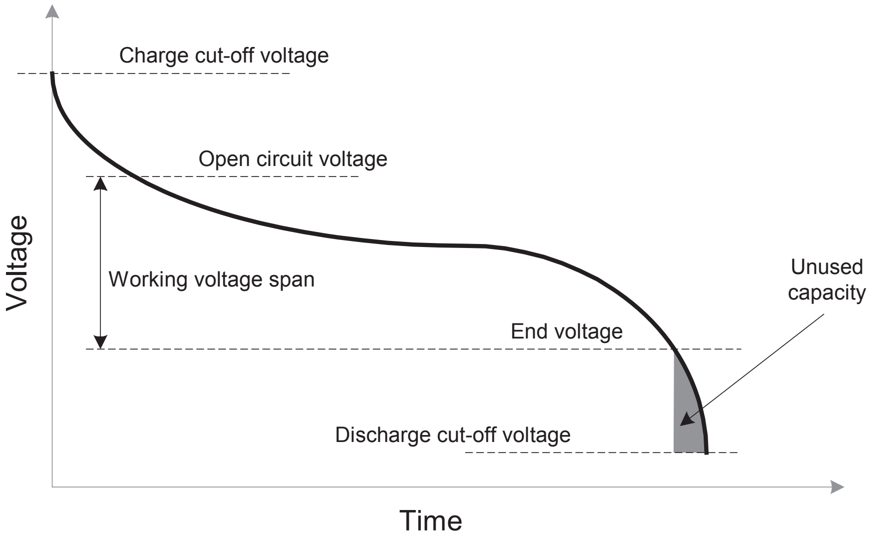

Figure 2.2: Typical discharge profile for a Lithium Ion battery. (image taken from [4])

2.1.3 Internal Resistance

Internal resistance in a battery is the non ideal effect that makes the discharge voltage lower than the open circuit voltage and the charge voltage higher than the open circuit voltage. This applies to any battery, not only lithium ion. It will also restrict the maximum current possible to draw from a battery. An ideal battery has zero internal resistance.

2.1.4 TrustFire Cells

Figure 2.3: TrustFire cell used in this thesis

In this thesis there has been used a specific type of cells. TrustFire cells are cheap Lithium Ion batteries with a built in protection circuit. They are not high performance cells, but since the principles for monitoring and balancing are more or less the same for all Lithium Ion batteries, they can be used for development purposes. These are the same type of batteries that comes with Atmel's SB200 Smart Battery development kit.

There has not been found any datasheets on these cells, but characterization has been done with advanced equipment. In figure 2.4 voltage versus state of charge is shown for different current loads. This is important data when making a voltage based gas gauge. More data on the TrustFire cells can be found in appendix A.

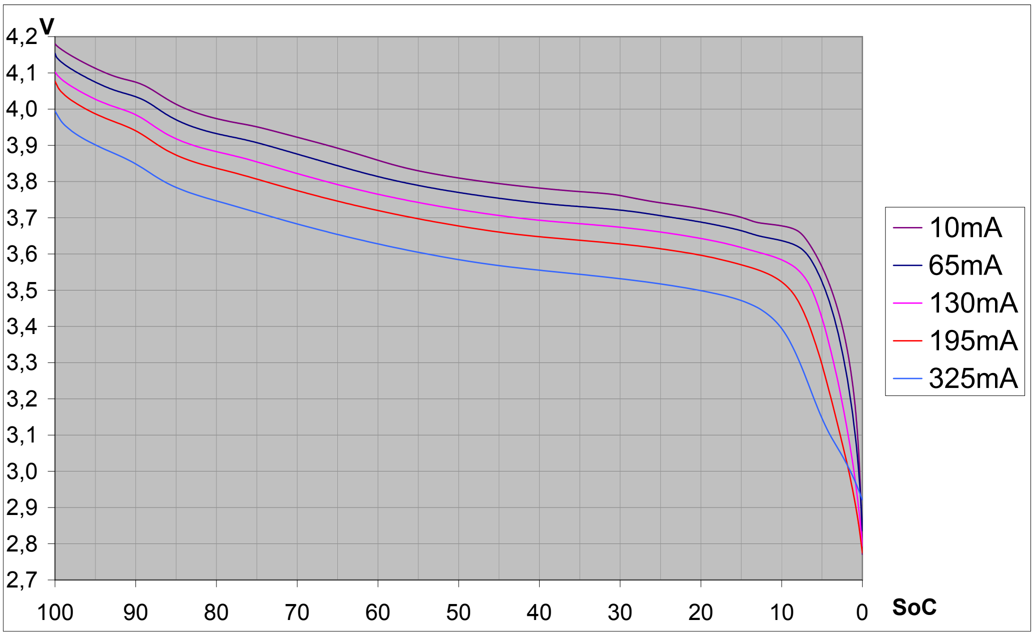

Figure 2.4: Voltage Curve vs SoC

2.2 Cell balancing

Cell balancing is a technique used to maintain equal or near equal voltage-levels on all cells in a battery pack. This applies only to cells connected in series, as cells connected in parallel will be self balancing. The main reason for keeping cells in balance is to keep the battery's capacity as high as possible throughout its lifespan.

Today manufacturers usually have very good control on matching cells, 50mV or less. However there are a number of ways that cells can end up being out of balance[5].

- Small variations in the cells chemistry resulting in different charge acceptable levels. This can drift over time making it worse.
- Variations in the ability to hold charge over time and usage cycles.
- Variations in self-discharge rates.
- Temperature will accelerate the effects stated above. This will again accelerate the imbalance in batteries with high temperature and even more with the ones with a temperature gradient inside the battery pack. E.g. a battery pack in a laptop may be warmer near the CPU.

It is important that the voltage level of a Li-Ion cell is within safe range. If it gets too low, the cell might be permanently damaged. If it gets too high, it might ignite or explode. The total capacity of a battery-pack will be determined by the weakest cell. The weakest cell will reach the lowest safe voltage first and thus trigger safety circuitry and gas gauging circuitry to shut down the battery regardless of the other cells voltage or SoC[2]. When charging a battery pack, some cells will reach maximum voltage before others. If there is no cell balancing circuit, the charging must halt at this point. This means that the overall capacity of an unbalanced battery is in practice not even equal to the weakest cell, but worse.

The effect of an unbalanced battery is illustrated in figure 2.5. Differences in self discharge rates and other things that causes imbalance often continues. Imbalance will thus only get worse as the battery ages.

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[2] State of Charge

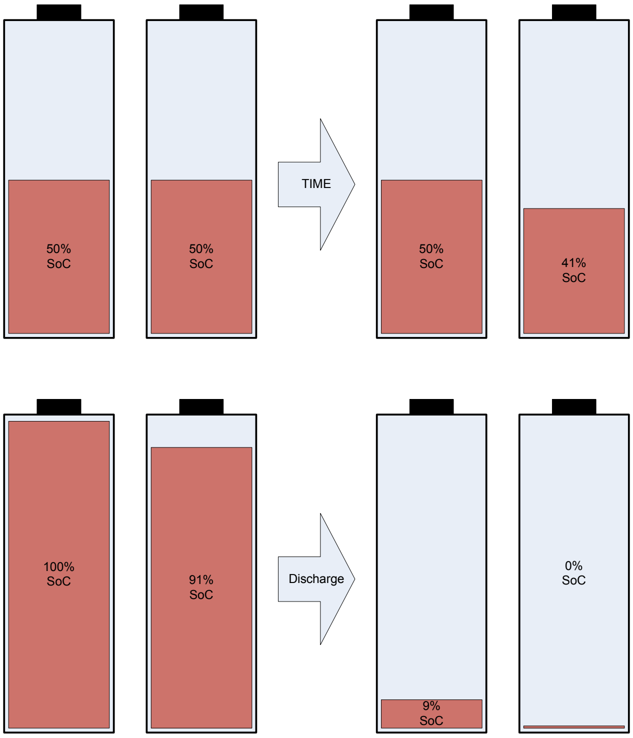

Figure 2.5: Capacity of an unbalanced battery

2.3 Gas gauging of Lithium ion Battery Packs

Gas gauging of a battery is very useful to estimate run time etc. There are two methods widely used for this purpose; voltage based gas gauging and charge counting. When these two are combined, state of charge can be estimated very accurately. Other factors like temperature and age can also be taken into account if higher accuracy is needed. However, the cost is a larger and more complex firmware code. The needed parameters must also be available, which is not always the case with all batteries.

2.3.1 Voltage based gas gauging

All cells have a voltage vs. state of charge curve similar to the ones shown in figure 2.2 and 2.4. By using these curves, one can calculate SoC based on a voltage reading of the cell. However, as seen in figure 2.4, the curve is dependent on the amount of current drawn from the cell. Also, when charging a battery, the voltage over the cell will be what the charger applies, not what is on the battery. When turning off the charger, the cells will use some time to return to its idle open circuit value.

Due to the disadvantages outlined in this section, voltage based gas gauging is not sufficient for an active system. In a system where the batteries are mostly in an idle state, like for example power tools, it can be used.

2.3.2 Charge counting

Since a cell can hold a specific amount of charge, a good way of measuring the SoC is to actually keep track of this charge. However, it cannot be measured by any means directly on a cell, one have to keep track of the current flowing in and out of the cell. This requires a high accuracy ADC to monitor the voltage across a shunt resistor in series with the cells.

To determine the state of charge, the system either need to be told an initial value, or it needs to calibrate itself over a few charge and discharge cycles. The later is often used as recalibration over time is needed, both due to inaccuracies of the counter and diminishing capacity due to aging of cells. By using this method together with voltage based gas gauging, a very accurate SoC and runtime can be calculated for both active and idle systems.

2.4 Smart Battery System

[12] The Smart Battery System is an open standard that among others describes a protocol for which a battery system can communicate. A battery system consists of three parts; a host, a charger and the battery itself. The host is the application which uses the power from the battery. The communication is to be done on an SMBus, which is a two wire interface derived from I^2C

Some of the parameters communicated are cell voltages, state of charge, cycle count etc. There are a lot of other features. Full description of SBS can be found in [12].

2.5 Similar Systems

2.5.1 TI bq77PL900

[13]This is an integrated circuit for managing a five to ten cell battery pack. It has among others built in balancing transistors, I^2C communication, $5V$ and $3.3V$ LDO[3] regulator and protection circuitry. It can operate in standalone mode for protection only, or it can operate as a slave for a microcontroller. It does not have ADC built in, so it cannot provide gas gauging directly. However, it contains all the necessary scaling circuitry so that a microcontroller can calculate state of charge, intelligent balancing algorithm etc.

Currently, this device is priced at 3.69 USD from Digi-Key. Competing with a device like this when using external components will be hard, most likely impossible. Both when it comes to size and cost. However, using this device together with an AVR might be one of the solutions.

2.5.2 TI bq78PL114

Quoted from [14]

> The bq78PL114 master gateway battery controller is part of a complete Li-Ion control, monitoring, and safety solution designed for large series cell strings.
>
> The bq78PL114 and bq78PL114S12 along with bq76PL102 PowerLAN dual-cell monitors provide complete battery-system control, communications, and safety functions for a structure of three up to twelve series cells. This PowerLAN system provides simultaneous, synchronized

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[3] Low Drop Out

> voltage and current measurements using one A/D per-cell technology. This eliminates system-induced noise from measurements and allows the precise, continuous, real-time calculation of cell impedance under all operating conditions, even during widely fluctuating load conditions.

This system is so complete and filled with features, that the only way to compete with such a system is probably to position the product in another segment by making it simpler and cheaper. However, there is a good chance that this also may be too big of a challenge.

2.5.3 LTC6802-1

Quoted from [9]

> The LTC6802-1 is a complete battery monitoring IC that includes a 12-bit ADC, a precision voltage reference, a high voltage input multiplexer and a serial interface. Each LTC6802-1 can measure up to 12 series connected battery cells with an input common mode voltage up to $60V$. Many LTC6802-1 devices can be stacked to monitor the voltage of each cell in a long battery string. In addition, the unique level-shifting serial interface allows the serial ports of these devices to be daisy-chained without optocouplers or isolators.

This is a fairly expensive device (about 10 USD). It is also quite new. However, this device is not a direct competitor. The stacking ability makes this device target electric and hybrid vehicles, backup battery systems and other large high power battery systems.

Chapter 3

Design Ideas and Challenges

3.1 The Idea - Overall Design

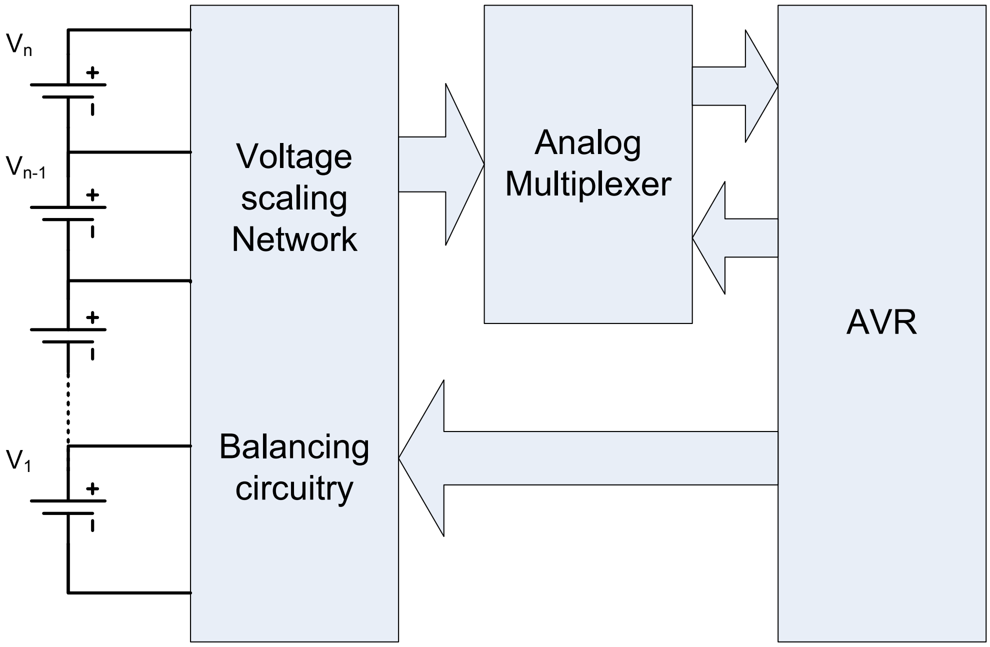

Figure 3.1: General block diagram of the system

3.2 Voltage monitoring

There exist MCUs[1] specially designed for battery applications, but these are often limited to battery packs with four cells or less. These MCUs can handle the voltages from the cells directly and measure them individually without need for external circuitry. When one looks at battery packs with seven to ten cells, the voltages can be up to 42 volts[2]. Most MCUs cannot handle this and we will thus need some kind of external circuitry to scale down the voltages to a level that the MCU can read.

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[1] MicroController Unit

[2] Assuming that one cell is 4.2 volt

Since this thesis is about designing a battery system with a standard MegaAVR or TinyAVR, the voltage levels must be less than $5V$. The AVRs also only has a 10-bit ADC for measuring[3]. This gives us only 1024 discrete steps for measuring, thus it is important that the dynamic voltage range of the cell is utilizing most of these steps. Otherwise the effective resolution will be degraded. To get a decent working gas gauge, it is important that we get as good resolution as possible.

Example

Let's say that we want to measure our cell from $2.5V$ to $4.5V$. Ideally the size of the steps is then $1.95mV$.

$$\frac{4.5V - 2.5V}{1024} = 1.95mV/step \tag{3.1}$$

We will not get this kind of resolution if the ADC is measuring from $0V - 5V$. The steps will then be $4.88mV$. This is Ideal numbers, and realistically the resolution will be slightly worse due to errors in the ADC. However, a voltage subtraction with high accuracy can be very hard to accomplish in real life and measuring from $0V - 5V$ might prove to give best result after all.

3.2.1 Resistor Voltage Divider

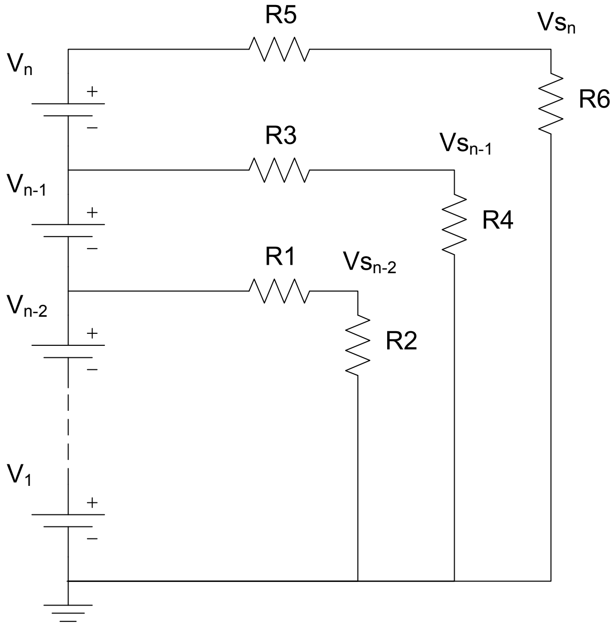

Figure 3.2: Resistor divider network

Using a resistor divider as outlined in figure 3.2 is the simplest way to scale down a voltage. If one pick resistor values in a certain way, one would get a voltage range at Vs_x that is the same as one cell.

However, in this application, using a resistor divider from each cell's positive pole down to ground will not be desired. We are interested in reading out a single cells voltage ($V_x - V_{x-1}$), but using a resistor network

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[3] Battery AVRs have 12 bit ADC for voltage monitoring

like the one in figure 3.2 the voltage V_x wil represent all the cells from this point down to ground and so will Vs_x. This effect will result in a very low resolution when measuring the cells at the top of the battery.

Example

- Assume a battery with 10 cells, $n = 10$
- Assuming all cells has the same voltage V_{cell} and voltage swing ΔV_{cell}
- define $R = R2 = R4 = R6$
- Pick $R5 = R \times 9$
- Pick $R3 = R \times 8$
- Pick $R1 = R \times 7$

At V_1 we will get to measure the whole range of the first cell ΔV_1, which is what we want. At the top of the battery V_{10} we will have a voltage $V_{cell} \times 10$ and a voltage swing $\Delta V_{cell} \times 10$. When scaling the voltage this way, we also scale the voltage swing with the same amount. In this example the scaling factor is proportional to the cells position in the battery. So $Vs_{10} = V_{cell}$ and $\Delta Vs_{10} = \Delta V_{cell}$. However, since these values are represented by all the cells in the battery, only one tenth of this value actually represent the cell at the top. This way the resolution will get worse the farther up in the battery one gets.

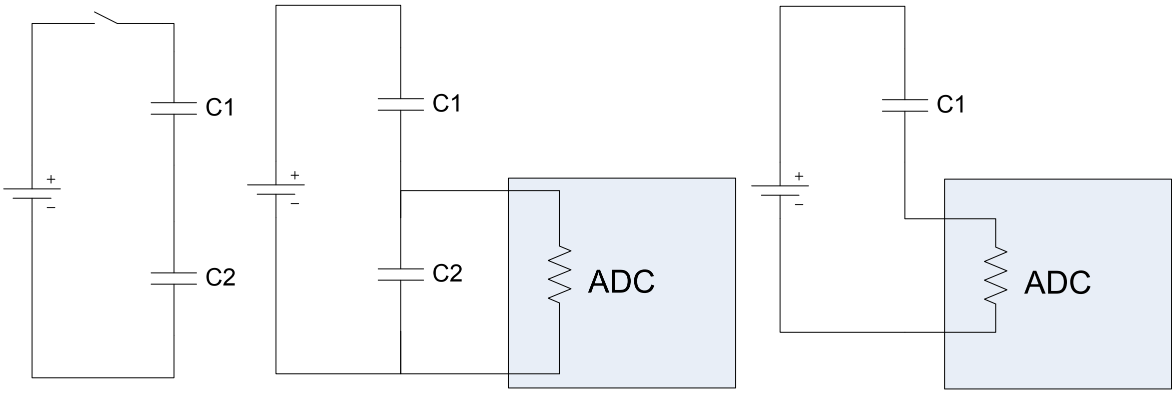
Another downside of using this kind of configuration is that there will always be currents running, thus draining the battery. This can be overcome by switching the resistor network on when one need to measure. This solution was rejected due to the major problem with resolution.

3.2.2 Capacitor Voltage Divider

A voltage divider using capacitors would work much the same way as using resistors. One would have the same issue with the resolution upwards in the battery, but the current will not run continuously and drain the batteries.

However, there is one big difference between using a capacitor divider compared to resistors. One would have to connect both ends of the divider to ground and then connect it to the battery before every measurement. The reason for this is that measuring the voltage implies draining charge from one of the capacitors and thus altering the voltage and eventually drains it down to 0 volts as depicted in figure 3.3c. One would have to reset the capacitor charge between the measurements.

$$v_c(t) = \frac{1}{C}\int_{t_0}^{t} i(\tau)\, d\tau + v_c(t_0) \tag{3.2}$$



(a) Capacitor voltage divider

(b) Measuring voltage with ADC

(c) Resulting circuit over time

Figure 3.3: Capacitor voltage divider

This solution was rejected for the same reasons as resistor dividing plus the requirement for complex switching circuitry.

3.2.3 Zener Diode Voltage Subtraction

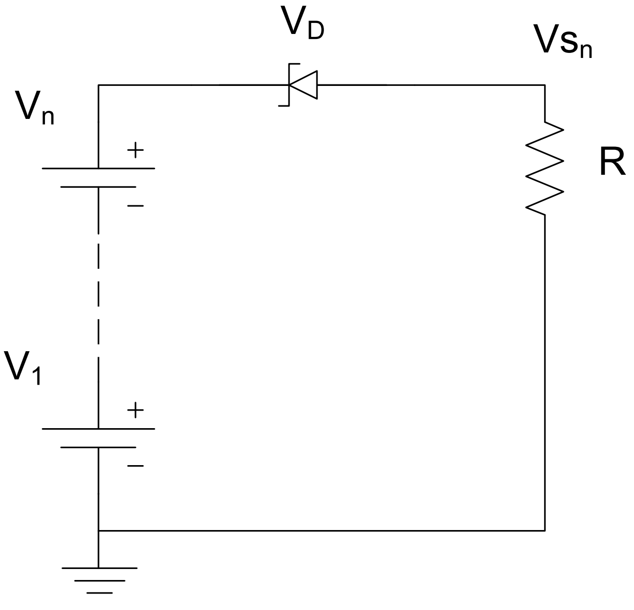


Figure 3.4: Subtracting voltage with zener diode

Another idea that came up was to use a zener diode together with a resistor to subtract the voltage. With this solution, the voltage will not be scaled the same way as with resistors and capacitors. Instead the voltage-drop across the zener will be constant and the voltage across the resistor will be $V_{resistor} = V_{node} - V_{zener}$. The solution was rejected due to resolution problems as with resistors and the fact that the voltage swing across the resistor is the same as on the node that needs scaling, in worst case N times the voltage swing on one cell where N is the number of cells in the battery.

3.2.4 S-H Circuit

To overcome the challenge that the higher cells have quite a large voltage span down to common ground, one could use some kind of switching circuitry to sample the voltage of one cell onto a capacitor and then move the capacitor down to a level readable by the ADC. One of the advantages with this approach is that the requirement to the actual reading circuit will not be as demanding when it comes to handling large voltages. The downside is that this approach might need a very complex switching circuitry and in addition the circuit needs to be operating on high voltages.

This idea was rejected due to the complexity of the required switching circuitry.

3.2.5 Differential Voltage sensing Amplifier

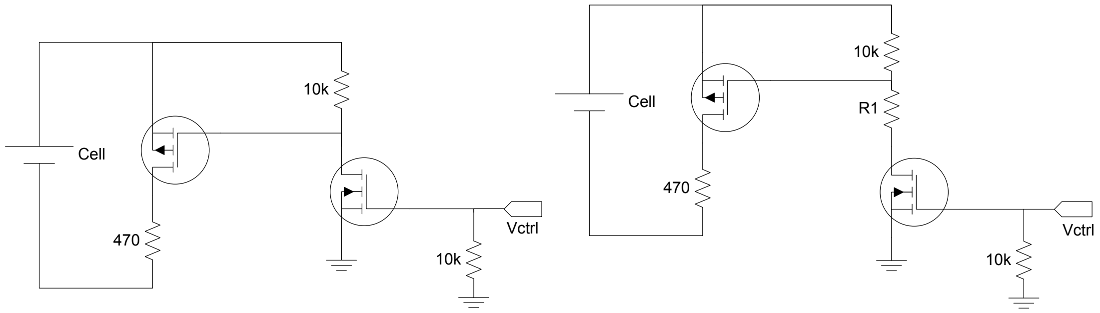
By using a differential amplifier one could measure the voltage over one single cell without the resolution problem depicted with regular voltage dividing to ground. The main problem with this solution is that one has to find an op-amp that can handle a large common mode voltage. However there is a special kind of amplifiers that has the properties outlined in this section. These are referred to as current sense monitors. They are measuring a small differential voltage on the inputs and give a voltage or current proportional to the input. It is often designed to handle large common mode voltages, which is exactly what we want in this battery application. An example of a current sense monitor is the AD8212 from Analog Devices.

As this method seems to be the best way of measuring cell voltages, it will be included in the design phase.

3.3 Balancing Circuit

With the application targeted with this thesis, there is no need for active balancing. High end power tools used by professionals are charged and discharged fairly often, thus regular balancing during charge will be fine. This will only require a way to turn on and of a dissipative resistor on each single cell.

Atmel's SB201-2 reference design is using a single chip dual transistor from Fairchild Semiconductor as a cell balance driver. These two transistors along with three resistors make it possible to control the balancing directly from a pin on the AVR. The transistors is rated for $60V$[6], so it should work with up to 14 cells, four more than in this specific design. The circuit from SB201-2 is shown in figure 3.5a. However a small change will be needed as maximum gate-source voltage is $20V$. This is solved by a simple voltage divider as shown in figure 3.5b.



(a) From SB201-2

(b) Modified for higher voltage

Figure 3.5: Basic balancing circuit with NDC701C

This balancing circuit will be included in the design phase and tested on voltage levels that a 10-cell battery will give.

3.4 Safety Circuitry

3.4.1 Current sensing

To prevent too much current being drawn from the battery, there must be a way to measure the current flowing in and out of the battery. Normally this is done with a coulomb counter. This is a very sensitive high accuracy ADC that monitors the voltage across a shunt resistor in series with the battery. This is also used for making the gas gauging more accurate. However, in this application it will only be used for safety purposes. The same technique as used for cell voltage monitoring can then be used with a small resistor in series with all the cells. The output from the current sensing device can then be connected to a regular ADC input on the AVR. Care must be taken to get the right input range to the ADC, both considering max voltage to the AVR and maximum current drawn from the battery.

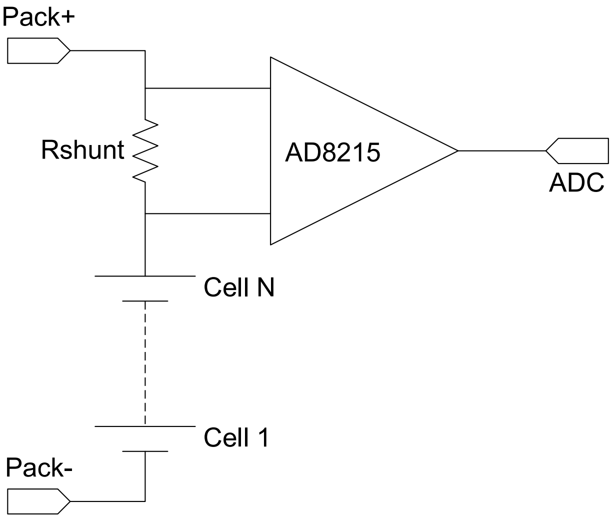


Figure 3.6: Circuit for current monitoring

3.4.2 Battery cut-off

When the current gets to large or when the voltage levels reaches the safe limits, there has to be a circuitry which can prevent any more current flowing. An example of this is shown in figure 3.7. The two transistors used are for discharge and charge cut-off. For this circuit, more transistors can be connected in parallel to be able to handle larger currents.

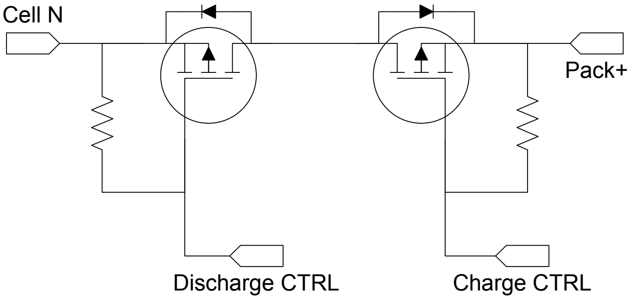


Figure 3.7: Circuit for switching off the battery

3.5 Choosing an AVR

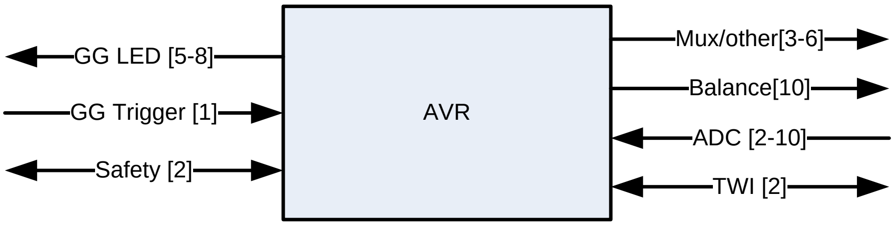


Figure 3.8: A scetch of needed pins

As seen in figure 3.8, there are a number of pins needed for various subsystems. Some of the functions can or must be multiplexed, but doing so will add more space requirement, extra cost and higher power consumption. Therefore it is desirable to find an AVR that has just the right number of IO pins combined with the hardware modules that is necessary.

Device	max I/O pins	Price	Comment
ATmega406	18	3.75 USD	Battery management AVR
ATmega162	35	3.88 USD	General purpose
ATmega164	32	3.18 USD	General purpose
ATmega165	54	3.79 USD	General purpose
ATmega48/88	23	1.50/2.04 USD	General purpose
ATtiny48/88	24/28	1.19/1.54 USD	General purpose

Table 3.1: Some different AVR devices

3.5.1 Requirements

ADC Input and Battery Selector

All devices listed in table 3.1 have eight or fewer ADC channels. Since it is needed to monitor ten cells, a multiplexer has to be used. An analog $8-1$ multiplexer placed between the AVR and the voltage scaling network seems to be a good solution due to the pricing. Multiplexers that can handle high voltages are often very expensive.

This means that this device needs at least three ADC channels free, one for the multiplexed batteries and two for the remaining cells. In addition, one need three lines for controlling the multiplexer plus two lines for controlling the measuring circuit for the two non-multiplexed cells, eight lines in total.

Balancing Control

Ten cells require ten controlling lines, however since balancing can be done one cell at a time, this signal can be multiplexed too. An $8-1$ multiplexer and one $2-1$ multiplexer would require four lines. However, if there are available lines on the chosen device, it is desirable to skip multiplexers. Balancing can then be implemented with a more effective algorithm.

Communication

Two Wire Interface To comply with the Smart Battery standard, the device needs to communicate with SMBus protocol. AVR devices of a certain size often have a TWI module which is compatible. It can be implemented as software[4], but a hardware module is more reliable and easier to use. Anyhow, as the name suggests, this require two lines.

Gas gauge Five LEDs and one button to trigger the light are sufficient.

Power Consumption

A battery application like this one does not require a continuously monitoring of the cells. A power tool is only used in periods and often has a relatively long period of storage. When the battery is charging, it is connected to a power source and the power consumption does not matter. When in storage, it is very important that the circuitry does not drain the battery. It should be programmed to only check on the cells every once in a while and sleep in the mean time.

Some AVRs has a technology called picoPower. This is a technology which allows for extremely low power consumption[7]. Most of the devices will be converted with picoPower, but today there are only a few which has this technology.

3.5.2 Best Candidate

From the criteria set above, the ATtiny48/88 seems to be the best choice. It has a hardware TWI module, picoPower, six ADC channels and a total of 28 I/O lines. It is also a very cheap device. It actually has enough pins to control the balancing circuitry directly which saves space and power consumption from one multiplexer. There is also a pin for monitoring the current drawn from the battery.

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[4] The author has successfully implemented a software TWI slave driver on an AVR ATmega16HVA

Chapter 4

Design Process

4.1 Voltage Monitor

A small selection of different current shunt monitors is reviewed in the following sections. The reasons for choosing these is among others that they seem to have the properties needed by this application, they are commonly available, and they are relatively cheap.

4.1.1 AD8212

The AD8212[1] is a high voltage current shunt monitor. It measures the voltage difference between two pins and creates an output current that is proportional to the input voltage. It can handle a common mode voltage up to $65V$ and will be suitable for measuring voltages generated by a 15-cell battery.

The output is a current, which is ok, but this requires a resistor from output to ground. This gives another way of adjusting the voltage range. However, the input impedance of an ADC might affect the result if it is too low. In the datasheet it is recommended to use an extra buffer on the output if one is to use it together with an ADC. This gives at least two extra components per cell, one resistor and one buffer.

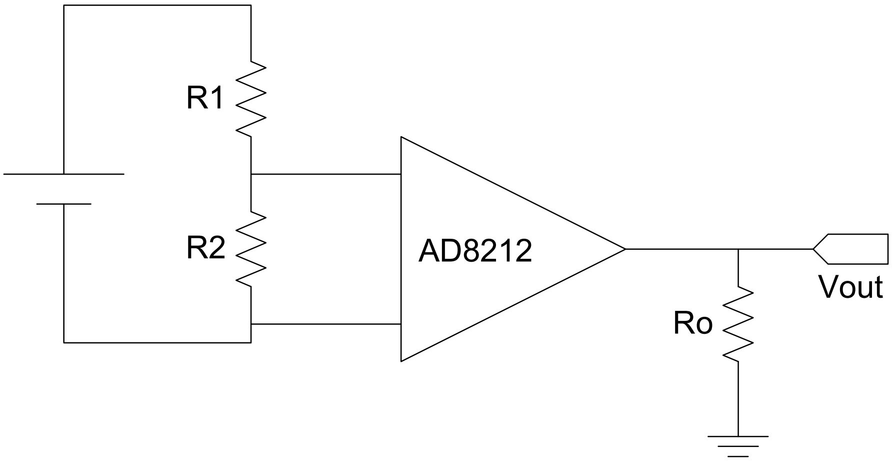

Figure 4.1: AD8212 Configuration

The downside of using the AD8212 is that it is powered through one of the input pins and that the lowest supply voltage allowed is $7V$. This makes it unsuitable on the three cells nearest ground using the configuration in figure 4.1. However using a different device for these three cells should not be a problem.

4.1.2 LT6106

The LT6106[8] is a current monitor with some of the same properties as the AD8112, but it has a separate power pin which possibly makes it suitable for all of the cells. There is no example circuits in the datasheet that are similar to the configuration needed in this battery application. It must therefore be tested to see if it works or not.

With a closer study of the datasheet, it seems that it is harder to use this one than the AD8212. It requires more external components, the supply voltage have to be no more than $500mV$ higher than the positive input. This makes it harder to monitor the lowest cell as the lowest supply voltage accepted is $2.7V$. The lowest voltage the cell can have is $2.6V$, so a supply voltage of $2.65V$ is too small. There is also the possibility that other cell types have even lower voltage. It is also limited to $36V$ on the upper limit, which makes it unusable on the highest cells also.

This current sense monitor will not be used in the design.

4.1.3 AD8215

This current sense monitor got the attention of the author late in the design phase. It seems to have all the properties that this application needs. It has a separate power pin, it can handle common mode voltages from $-2V$ to $65V$, and it has a buffered output which means that it can interface an ADC directly.

The large voltage range makes it suitable for all the cells. It is physically a little bit bigger than the AD8212, but it is still in a small SOIC8_N package. It is a major advantage that the same device can be used on all cells and that the output is a voltage and not a current. With the AD8212, the output voltage will vary with the output resistor, thus with the AD8215 one error source is removed. Since the scaling method is equal on all cells, the software for reading and interpret the ACD signal can be equal.

This device will be used in the final design of the prototype. When the author discovered the AD8215, the AD8212 was already tested. However since this worked exactly as expected, it was decided to use the AD8215 in the full-scale prototype due to the similarities in these two devices.

4.2 Single Cell Module with AD8212

A single cell module is designed to verify that datasheets are understood correctly and to test the common building blocks. This module consists of the AD8212 together with the necessary scaling resistors, circuit for switching on the measurement and a balancing circuit. Testing of this module showed some strange results, and the design was because of this changed during testing. The balancing and switch circuitry was tested separately since the modifications made it necessary to remove those on the single cell module. Figure 4.2 shows the original design.

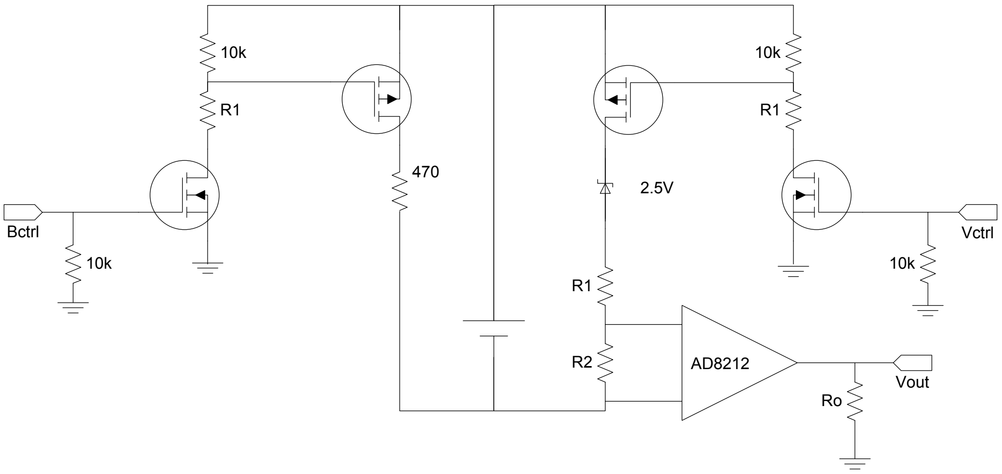

Figure 4.2: Original single cell module

4.2.1 Voltage Scaling Circuit

The circuit for scaling voltage consists of a zener diode, a voltage divider and an AD8212 current shunt monitor. The zener is present to give as much voltage swing as possible into the ADC. Since the lowest voltage of a TrustFire cell is $2.6V$, the zener is chosen to be $2.5V$. It will ideally subtract $2.5V$ from the voltage that is to be measured. This is a way to get the range from $2.6V - 4.2V$ to $0.1V - 1.7V$. The voltage divider in series with the zener is only to adjust the output voltage range on the amplifier. The ideal graph for cell voltage versus ADC input is shown in figure 4.3.

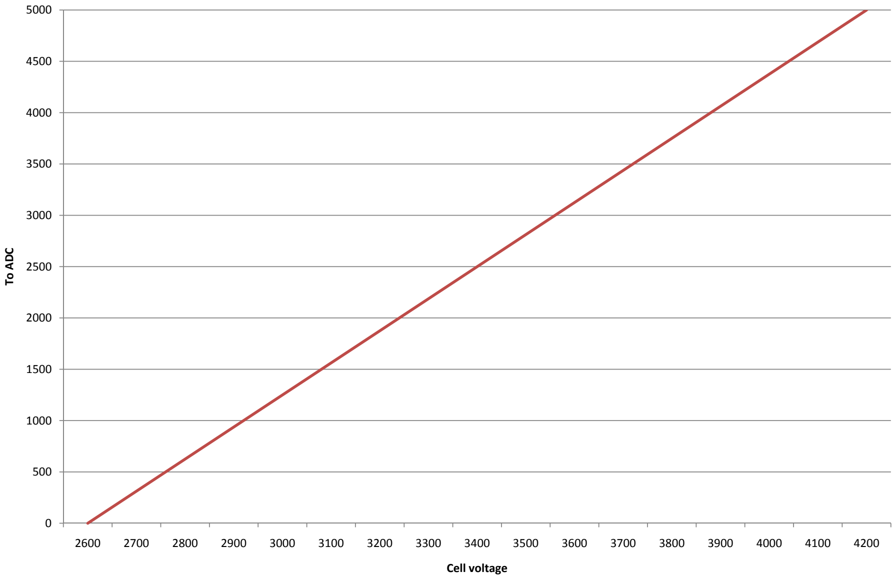

Figure 4.3: Ideal battery voltage vs ADC input

It is also possible to connect a switch to turn on and of the voltage scaling circuit. This switch is built with the same transistors as used in the balancing circuit.

4.2.2 Expected Errors

According to the selected zener diode's datasheet[11], the zener voltage is measured at $20mA$. This current will vary a lot since the resistors are fixed and the voltage on the cell will vary. It is also not desired to have a lot of current running unless it can be turned off when the voltage is not measured.

As long as the result is known and consistent, it should be possible to compensate for it in the firmware.

4.3 Full Scale System

After testing and evaluation of different methods for voltage monitoring, the design in figure 4.4 shows how a prototype will be made. All in all 27 I/O pins is needed where two is for TWI and four is ADC. The 32-pin version of the ATtiny48/88 has 28 I/O pins, which makes it suitable for this design.

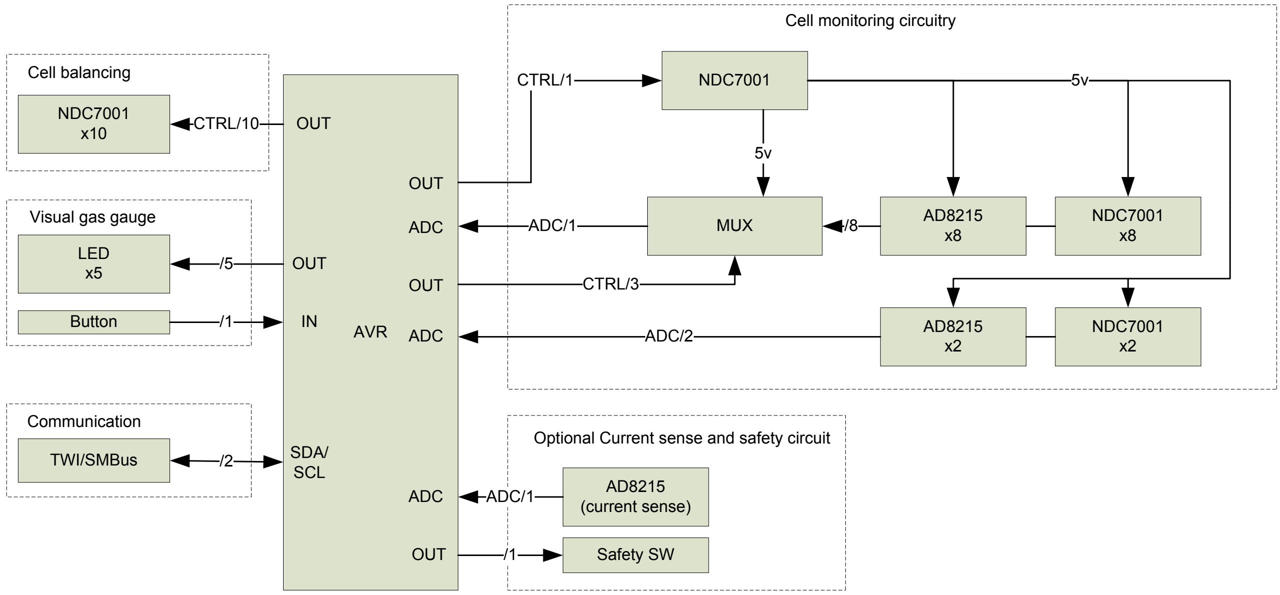

Figure 4.4: Block diagram of full battery system

4.3.1 Cell balancing

The cell balancing design is identical to the one in figure 3.5. The four lowest cells have the structure shown in figure 3.5a while the six highest cells have the structure shown in figure 3.5b. The reason for using two different structures is to make sure the transistors operate within limits set by the datasheet. The resistor values chosen and full structure can be found in appendix B.2.

The $470R$ resistor can be replaced by another value depending on required balancing time. One just has to consider maximum current the transistor can deliver and maximum power that can be dissipated in the resistor. The current drawn from the cell must also be considered, but most likely, the cells are rated for a lot more than the transistor can handle.

4.3.2 Visual Gas Gauge

As the visual gas gauge consists of only a button and five leds, this is purely a software task. Both the leds and button will be connected directly to the AVR. This feature will not be implemented on the prototype that is made because buttons and leds are found on STK600 which will be used for controlling the prototype.

4.3.3 Communication

Again, this is purely a software task. Due to lack of charger and host system, this will not be implemented in the prototype. UART[1] will be used for easy computer interface in the demo firmware.

4.3.4 Cell monitoring Circuitry

This is the most critical part as it will give the only information regarding the state of charge. It consists of one 8 to 1 analog multiplexer, 10 AD8215 for voltage scaling, 11 NDC7001C, where one is for controlling power to the entire circuit and ten for controlling the current flowing when measuring the voltage. In addition, there are a number of resistors. The entire circuit can be found in appendix B.2

NDC7001 as Power Switch

Since measurements is only required once every few seconds, there is no need for the circuitry to be turned on and consume power at all times. The measurements of all the ten cells will only take a fraction of a second, so turning off all power when not doing measurements will result in a mean power usage close to zero. However, the AVR needs power at all times, but it too can be put in sleep mode most of the time to save power. The key is to find an effective regulator. Doing so has not been a priority, so a regular $5V$ LM1117 regulator has been used. The NDC7001 require one line from the AVR.

Multiplexer

This multiplexer is used to reduce the number of ADC channels needed on the AVR. The scaling results from the eight highest cells are put into the multiplexer. It requires one ADC channel and three control lines from the AVR. Power and enable are connected to the power switch (NDC7001). The three control signals must be kept in a defined state at all times as strange behavior might happen if they are floating. This will not be a problem as output pins on an AVR are known.

As the ADC is supposed to draw close to zero current, it is expected that the multiplexer will not affect the voltage signal from the scaling circuit. According to [3], the input resistance of AVRs ADCs is about $100M\Omega$.

Voltage Scaling

For level shifting, the AD8215 is used. However, it has a fixed gain of $20V/V$ and a voltage divider on the input is needed to scale the output. The internal resistance between the input pins are $5k\Omega$ [2], and because of this it is desired to use an input resistor well below this value. A simple calculation shows that a resistor divider with 1 to 16 ratio is a good choice. A full scale output from the amplifier must be $5V$,

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[1] Universal asynchronous receiver/transmitter

which means that the input needs to be $250mV$. Resistor values of 100Ω and 1600Ω is chosen to lie well below the $5k\Omega$ input resistance and large enough to get only a small current running.

$$V_{amp} = V_{cell} \times \frac{R_1}{R_1 + R_2} \tag{4.1}$$

$$V_{ampmax} = V_{cellmax} \times \frac{R_1}{R_1 + R_2} = 4200mV \times \frac{1}{1 + 16} = 247mV \tag{4.2}$$

It is not desirable to have current running at all times. At a cell voltage of $4V$ the current running is about $2mA$. Not taking the voltage drop happening during discharge into account, this current would drain a $1000mAH$ battery empty in 20 days, which is of course completely unacceptable. A switching device would therefore be necessary. It has been made a choice to use the NDC7001C to handle this task as it performed very well for balancing. However, testing will show if this is a good choice or not.

Two ADC channels are required for the two lowest cells. The remaining eight is going through the multiplexer.

The AD8215 is included for all the cells. However, it can be left out on the lowest cell, as the voltage range of one cell is within the $5V$ range of an AVR. The only penalty is a slight variation in the software. It has been included to make readings on all cells identical and for testing purposes.

Accuracy and expected Errors

There are three main sources for errors; resistor values, amplification and the resistance of the NDC7001.

Resistor Values In the prototype, it has been used resistors with 1% accuracy due to cost. However, as seen in equation 4.3 and 4.4, a deviation of 1% on the resistors can give a $9.2mV$ error on the same cell voltage. Amplified 20 times, this gives an error of $184mV$ into the ADC which again translates into 38 steps on the ADC reading. Resistor accuracy of 0.1% or better is preferred.

$$V_{amp} = V_{cell} \times \frac{R_1}{R_1 + R_2} = 4200mV \times \frac{1 \times 1.01}{(1 \times 1.01) + (16 \times 0.99)} = 251.6mV \tag{4.3}$$

$$V_{amp} = V_{cell} \times \frac{R_1}{R_1 + R_2} = 4200mV \times \frac{1 \times 0.99}{(1 \times 0.99) + (16 \times 1.01)} = 242.4mV \tag{4.4}$$

Amplification According to the AD8215's datasheet [2] the accuracy is $\pm 0.15\%$ and accuracy over temperature is $\pm 0.3\%$. Worst case a error of $\pm 15mV$ into the ADC. There is practically nothing to do about this error source, so by using the AD8215, one would have to live with this.

Resistance of NDC7001C As demonstrated with the resistor values only minor errors are enough to give a huge deviation. It is therefore really important that this switching circuit has as low resistance as possible.

According to the datasheet [6], $R_{DS(on)}$ is 7.5Ω when V_{GS} is $-4.5V$. 7.5Ω in added resistance in the resistor divider will give a difference of about $1mV$ into the amplifier. A little lower would have been preferred. However, for the two lowest cells V_{GS} can be even closer to zero than $-4.5V$. Testing will reveal the performance, but already at this stage it can seem that the NDC7001C might be a bad choice of switching device for the lower cells.

4.3.5 Current Sense and Safety Circuit

Due to shortage of time, this circuitry has not been included. This kind of circuitry has been made before and is common in most Li-Ion batteries. The priority has been on the scaling circuitry as this is the most challenging task.

Chapter 5

Hardware and Test Rigs

A design like this is based on both new ideas that could or should work and elements from existing designs that has already been tested. It is unnecessary to say that any electronic design must be prototyped and tested. It is important to confirm that a device really works the same way that the designer had intended when reading the datasheet.

Since this design is composed of several different parts, it has been built modules that can be connected. Tools like Atmel's SB200/SB201[1] and STK600[2] has been utilized.

5.1 Cell Rig

It has been built a card with holders for ten cells shown in figure 5.1. The rig is configured to use cells with size 16340/RCR123A, which is the size of the TrustFire Cells described in section 2.1.4. It has large tracks on the PCB and all voltages throughout the battery is available through pin headers and screw terminals.

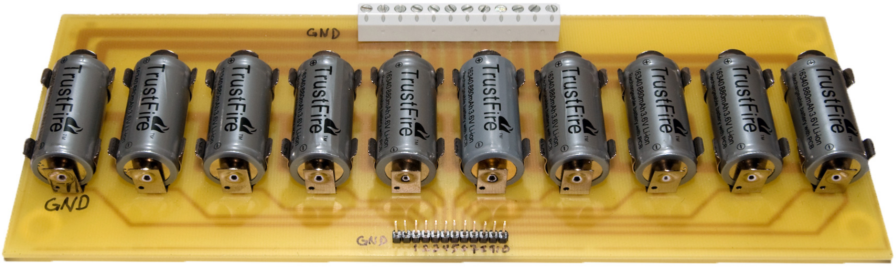

Figure 5.1: 10-Cell battery rig

5.2 AD8212 as Voltage Monitor

Due to the high voltages that must be dealt with in this design, the components that will connect directly to this voltage must be tested to confirm that they actually behave as expected. Since the circuit is more or less equal for every cell in the battery, it has been built a module with the AD8212 together with the necessary resistors. This module is described in section 4.2.

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[1] Smart Battery Demonstration Kit

[2] Development kit for AVRs

5.3 NDC7001C Transistor Pair

This transistor pair chip is mounted on a card with pin headers. It can then be connected together with the battery rig and the AD8212 to test both the ability to be used as a power-switch for the AD8212 and as a balancing transistor.

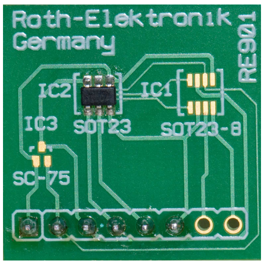


Figure 5.2: Testboard with NDC7001C

5.4 Full Scale Prototype

A PCB with the final prototype design has been built. It is a modular design that will interface with the battery rig described in section 5.1. It also has pin headers for all the pins that will go to the AVR. This way it can be tested with multiple AVRs through STK600 or a similar development kit. It is built from the block diagram in figure 4.4, but without the current sense and safety circuitry. The visual gas gauge and communication is closely connected to the AVR and will not be on this board either. The full drawing for this circuit is found in appendix B.2.

It also has pin headers for testing of different parameters like balancing current, total current consumption.

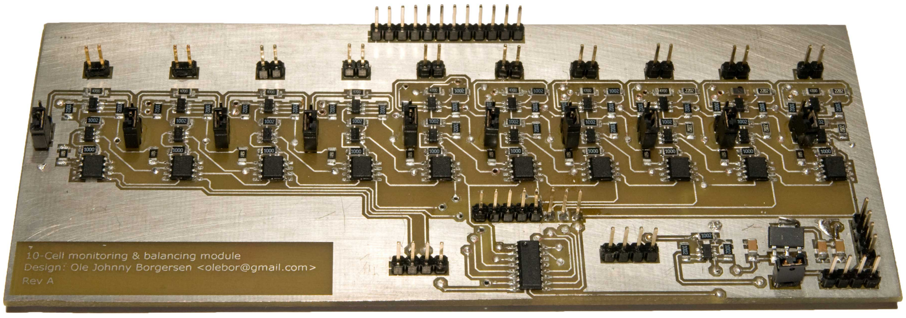


Figure 5.3: Full scale prototype

5.4.1 Interface

Cell Connection It has a 12-pin header which is intended to connect directly to the battery rig with a ribbon cable. Two of the pins is ground while the others are all the individual cells.

Voltage Output The prototype has three voltage outputs intended to go directly to the AVR's ADC. Two pins from cell one and two, and one pin from the multiplexer for measuring the other eight cells.

Control Input There are four control lines, one line for controlling power to the entire scaling circuitry and three lines for controlling the multiplexer. The power control line has a $10k$ pull-down to keep it from floating. However, the lines controlling the multiplexer have no pull-up or pull-down resistors. These must be driven to a known value to avoid strange results.

Balancing Control Input It has ten headers for balance control. These are intended to connect directly to an AVR. They have a $10k$ pull-down resistor which keeps them from floating when there is no connection.

Other Pins In addition there are jumpers available to measure balance current and one jumper to measure the overall current consumption on the $5V$ side of the circuit.

For measurement of all the amplifiers output, an 8-way pin header is placed before the multiplexer. This also makes it easy to measure the multiplexer's effect.

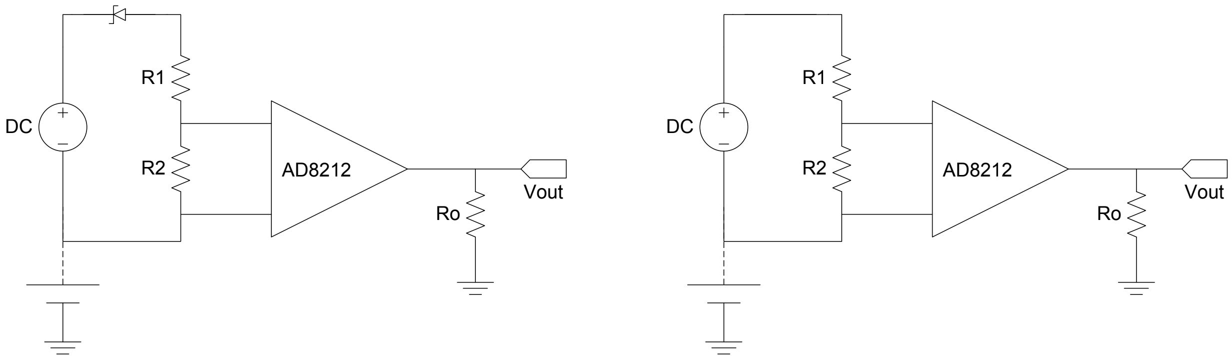
Chapter 6

Testing and Results

6.1 AD8212

The AD8212 is a current sense monitor and is meant to measure a voltage over a small resistor. Since it in this application is used to measure a voltage over a large resistor, it is important to test that it actually does what it is meant to do. To verify that the AD8212 is behaving as expected, it has been tested in various configurations. The module described in section 4.2 has been used for this purpose. Results with the zener diode was expected to deviate a little from ideal values as the current through it will vary a lot as a function of the cell voltage. However, additional measurements were made without the zener diode, since the measurements deviated too much from the expected values.

All the tests were made with an adjustable voltage source connected in the cell rig (section 5.1) as the tenth cell. The output from the AD8212 was measured relative to ground. As the AD8212 outputs a current, a 10k resistor was connected from the output to ground to generate the correct voltage range. The output from the power supply was measured with the same multimeter that measured the output to confirm that the display showed the right value. All the resistor values were also measured with the multimeter to make the basis for the calculated ideal voltage curves.



(a) With Zener

(b) Without Zener

Figure 6.1: Test setup

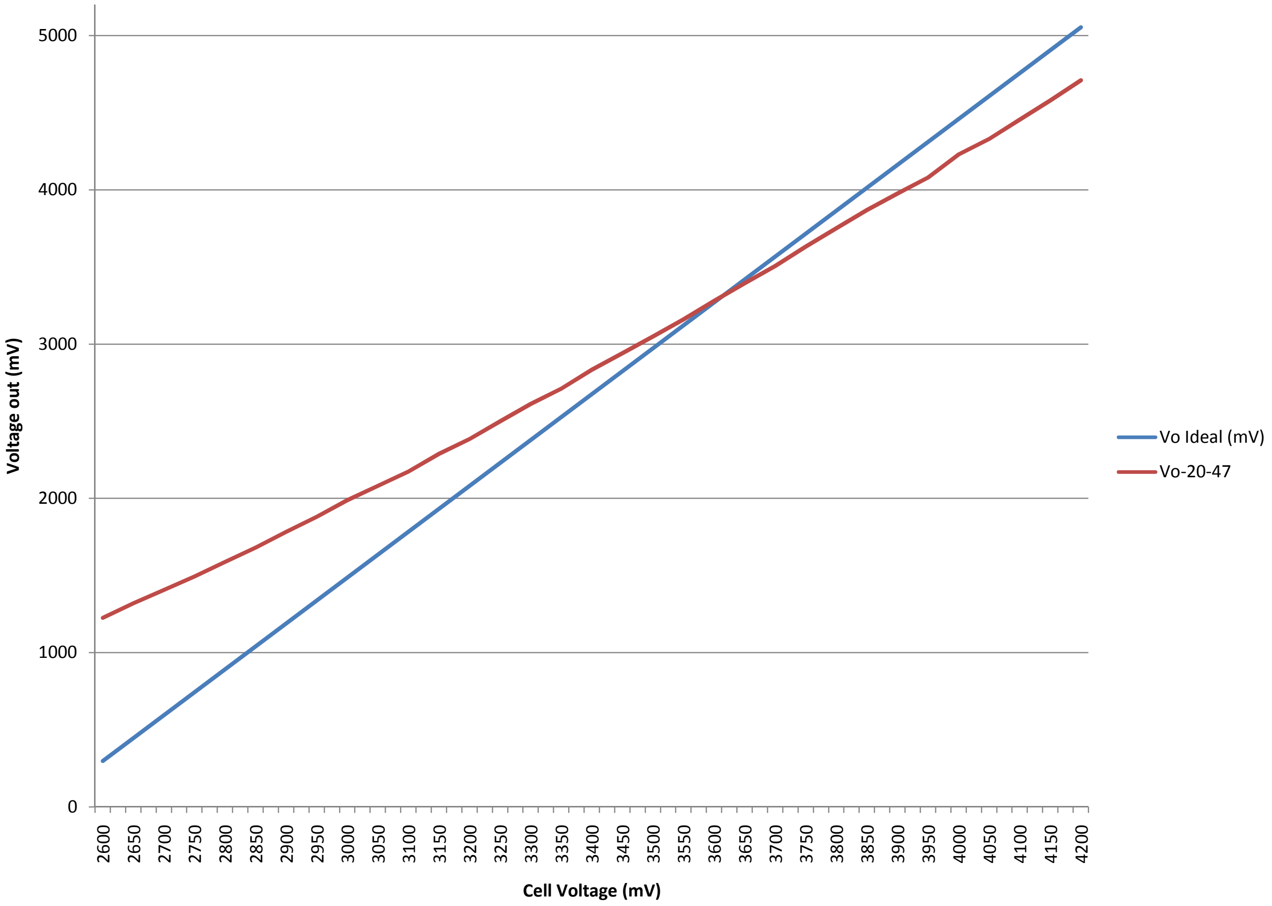


Figure 6.2: Measured and estimated output voltage with zener diode. R1 = 47, R2 = 20

Figure 6.2 shows output voltage as a function of cell voltage. The curve representing the ideal output is calculated as a linear function with the assumption that the zener is always $2.5V$. According to the zener diode's datasheet[11] the reverse zener voltage is valid at $20mA$ and will increase with the current. It also has a tolerance of $\pm 5\%$ from device to device.

With the resistor values used, the current flowing in the resistor divider and zener diode will be $20mA$ when the cell voltage is $3.84V$. The two lines are crossing at approximately $3.6V$ which is not very far from this point. This result was as expected.

This circuit has small resistor values and will thus drain the batteries empty in short time if it is always on. It is desirable to have a switch of some kind, but with this small resistor values the resistance of a switch will significantly alter the results. The next test is, because of this, tested with a lot larger resistor values.

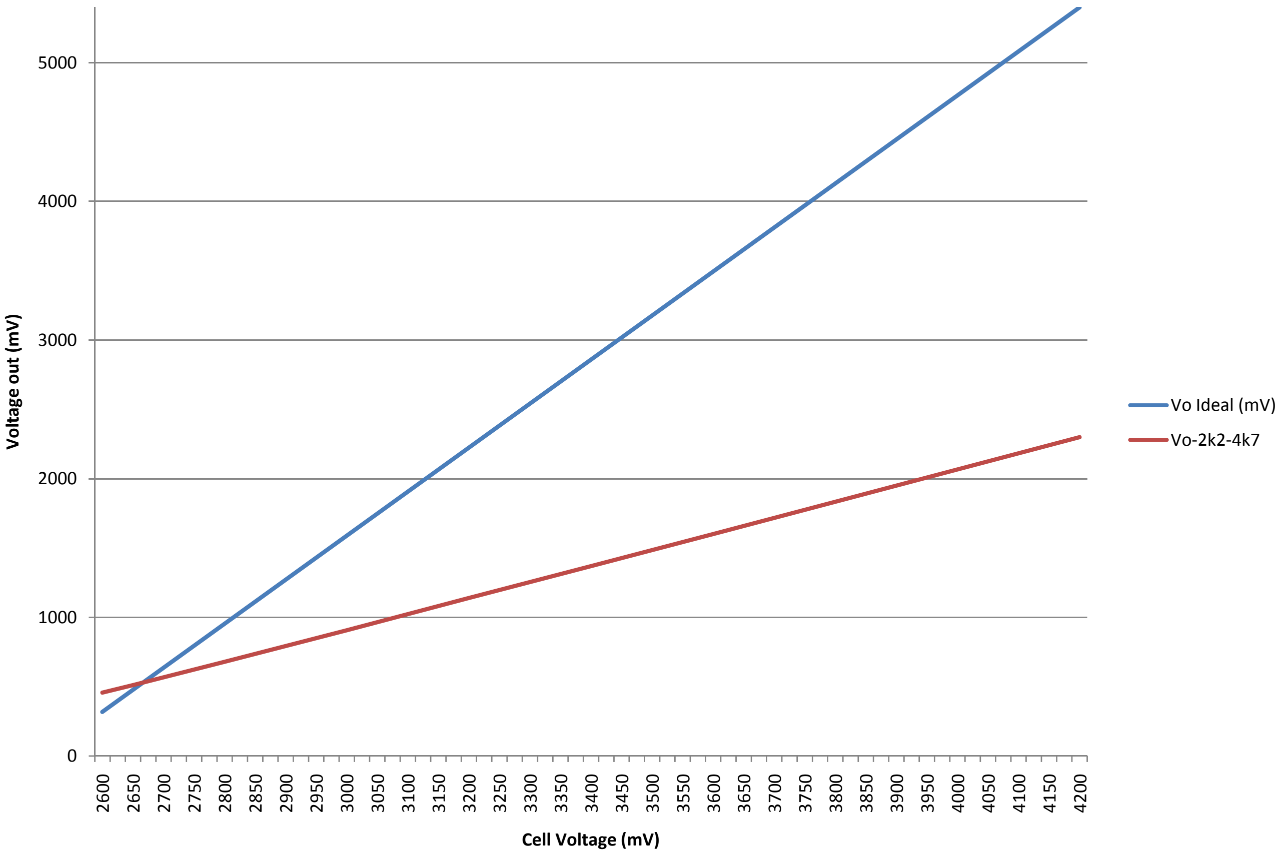


Figure 6.3: Measured and estimated output voltage with zener diode. R1 = 2k2, R2 = 4k7

Figure 6.3 shows the same same test circuit as the first test, but with significantly larger resistor values. As can be seen, the deviation from the calculated curve is huge. At first the blame was put on the zener, but if that was the case, the measured curve would have been higher than the calculated one. According to the datasheet and normal zener diode behavior the voltage accross them decreses with decreasing current. This fact should lead to an output voltage curve that is larger than the calculated, which is not the case here. To rule out the zener, the next test is done without it.

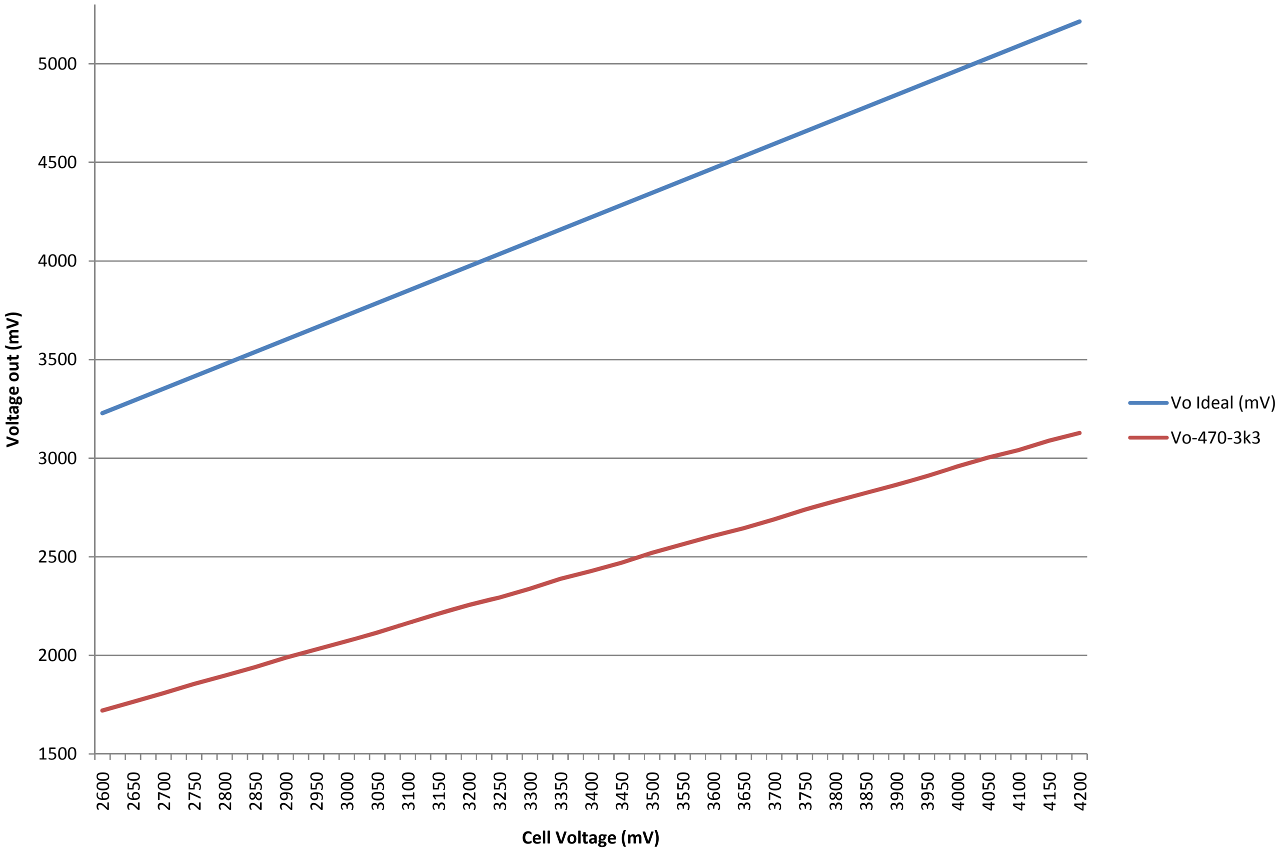


Figure 6.4: Measured and estimated output voltage without zener diode. R1 = 470, R2 = 3k3

The results in figure 6.4 is done without the zener diode. However, the deviation is enormous. The AD8212 is designed to measure large currents and it actually uses the positive input as a power pin as well. It seems like these resistors are too big and thus limiting the current too much for the amplifier. The configuration was altered a little bit to check if this was causing the deviation. The next test, the voltage divider was turned around and the amplifier was put on top as shown in figure 6.5.

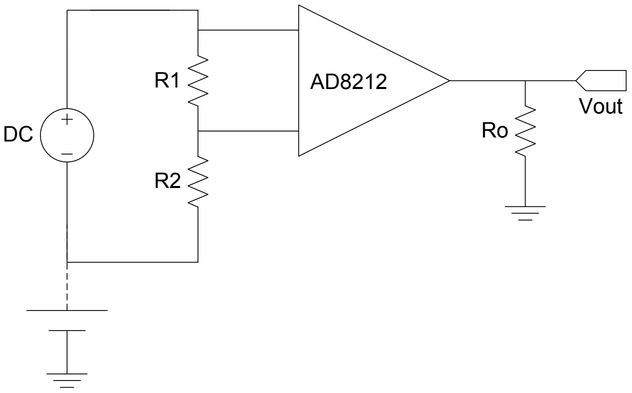


Figure 6.5: Test setup with the amplifier on top

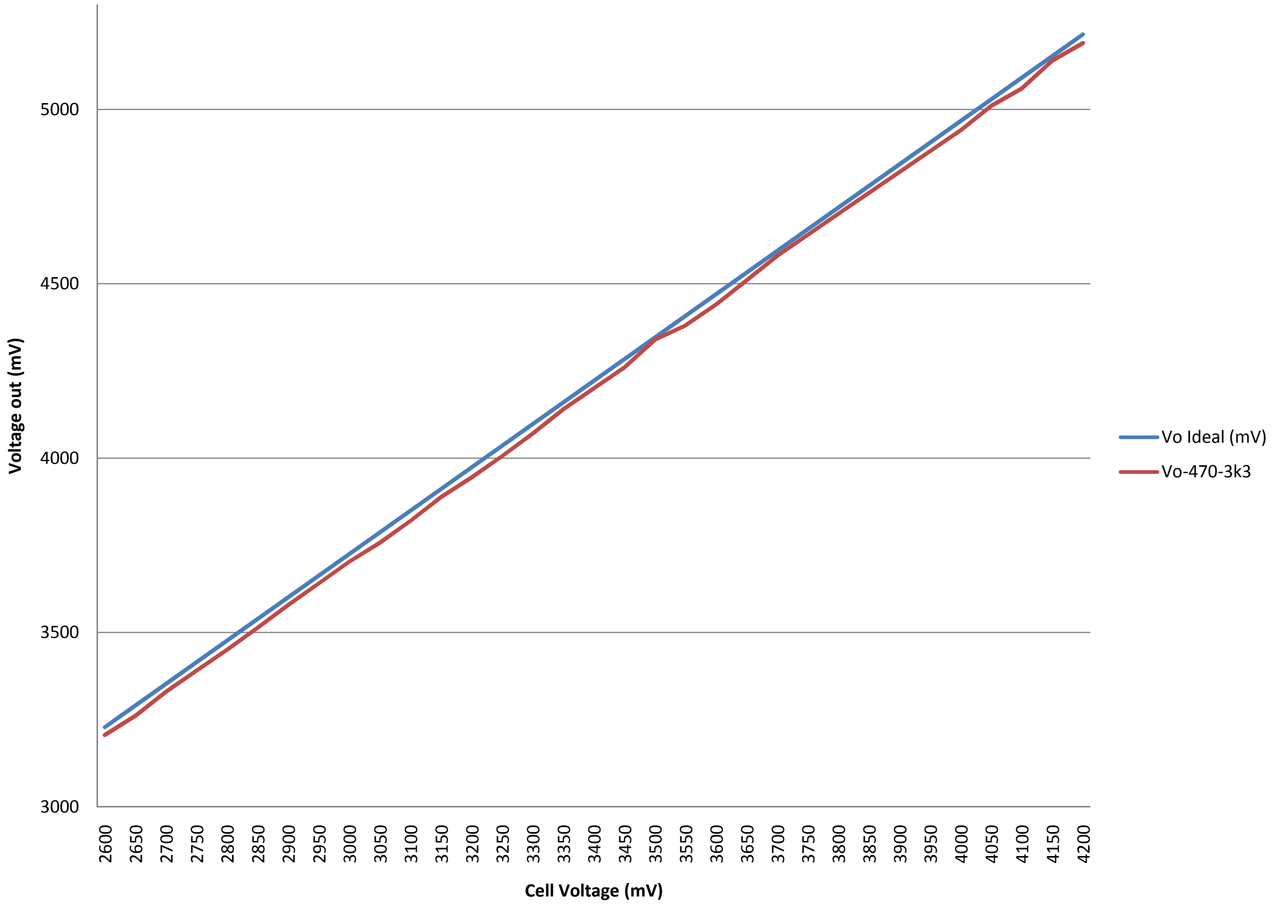


Figure 6.6: Measured and estimated output voltage without zener diode. R1 = 470, R2 = 3k3

Figure 6.6 shows the output with the amplifier placed on top near the positive pole. As one can see, it now follows really well. It has an offset of $40mV$, which is ok. This little deviation can simply be the difference between the multimeter and the voltmeter inside the voltage supply. This result shows that the AD8212 is accurate enough for this application as long as it is used correctly.

All these tests were done with the AD8212 connected to the 10th cell. However, to test that it gives the same result down the chain of cells, some sampling tests was done. As expected it shows exactly the same value for all the cells down the chain except for the first cell. The AD8212 requires at least $7V$ on the positive input. When the batteries are fully charged, the voltage on top of cell number two is about $8.4V$.

6.2 NDC7001C

According to the datasheet[6], Q2 that is used as the switch in this application, have a $R_{DS(on)} = 5\Omega$ @ $V_{GS} = -10V$. The resistance was tested with the setup shown in figure 6.7.

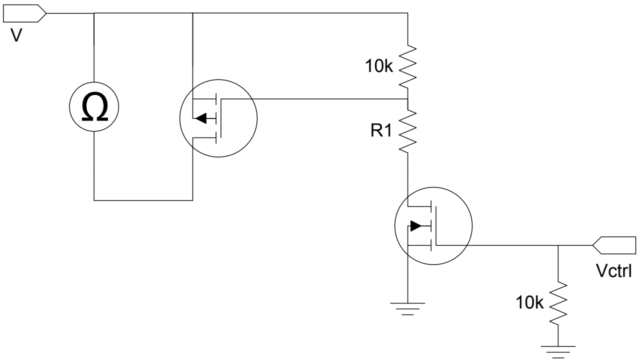


Figure 6.7: Test setup for resistance measurement

All measurements showed an $R_{DS(on)} = 1\Omega$. This is better than expected and apparently makes it very suitable for this application. However, testing like this might give false results due to the small test voltage generated by the multimeter. Anyway, the current supposed to run in the voltage divider is also small and thus gives a resistance close to the value found by using a multimeter.

6.2.1 Balancing Circuit

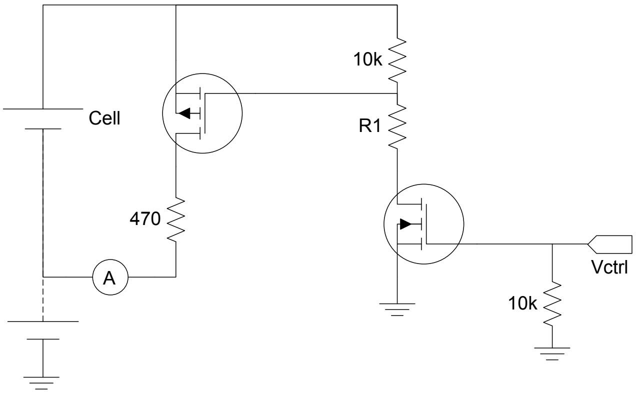


Figure 6.8: Balancing circuit test setup

The NDC7001C was connected as shown in figure 6.8 and the current was measured. As expected a small current flowed. As the test equipment used in this test only had a resolution of $10mA$, an accurate measurement was not done. However, an accurate measurement is not necessary as long as it is within expected limits.

With a 470Ω shunt resistor an $8mA$ current was expected. The ampere meter was showing $10mA$ which is close enough to give an indication that it works. As this is a balancing circuit, the resistor can be chosen smaller or bigger depending on how much balancing current needed. However the current must not exceed maximum drain current which is $340mA$ and a resistor that can handle the power dissipated in it must be chosen.

6.2.2 Switch for AD8212

The transistor is with its low $R_{DS(on)}$ well suited to turn on and off the voltage scaling circuit. It was connected as shown in figure 6.9. Then a few spot tests were done to verify that the results is the same as in figure 6.6. As expected the NDC7001C had no effect on the output voltage of the AD8212 in this configuration.

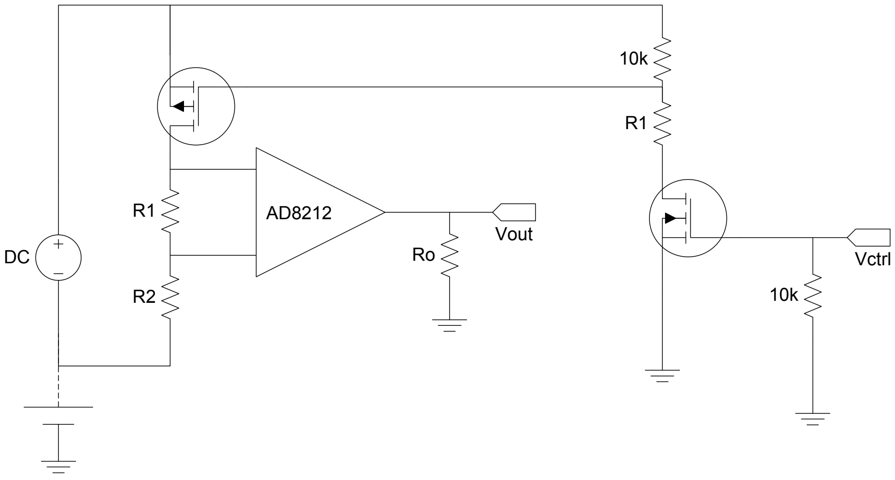


Figure 6.9: NDC7001C as switch for AD8212

6.3 Full Prototype

The prototype is connected to the cell rig with a ribbon cable for all the cells. Control signals for the multiplexer and the power switch were set manually. Additionally a simple demonstration program that reads all cells and presents it over UART has been written. STK600 was used for this purpose.

All the tests of the prototype were done with a Fluke 177 multimeter. All the cells were connected except for the one under test. The cell was replaced with a BSD PSD30/3B voltage source. Both instruments were calibrated less than two weeks before the tests was done. The temperature was about 20 degrees Celsius.

6.3.1 Balancing Circuit

The circuit in the prototype is identical to the one described in section 6.2.1 and has already been tested to work. Its behavior has been verified and it will not be tested beyond this.

6.3.2 Power Consumption

The circuitry is powered by the three cells lowest in the chain. This is because the regulator needs more than $5V$ to operate. Two empty cells will not have enough voltage. In the design phase, finding an effective regulator has not been a priority, thus the power usage after the regulator is the one that is of interest. The power usage of the AVR is not tested either, because it will be dependent on programming, which device is used etc.

Basically, the circuitry of interest is the voltage scaling circuit as this is the biggest one. It is designed to be completely shut down when it is not doing measurements. This feature is working as there is no measurable current when all control signals are low. It draws $14.35mA$ when operating. This current was independent of the multiplexer state.

6.3.3 Voltage Scaling

It is critical that the scaling circuitry is working as expected. At least all of the parameters need to be known, so it can be factored in when writing software. As the circuitry consists of an amplifier and a voltage divider, there are at least two major error sources; resistor values and amplification. As the NDC7001C is a part of the resistor divider, it too can be an error source if it does not behave as first expected.

All the circuits were tested with a voltage range from $1000mV$ to $4400mV$. The resistor values in the voltage divider were measured. Both the input and output voltage of the AD8215 was also measured. Amplification of the AD8212 was then calculated from these values. Other interesting parameters like the resistance of the NDC7001 were calculated. However, some strange results were found.

Resistor Values

In the prototype, there are used resistors with a 1% tolerance. 1% is too much for this application, and the values were therefore measured. They can then be taken into account when reading from the ADC. Results are given in table 6.1. These values were measured without any voltage applied to the circuit.

Cell number	R1	R2
1	99.9 Ω	1601 Ω
2	99.7 Ω	1598 Ω
3	99.8 Ω	1598 Ω
4	99.7 Ω	1600 Ω
5	99.8 Ω	1598 Ω
6	99.8 Ω	1599 Ω
7	99.7 Ω	1596 Ω
8	99.7 Ω	1597 Ω
9	99.7 Ω	1596 Ω
10	99.8 Ω	1596 Ω

Table 6.1: Resistor values in the voltage divider

Cell 1

Cell 1 was included only to get more data on how the other components are behaving. It is not necessary as the voltage range from this cell is within the range of the ADC.

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{out}[mV]$	A	$I_{calculated}[mA]$	$R_{tot}[\Omega]$
1000	31.50	625	19.84	0.32	3171
1200	37.20	736	19.78	0.37	3223
1400	41.50	822	19.81	0.42	3370
1600	59.50	1 184	19.90	0.60	2686
1800	74.60	1 485	19.91	0.75	2410
2000	88.90	1 770	19.91	0.89	2247
2200	103.30	2 058	19.92	1.03	2128
2400	117.20	2 337	19.94	1.17	2046
2600	131.00	2 620	20.00	1.31	1983
2800	145.60	2 904	19.95	1.46	1921
3000	159.70	3 188	19.96	1.60	1877
3200	173.80	3 468	19.95	1.74	1839
3400	187.70	3 749	19.97	1.88	1810
3600	202.40	4 038	19.95	2.03	1777
3800	216.30	4 319	19.97	2.17	1755
4000	230.60	4 603	19.96	2.31	1733
4200	244.70	4 885	19.96	2.45	1715
4400	258.80	4 960	19.17	2.59	1698

Table 6.2: Measurements and calculated values for Cell 1

Cell 2 to 10

Results from cell 2 is shown in table 6.3. Results from rest of the measurements can be found in appendix C. They are not presented here as they are very consistent and have the same pattern as cell 2.

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.40	58.55	6.85	1 312	20.06	0.66	1524
1200	77.30	70.26	7.04	1 548	20.03	0.78	1548
1400	89.10	81.98	7.12	1 785	20.03	0.89	1567
1600	100.60	93.69	6.91	2 017	20.05	1.01	1586
1800	112.50	105.40	7.10	2 252	20.02	1.13	1595
2000	124.20	117.11	7.09	2 489	20.04	1.25	1605
2200	136.00	128.82	7.18	2 723	20.02	1.36	1613
2400	147.70	140.53	7.17	2 958	20.03	1.48	1620
2600	159.50	152.24	7.26	3 194	20.03	1.60	1625
2800	171.30	163.95	7.35	3 430	20.02	1.72	1630
3000	183.20	175.66	7.54	3 664	20.00	1.84	1633
3200	194.80	187.37	7.43	3 900	20.02	1.95	1638
3400	206.70	199.08	7.62	4 135	20.00	2.07	1640
3600	218.50	210.79	7.71	4 369	20.00	2.19	1643
3800	230.20	222.51	7.69	4 605	20.00	2.31	1646
4000	242.00	234.22	7.78	4 840	20.00	2.43	1648
4200	253.70	245.93	7.77	4 958	19.54	2.54	1651
4400	265.40	257.64	7.76	4 960	18.69	2.66	1653

Table 6.3: Measurements and calculated values for Cell 2

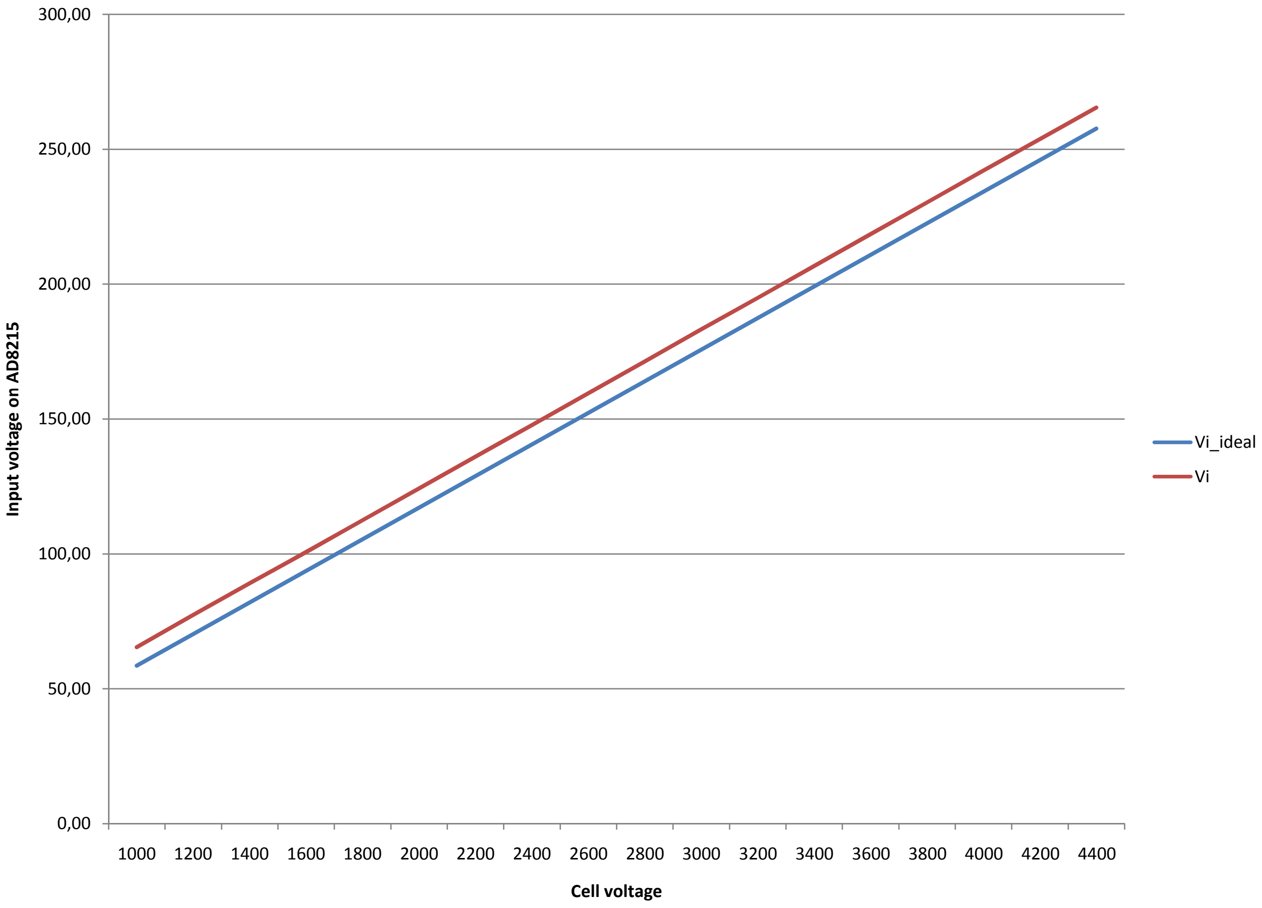


Figure 6.10: Input voltage to AD8215 as function of cell voltage

Amplification of the AD8215

According to the datasheet [2], the gain is fixed $20V/V$ with an accuracy of $\pm 0.15\%$. With a full scale input signal of $250mV$ this deviation will make $3.75mV$ difference on the output, which is acceptable. However, the AD8215 is designed to be used with a small resistor for current monitoring thus different behavior might occur. As shown in the tables for all cells, the amplification is very close to $20V/V$ except when input voltage are getting close to $250mV$. The amplifier's power source is $5V$ and it will as expected go to saturation when the input gets large enough.

Chapter 7

Discussion

7.1 AD8212

The AD8212 performs just as expected as long as the positive terminal is connected directly to the positive end of the cell. It requires at least $7V$ supply voltage, so it can be used on the seven highest cells.

The output of the AD8212 is a current, thus the voltage can easily be scaled by changing the output resistor. The output from the AD8212 must be multiplexed into one ADC channel on the AVR. Since the multiplexed signal is a current, the resistance of the multiplexer will not affect the voltage that goes into the AVR. However great care must be taken so that the AD8212 is turned off when the multiplexer is closed. Otherwise it will ramp up the voltage to maintain the output current. The upper voltage limit it can give is the same as the positive input[1], in this case up to $42V$.

The input resistance of the ADC must also be taken into account, but as long as it is significantly bigger than 10k, it should not affect the result much. According to [3] it is in the $100M\Omega$ range.

7.1.1 Zener Diode

At some of the tests a zener was connected in series with the voltage divider. The main idea behind this was to subtract the lowest voltage a cell can have so that one can get better resolution on the ADC. On a 10-bit ADC one has 1024 steps. With a range from 0 to $5V$ one ADC step is $4.88mV$. If the dynamic area can be shrunken to the actual area one is going to measure, the steps could in theory be smaller. By subtracting $2.5V$ from the cell voltage, the measured range would be $4.2V - 2.5V = 1.7V$. This would give ADC steps which are $1.66mV$.

The thought is good, however, there is one parameter that is not taken into account; the large tolerance of $\pm 5\%$ on the zeners. For a $2.5V$ diode, the variance will be $250mV$. Taking this into account, the measurement circuit will have a horrible accuracy and will be useless for this application.

The decision was made to not use the zener. Resistors can be obtained with very good accuracy, depending how much money one are willing to spend. This will also give the ability to detect deep under-voltage[1] and if a cell is present or not. By using the right resistor values, the measurement range can be scaled from zero to whatever is desired. In this case $4.2V$ should be sufficient. This will give $4.1mV$ ADC steps.

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[1] Voltage level far below spec

7.2 NDC7001C

The extremely low on resistance of the NDC7001C makes it ideal for switching. Used for balancing, it does not really matter if it has very low resistance or not since it will be coupled in series with a resistor. However when it is used for turning on and off the voltage scaling circuits, it is important that it is either consistent or significantly smaller than the resistors in the voltage divider. In this case it does not matter if it is 1Ω or 10Ω. This will not affect the results.

7.3 Full Scale Protoype

7.3.1 Cell 1

The first cell has different results than the rest of the cells. As suspected, this has to do with the NDC7001 that is used for switching on the measurement current. When the cell voltage is low, V_{GS} on the switching transistor is also low. On this first cell, it is the same as the cell voltage itself. One can see that R_{tot}, which is a calculated resistor value based on cell voltage and the known resistances, is decreasing as the cell voltage goes up. This can be translated to decreasing R_{DS} on the transistor.

A solution to this problem can either be to only use one N-channel transistor or connecting cell one directly to the ADC. The later will be preferred both due to minimizing cost, area and error sources. However, using an N-channel transistor can be used for cell number two due to the low voltage that can occur on that cell if both cell one and cell two is low.

There is one strange result here that stands out; looking at the last line in table 6.2 one can see that the calculated total resistance is actually lower than the sum of $R1$ and $R2$. Which means there are some non-ideal effects that was not thought of at first. This means that the resistance from the NDC7001 cannot be calculated from this measurement data. However, since in a real application cell one would be connected directly to the ADC, it is what cell two to ten reveals that is of biggest interest.

7.3.2 Cell 2 - 10

Amplification of the AD8215

As seen from the results, the amplification is very consistent and very close to $20V/V$ as stated in the datasheet. There was some concerns for using a larger resistor than the amplifier was designed for, but it did not seem to affect the amplification.

The amplification is a little smaller for cell-voltages above $4000mV$, however, this can easily be fixed by adjusting the voltage divider a little bit so that maximum cell voltage give a little bit less than theoretically maximum output on the AD8215. The prototype is using a 1 to 16 ratio on the voltage divider. A cell voltage of $4200mV$ should then give $247mV$ on the amplifiers input. Adjusting the ratio should fix the problem. There is also in general a little bit bigger deviation on the amplification for low cell voltages than for higher. However, cell voltages should not go below $2600mV$ anyway, which will give a little bit more accuracy in our favor.

By looking at a range from $2400mV$ to $4000mV$ which is of most interest, the largest deviation of the amplification is $0.07V/V$. This occurs in cell five and cell seven. A 0.35% deviation as measured here is slightly larger than the $\pm 0.3\%$ stated in the datasheet. However, since the difference from 0.35% to 0.3% only result in a deviation of $1mV$, it can be concluded that for this purpose, the data sheet can be trusted.

An amplification accuracy of $\pm 0.3\%$ will at maximum input ($250mV$) introduce an error of $\pm 15mV$ into the ADC. So by not measuring the amplification and adjusting for it in the firmware, the fundamental lowest accuracy by the system will be $30mV$. However, this is worst case at full input, so the accuracy will be better most of the time.

Voltage Divider

To generate an input voltage to the AD8212 it has been used a voltage divider that can be switched on and off. The main concern has been how the NDC7001 which is used for switching will perform. The thought was to measure the two resistances, R_1 and R_2, and the voltage over the smaller resistor. From this the total resistance and thus the resistance over the switching transistor can be calculated.

However, from the results, it seems there is another error source that at first sight seems of a lot bigger concern than the resistance of the NDC7001. It seems like the input resistance of the AD8215 is significantly altering the resistor divider. As seen from the tables representing cell two to ten, the calculated total resistance is smaller than the total resistance in the voltage divider alone. This means that the input impedance of the amplifier is low enough to affect the voltage divider more than first assumed. This was not discovered until after measurements were done as the resistance of the voltage dividers (table 6.1) was measured with no power applied on the circuit.

The resistance of the NDC7001 cannot be determined with the data from the measurements. This is because of the resistance from the AD8215 that was not taken into account from the beginning. However, as long as the resistance is small, the effects can be neglected. It was chosen to use 5Ω as the resistance of the NDC7001 for calculation. This is taken from the datasheet[6].

A closer look at the results reveals that the resistance introduced by the AD8215 is fairly stable and because of this, the error can be modeled as an offset. There is also a tiny gain error[2] there, but in the range of interest[3], this gain error is less than $0.6mV$ and will thus be neglected. Figure 6.10 shows the input voltage as a function of cell voltage on cell number two. Cell number two is the one with the largest gain error.

By taking the mean value of Δ_{Vin} of all cells in the range of interest, one get $7.48mV$. In this application, this is probably a good number for the offset caused by the AD8215. In the dataset available from the measurements, the largest deviation from this chosen offset value is $+0.38mV$ and $-0.36mV$. The dataset is too small to get an entirely correct statistical result, but from what is measured here, one can determine that a reasonable accuracy from the offset is $\pm 0.4mV$ over the interval from $2400mV$ to $4000mV$.

$$V_{AD8215-in} = V_{cell} \times \frac{R_1}{R_1 + R_2 + R_{sw}} - 7.48mV \pm 0.4mV \tag{7.1}$$

Equation 7.1 shows a valid model for the prototype constructed. Valid for $R_1 \simeq 100\Omega$, $R_2 \simeq 1600\Omega$ and $R_{sw} = 5\Omega$. As mentioned, the AD8215 goes to saturation a little bit before the cell voltage reaches $4200mV$ thus the resistor values needs a little bit tweaking. The model should still be valid, but only testing will

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[2] Gain error in this case referrers to the slope of the curve showing input voltage to AD8215 vs cell voltage and has nothing to do with the gain of the AD8215

[3] Cell voltage from 2400mV to 4000mV

reveal that. After amplification, the accuracy on the ADC end will be $\pm 0.4mV \times 20 = \pm 8mV$ or about three ADC steps.

7.3.3 Summary

As it is the external circuit that has been constructed, the accuracies from the result are what this circuit is able to deliver to the ADC. For the total system, the accuracy of the ADC used will contribute additionally.

The inaccuracies introduced by the AD8215 is in worst case $\pm 15mV$ into the ADC. The resistor network is contributing $\pm 8mV$ given that the resistor values are known. In total, the accuracy of the external system is $46mV$ or ten ADC steps. In addition comes one to two steps of the ADC itself[3].

Chapter 8

Concluding Remarks

There has successfully been constructed a circuit for monitoring and balancing a multicell battery pack with ten cells. The accuracy has been tested to about $46mV$. However, the system was realized by using current shunt monitors, switching transistors and a significant amount of resistors. The problem description depicts a system based on only a resistor network, however it was found better to construct it this way due to accuracy. In chapter 9 there will be discussed some other architectures that got the attention a little too late in the design process.

This system was intended to be used commercially in power tools and other high voltage applications. However, the system is taking up a significant PCB area and is with its many components fairly expensive. The physical space requirement will probably be ok, since a ten cell battery is also physically big. What is really killing this design is that there exist single chips that can do the task better and cheaper with or without help from an external microcontroller. Some of these products are released in 2009; the others found were released in 2008. As a commercial product, the design in this thesis will not stand a chance against these battery management chips.

The only way to compete must be to be able to make this design work with only a resistor network or make use of some of the battery management chips. The bq77PL900[13] from Texas Instruments is a battery management chip, but as standalone it can only do simple tasks with the battery pack. In practice this chip can do about the same things as the circuit in this thesis when controlled by a microcontroller. An idea can be to use this one together with an AVR. Further discussion of this topic can be found in chapter 9.

Due to mentioned reasons, only a simple demo firmware has been written. The only thing this firmware does is to control the multiplexer and power switch, read the voltages and present these via UART.

Seen from a pure technical view, the product is working and has been tested to have an acceptable accuracy to be able to determine state of charge of the battery pack. In the real world, it can be concluded that this design will not be used in any applications due to the superiority of the competitors.

Chapter 9

Future Work

9.1 Other Solutions

As concluded, the design will not stand a chance against the competitors. Other ways must be found if one wants to be in the game.

9.1.1 Pure Resistor Divider

If one can get a circuit working purely on resistor dividers, the cost and size can be greatly reduced.

The main idea is to use the same scaling ratio on all the cells and measure the voltages with a differential ADC. The obvious problem here is that the differences will be very small and an accurate gain stage is needed before the ADC. If an AVR can amplify and measure this small differential voltage with an acceptable accuracy, it might be a chance to get back in the game.

For this to work, an AVR with enough differential channels must be used. To avoid using an external multiplexer, all the differential ADC channels must also have a gain stage. As long as the criteria are fulfilled, it might actually work.

What must be taken into account is that the balancing circuit is also contributing to some of the cost and a significant part of the area used. The battery management devices on the market have internal balancing circuitry.

If a product like this, which probably has lower performance than the battery management devices, is to be commercially successful, it must be significantly cheaper than its competition. If the competition is better, you have to be cheaper.

9.1.2 A System with TI bq77PL900

If one can't beat it, join it. A system based on an AVR and a bq77PL900 should make a very potent combination. The bq77PL900 need a microcontroller to be able to intelligently manage and protect a battery. There would not be any need for multiplexers, amplifiers or external balancing transistors. It also has a built in regulator so the AVR can be powered directly from this chip. An application note based on this chip might be a good idea.

9.1.3 Multiple AVRs

By stacking multiple high voltage AVR devices, one can in principle monitor as many cells as one like. The only external circuitry needed will then be level shifting of the communication lines. As long as this can be done in an effective way, this solution could prove to be highly usable. By utilizing battery AVRs, one also gets the advantage of high precision ADCs and current counting.

9.2 Software

As the firmware for this application is only written simple to show a proof of concept, it is necessary to write a complete firmware. However, this firmware cannot be entirely complete without a charger and a host system present. When this is in place, a complete firmware and software package can be written. It could also be an idea to have a similar interface to a PC as the SB200 has together with AVR BatteryStudio. However, software and firmware should be based on a product that can be commercialized.

9.3 Additional Hardware

As the design in this thesis is only of what goes inside the battery, a design of a charger and a host could also be useful for demonstrating a complete Smart Battery system. The battery system cannot be fully demonstrated in the current state due to lack of a charger.

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Appendix A

TrustFire characterization data

A.1 Voltage

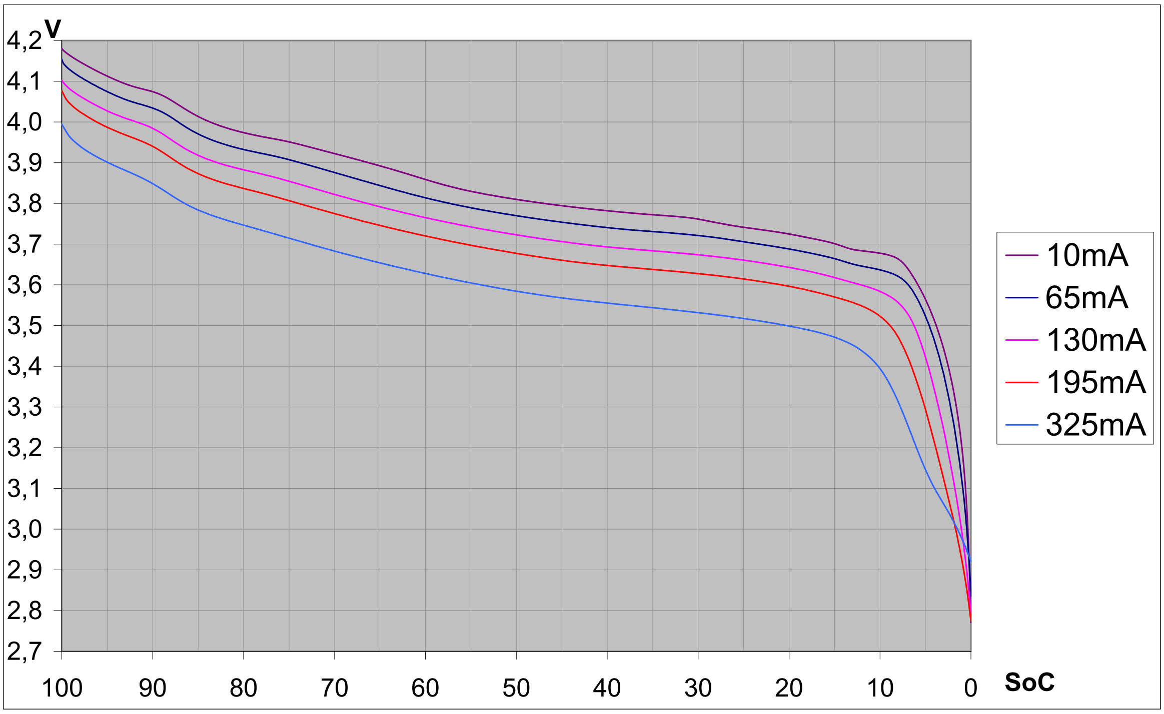

Figure A.1: Voltage vs SoC

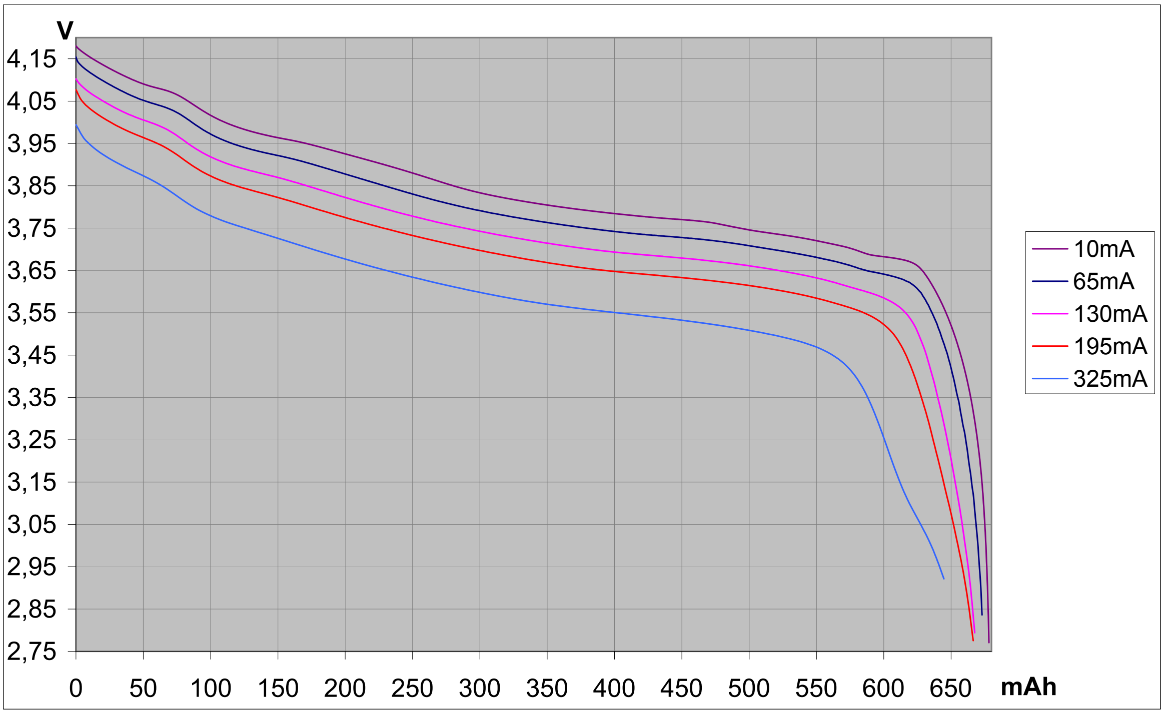

Figure A.2: Voltage vs Capacity

A.2 Resistance

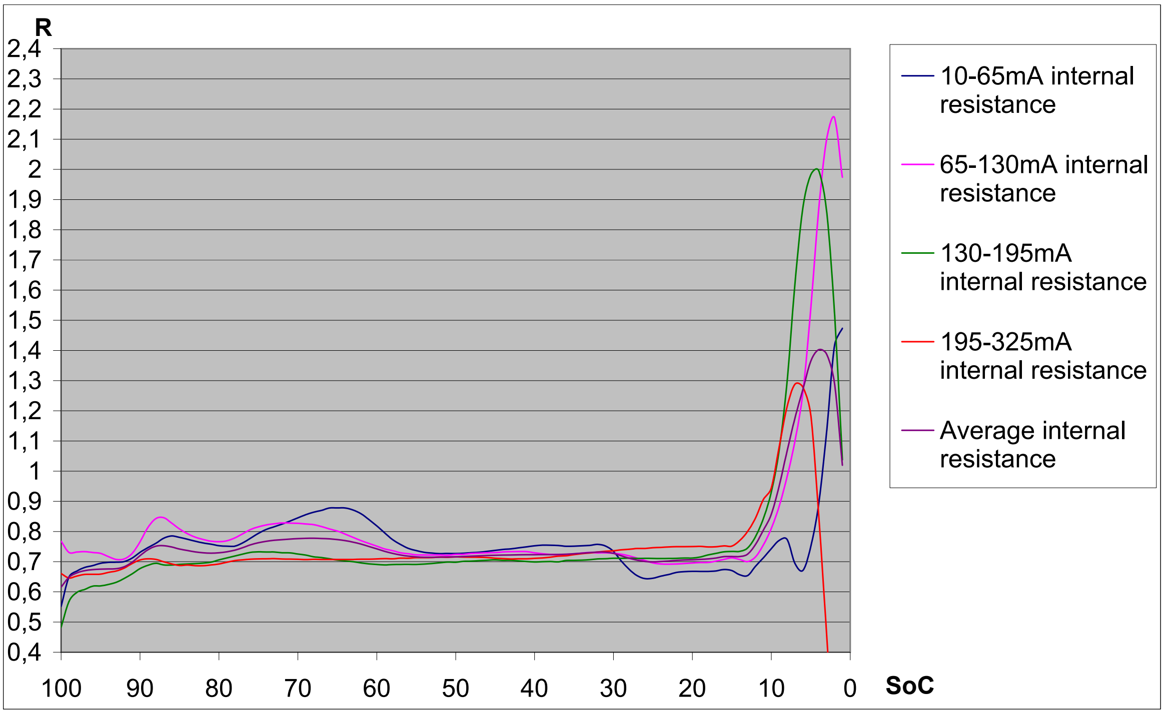

Figure A.3: Resistance vs SoC

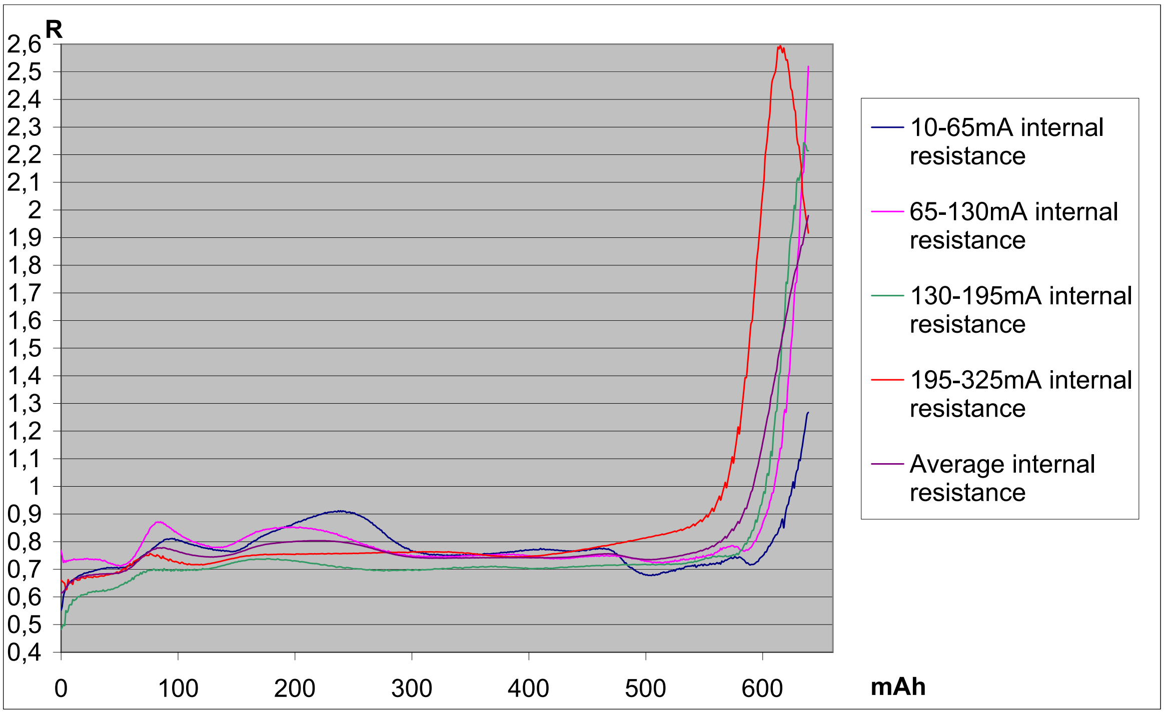

Figure A.4: Resistance vs Capacity

Appendix B

Built hardware

B.1 Cell rig

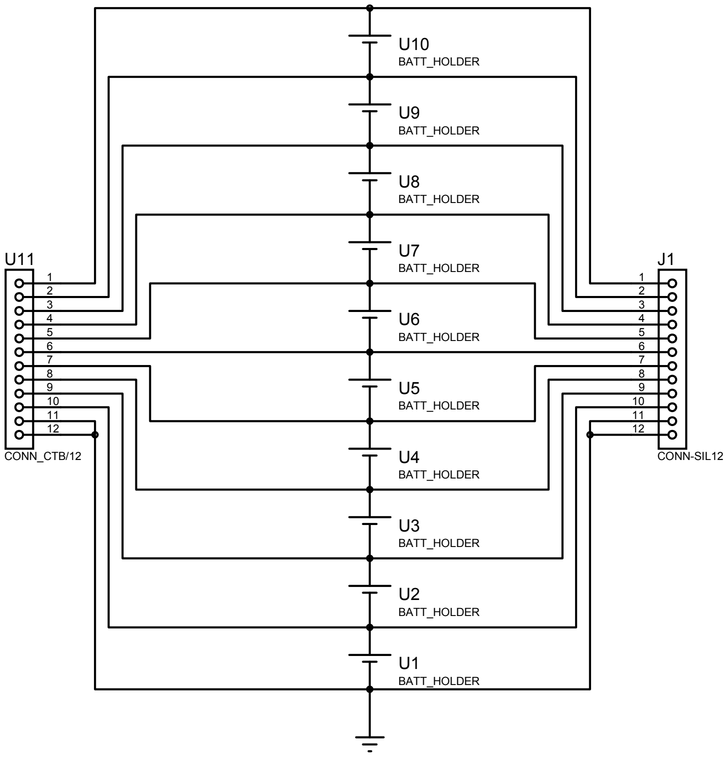

Figure B.1: Schematics of the cell rig

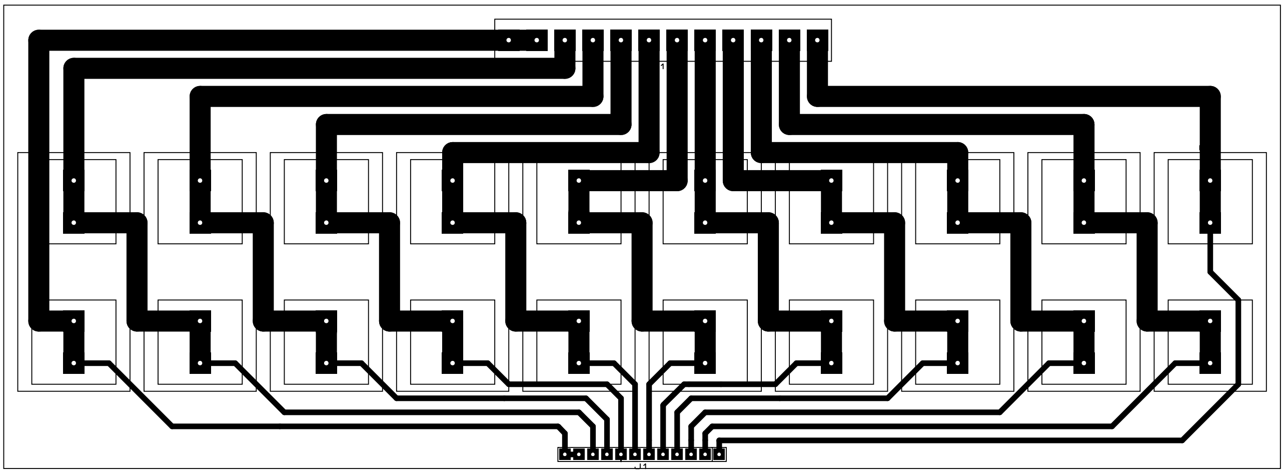

Figure B.2: Physical layout of the cell rig

B.2 Prototype

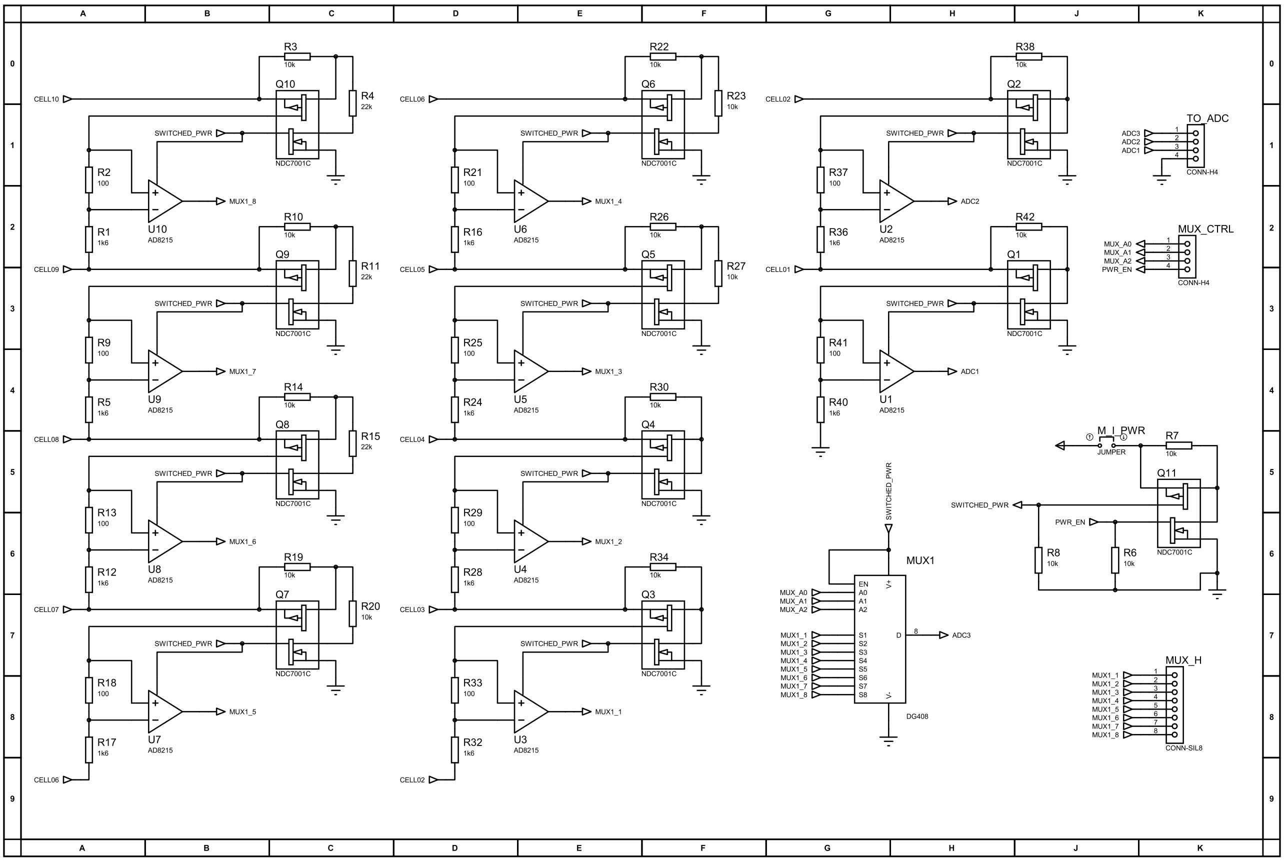

Figure B.3: Voltage scaling circuitry and power switch

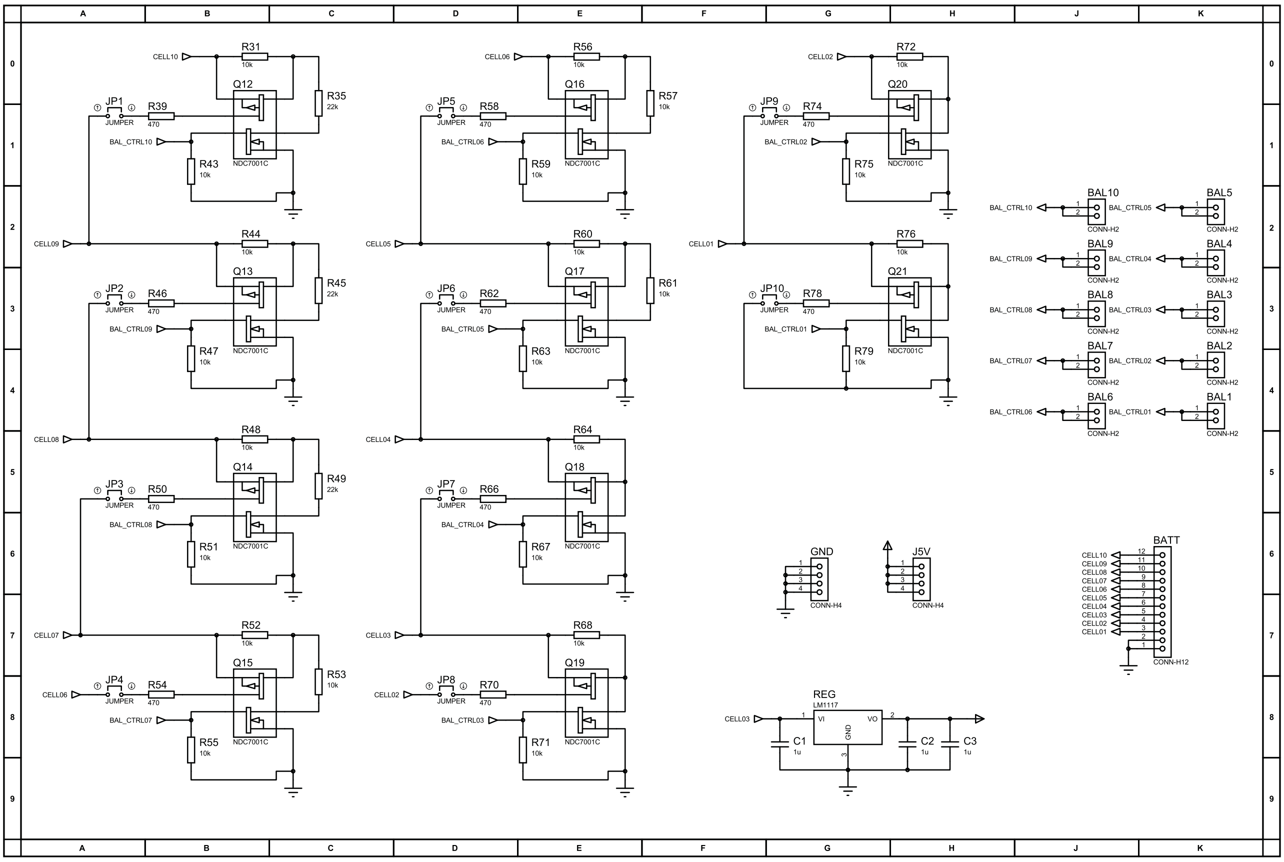

Figure B.4: Balancing circuitry

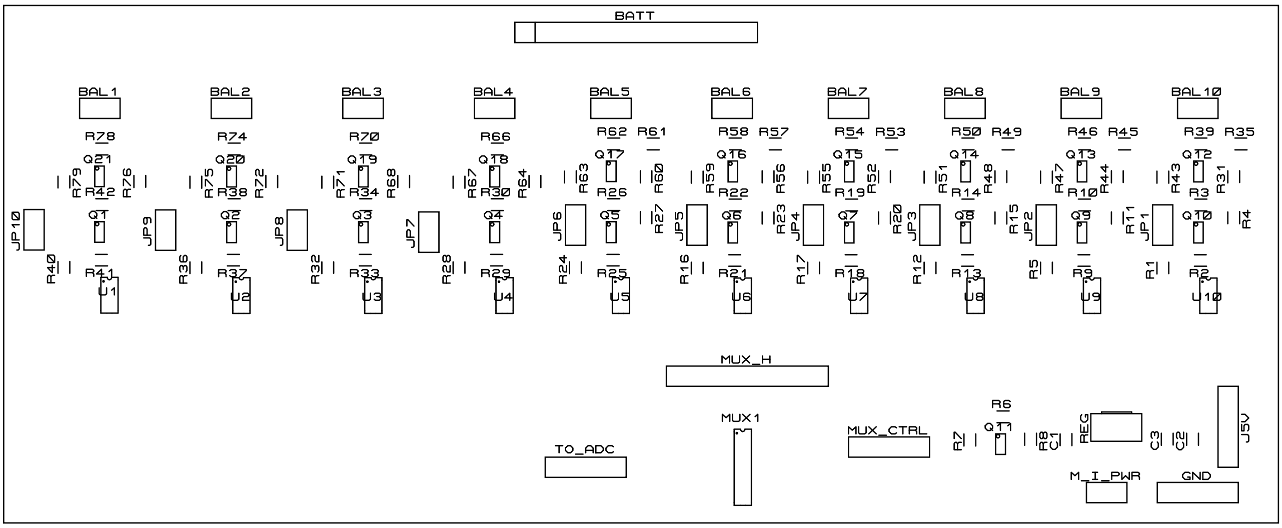

Figure B.5: Component layout

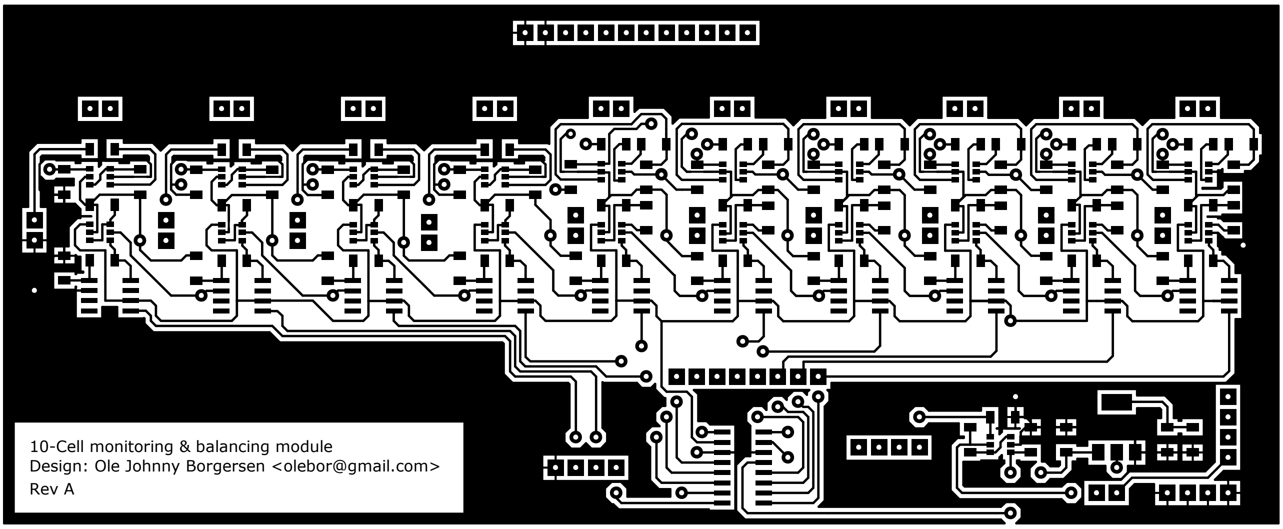

Figure B.6: Top copper

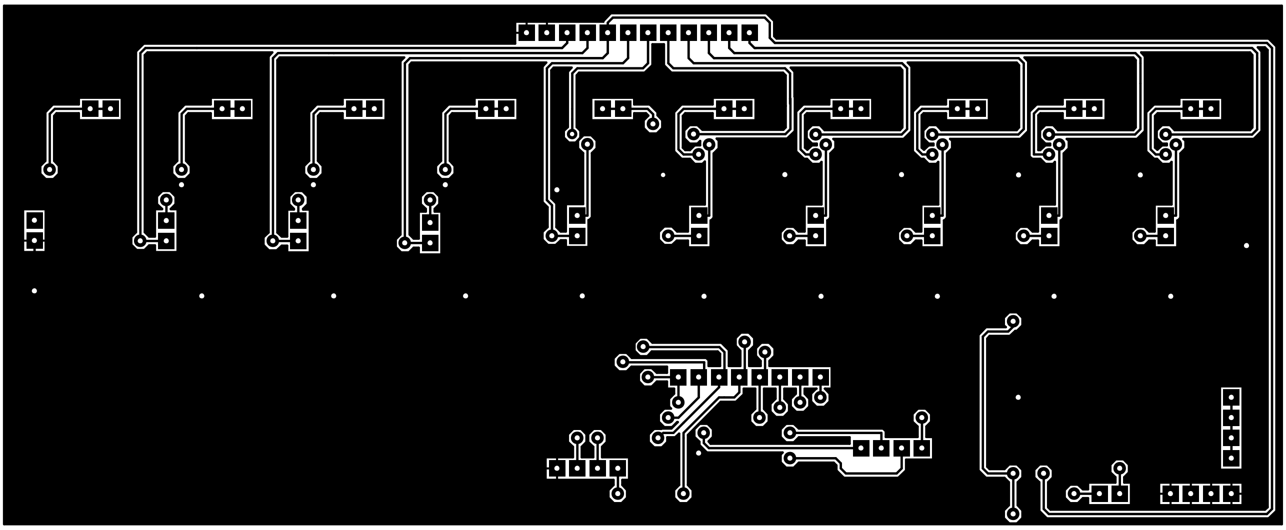

Figure B.7: Bottom copper

Appendix C

Measurement results

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{out}[mV]$	A	$I_{calculated}[mA]$	$R_{tot}[\Omega]$
1000	31.50	625	19.84	0.32	3171
1200	37.20	736	19.78	0.37	3223
1400	41.50	822	19.81	0.42	3370
1600	59.50	1 184	19.90	0.60	2686
1800	74.60	1 485	19.91	0.75	2410
2000	88.90	1 770	19.91	0.89	2247
2200	103.30	2 058	19.92	1.03	2128
2400	117.20	2 337	19.94	1.17	2046
2600	131.00	2 620	20.00	1.31	1983
2800	145.60	2 904	19.95	1.46	1921
3000	159.70	3 188	19.96	1.60	1877
3200	173.80	3 468	19.95	1.74	1839
3400	187.70	3 749	19.97	1.88	1810
3600	202.40	4 038	19.95	2.03	1777
3800	216.30	4 319	19.97	2.17	1755
4000	230.60	4 603	19.96	2.31	1733
4200	244.70	4 885	19.96	2.45	1715
4400	258.80	4 960	19.17	2.59	1698

Table C.1: Measurements and calculated values for Cell 1

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.40	58.55	6.85	1 312	20.06	0.66	1524
1200	77.30	70.26	7.04	1 548	20.03	0.78	1548
1400	89.10	81.98	7.12	1 785	20.03	0.89	1567
1600	100.60	93.69	6.91	2 017	20.05	1.01	1586
1800	112.50	105.40	7.10	2 252	20.02	1.13	1595
2000	124.20	117.11	7.09	2 489	20.04	1.25	1605
2200	136.00	128.82	7.18	2 723	20.02	1.36	1613
2400	147.70	140.53	7.17	2 958	20.03	1.48	1620
2600	159.50	152.24	7.26	3 194	20.03	1.60	1625
2800	171.30	163.95	7.35	3 430	20.02	1.72	1630
3000	183.20	175.66	7.54	3 664	20.00	1.84	1633
3200	194.80	187.37	7.43	3 900	20.02	1.95	1638
3400	206.70	199.08	7.62	4 135	20.00	2.07	1640
3600	218.50	210.79	7.71	4 369	20.00	2.19	1643
3800	230.20	222.51	7.69	4 605	20.00	2.31	1646
4000	242.00	234.22	7.78	4 840	20.00	2.43	1648
4200	253.70	245.93	7.77	4 958	19.54	2.54	1651
4400	265.40	257.64	7.76	4 960	18.69	2.66	1653

Table C.2: Measurements and calculated values for Cell 2

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.50	58.61	6.89	1 315	20.08	0.66	1524
1200	77.30	70.33	6.97	1 550	20.05	0.77	1549
1400	88.90	82.05	6.85	1 785	20.08	0.89	1572
1600	100.50	93.77	6.73	2 017	20.07	1.01	1589
1800	112.60	105.50	7.10	2 257	20.04	1.13	1595
2000	124.20	117.22	6.98	2 490	20.05	1.24	1607
2200	136.00	128.94	7.06	2 726	20.04	1.36	1614
2400	147.80	140.66	7.14	2 961	20.03	1.48	1621
2600	159.50	152.38	7.12	3 197	20.04	1.60	1627
2800	171.40	164.11	7.29	3 432	20.02	1.72	1630
3000	183.20	175.83	7.37	3 668	20.02	1.84	1634
3200	194.90	187.55	7.35	3 903	20.03	1.95	1639
3400	206.70	199.27	7.43	4 138	20.02	2.07	1642
3600	218.50	210.99	7.51	4 373	20.01	2.19	1644
3800	230.10	222.72	7.38	4 607	20.02	2.31	1648
4000	242.00	234.44	7.56	4 844	20.02	2.42	1650
4200	253.80	246.16	7.64	4 959	19.54	2.54	1652
4400	265.60	257.88	7.72	4 960	18.67	2.66	1653

Table C.3: Measurements and calculated values for Cell 3

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.60	58.49	7.11	1 309	19.95	0.66	1520
1200	77.40	70.18	7.22	1 543	19.94	0.78	1546
1400	89.10	81.88	7.22	1 780	19.98	0.89	1567
1600	100.70	93.58	7.12	2 011	19.97	1.01	1584
1800	112.60	105.27	7.33	2 247	19.96	1.13	1594
2000	124.20	116.97	7.23	2 480	19.97	1.25	1605
2200	136.10	128.67	7.43	2 716	19.96	1.37	1612
2400	147.80	140.36	7.44	2 951	19.97	1.48	1619
2600	159.50	152.06	7.44	3 186	19.97	1.60	1625
2800	171.20	163.76	7.44	3 420	19.98	1.72	1631
3000	183.10	175.46	7.64	3 656	19.97	1.84	1634
3200	194.80	187.15	7.65	3 890	19.97	1.95	1638
3400	206.50	198.85	7.65	4 125	19.98	2.07	1642
3600	218.30	210.55	7.75	4 361	19.98	2.19	1644
3800	230.00	222.24	7.76	4 594	19.97	2.31	1647
4000	241.80	233.94	7.86	4 829	19.97	2.43	1649
4200	253.40	245.64	7.76	4 959	19.57	2.54	1652
4400	265.20	257.34	7.86	4 960	18.70	2.66	1654

Table C.4: Measurements and calculated values for Cell 4

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.60	58.61	6.99	1 305	19.89	0.66	1521
1200	77.40	70.33	7.07	1 540	19.90	0.78	1547
1400	89.10	82.05	7.05	1 774	19.91	0.89	1568
1600	100.90	93.77	7.13	2 009	19.91	1.01	1583
1800	112.50	105.50	7.00	2 243	19.94	1.13	1597
2000	124.50	117.22	7.28	2 480	19.92	1.25	1603
2200	136.20	128.94	7.26	2 715	19.93	1.36	1612
2400	148.00	140.66	7.34	2 950	19.93	1.48	1618
2600	159.80	152.38	7.42	3 186	19.94	1.60	1624
2800	171.50	164.11	7.39	3 420	19.94	1.72	1629
3000	183.40	175.83	7.57	3 657	19.94	1.84	1632
3200	195.00	187.55	7.45	3 891	19.95	1.95	1638
3400	206.80	199.27	7.53	4 125	19.95	2.07	1641
3600	218.50	210.99	7.51	4 360	19.95	2.19	1644
3800	230.40	222.72	7.68	4 597	19.95	2.31	1646
4000	242.10	234.44	7.66	4 833	19.96	2.43	1649
4200	253.80	246.16	7.64	4 957	19.53	2.54	1652
4400	265.70	257.88	7.82	4 958	18.66	2.66	1653

Table C.5: Measurements and calculated values for Cell 5

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.50	58.57	6.93	1 311	20.02	0.66	1524
1200	77.20	70.29	6.91	1 545	20.01	0.77	1551
1400	89.00	82.00	7.00	1 781	20.01	0.89	1570
1600	100.80	93.72	7.08	2 017	20.01	1.01	1584
1800	112.40	105.43	6.97	2 250	20.02	1.13	1598
2000	124.20	117.15	7.05	2 485	20.01	1.24	1607
2200	136.00	128.86	7.14	2 721	20.01	1.36	1614
2400	147.90	140.58	7.32	2 957	19.99	1.48	1619
2600	159.60	152.29	7.31	3 192	20.00	1.60	1626
2800	171.40	164.01	7.39	3 427	19.99	1.72	1630
3000	183.20	175.72	7.48	3 663	19.99	1.84	1634
3200	194.90	187.44	7.46	3 897	19.99	1.95	1639
3400	206.70	199.15	7.55	4 134	20.00	2.07	1642
3600	218.50	210.87	7.63	4 368	19.99	2.19	1644
3800	230.10	222.58	7.52	4 602	20.00	2.31	1648
4000	241.90	234.30	7.60	4 838	20.00	2.42	1650
4200	253.70	246.01	7.69	4 957	19.54	2.54	1652
4400	265.40	257.73	7.67	4 959	18.69	2.66	1655

Table C.6: Measurements and calculated values for Cell 6

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.60	58.62	6.98	1 302	19.85	0.66	1520
1200	77.60	70.35	7.25	1 539	19.83	0.78	1542
1400	89.30	82.07	7.23	1 774	19.87	0.90	1563
1600	100.90	93.80	7.10	2 007	19.89	1.01	1581
1800	112.80	105.52	7.28	2 245	19.90	1.13	1591
2000	124.60	117.25	7.35	2 480	19.90	1.25	1600
2200	136.40	128.97	7.43	2 716	19.91	1.37	1608
2400	148.10	140.70	7.40	2 949	19.91	1.49	1616
2600	159.90	152.42	7.48	3 187	19.93	1.60	1621
2800	171.60	164.14	7.46	3 420	19.93	1.72	1627
3000	183.50	175.87	7.63	3 657	19.93	1.84	1630
3200	195.20	187.59	7.61	3 891	19.93	1.96	1634
3400	206.90	199.32	7.58	4 126	19.94	2.08	1638
3600	218.80	211.04	7.76	4 362	19.94	2.19	1640
3800	230.50	222.77	7.73	4 596	19.94	2.31	1644
4000	242.30	234.49	7.81	4 833	19.95	2.43	1646
4200	253.90	246.22	7.68	4 957	19.52	2.55	1649
4400	265.80	257.94	7.86	4 959	18.66	2.67	1650

Table C.7: Measurements and calculated values for Cell 7

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.60	58.59	7.01	1 308	19.94	0.66	1520
1200	77.40	70.31	7.09	1 545	19.96	0.78	1546
1400	89.10	82.02	7.08	1 778	19.96	0.89	1567
1600	100.90	93.74	7.16	2 014	19.96	1.01	1581
1800	112.60	105.46	7.14	2 249	19.97	1.13	1594
2000	124.20	117.18	7.02	2 483	19.99	1.25	1605
2200	136.10	128.89	7.21	2 719	19.98	1.37	1612
2400	147.90	140.61	7.29	2 954	19.97	1.48	1618
2600	159.60	152.33	7.27	3 189	19.98	1.60	1624
2800	171.40	164.05	7.35	3 424	19.98	1.72	1629
3000	183.10	175.77	7.33	3 660	19.99	1.84	1634
3200	194.80	187.48	7.32	3 894	19.99	1.95	1638
3400	206.50	199.20	7.30	4 127	19.99	2.07	1642
3600	218.50	210.92	7.58	4 365	19.98	2.19	1643
3800	230.20	222.64	7.56	4 601	19.99	2.31	1646
4000	242.00	234.35	7.65	4 834	19.98	2.43	1648
4200	253.70	246.07	7.63	4 958	19.54	2.54	1651
4400	265.40	257.79	7.61	4 960	18.69	2.66	1653

Table C.8: Measurements and calculated values for Cell 8

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.40	58.62	6.78	1 302	19.91	0.66	1524
1200	77.30	70.35	6.95	1 539	19.91	0.78	1548
1400	88.90	82.07	6.83	1 773	19.94	0.89	1570
1600	100.60	93.80	6.80	2 008	19.96	1.01	1586
1800	112.70	105.52	7.18	2 249	19.96	1.13	1592
2000	124.40	117.25	7.15	2 483	19.96	1.25	1603
2200	136.20	128.97	7.23	2 719	19.96	1.37	1610
2400	147.90	140.70	7.20	2 954	19.97	1.48	1618
2600	159.60	152.42	7.18	3 188	19.97	1.60	1624
2800	171.50	164.14	7.36	3 424	19.97	1.72	1628
3000	183.30	175.87	7.43	3 660	19.97	1.84	1632
3200	195.00	187.59	7.41	3 895	19.97	1.96	1636
3400	206.80	199.32	7.48	4 131	19.98	2.07	1639
3600	218.50	211.04	7.46	4 365	19.98	2.19	1643
3800	230.40	222.77	7.63	4 601	19.97	2.31	1644
4000	242.10	234.49	7.61	4 837	19.98	2.43	1647
4200	253.80	246.22	7.58	4 957	19.53	2.55	1650
4400	265.60	257.94	7.66	4 959	18.67	2.66	1652

Table C.9: Measurements and calculated values for Cell 9

$V_{cell}[mV]$	$V_{in}[mV]$	$V_{in-ideal}[mV]$	$\Delta_{Vin}[mV]$	$V_{out}[mV]$	A_{AD8215}	$I_{calc}[mA]$	$R_{tot}[\Omega]$
1000	65.60	58.68	6.92	1 320	20.12	0.66	1521
1200	77.40	70.41	6.99	1 555	20.09	0.78	1547
1400	89.00	82.15	6.85	1 788	20.09	0.89	1570
1600	100.90	93.89	7.01	2 026	20.08	1.01	1583
1800	112.80	105.62	7.18	2 263	20.06	1.13	1593
2000	124.60	117.36	7.24	2 498	20.05	1.25	1602
2200	136.40	129.09	7.31	2 734	20.04	1.37	1610
2400	148.10	140.83	7.27	2 968	20.04	1.48	1617
2600	159.90	152.56	7.34	3 205	20.04	1.60	1623
2800	171.70	164.30	7.40	3 439	20.03	1.72	1627
3000	183.50	176.03	7.47	3 676	20.03	1.84	1632
3200	195.20	187.77	7.43	3 910	20.03	1.96	1636
3400	207.00	199.51	7.49	4 146	20.03	2.07	1639
3600	218.80	211.24	7.56	4 382	20.03	2.19	1642
3800	230.50	222.98	7.52	4 618	20.03	2.31	1645
4000	242.40	234.71	7.69	4 853	20.02	2.43	1647
4200	254.10	246.45	7.65	4 958	19.51	2.55	1650
4400	265.90	258.18	7.72	4 959	18.65	2.66	1651

Table C.10: Measurements and calculated values for Cell 10