Power peak reduction and control of automatic sliding doors

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Abstract

When a sliding door is opened there is a sudden current peak that the electric network is subjected to. As a result of this it is difficult to design a power supply that operates the door with adequate performance while still maintaining a low power rating. In the current solution the power rating is designed for the sudden peaks and as there is no buffer of energy everything has to be taken directly from the power grid at the instance of a door opening. This thesis aims to use an energy buffer to store energy between openings and then utilize this when it needs to open. As a result of this the power grid will suffer from less sudden peaks. The power supply will also be allowed to be rated for the continuous power rather than the peaks.

Throughout different solutions to solve the energy buffer have been discussed, investigated and tested. The most prevalent and thoroughly tested was supercapacitors, which are an evolution of regular capacitors and nickel metal hydride batteries. Supercapacitors have the possibility of delivering a large current and being charged with equally large current allowing for fast charge as well as discharge. However, they do have a low voltage rating, which results in a small capacity of maintaining charge. Batteries on the other hand have a large voltage while having a lower current capacity. The differences of these have been discussed at large in the report.

The work shows that both batteries and supercapacitors are able to power the door. They are both able to offer a smoother power consumption and a lower power rating of the power supply. However, they have different capacities with regards to the door that they can power. Batteries are limited by the speed, weight and run style of the door. This limit is set by the charging current that the batteries can handle. Supercapacitors on the other hand are able to handle every scenario tested due to the large current capacity.

Acknowledgements

We would like to extend our sincerest gratitude to everyone who has contributed to the work that has gone into this thesis. Firstly, to Anton Cervin at the department of automatic control for always being available to have meetings and discussions regarding the work as well as writing process.

We would also like to offer our greatest appreciation to all the people at ASSA Abloy who have contributed to the results and offered their experiance and knowledge when we have needed it. Above all, thank you to our supervisor Roger Dreyer for always offering help and to Paul Durand-Estèbe for sharing his knowledge regarding supercapacitors and electronics. Your help has been vital to the process of this thesis and without the discussions regarding electronics that we have had the achieved results would not be what they are today.

Lastly, thank you to all the other thesis students for making our time at ASSA Abloy very enjoyable.

Contents

1

Introduction

This master's thesis was performed at ASSA Abloy Entrance Systems, AAES. A company founded in 1994 when the Swedish company ASSA and the Finish company Abloy merged to gain an even larger share of the door and lock market. They are now one of the world leading developers of opening solutions and have acquired companies such as Yale doorman, Cardo and Essex. They are constantly expanding into new markets by acquisitions of different companies in markets related to where they are currently present. AAES works on a global market and as of 2018 has 48 500 employees in over 70 countries [1]. In 2016 ASSA Abloy was part of the prestigious list of the worlds most innovative companies published by Forbes magazine [2].

AAES is a division within ASSA Abloy that develops several types of automatic entrance products and solutions. The products can be found in a multitude of places including airports, grocery stores, and wherever else an automatic door is needed. A substantial amount of research and development is performed in Landskrona, Sweden, which is where this thesis has been conducted.

In their catalog of products there are revolving doors, cargo ports, swing doors and sliding doors among other things opening related. This thesis has been performed with a sliding door of model SL500, one of the most common sliding doors. Sliding doors can however take many forms. For example, there can be one or two leafs that are being moved during an opening. They can also vary with regards to weight and size. In order to test everything there is a large test lab located in Landskrona which has been used in order to conduct the tests that follow in this thesis.

It should be noted that sensors utilized by the door have been disconnected during most testing and are therefore not active during any of the figures that are shown. Otherwise they will contribute a constant power consumption due to them always being active and scanning for someone approaching the door. There are also safety sensors that are always active to prevent accidents such as people being hit by a door leaf. The main reason for them being omitted is that the door that the tests were performed on was not equipped with sensors but also that they are not part of the concern that this thesis aimed to solve. However, for calculations of the total power that the door required they are accounted for in the calculations.

When an automatic sliding door is opened or closed, the motor opening the door draws a high current. However, when the door is idle, it only requires a current large enough to keep the lock active and run the sensors. The result of this is a low average power consumption with large power peaks, caused by the current peaks from opening and closing the door. The electronics supplying the door have to be designed to handle the peak values, which is costly both in parts and installation. The alternative this thesis aimed to investigate was to instead design the power supply around the average consumption and store the excess energy from when the door is idle in an energy buffer, such as batteries or supercapacitors. The end goal was to be able to power a door during normal operation using a plug power adapter with a result of easier and cheaper installation. The main points of focus were in choosing the best energy buffer for the application, design that to work as required and asses the viability of the solution. There was done extensive concept generation and assessment in order to determine the best option for storing energy. Concepts that are discussed in this report include supercapacitors and batteries. There were also discussions regarding usage of mechanical energy, these included solutions using a flywheel, potential energy stored in weights and water tanks and using an air compressor and a wind turbine. All of these were evaluated and later graded on their assumed performance in multiple areas that were of importance for this solution.

Apart from possibly reducing the total cost of the doors, there are other areas were the application could be useful. If the energy is harvested during the night, when the energy is cheap and spent during the day the energy cost is decreased. There is also the application in smart buildings operating on an energy budget. If the energy is harvested when most other power consuming devices are turned off, perhaps the night, then more energy is available to be spent elsewhere when the energy is not being harvested.

All figures and pictures used in the report are self made with computer software or taken by the authors if not stated otherwise.

1.1 Purpose

The purpose of the master's thesis was to investigate the possibility to reduce the power peaks drawn from the mains when an automatic sliding door is opened. The driving hypothesis was that a door sits idle most of the time and only draws high power when opening and closing. As a result the average power consumption should be much lower than the maximum power consumption, which the power supply is rated for. Therefore a power supply rated for the average power consumption used in conjunction with an energy reserve to supply the power peaks should be able to run the door without any drop in performance.

1.2 Problem formulation

The main problem studied in this thesis is, can an automatic sliding door be run with a power supply rated for the average power consumption coupled with an energy storage? This problem can be divided in to several smaller problems:

- What type of energy storage is the most suitable for the application?
- What are the average power requirements to run the door?
- Can the average power consumption be reduced?
- Would there have to be any reduction in performance of the door for this to work?

1.3 Previous work

No research has previously been conducted at ASSA Abloy regarding anything similar to what has been performed in the master's thesis. Therefore this work has not been founded directly on any already existing work. Nevertheless, there has been one bachelor's thesis [24] conducted by ASSA Abloy in which the writers performed several endurance tests with doors and observed different usages that exist. As the goal for this thesis was to develop realistic test cases these have used to assure proper testing as well as allow for ASSA Abloy to use the results from this thesis further in the future.

With regards to research and work done outside of ASSA Abloy none have influenced the thesis enough to be credited as a key reference.

1.4 Division of work

The work of this thesis has been divided as such that Per Josefsson has had the main responsibility of construction the mathematical formulas that are used to calculate energy, power and time required for opening.

Nicklas Norborg Persson has had the main responsibility for constructing tests and structuring the report and performing the corrections that were needed after meetings with the supervisor at Lunds University.

Tests with supercapacitors have been performed together and conclusions regarding these results found in cooperation. However, tests with batteries and conclusions regarding these such as comparisons of new versus old was performed by Nicklas Norborg Persson alone.

Due to long time illness everything performed in the last month of the thesis as well as finishing the report was also done by Nicklas Norborg Persson alone.

1.5 Outline

The rest of this thesis is structured as follows:

Chapter 2 is the background chapter which begins by discussing how supercapacitors and batteries work and what their limitations that need to be considered are. It then presents theory on other ways to store energy. The theory is then used to present the concepts evaluated. In addition the test rig used is described as well as what safety regulations need to be followed.

Chapter 3 describes the methodology of the thesis. It is divided into three parts. Section 3.1 focuses on concept generation and evaluation, Section 3.2 covers the design of the circuitry used and finally Section 3.3 describes the tests that were performed.

Chapter 4 presents the results gathered in Chapter 3. There are also results regarding the cost of the solutions are also mentioned.

Chapter 5 discusses the results found in Chapter 4 as well as the theory from Chapter 2. Points are made at future development and some comments on safety are also discussed.

2

Background

In the following chapter the theory that is needed will be explained in order to lay the foundation for the remaining report. The theory is based on what is later used in the concepts that are developed for solving the energy buffer. After the theory has been presented each concept is then described in detail so that the grading of these can later be understood.

Also presented is what test rig has been used and how it operates. There is an in depth section describing the current that is required to perform one opening. The reason for including this is that it would increase comprehension and understanding of the problem that this thesis aims to solve and in that way allow for the reader to have a better understanding of the concepts.

Lastly, there is a discussion regarding safety and in what way that has had to be taken into account when designing a solution.

2.1 Supercapacitors

Capacitors have been used to store energy for a long time, however the amount of energy that has been possible to store has been small for their size. This was solved when supercapacitors were introduced. The first supercapacitors were sold in the mid 1970's, but as the technology has advanced they have become increasingly popular, especially in the past fifteen years. Areas where they are being implemented are transportation, such as hybrid and electric vehicles and racing cars, but also as power buffers and as a fast charge alternative to batteries. Supercapacitors, also called double layer capacitors or ultra capacitors, have a high capacitance in a small volume allowing for larger amounts of energy to be stored in them compared to regular capacitors. A normal capacitor with a capacitance of 1 F can have a volume of 1 litre and weigh 1 kg [11] a supercapacitor with the same capacitance can have a volume of 2.9 ml and weigh less than 10 g [5]. The energy stored in a capacitor can be described by,

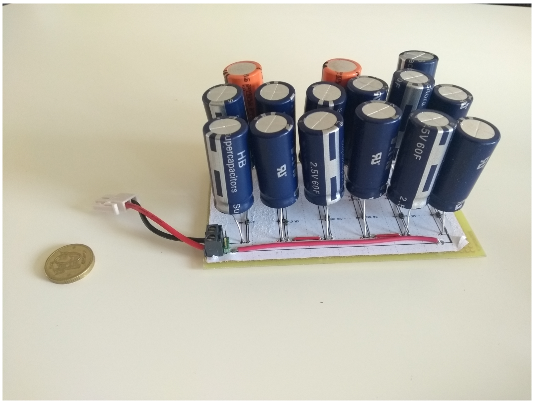


Figure 2.1: Shown in the picture is the cell of supercapacitors used in this thesis. Depicted are 15 supercapacitors connected in series with a resistor of 50 Ω connected in parallel for balancing purposes. The supercapacitors are 2.5 V and 60 F giving the resulting cell 37.5 V and 4 F. Next to the supercapacitors is a 10 SEK coin for scale.

$$E = \frac{1}{2}V^2C \tag{2.1}$$

where V is the voltage and C is the capacitance [6].

Supercapacitors have a high surface area on the electrodes, giving a high charge storage area. They also have no dielectric, the charge separation is in nanometers [23]. Since the capacitance of a capacitor is proportional to the surface area and the inverse of the charge separation, the resulting capacitance is high. The lack of dielectric in the supercapacitors limits their rated voltage to the voltage at which the electrolyte starts reacting. Depending on the dielectric used, supercapacitors have a rated voltage of between 0.9 – 3 V per cell. As a result several capacitors need to be connected in series if they are to be used for an application that requires a higher voltage. The supercapacitor cell that has been used in this thesis can be seen in Figure 2.1.

Supercapacitors, and capacitors in general, have a low equivalent series resistance, ESR, which allow for high current draws. As a result supercapacitors can deliver high power for short amounts of time. Since they get charged by accumulating charges they do not get warm when charging or discharging and have no factors limiting charging or discharging current other than the ESR. The limiting factors will instead, for the most part, be in the limitations of the surrounding circuitry.

While supercapacitors have a high specific energy compared to regular capacitors, it is not high compared to other ways to store energy. A 2.5 V, 60 F cell can store about 42 mAh. In comparison a lithium ion, Li-ion, battery with a comparable cell voltage can have a capacity at least one order of magnitudes higher [18]. In systems that require a minimum voltage to function supercapacitors have another drawback. The voltage in the capacitors drops with the energy used and as a consequence large portions of the energy stored may not be available to use. A voltage drop would in this application turn off the door or at least reduce the speed. Therefore it is important that voltage is kept as constant as possible.

Supercapacitors are considered to have a long life time [10]. Often being rated for more than 500.000 cycles or more than 1000 hours at full charge and maximum rated temperature, which is in most cases around 80 centigrade. The life time is even higher if the capacitors are not charged fully or kept at a lower temperature. Typically the life time is considered expired when the ESR has risen to a few times the initial value and the capacitance has dropped about 30 %. Depending on the application, these changes to the values of the capacitor may not be detrimental to its use and operation could continue past the rated life time.

Supercapacitors are safe components as they can take some abuse. Short circuiting them or accidentally charging them with a high current will not break them, they can also generally take small amounts of overcharge. When they break they often release some gas, but with serious abuse, they can explode. The are also not sensitive to temperature fluctuation in the same way as batteries are.

Limitations

There are a few concerns regarding charging of supercapacitors. The main limitation is the low voltage rating of individual supercapacitors as they can take harm if overcharged too much. Keeping the capacitors at full charge also wears them quicker and significantly reduces the lifespan according to distributors. There is also the concern of polarity as most supercapacitors have a preferred polarity and reversing it could result in them having a lower breakdown voltage or the capacitors being damaged.

When charging supercapacitors the current and voltage need to be regulated. The uncharged supercapacitors can be seen electrically as a small resistance with a value equal to the the sum of the ESR of the supercapacitors. As a result the charging current will be given by the voltage difference between the voltage source and the capacitors divided by the sum of the ESR in the capacitors. Unless the voltage source and the capacitors are close in voltage, this yields high currents. A way to combat this issue is to put a resistance in series with the capacitors to limit the current, but it would cause unnecessary losses and cause the charging to slow down when near maximum voltage. A commonly used, more complicated way to fix this is to use a constant current charger. A constant current charger uses a switching regulator to regulate the voltage so that it outputs a constant current.

When supercapacitors are charged they will gain voltage at different speeds depending on their capacitance. This can be seen by the relationship

$$\frac{dV(t)}{dt} = \frac{I(t)}{C}, \tag{2.2}$$

which describes the rate of voltage change with respect to current I and capacitance C. Ideally the capacitors would be of equal capacitance, but in reality there is a tolerance on the capacitance. The result is a circuit where charging and discharging the capacitors results in different charge on each capacitors. With many charges and discharges this could lead to a majority of the voltage being on one or a few capacitors. If this voltage is higher than the capacitor's rated voltage, it could break the capacitor.

Balancing and charging capacitors

There are several approaches to a balancing circuit, however, the idea is to discharge capacitors with a higher voltage relative to the other capacitors if they are charged above the average level and charge capacitors with lower relative voltage than the remaining. A common way to balance supercapacitors can be seen in Figure 2.2. The resistors are used to divide the total voltage over the capacitors equally. The operational amplifiers are then used in a voltage follower configuration to ensure that the capacitors keep equal charge. This is an effective balancing circuit as it charges capacitors that are too low and discharges capacitors that are too high. The capacitors that have the correct charge however are neither charged nor discharged by the balancing circuit resulting in low losses.

The issue with charging the capacitors to a too high voltage can be solved by having the charging current cut off at a voltage where the capacitors are not harmed. A power supply that cannot supply higher voltage than the capacitors combined maximum rating is also a solution to the problem. There would still exist a possibility of the capacitors being unevenly charged, which could lead to one or more of the capacitors exceeding the rated voltage or getting a negative voltage. The solution to this would be a balancing circuit, which is discussed in the *Balancing circuit* section of Chapter 3.

2.2 Batteries

Batteries are a widely used way to store electrical energy. They produce electrical energy through a chemical reaction. While they have low energy density compared to other energy sources, such as gasoline or liquid hydrogen, they have several other properties that make them desirable. First and foremost they deliver the energy electrically, without needing to use a energy converter such as a generator. This gives a simple system that is virtually loss less. In addition batteries do not produce any emissions when in use, making them great for confined spaces and indoor use. Batteries are also safe as they have a low limit to how fast they can deliver their energy.

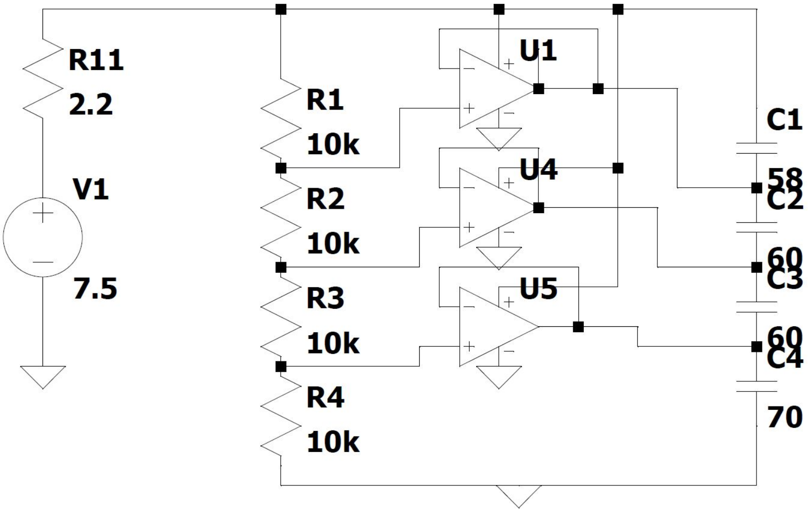


Figure 2.2: A typical way to balance supercapacitors. Here four supercapacitors with different capacitance are used.

Perhaps the most important trait of batteries is the fact that many types are rechargeable, meaning that their energy can be replenished so that they can be used multiple times. Recharging batteries is often and easily done by connecting them to a charger.

On a small side note, most of the numbers used to describe the performance of batteries in this thesis use the numbers of Nickel metalhydride, NiMH, batteries. The reason for this is that this type of batteries are currently used in the doors the tests were performed on and were available to be tested on. A picture of these can be seen in Figure 2.3.

Compared to other electrical ways to store energy, batteries are the most energy dense way to do so, having an energy density that is $10-50$ times higher than that of supercapacitors. NiMH batteries have a gravimetric energy density of $60-120$ Wh/kg [26], which is equivalent to $2\cdot10^5-4\cdot10^5$ J/kg, and a volumetric energy density of $200-400$ Wh/l $=7.2\cdot10^5-1.4\cdot10^6$ J/l [7]. While batteries, as mentioned, have a relatively low power density and as a consequence are limited in the speed at which they can deliver their energy. The NiMH batteries used in the door are suited well for the application as they have low ESR, less than 0.1 Ω [17]. This allows them to handle power peaks in a good way.

Batteries are not durable and they have a short life time, generally rated at $300-2000$ cycles. Since batteries store energy through chemical reaction, charging or discharging them rapidly will cause the battery to heat up adding a risk of starting a fire. Batteries are also susceptible to temperature changes. As a result, temperature changes will significantly alter the voltage of a battery. Batteries cannot handle misuse well either. Charging is difficult and using too high current or overcharg-

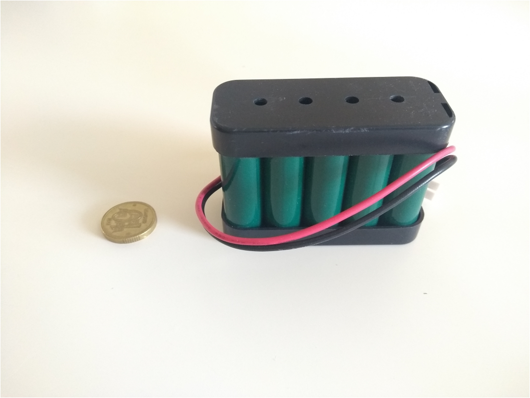


Figure 2.3: Batteries used as backup batteries at ASSA Abloy and also used as power supply in the thesis. This is one 12 V battery pack, two would be needed in order to operate the door at 24 V. Next to the batteries is a 10 SEK coin for scale.

ing them will reduce their life time or cause permanent damage. The same is true for drawing too much current from the batteries. Some battery types, specifically lithium based versions, will be irreversibly damaged if discharged too much.

Another aspect of batteries to take into consideration is their environmental impact. Many use minerals and chemicals that are dangerous or harmful in some way. Also some of the minerals that are used to create batteries come from areas of conflict or have a declining availability. Many are also mined in areas where the working conditions are poor. Minerals such as cobalt, which is used in Lithium-Ion, Li-Ion, batteries are often mined in Congo where there is prevalent child labor as well as poor safety for the worker [4]. Therefore, this had to be considered when evaluating these concepts.

Limitations. Similarly to the supercapacitors the batteries have a voltage rating and exceeding it can damage the batteries. The batteries do however have a charging current limit as well. Charging at a higher current could cause damage to the batteries and could also cause to batteries to generate heat. This issue can be solved by stopping the charging at a certain voltage and also limiting the charging circuit. The main difficulty when charging batteries is detecting full charge. Although some batteries can detect full charge by setting a voltage limit, it is not the case with all types of batteries, such as with NiMH-batteries [14]. Detecting full charge in these batteries require a more sophisticated method. At full charge the batteries will heat up and the voltage will depress a little. Detecting these changes to the voltage are key as to not overcharge the batteries.

Furthermore, it should also be noted that the charger that has been used in this master's thesis is not ideal for charging batteries. The characteristic of batteries is that when they are used the voltage level suffer from a temporary dip while under stress. However, the voltage level is quick to regain its voltage while not regaining the energy that was consumed. As the charger that has been used is constructed to detect low voltage and then initiate charging this is not ideal for batteries. They will activate the charger for a short period during strain and then deactivate most of the charging while under constant stress. Thus, batteries will not allow for the same amount of charge as the supercapacitors do as they have a different characteristic with regard to how the voltage level is depleted. A better charger could perhaps have been built using another technology, however, then the results may not have been as comparable for the testing that has been done. If software had been involved in the charger there could also have been a charger constructed that was able to detect in what way the door had been operated and then charged it thereafter. Due to comparability this has not been done for this thesis.

2.3 Flywheel

A flywheel is a large wheel that stores energy by rotating and keeping in motion. Thus the energy would be stored in kinetic energy that can be transformed and be used as electrical energy. This technology is old, however, this way of using it is not. For example, NASA has been researching the possibility of using flywheels on their space shuttles as a means of storing energy [9]. The major argument for doing this would be that flywheels are able to store large quantities of energy while still remaining relatively small in size. The energy density is thus large, something regarded as important aboard a space shuttle as well as for a door inside a building. The specific energy that can be stored in a flywheel would be determined by the following equations [8]:

$$J_m = \int_m r^2 dm \tag{2.3}$$

$$\omega_m = 2\pi \cdot n_m \tag{2.4}$$

$$W_{kin} = \frac{1}{2} J_m \omega_m \tag{2.5}$$

Here, J_m is the moment of inertia, r is the radius, m the mass, ω_m the angular velocity, n_m the rotational speed and lastly W_{kin} the stored rotational energy.

As can be seen, important factors are the weight, radius and the speed with which the wheel rotates. If these are increased the energy will thus also increase. Therefore, these factors should be kept as large as possible in order to maximize the amount of stored energy.

As flywheels are usually built of steel the wear of these are small when they are in use. The weakest part of the construction are the bearings that are located at the center of the wheel and used to enable rotation. Therefore they have a significantly better lifespan than most batteries and thus make for great energy storages.

However, as this technology is relatively new it may prove harder to implement than what is possible for the thesis.

2.4 Superconductive magnetic energy storage

Using a coil made of a superconductor, i.e. materials with zero electrical resistance and magnetic expulsion, energy can be stored in the magnetic field created by the current flow. The coil would have to be cooled down to temperatures where the material is superconducting, which requires cooling with liquid nitrogen. Since the coils are superconducting, there will be no losses in the storage. Since there are no conversions between different types of energy, it is always electrical, overall losses are low. From [19], some numbers can be found. The round-trip efficiency is about 95 %. ScMES typically have specific energy density of $1-10$ Wh/kg and volumetric energy density of less than 40 kJ/l. The specific power density is roughly $10-100$ kW/kg. The total energy stored can be described by

$$E = \frac{1}{2}LI^2 \tag{2.6}$$

where L is the inductance and I is the current.

2.5 Potential energy storage using gravity

One way to store potential energy is using gravity. Energy can be stored as an elevated weight, according to the formula

$$E = mgh. \tag{2.7}$$

where m is the mass of the weight, g is the gravitational constant and h is the relative elevation of the weight. It can be converted to kinetic energy

$$E = mv^2 \tag{2.8}$$

where m is the mass of the weight and v is the velocity of the weight, by letting it fall and then the energy can be converted into electricity. In order to store sufficient quantities of energy, large elevations and or large masses need to be used as they are the only variables that are able to be affected. The g in Equation 2.7 is the gravitational acceleration, which is constant at a certain altitude. One way this type of energy storage is used on a large scale is through pumped-storage hydropower [15]. This type of energy storage pumps water to a reservoir at a higher altitude to store energy and generates electricity as water moves down through a turbine.

2.6 Compressed air

In a tank filled with air, energy can be stored through pressure differential between the inside and outside of the tank. This is a type of potential energy storage, and it also allows for large amounts of energy to be stored. The energy would be introduced into the storage by operating a compressor that is powered from the mains. Then energy could then be extracted through emptying the tank via a turbine that then would generate electrical energy. The turbine would be the limiting factor when it comes to power output as they are limited in the amount of electricity that they can generate and how quickly this can be done.

Other limiting factors are the volume of the tank and the compressor used. A larger tank will allow for more air to be contained and thus also more energy to be stored. This solution would be possible if one large tank could contain energy for multiple doors as well as if a smaller tank would be connected to each door. However, the size may be an issue as they can get rather large if much storage capacity is needed. The compressor as well as quality of tank would limit the pressure that is possible to be kept inside the tank. More expensive tanks would allow for higher pressure to be kept inside the tank and thus a larger amount of energy to be stored in a smaller volume. However, a bottleneck would be the compressor as the type of compressor limits the pressure with how well it could perform and how fast pressure can be generated.

The pressure in a tank is often measured in the unit *PSI*, *Pounds per Square Inch*, which is the force per area. If this is to be translated to energy per unit volume this is done through the following equation:

$$\frac{Force}{Area} = \frac{F}{A} = \frac{F \cdot d}{A \cdot d} = \frac{E}{V} = \frac{Energy}{Volume} \tag{2.9}$$

where d is distance.

2.7 The test rig

The testing that has been performed for the thesis has been done in the test lab at ASSA Abloy entrance systems in Landskrona. The test lab contains multiple doors that resemble regular doors that are sold by ASSA Abloy with the only difference that they do not have sensors connected to them. They also do not have a regular glass door in the frame but rather have a frame where weights can be loaded. This is so that all tests for all different doors with different weights can be done with the same motor and the same equipment. Therefore, every measure has been done to assure that the tests are as similar as possible and no unforeseen variables impact the results. A picture of the door can be seen in Figure 2.4.

In order to assure fairness of the tests the motor and computational unit of the door was exchanged after testing was completed. Then tests were remade and sim-

Figure 2.4: The test door that was used during testing.

ilar results achieved. Therefore, it could be confirmed that the results were not impacted by a specific piece of equipment.

The door can use a battery pack for backup power. However, this is only active if the main power supply is not. Two packs were used and each is 12 V and contains 1200 mAh. The individual cells in the battery pack are of the NiMH type battery.

2.8 Opening

The most important aspect to examine when designing a new power supply was the current that was drawn during one opening. This would determine how the power supply should act, what specifications were needed and what energy was used. Therefore it was important to understand what the current represented in an opening as well. In order to understand this the current for that the automatic sliding door requires in an opening can be seen in Figure 2.5 and following will be a description of each time interval.

Interval 1: At the beginning the door has initiated an opening. This has required a large current in order to accelerate the door to required speed. Larger door weight would result in a larger current as there is more mass that need to be accelerated. As current is related to torque in a DC-motor this conclusion can be made. When the door has begun reaching the target velocity, after approximately 0.7 seconds the current is reduced as the torque is not required to be as large. This can be seen by the declining current at the later half of Interval 1.

Interval 2: When the door has truly reached its full speed the current is even more reduced than what could be seen in Interval 1. Here it has reached maximum speed and as friction has low low impact not the current does not need to be as large. Therefore, here can be seen a significantly lower current than in Interval 1. At the

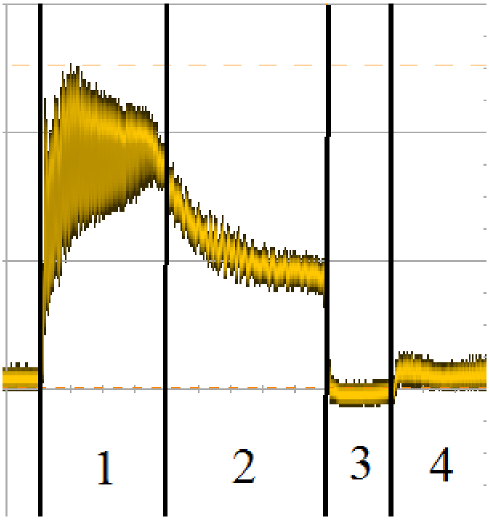


Figure 2.5: Typical current profile for one opening of the automatic sliding door divided into time intervals. Each square is 2 A and 2 seconds wide.

end the door has reached the position where is needs to start breaking in order not to reach the end point at a too large speed.

Interval 3: Here the door has reached a breaking state. No current can be seen, however, the motor is subjected to a negative current to allow for breaking. This current is later run through break chopper resistors and converted into heat, something that will later be discussed as a solution for regenerative charging with the current. In this interval the only action that is taken is this breaking current.

Interval 4: At this point the door has reached its final position and reduced its speed to allow for a smooth stop. The current is has reached 0 A and the door is in the state that is idle. It is this interval that can be increased before initiating a closing in order to allow for a longer recharge time. It should be noted that if the door had sensors connected this current would not be 0 A here but rather have a constant current.

After an opening has been performed it is in most cases followed by a closing sequence. This looks identical and is therefore not shown in Figure 2.5. However, when closed the door has one additional current that is constant and that is the lock current that is used to keep the lock active at all time. This is not seen in figures in this thesis either as there was no lock present on the door where tests were run.

As a comment to the noise seen in Figure 2.5, it is due to a switched operation that is performed by a DC/DC converter in the engine. It is therefore present in all measurements and was not possible to eliminate.

2.9 Safety regulations

It is required for a door to have a safety function where if there is a power failure or a system malfunction the door would still open. In the current door this is solved by implementing a battery which is able to run the door for at least an hour after the main power supply has failed. The minimum requirement for a door to pass the certificate of safety is that it should be able to perform at least one opening in case of power failure. In most countries this is enough for the door to be considered safe and for it to be allowed on the market. This is of course a parameter that has to be considered carefully when designing a new solution for the power supply. If this is not possible the concept will have to be discarded. Another safety regulation to take into consideration is that the door has to open quickly. For the door the testing was performed on this means opening 160 cm, or 80 %, of the total 2 m opening in less than three seconds. This is according to European regulation EN 16005:2012 by FAAC guidelines for fire escapes [21]. The reason that this regulation exists is to prevent people getting hurt in case of a fire or other situations where a quick escape is necessary.

2.10 Concepts

Here are descriptions of the various concepts that were researched and considered when finding a solution for how to store the energy needed for the door. Most are described in general terms as they did not go further than being a concept.

Gravitational potential energy water storage

The idea for this concept was essentially to create a small hydro power plant. The excess energy from the power supply when the doors are idle would be used to pump water to a reservoir elevated above the pump. When power is needed the water would fall down into a turbine which would generate power. A flowchart can be seen in Figure 2.6. The energy stored would be is described in Equation 2.7, where m is the mass of water stored, g is the gravitational acceleration and h is the drop height. A generator, a pump, tubing and two water tanks would be needed to implement this solution. Each of the water tanks would need to be able to store all the water, one tank when the energy is fully stored, and one tank when all the energy has been depleted. As a result the solution would have a higher specific energy than volumetric energy density. That said, this is not an energy dense solution as the specific energy and volumetric energy densities are roughly 10 J/kg per meter drop height and 5 J/litres per meter drop height respectively. These values are assuming that all weight but that of the water is negligible and almost all of the volume is from the tanks. As comparison, batteries typically have both specific and volumetric energy densities five order of magnitudes higher. To increase the volumetric energy density a denser liquid, such as mercury, could be used. Although there exists non-

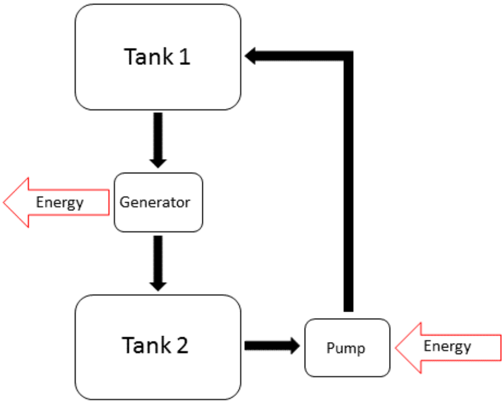


Figure 2.6: An energy water storage.

toxic liquids at room temperature with a density significantly higher than that of water, they are expensive. Sodium polytungstate, with a density between $2-5$ times that of water, is listed between $1000-2000$ SEK/kg [3].

The large size and weight as well as the need for water tight piping results in an installation that is both complex as well as time consuming.

Flywheel

The idea of how to use flywheels was either to have one large wheel that is able to store energy for multiple doors. Another was to always keep a small flywheel next to the door that it was connected to. This would allow for energy to be stored for the door while still remaining small in size.

The price of the wheel is largely dependent on the size, material and the speed that it will be rotated at. If it is readily available and not made to order they can be fairly cheap. However, if they have to be made specifically for this purpose they may become expensive. For this thesis they will also be hard to test as well as prototype as they require certain equipment to use.

Superconductive magnetic energy storage, ScMES

The concept using ScMES would consist of a coil to store the energy as mentioned in Section 2.4, the coil would need to be made of a superconducting material and cooled to low temperatures. The device would also have to be installed in an isolated confinement and new liquid nitrogen would need to be added regularly. This results in extensive costs for material as well as high maintenance cost to operate the door.

Gravitational potential energy weight

This concept uses the approach of having a heavy weight that can be raised to a higher relative energy and thus store energy. The energy that is supplied when the weight is raised can later be utilized when it is released and the converted to electrical energy. However, this solution may have a longer delay for recharging the system depending on the method used for raising the weight.

This method would require a weight to be place next to each door utilizing this way of storing energy. It is also depending on the height of the room as larger amounts of energy can only be found if the height or the weight is large. As these are the only constants that can be altered while the gravitational pull is constant.

The durability of this solution is largely dependent on the materials used. Therefore the price also varying. If a good motor and quality suspension is used the durability as well as price will increase. While the price is difficult to estimate as a result of this, this concept will for the most cases be a more affordable solution than the majority of the other concepts.

Compressed air

Using compressed air as an energy storage would require an compressor, a tank to store the compressed air in as well as a turbine to generate the electricity. Equation 2.9 has been important as the rating for most compressors, tanks and turbines has been done in force per unit area and the grading used to evaluate the concept was done by comparing energy per unit volume.

Another factor that was considered regarding using compressed air as an energy storage was the noise level. As many of the doors would be located inside of a building, perhaps within an office area, the noise level of the compressor was a determining factor for the concept. Most compressors would generate an amount of noise pollution that would not be acceptable to residents of the buildings.

Batteries

There were multiple concepts that utilized batteries to some extent. An overview of the basic characteristics of batteries can be found in Chapter 2, Section 2.2.

Backup battery. One concept that was evaluated and considered was to utilize only the battery that has already been implemented and installed in the doors at the current time. This would allow electronics to be removed from the current solution while adding only smaller circuits. This would require the backup battery to be large enough to still be able to use as a backup in case of power outage, otherwise it would not be a safe solution and therefore not possible. However, if it could be solved in a way such that the backup battery was in constant charging and thus running normal operation on it would not affect the capacity, this would be a good solution with respect to price, environment and complexity.

Extra battery. Another concept was to add an additional battery. The new battery would be similar to the backup battery while being charged by the mains during normal operations. This solutions is simple in terms of complexity as it would only require a battery as well as a charging circuit. However, the most important aspect of this is to find a battery that is able to discharge as well as charge fast enough to keep multiple door openings in one charge while still maintaining the peak current to account for opening speed.

One difficulty would be to find the best type of battery that has all the desired qualities while still not having a too large environmental impact. Therefore, this solution may be more suitable in the future than it has been during this master thesis.

Battery combination with supercapacitor. The final concept utilizing batteries is a hybrid of two concepts. The first being using one battery and the second being using supercapacitors. This would utilize supercapacitors to open the door, as they are fast to charge as well as discharge. However, the major drawback that was found in supercapacitors was that they were not able to keep charge for as long or in as large volumes as a battery. This would here be solved by connecting a battery as a buffer for the capacitors so that they could provide and charge them, however, when a fast discharge is needed the capacitors are used. Doing this would increase the peak current as well as the overall capacity with respect to the other concepts.

Disadvantages are the use of multiple components in this way which will increase cost as well as complexity. This added complexity may increase the amount of service needed as well as component cost, which is undesirable.

Supercapacitors

There were multiple concepts that utilized capacitors to some extent. An overview of the basic characteristics can be found in Chapter 2.

The dimensions and weight of the capacitors are given from the data sheet. From this the volumetric and specific energy density can be calculated.

Only supercapacitors. This concept would require the use of only supercapacitors as a source of operating the door regularly. This would require few components and simple mechanism as it would consist only of a cluster of capacitors connected. Although, a difficulty would be to keep a high enough voltage such that the door is able to operate with that as a source alone. As the current was not an issue this could possibly be solved by connecting multiple in series in order to increase the voltage while still maintaining the current.

Another issue that is constant with all solutions using supercapacitors is the price. While useful they are often expensive and as multiple components are needed it may prove difficult to restrict the cost if this concept was to proceed.

Supercapacitors with DC/DC converter. Another concept using supercapacitors was to use a boost converter to up the voltage from the capacitors instead of connecting many in series. This would allow for a few, larger capacitors to be used. The main issue with this concept was the large current from the capacitors to the DC/DC converter. If the voltage needed to be boosted by a factor of ten, the current into the boost converter needed to be ten times larger than the current needed at the output. This issue would give rise to a number of problems, the first being heat, as large current through wires and components lead to high losses. Another problem would be the voltage drop in wires as well as from the ESR of the supercapacitors, as Ohm's law states that the voltage drop is the product of the resistance and the current. With large currents even small resistances like the wire resistance and the ESR of the supercapacitors would give rise to significant voltage drops.

This concept would also require multiple different components for the boost converter, which would increase the cost. In addition control for the converter would be needed, further adding complexity and possibly a micro controller to the cost.

3

Method

This chapter will explain the method used to perform the master's thesis and what has been done in order to achieve the results that can later be read.

First there will be an explanation of the brainstorming of concepts and in what way that was done. Then there is an explanation of each step in the concept selection process and how that was done and finally the winning concept is presented and how to winner was selected is described.

Following this there is and explanation of the circuits that were designed for the thesis. It is explained for what reason they were designed and the process that lead to the final design.

Lastly there is a description of the testing that was done and why each test was necessary. Understanding of this is important in order to allow for comprehension of the result and why conclusions could later be drawn.

3.1 Information and brainstorming

Initially information regarding various methods of storing energy was researched. The methods of storing energy were then evolved into a number of concepts that could solve the problem. Each concept was researched to the point where attributes like size, cost, energy storage capacity and more could be put in relation to each other. This can be seen in Chapter 2.

Initially, each concept existed only as a simple idea that could potentially solve the task. Examples of these are flywheel, using counter weights, supercapacitors or using a perfect conductor and an inductance. Following this the ideas were refined into working concepts that could possibly be implemented. A simple sketch of each method was made and the mechanics of how it would work was considered. This allowed for some concepts to be disregarded due to them being impossible, however no concept was discarded due to aspects such as size, weight or price. This process resulted in 11 concepts that appeared viable and would possibly work in order to fulfill what was needed.

In order to be able to continue the development of the best concepts, regardless of any bias, they were evaluated based on various criteria. Therefore, some criteria of evaluation such as easier installation and sufficient storage capacity were listed. In order to account for different criteria not being of the same value for ASSA Abloy each was evaluated and weighted with a number between 1 and 5. A larger number indicated a greater importance, thus that number would increase the impact of that score in the final calculation. For example, the noise level might not be as important for the finished product as the cost or how easy it is to install. This unbiased evaluation was done in order to evaluate multiple different concepts and thus not exclude anything too early in the process.

Finally, the concepts that had the highest score after adding every grading were then considered the winning concepts. It was not previously decided how many concepts that would be worked on after the evaluation process was done, however this was impacted by how each of the concepts performed. If two similar solutions were both given high scores both may be worth continuing with. Although when the work had been initiated, one would potentially appear superior and thus only one of the concepts would be used.

Concept development

The criteria determined can be seen in the Table 3.1 below and the were weighted based on discussions with supervisors at ASSA Abloy regarding their respective importance. The resulting grading of each concept can be seen in Appendix C.

Table 3.1: Attributes that are desirable in the finished product.

Number	Desirable attribute
1	Quiet
2	Small
3	Low cost
4	Long durability
5	Easy installation
6	Small impact on environment
7	Light weight
8	Low power consumption
9	Sufficient peak current
10	Sufficient storage capacity
11	Re-energizable

Table 3.2: Criteria, what attribute they affect and the weight assigned to them.

Criteria	Affects attribute	Weight	Unit
Installation cost	3	5	SEK/Unit
Storage capacity	10	4	Wh
Peak current	8, 9	5	A
Simple mechanism	6, 8	4	Number of parts
Leakage	6, 8	2	mA
Installation time	3, 5	4	Hours
Mean time between failure	3, 4, 6	5	Years
Installation complexity	3, 5	3	Educational hours
Cost	3	4	SEK/Unit
Size	2, 5	3	m^3
Weight	5, 7	2	Kg
Noise level	1	3	dB
Regenerative energy	3, 8	2	%
Re-energizing time	10, 11	4	J/hour

Component research

Following the concept development several concepts had been decided to be worth continuing with. The next step was to research components that could potentially be used for the concepts if the were to be made into a prototype. This would allow for some of the concepts to be discarded based on the components that were available to be ordered.

However the most important research done was to determine what type of component was needed and in what configuration this was going to be connected to the circuit. For example, there are multiple brands that design supercapacitors, all offer different performance as well as different values. Because of this it was important to consider multiple brands and compare them to find the most suitable for this implementation. Concepts using supercapacitors also allowed for different configurations of them in order to reach the desired performance. This is due to the behaviour of capacitor in series and in parallel.

Electronic evaluation design

When the concepts had been evaluated it was clear that one or more solutions using supercapacitors would be examined further. Multiple 60 F supercapacitors were purchased and design of the balancing circuit as well as the overcharge protection circuit initiated. The design of these circuits started simple and progressed into more complicated to satisfy requirements that seemed reasonable. The requirements that were set to make the supercapacitors a reasonable solution were fast charging as well as self balancing. They were deliberately not specific as supercapacitors was a new area and their characteristics such as charge time, amount of imbalance were unknown.

3.2 Circuit design

Supercapacitors

Charging circuit. In order to charge the capacitors quickly a large current was needed. When testing different balancing circuits and experimenting with the capacitors a DC power supply was used to charge them. This was done by simply connecting the power supply to the positive and negative pole of the capacitor cell and thus charging them with a constant voltage. This would make sure that the voltage was never larger than what was safe. However, as the voltage increased the current decreased, making charging slow. In order to solve this issue a charging circuit needed to be designed which allowed for constant current charging until the voltage limit was reached. Once the total charge of the capacitor cell has reached full charge the charger should be turned off and no current supplied.

The charging circuit that was designed came from a datasheet of a buck converter produced by Linear Technology [12].

Balancing circuit. The balancing circuit was designed based on already existing designs that are commonly used for applications as this. The one tested can be seen in Figure 3.1. This was later simulated by using LTSpice, a free simulation tool for electrical applications. It was also implemented on a smaller capacitor cell as a proof of concept.

Due to difficulties when applying this to the full capacitor cell a simpler solution was later designed and built which only consisted of resistors in parallel with each supercapacitor. This circuit can be seen in Figure 3.2.

Battery pack and charging circuit

The charging circuit used to charge the capacitors was used to charge the batteries. However, because of the limitations of the batteries, the second more powerful charging circuit was not used with the batteries without changing the output current of the charging circuit to accommodate the limitations.

Redesign

Later a redesign was made for the capacitor cell as to make it possible for connection directly into the input for the power supply. As this required a minimum of 32 V more capacitors were added and the balancing extended to accommodate them. Otherwise no changes were made.

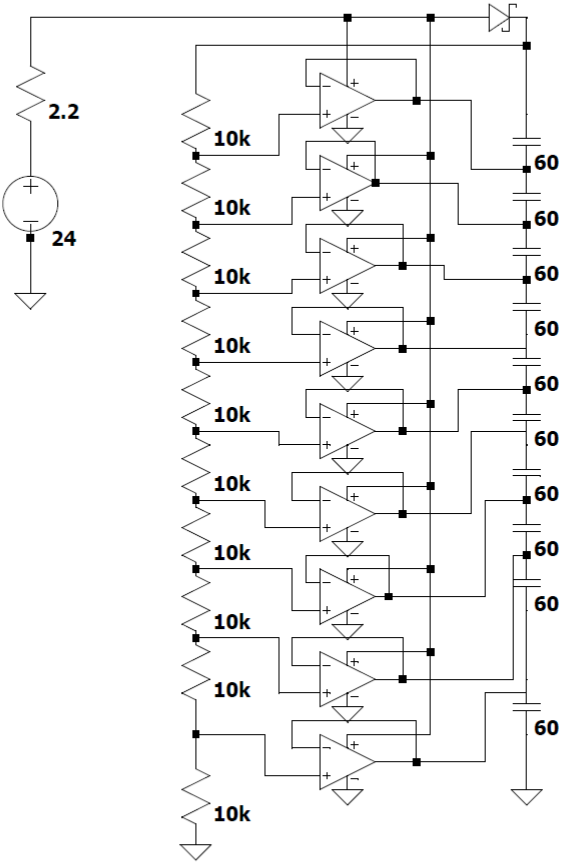


Figure 3.1: The balancing circuit built using OP-amps

3.3 Testing

Profile evaluation

In order to test the various solutions and determine if they would work tests had to be developed and executed. The aim with these tests was that they should be done with a wide range of different doors and with different parameters. Weight and opening speed were determined to be the two parameters that would impact the results the most. In addition the result from experiments with different weights and speeds would be telling with regards to where the solution would be relevant to implement. Therefore each test was done with three different weights and with two opening speed options.

The three weights were determined by using the weight of the heaviest as well

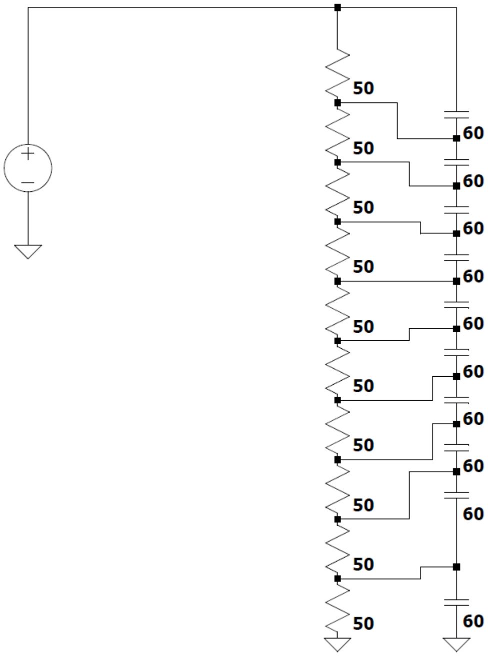


Figure 3.2: The final balancing circuit using resistors

as the lightest singe leaf door that is offered by ASSA Abloy. Therefore the largest weight would be 240 kg and the lightest weight 50 kg. Medium weight option was chosen to 150 kg as it was between 50 kg and 240 kg and the weight could only be increased in 10 kg increments.

Furthermore, the speed was determined by using the maximum speed possible for opening the door which is 70 cm/s. This speed was the most demanding for the power supply, as it requires a higher acceleration to reach the desired speed in time, and as a result has a high power peak.

There is a slowest setting that is allowed for a door to operate at. This is determined by calculating that the door should be opened to 80 % of the potential distance after 3 seconds, according to the safety regulations discussed in Section 2.9. Therefore, as an opening width of 2 meters was being used this would equate the slowest possible setting to be 55 cm/s.

As for the remaining settings for the door that were to be altered, they were based on a previous bachelor thesis [24] that had been performed at ASSA Abloy where parts of the thesis consisted of developing a good test that could be used in order to test the door. These were constructed to simulate real scenarios as closely as possible while covering as much of the different modes of operation as possible.

Therefore, using these tests would be beneficial for ASSA Abloy as the results from this thesis could be compared to the previous results.

Table 3.3: Profiles for testing from [24].

Profile	A	B	C	D	E	F	G
Closing speed	70	70	25	70	70	25	70
Hold open time	3	1	2	3	1	2	3
Run mode	3	5	5	1	1	1	5

As can be seen in Table 3.3, there are three settings that are altered in the between the different tests. These are selected as they are the parameters that can be modified for a real door in order to preserve energy while still maintain the appropriate performance required. The setting "Closing speed" is the speed with which the door closes after having performed an opening. The value of the parameter is set in cm/s. As the closing speed usually does not affect the user this could be altered and decreased if it proves that a slower speed would allow for a better or more efficient solution.

"Hold open time" is the time that the door stays open before beginning to close. If this is increased the energy reserve would be allowed to recharge and therefore have more energy when closing the door. The unit for this value is seconds. Lastly "Run mode" is valued from 1 to 5 where 1 is the run mode for the lighter doors and run mode 5 is mostly used for heavier doors. However, at its core this will mostly alter the breaking speed and how aggressive the door is while running. Therefore, this can be used to find the optimal setting for preserving power with the developed power supply. This is also the only parameter that could be altered that impacted the acceleration as this is otherwise not a setting that can be changed by the user. The acceleration speed is also set so that the door should reach the speed that has been set in a timely manner.

Initially, in order to be able to determine the upper level, the different profiles had to be graded from easiest to hardest. This was done by setting a relay that gave an impulse to open the door with the same time interval and counted the impulses in order to determine how many openings had been done. The tests to compare the profiles were performed by running the door continuously, meaning that the door would open with a fixed time interval, set on the aforementioned relay. The frequency with which the openings were performed was set for each test such that the opening cycle was just allowed to complete before initiating a new opening. During testing the door was powered by the supercapacitors and a constant charging current until the door stopped or it could be assumed that it would not stop. Evaluating whether the door would stop or not was done by inspecting the voltage level in the capacitors and noting if the voltage was still decreasing in the turning points. The tests were performed with a predetermined speed and weight and were started with the same initial voltage over the capacitors to keep the initial energy available the same for each test. With the tests done the profiles were graded. The profile where the door stopped after the least amount of time was considered the most difficult profile while the profile that allowed for the charging current to stabilize the quickest was considered the easiest. This test was performed multiple times for each setting and a mean value was then calculated. This allowed for more accurate results.

All these tests were done using a programmable power supply as the charging source. This allowed for control during testing as well as a clearer indication of what current and voltage was used. The power adapter was dimensioned based on the values seen from the power supply.

To determine the limitations of the power source in relation to door performance, the profiles were tested for each door weight and speed. These tests were performed similarly to the grading of the profiles. The door was set to open continuously, in the same way as in the grading of the profiles, and whether or not the input power was enough was evaluated. This evaluation was seen as a binary *yes* or *no* as the input power is either higher or equal to the average power consumption or it is lower than the average power consumption. Whether or not the power was enough was for each test initially determined by measuring the voltage over the supercapacitors. If the voltage was seen decreasing with each cycle, the total energy of the system was decreasing and the tests were aborted early and noted *no*, as the input power was less than the output. If the voltage seemed constant over the first few minutes the door was left to run for an extended period of time. No fixed time was used, but it was generally 30 – 90 minutes. Not having a fixed time was not seen as an issue, as if the door could run for 30 minutes, it could probably run for 90. If the door was still running after the extended period of time, and the voltage was still at a stable level, the test was seen as a success and noted *yes*. Another value used in parallel with the voltage measurements was the current supplied by the programmable power supply. If the energy reserve had a voltage above a certain level the supplied current would drop significantly as the voltage reached the highest the charger could supply. This could be used when evaluating as if the current could be seen dropping significantly when the voltage reached its peak, then not all the available power was used. If was still happening after the extended period of time it was assumed that the average power consumption was lower than the maximum available power.

The first test for each door weight was the most difficult profile at the highest speed. The reason being that a successful test with the most difficult set of parameters would also yield successful results for easier sets of parameter. If the most difficult profile was not successful the easiest profile was tested to see if the power supply could handle the combination of the set weight and speed at all. If the easiest test was completed then the toughest profile the power supply could handle was determined by increasing the difficulty gradually until the door was not able to run continuously.

Power limitations

The limitations on what power could be used to run the door indefinitely were partially made in parallel with the profile testing. The input power was always known and thus an estimation of what power could be used to drive the system was made. As the voltage in the energy reserve would drop during an opening, the supplied current would too. The result was a power that had large fluctuations during an opening, hence the estimation from these readings was seen as rough. More accurate observations on the power limits were made from the plots of input current during an opening cycle. These plots were gathered with an oscilloscope using a current probe to measure the current supplied to the door during an opening. The total amount of energy consumed by an opening could be calculated by multiplying the area under the graph with the system voltage. These amounts of energy were used to create an energy balance of an opening cycle, which can be expressed by

$$2 \cdot E_{opening} + E_{lock} + P_{standby} \cdot t = t \cdot P_{in}, \tag{3.1}$$

where $E_{openning}$ is the energy for performing one opening or closing, E_{lock} is the energy consumed by the lock of the door, $P_{standby}$ is the constinous stand by power of the door, P_{in} is the supplied power and t is the time of operation.

From the energy balance both the input power needed for a specific cycle time to be sustainable and the time needed at a specific input power was calculated.

Additional testing

Losses. The losses in the cables were measured by measuring the resistance in the cables between the charger and the control board and calculating the losses from the current when driving the door. It was also cross checked by measuring the voltage on both sides of the cables

The losses in the charging circuit were measured by supplying the charging circuit with a programmable power supply and sinking the output into an electrical load. The input voltage and current, and from that power, can be read from the programmable power supply's display and the output power is displayed on the electrical load. With the input and output power available, the losses in the charging circuit could be calculated by subtracting the output power from the input power. With the losses in the charger known, the efficiency of the circuit could be calculated.

Regenerative breaking. In an attempt to reduce the net energy drawn from the energy reserve during an opening some of the changes were made to the electronics on the control board. Two diodes with the purpose to protect the battery packs from the 32 V power supply were bypassed with a switch to allow the breaking current from the motor to re-energize the energy storage. With the switch in place, the system could safely be started with the 32 V power supply and when it was disconnected the switch could be flipped to allow for regenerative breaking. Initially the current was measured between the charger/supercapacitors and the control board with a current probe. The measurements were made with the oscilloscope and saved as pictures. From these pictures the energy fed back to the system could be calculated. The percentage of energy retention was found as the energy fed back divided by the energy fed into the system. As to only account for the energy used to open the door, the current used when idle was set as the zero value. These measurements were followed by measurements on the voltage on the supercapacitor bank as well as the current directly into the capacitor bank. The final tests were done by finding the tipping point where the charging current was only a little bit lower than what was needed to run the door indefinitely. The switch was then flipped to allow the braking current to re-energize the capacitor bank and the door was run again with the only difference being the energy from the braking current.

Emergency opening. In order to test if the solution was up to the safety standards an opening had to be performed with one of the systems disconnected. First the energy reserve was tested. The charger was disconnected and and opening was performed. If needed the opening force and speed was reduced to allow for an opening with lower current draw. The charger was then tested with the energy reserve disconnected. Again an opening was performed. If needed the opening force and speed was reduced to allow for an opening with lower current draw.

Endurance test. At ASSA Abloy, one thing that is commonly used to perform testing is a sequence of opening called endurance test. What is done is that initially the door opens as usual. Following this a hold open time set by the tester. When the door is closing, it is then stopped half way and re-opened. Lastly it performs a regular closing sequence.

This test has also been done to determine if it was possible with the concepts that were developed. This was done as it was regarded as the toughest and most difficult test that could be performed and if this test was passed, the solution could truly be used in real applications.

Testing was done with charging at 2 A and 30 V for supercapacitors which is slightly higher than for the profiles. This is due to this test being more difficult and thus requiring more energy.

The settings were, maximum speed at 70 cm/s and 3 seconds hold open time. The speed was set to the highest possible to increase the difficulty as well as obtain as good results as possible. As for the hold open time. This was set long enough to allow for possible test success, however, so short that it would not be unreasonable for testing purposes. The weight for all endurance tests were the highest allowed weight, 240 kg.

4

Results

This chapter presents the results of each step of the thesis. Initially there is the results from the concept generation. Following this, there is a presentation of the results of each circuit. The performance of them is rated and explained with figures and numbers.

Thereafter, there is an extensive presentation of the results from each test that has been performed. These, are later reflected upon in the next chapter. The tests are accompanied by calculations with equations of power limits and as well as the charging currents that is needed to operate the door. Lastly there is a brief explanation of how regenerative breaking could be used and what the result from this was.

The losses that has been detected in the system is then described and showed in order to give an understanding of where energy is lost and where efficiency is low. After that an economic estimation is made and an attempt is done to perform a calculation of what the gain of these solutions would be.

4.1 Concept generation

The concept generation resulted in multiple concepts that were to be put through thorough testing in order to determine which was best or if different applications would require different results. The rating for each concept can be seen in Appendix C. The concepts that were considered important enough and had significant higher score during the concept generation was: using only supercapacitors, using only a battery, combining supercapacitors with a battery and lastly having supercapacitors with a backup battery included.

Others that seemed interesting did not score high enough or still had some aspect which made them difficult to examine. Despite high scores some were unfeasible due to for example size or difficulty in building a prototype.

4.2 Circuits

Balancing circuit

The first working solution used a zener diode and an operational amplifier, an OP-amplifier to activate a discharge current for each capacitor. While this solution stopped the capacitors from overcharging, the zener diodes had a tolerance on the zener voltage of roughly 10 %. This resulted in the capacitors' discharge starting at different voltages and ultimately introduced imbalance to the circuit. Another issue with this design was the fact that the capacitors would always be discharging when near full charge, which would result in unnecessary losses.

The second solution in order to balance the circuit was to use an OP-amplifier as a unity gain amplifier in conjunction with equal, large resistors parallel to the capacitor bank, seen in Figure 3.1. The intended result being equal voltage over every resistor and then the unity gain amplifiers keep the voltage over every capacitor the same. This circuit worked as intended, however the balancing current is limited. The circuit did not have much losses as the capacitors will not discharge if balanced. It does not, however, stop charging when full charge has been achieved. In simulations this variant of a balancing circuit works satisfactory and also performed well when built with only a couple of capacitors. When scaled up however the circuit for some reason did not perform as expected.

The final attempt at balancing resulted in the circuit seen in Figure 3.2. The resistors will discharge different amounts of current from each capacitor depending on the voltage over the capacitor and will over time result in a balanced circuit. It is however quite slow in the balancing as the resistors need to be chosen large enough to not allow too much leakage current. Due to difficulties during implementation this was the most successful of the solutions. The implemented solution have losses calculated by

$$P_{losses} = \frac{V^2}{R} = \frac{30^2}{12 \cdot 50} = 1.5 \text{ W}. \tag{4.1}$$

The resistors were chosen to 50 Ω and the calculations of the losses seen in 4.1 is done for 12 capacitors charged to 30 V.

In Figure 4.1 the effects of the balancing circuit can be seen. The three capacitors in the capacitor bank with the lowest total voltage. The middle capacitor had been discharged into the capacitors with the lowest voltage. Over the 500 seconds the voltage in the discharged capacitor rose a little, whereas the other capacitors kept a constant voltage. Over a longer period of time these too would be affected by the balance, but it is not fast. The capacitors were discharged in a similar fashion to this test and the next day they were balanced.

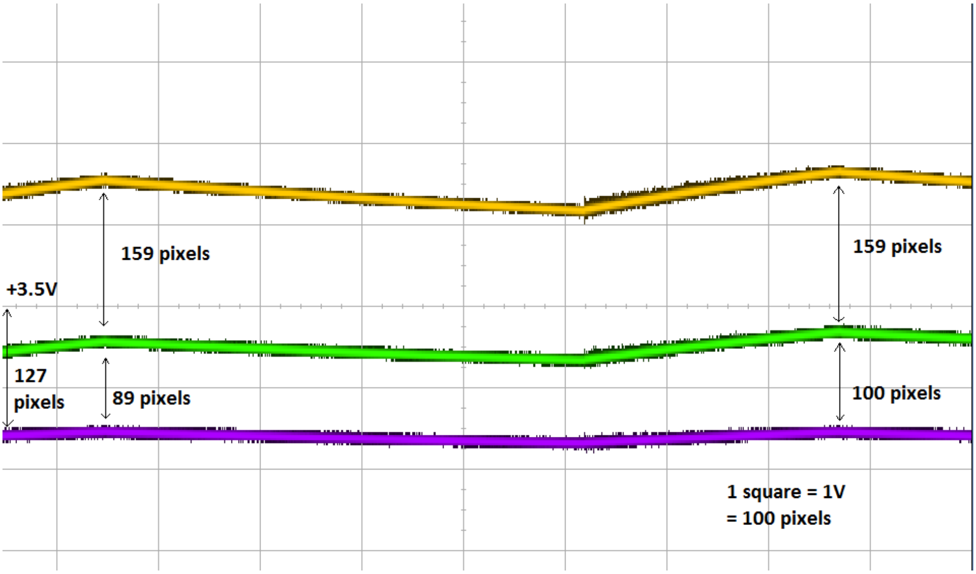


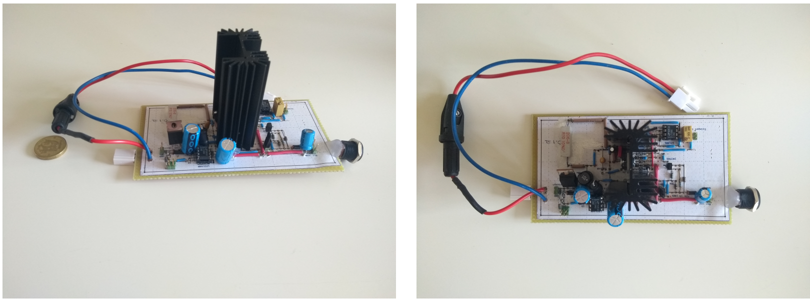
Figure 4.1: Voltages of three capacitors being balanced by the balancing circuit offset by -3.5 V. Each square is 1 V x 50 s. The lowest line is the voltage of the first capacitor. The voltage of capacitor two is the difference between the middle and bottom. The voltage of capacitor three is the difference between the top and the middle line.

Charging circuit

The charging circuit was designed in order to achieve constant current charging as well as charging which stopped at a certain voltage as to allow for the charger to be constantly connected to the power reserve. This goal was met and by implementing a variable potentiometer the charging current can be changed by changing the resistor. This was also practical as it allowed for the same charger to be used regardless of if the power reserve was a battery pack or the capacitors.

Another feature that was added by using the circuit was that it constantly topped off the capacitors when they self discharged. Once the entire cell had discharged to 1 V below the set limit the charger was again enabled and charged until the limit was again reached.

A picture of the finished circuit can be seen in Figure 4.2. One thing that was also important to note and is clearly visible in the picture is the heat sink. As the DC/DC amplifier that is used in the circuit had a tendency of generating large amounts of heat that resulted in the large heat sink being installed.



(a) Charging circuit from the side. Next to the charger is a 10 SEK coin for scale.

(b) Charging circuit from the top.

Figure 4.2: Two pictures of the finished constant current charger. A circuit diagram can be seen in B.1.

4.3 Testing run modes

Profile evaluation results

The first result that was obtained was testing the profiles from the previous thesis [24]. The different tests from there had to be graded with regards to difficulty as to make it simpler to construct future testing.

When speaking of difficulty level what is considered is the duration that the door was able to run at a certain profile from start until it stopped working. From doing this with every profile from Table 3.3 at a set weight as well as opening speed the results in Table 4.1 were achieved.

Table 4.1: Grading of the difficulty of the test profiles with difficulty 1 being the most difficult.

Test Profile	Difficulty
A	4
B	1
C	6
D	5
E	2
F	7
G	3

Test results with profile testing

From Table 4.2 and Table 4.3 results from running tests based on the given profiles are presented. The *Speed* column denotes the set maximum speed of the door. There was no noticeable drop in performance when using either supercapacitors or batteries compared to when using the regular power supply. As a result it is assumed that the door reached the desired maximum speed. A *Yes* in the *Works* column denotes that the current/energy reserve combination was able to run the door indefinitely, whereas a *No* denotes that it was not. These show what the upper limit is by presenting if the door worked or if it stopped running before reaching a stable point where the energy supplied was equal to the energy consumed.

The charging current for the batteries is limited to 1.3 A as specified by the datasheet. However, the charging current for the capacitors is on the other hand unlimited. It is only limited by the components in the charger.

These tests were performed with the power source connected to the input for the backup battery and the door set to *Convenience mode* which means that it is set to run on a backup power supply and does not mind that the main power supply has been disconnected. This also means that the system will run on a voltage around 24 V instead of the normal 32 V.

Another aspect that should be mentioned is the state of the batteries that tests have been performed on. Results in Table 4.3 are performed with batteries that are approximately 2 years old which means that they have been subjected to previous use and aging. However, new tests were performed on the cases that were not successful and for these the batteries were brand new and of an age of only 1 week. The results from these tests can be seen in Table 4.4.

There was also information from employees that are knowledgeable regarding the batteries that this model can handle some overcharge. In this case overcharge is defined as charging above rating which is 24 V for the entire cell of 20 Batteries which is also 1.2 V for each battery within the cell. However, the amount of charging voltage was determined by measuring the entire cell when they had been charged in a charger that is specifically made for these batteries. The voltage measured for a recently charge battery was 27.6 V evenly distributed over the two packs of 10 batteries. Therefore the charging current was chosen to 28 V based on information from employees. Although, this would not work for older batteries as overcharging these can cause them to generate gasses that are dangerous or explosive. Also, it might result in generation of heat which is not optimal and should therefore not be done in commercial use. During these tests close attention was paid to the batteries to assure no excessive temperatures were reached. Results from these tests can be seen in Table 4.5

Table 4.2: Results from testing with capacitors.

Door weight [kg]	Speed [cm/s]	Profile	Charging [A]	Works	Caps./Battery
50	70	B	1.3	Yes	Caps.
150	70	F	1.3	Yes	Caps.
150	70	A	1.3	Yes	Caps.
150	70	G	1.3	Yes	Caps.
150	70	E	1.3	Yes	Caps.
150	70	B	1.3	No	Caps.
150	55	B	1.3	No	Caps.
240	70	F	1	Yes	Caps.
240	70	C	1	No	Caps.
240	70	C	1.3	No	Caps.
240	70	A	1	No	Caps.
240	55	B	1.3	No	Caps.
240	70	B	1.5	No	Caps.
240	70	B	1.6	Yes	Caps.

Table 4.3: Results from testing with aged batteries.

Door weight [kg]	Speed [cm/s]	Profile	Charging [A]	Works	Caps./Battery
50	70	B	1.3	Yes	Battery
150	70	F	1.3	Yes	Battery
150	70	A	1.3	Yes	Battery
150	70	G	1.3	Yes	Battery
150	70	E	1.3	Yes	Battery
150	70	B	1.3	No	Battery
240	70	F	1.3	No	Battery
240	55	F	1.3	No	Battery

Table 4.4: Results from testing with new batteries with 24V charging.

Door weight [kg]	Speed [cm/s]	Profile	Charging [A]	Works	Caps./Battery
150	55	B	1.3	No	Battery
150	70	B	1.3	No	Battery
240	55	F	1.3	No	Battery
240	70	F	1.3	No	Battery

Table 4.5: Results from testing with new batteries with 28V charging.

Door weight [kg]	Speed [cm/s]	Profile	Charging [A]	Works	Caps./Battery
150	55	B	1.3	Yes	Battery
150	70	B	1.3	Yes	Battery
240	70	F	1.3	Yes	Battery
240	55	G	1.3	No	Battery
240	70	G	1.3	No	Battery
240	55	B	1.3	No	Battery
240	70	B	1.3	No	Battery

Power limits

From plots of an opening the energy spent on an opening could be estimated. The area under the graph in Figure 4.3b multiplied by the system voltage gave an approximation of the amount of energy used during an opening. Calculations from these values say that a charging current of 2 A would allow for an opening every 13 seconds according to the following equations,

$$2 \cdot E_{opening} + E_{lock} + P_{standby} \cdot t = t \cdot P_{in} \tag{4.2}$$

$$t = \frac{2 \cdot E_{opening} + E_{lock}}{(P_{in} - P_{standby})} \approx 13 \text{ s} \tag{4.3}$$

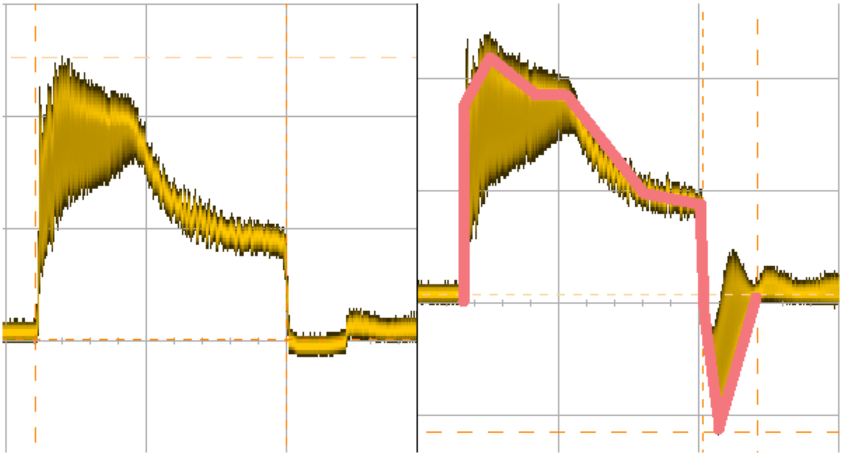
These numbers can be compared to the experimental values found in the Table 4.2. An opening cycle for the toughest profile setting, B, at maximum speed and weight was 17 seconds long. Comparing this to the minimum power required for an opening every 15 seconds, seen by

$$P_{in} = \frac{2 \cdot E_{opening} + E_{lock}}{t} \approx 43.3 \text{ W} \tag{4.4}$$

and assuming a constant system voltage of 25 V gives a theoretical limit on what the minimum charging current needed to run the door indefinitely as

$$I_{min} = \frac{15 \text{ s} \cdot 43.3 \text{ W}}{17 \text{ s} \cdot 25 \text{ V}} \approx 1.53 \text{ A}. \tag{4.5}$$

This confirms the experimental values found in Table 4.2. It further shows that measurements of the current into the system can be used to approximate the input current needed to for sustainable operation. Theoretically this should also be the case as the input power should be equal to the output power for a system in equilibrium.



(a) Without regenerative breaking.

(b) With regenerative breaking. The line in drawn is an approximate outline used for calculations.

Figure 4.3: The current drawn from the power source during an opening. One square is 2 A high and 2 s wide.

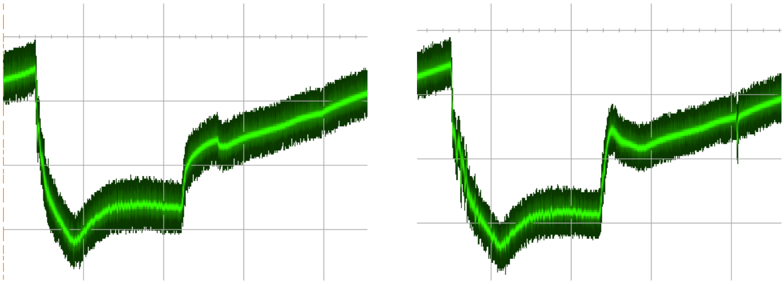
As the batteries could not be charged with as high current as the supercapacitors, they are limited by the input power and thus have a different minimum cycle time to be able to be used indefinitely. They can be charged at 1 C which is equivalent to 1.3 A and 31.2 W, The resulting minimum cycle time can be calculated with

$$t = \frac{2 \cdot E_{opening} + E_{lock}}{(P_{bat} - P_{standby})} \approx 21 \text{ s}. \tag{4.6}$$

Endurance test

Results from the endurance tests are that for supercapacitors were able to run endurance test with the settings described in Chapter 3. They kept charge well and had no indication of stopping after 2 hours, charge was also unchanged between openings 30 minutes apart.

Furthermore, an endurance test was also performed with brand new batteries. These were charged at the maximum allowed voltage of 24 V and current of 1.3 A. They did however not succeed and could only operate around 1 hour before failing and turning off.



(a) Without regenerative breaking.

(b) With regenerative breaking. Notice the peak in voltage corresponding to the regenerative current seen in Figure 4.3b.

Figure 4.4: Voltage over the supercapacitors during an opening. One square is 1 V high and 2 s wide. The plots are also offset in the Y-axis by 25 V, which is the top line in the plots.

Regenerative breaking

From plots of regenerative current and the system voltage, the energy returned to the system from regenerative breaking during one opening can be calculated. The drawn outline in Figure 4.3b was used for this. The area under the graph was multiplied with the system voltage, assuming constant voltage, and gave the energy used for opening and the energy fed back to the supercapacitors. These were then used to calculate the percentage of energy that was retained,

$$\frac{E_{regen}}{E_{in}} \approx 8.4\ \% \tag{4.7}$$

With the regenerative current being estimated as a triangle with a height of 2.325 A and a base of 0.75 s the energy gained for an entire opening cycle, one opening and one closing, can be calculated as

$$E = \frac{2 \cdot 2.325\ \mathrm{A} \cdot 24\ \mathrm{V} \cdot 0.75\ \mathrm{s}}{2} = 41.85\ \mathrm{J} \tag{4.8}$$

With an opening cycle being 17 s long the input power should be able to be reduced $\frac{41}{17} = 2.46$ W. Experiments suggested a value between 1.5 W and 2 W.

The energy can also be compared to the kinetic energy available when the door breaks. The door had a speed of 0.7 m/s and weighs 240 kg. The kinetic energy can then be calculated as,

$$E_{kinetic} = mv^2 = 240 \cdot 0.7^2 = 117.6 \text{ J} \tag{4.9}$$

The percentage reclaimed can be calculated as follows,

$$\frac{E_{regen}}{E_{kinetic}} = \frac{20.925}{117.6} \approx 17.8 \text{ \%} \tag{4.10}$$

Re-openings

The thesis which founded many of the tests performed [24] discussed re-openings as something that was straining for the door. A re-open is where the door is closing but rather than closing entirely there is someone new that approaches the door and thus the door needs to re-open before closing entirely. This has not been found to have any effect on the power supplies tested. They have remained stable during re-opens regardless of time during the opening cycle that they appear and have thus not been of focus for the thesis.

4.4 Losses and efficiency

The efficiency of the charging circuit was measured as described in Section 3.3 in the part discussing *Losses*. This gave the following calculation.

$$P_{in} = 30 \text{ V} \cdot 1.77 \text{ A} = 53.1 \text{ W} \tag{4.11}$$

$$P_{load} = 47.5 \text{ W} \tag{4.12}$$

$$\eta = \frac{P_{load}}{P_{in}} = \frac{47.3 \text{ W}}{53.1 \text{ W}} = 89.5 \text{ \%} \tag{4.13}$$

The resistance in the cables used was measured to 0.2 Ω. From these a peak power loss of 10 W was calculated. From Figure 4.3b the energy lost during an opening was calculated according to,

$$P_{cable} = I^2 \cdot R_{cable} \tag{4.14}$$

The total energy lost during an opening was calculated to 3 % of the energy used to drive the door.

The losses in the balancing circuit was calculated in 4.1 and were approximately 1.5 W. During peak currents there are additional losses in the supercapacitors as well due to their ESR. Each of the capacitors have an ESR of 0.023 Ω. With 15 capacitors the total ESR is $R_{ESR} = 15 \cdot 0.023 \ \Omega = 0.345 \ \Omega$. The power generated in the capacitors due to ESR can be calculated with,

$$P_{ESR} = I^2_{capacitors} \cdot R_{ESR} \tag{4.15}$$

where P_{ESR} is the power and $I_{capacitors}$ is the current in the capacitors. The resulting losses are about 2 % of the total energy to open the door. There are also some losses when charging the capacitors, around 2.75 %.

4.5 Economy

It is difficult to estimate the cost difference for using either supercapacitors or batteries. However, an attempt has been made based on different factors brought up by either supervisors or employees at ASSA Abloy that has been offering input regarding what is relevant to consider during a cost analysis.

The batteries that tests have been performed with are in packs of 12 V where two packs are needed in order to achieve appropriate voltage level to operate the door. The price has been estimated by an employe at ASSA Abloy. Regarding the supercapacitors, a price estimate for purchasing the quantities that is relevant for ASSA Abloy was asked for at three different retailers. One of the retailers was not able to give an estimate as the quantity was to large and another did not answer the request. One however gave a price they would be willing to offer. If the capacitor cell was to reach the same voltage as the batteries this would require 10 capacitors and the price would equal approximately 4 times as much as for the batteries in total.

However, what needs to be taken into account is the price of installation and service. Installation of the current solution requires an electrician that is professionally trained to install the power supply whereas these new solutions only require a plug to be connected to the wall socket. This can be done by anyone, thus reducing the cost of installation.

Also, an argument needs to be made that the supercapacitors will likely have a longer life than the batteries. It has been difficult finding data with comparisons of how long capacitors last compared to batteries as this is not something that has been able to get researched extensively due to the technologies of supercapacitors being so new and constantly evolving. However, multiple articles and blog posts have been giving approximately the same conclusion which is that capacitors will last somewhere around two times as long as batteries if used in the same way [16]. This would in turn equate to double the price for the batteries as compared to the capacitors. However, this is only valid if the door will be in use for the amount of time that it takes for the batteries to fail and break which according the the blog post would take around 10 years. Although, in this heavy usage scenario with constant charging and discharging this would possibly be even sooner due to them reaching their respective maximum cycle count.

An approximation would also have to be made regarding service cost. This is also difficult as different service could be needed for every concept. However, what can be said is that there are not many things that can break other than the batteries or the capacitors for either solution. As the charger is the same this should not be different for either concept. Furthermore, both solutions would require less extensive service than the current power supply as neither would require extensive electrical procedure being performed in order to change or mend the faulty equipment.

4.6 Conclusion of results

After testing it could be argued that multiple concepts were the winner. However this was based on what door to run and what situation this concept will be implemented in. Economically the batteries are the cheaper option as far as this thesis has been able to evaluate it. However, they are not able to operate a heavier door if they are not charged above the voltage specified in the datasheet. For a general case supercapacitors would be better as the are more stable and also have a better performance in most cases.

There could be made two options where the batteries can be chosen for a lighter door in an environment where it is not opened as frequently as what was done in the testing. Also, one power supply could be sold as heavy duty and only used for heavier doors.

Another comment is that if a more sophisticated charger was developed for being able to charge the batteries at a more constant rate than when the voltage is too low this may impact the results. However, this may also add cost to the solution as well as complexity which is also not desired.

5

Discussion

The aim of this chapter is to interpret the results that were presented in the previous chapter. All results are discussed and the effect of the results are also further debated. Initially there is a discussion regarding supercapacitors versus batteries where attributes, test results and their performances are evaluated.

There is also a discussion regarding further work that could be performed in the field of supercapacitors or batteries as a power supply. Both further developments as well as future applications are presented. Developments involve what could be done to improve the existing product and increase efficiency as well as performance. As for future applications, that goes further than ASSA Abloy and discusses where this solution could be used outside of this company.

Lastly, a final conclusion of the work that has been performed is presented.

5.1 Batteries versus supercapacitors

The strength of batteries lies in their energy density, while the supercapacitors have almost limitless charge and discharge current capabilities. As a result supercapacitors have the options of being charged at a high enough current to drive a door of the heaviest version with openings at the maximum possible frequency indefinitely. On the other hand battery can be at a power deficit for an extended period of time without running out of energy. The benefit from this is that the power supply could be designed for the average power consumption of the most hectic day of the year, and it is possible that the batteries could supply the peaks. A power supply used with the supercapacitors on the other hand would have to be designed for peak hours, resulting in a higher power rating and a less smooth power draw from the mains.

The biggest drawback with the batteries is their lifetime. The batteries used have a listed lifetime of less than 500 cycles, whereas the supercapacitors have a lifetime of less than 500.000 cycles. However a cycle is usually defined as a full charge and discharge, which is not the use in this application. While the lifetime of the supercapacitors is larger than that of the batteries, further testing would need to be performed to decide whether the batteries are unsuitable for the application.

What does however impact the lifespan of batteries is fluctuations in temperature. They are designed for a stable temperature around room temperature. However, this has minimal impact on capacitors. They would most likely take damage if the temperature was constantly fluctuation from one extreme to another although not as much as a battery would. Therefore, from that viewpoint capacitors are more durable. The voltage level is not nearly as impacted by temperature for capacitors as it is in a battery. Testing did find that old batteries could not perform a single opening for heavy doors. This was due to the ESR causing the supplied voltage to drop beneath the threshold where the system shuts off. It is obvious from these tests that the lifetime of the batteries is of the highest concern as a system that stops working completely when the batteries are worn out is unacceptable in the application. The effects of the aging of supercapacitors is also an issue, but the time for problems to occur is longer and hence the issue is not as pressing as for batteries. However, the supercapacitors will age and the point at which they are no longer usable will need to be explored.

Batteries ageing. As a comment to the results seen in Table 4.3 and Table 4.4 there needs to be a disclaimer regarding the impact of age on the batteries. From the tests there can not be seen any difference in how they were able to perform. This is true for the absolute result that is seen in the tables. Although true, this is not entirely correct. For these tables what was evaluated was if the door could be run continuously which is important in order to see if the charger could supply more power than what was needed to operate the door. However, something that is not seen in the tables is that for doors run with new batteries, they were able to operate for hundreds of cycles prior to malfunction while the older batteries could barely start the door even with constant charging.

This is a clear argument for the aging of batteries and should be taken into account when considering batteries for a solution. Those that are referred to as older are only around 2 years old and have already worsened their performance this much. What has to be considered then is if it is better to continuously change the batteries in a door and in that way ensure that they are able to operate and keep performance constant or if they are simply not good enough to use in this implementation. The normal operation of these batteries in the door is performing one complete charge and then only using them if there is a malfunction to the normal power supply of if there is a power outage. They are not used as a constant power supply where constant charging and discharging is performed. This is also likely the usage that these batteries had been subjected to prior to testing performed for this thesis. Thus, there would likely be even more declination in performance for batteries of the same age with the usage needed to continuously operate the door.

All batteries were charged prior to testing with the same charger and should thus have the same opportunity of success. This charger completely discharges the batteries prior to charging them with a set amount of energy.

Unfortunately similar test of ageing could not be preformed on supercapacitors due to not having any older components available. Therefore information regarding their ageing will have to be studied base on other sources.

5.2 Summary of findings

The concepts that were chosen to continue working with were all fairly similar. There was not any solution that was tested that truly utilized mechanical energy while there were multiple concepts that discussed using that. This was mostly due to difficulties implementing as well as prototyping these. Many were large and also intricate in their construction, which is also a reason why they scored lower in the evaluation. This was one thing that was considered important for ASSA Abloy from the beginning, it was even one of the reasons why this project was conducted. If complexity would be decreased installation could be simpler which would keep cost to a minimum for service as well as installation. This is important both for the customer as well as ASSA Abloy.

Also, there was substantial gain in not being required to convert mechanical energy into electrical energy but instead storing it in such a way from the beginning. This allowed for less cost, reduced space and increased efficiency. All those attributes were important in designing a new solution.

Reducing the space required for the solution is crucial as either it needs to be stored and installed adjacent to the door, or it would have to be wired from farther away. If it is located right by the door more space would be required by the space that it is located in. In some cases this is not possible. If the solution is so large that it does not fit on the wall next to the door it would be stored in the ceiling or on the ground. This would also require space but also add losses due to large amount of wires. A larger solution would in many cases require a more extensive installation which would also increase cost of the product. For example, using large water tanks requires large tanks to be installed, they need to be at different levels and everything needs to be waterproof.

One more difficulty when realizing concepts was the limitation of the components that were available for purchase. There was an attempt made to find a DC/DC converter that would allow for less capacitors to be used. However, this was not possible as this usage of the converter would require large currents to be run through it. There could not be found any DC/DC converters that had the capacity of handling these and the concept was then dismissed.

When designing the circuits multiple designs were tested for each of them. The goal was always to have as small losses and as good result as possible. Everything was also tested at a smaller scale in a lab before it was scaled up and finalized. For example, the balancing circuit was initially designed as seen in Figure 2.2 and then as seen in Figure 3.1. It worked fine on the small scale, but not when scaled up. Most likely due to a design fault that was also present in the small scale version. However, they would probably have worked with minor adjustments. Investigating those adjustments further and finding what was wrong was too time consuming and thus the alternate solution that was implemented, seen in Figure 3.2, was designed. The circuit has some issues that would make it unsuitable to implement in a product, but it did fulfill all of the requirements. The negative aspect with the chosen design was larger losses as well as that balancing was more time consuming. However, this did not affect the end result that much and was therefore determined to be acceptable.

The testing of the supercapacitors and the batteries with the profiles found in [24] was found to be a good way to determine what was the upper limit for the different solutions. For example, as the batteries can not be charged with a larger current than 1.3 A they are limited in the performance that can be obtained from only using them to operate the door. This can be seen in Table 4.3. With only batteries and no overcharge no door at 240 kg was able to operate, it also struggled with doors that had weight 150 kg if the run mode was to aggressive or cumbersome. For the supercapacitors what can be seen in Table 4.2 is that they are able to operate every door and the largest door with the most requiring profile could operate at a charging current of 1.6 A. This information would be useful when designing and optimizing this solution for a real door. What should however be mentioned as a comment to the results for tests with batteries is that when the batteries were exchanged to brand new they performed much better. Where the older more worn batteries could barely perform one opening newer batteries were able to operate the door for a longer time and could do cycles in the hundreds prior to failing. Therefore, this not only speaks for the importance of new batteries but also that they wear out fast. The batteries referred to as older were around 2 years old and were not visibly damaged. However, they performed much worse and were not close to as good as brand new batteries were. This speaks to the poor aging of batteries, something that should be considered when deciding on what solution to use.

What did show large impact on the way that batteries performed was how large the voltage was for charging. It seemed that if there is some overcharging allowed at the implementation this could possibly be a solution that allows for use of batteries instead of supercapacitors. At least for lighter door that still have an aggressive run mode. Therefore, if this is allowed and how large should be investigated.

The charging circuit was also iterated in different designs prior to deciding on which worked the best. However, the result for the charging circuit was more clear than when balancing was good enough. The charger needed to be constant current and thus not differ in charging current regardless of the voltage in the capacitors that were being charged. This was finally designed by utilizing a circuit in a datasheet from Linear Technologies [12]. The changes that were performed was after simulations had been done in LTspice and large amounts of noise had been detected. In order to avoid this for the final charger filters were designed at the output of the charger and this smoothed the signal to an acceptable amount.

It was declared in Section 4.6 that the solution that is the most suitable as a replacement to the current power supply depends on what application it would be used for. The reason for this is that you always want the power supply to work and perform at enough power to operate the door at the given situation. However, it is not necessary to have a power supply that can handle the toughest situation if it never occurs. For example, the largest power supply might not be needed if the door is of the lightest model with a light traffic situation. Therefore a conclusion is that it is important to decide what concept to use for the door based on where it will be installed.

Furthermore, a conclusion is also that there is power to be saved by implementing either solution as they will require substantially less power to operate. Also, there is proof that if the power system that it is connected to has a limited energy budget, this is a good way to still use sliding doors regardless.

As for the regenerative breaking, retaining 8 % of the energy used to open the door is a reasonable amount given all the losses in the system. With a more effective system more energy could be retained. The energy returned is not an amount that would allow for a power supply that is drastically smaller, but there is no reason to not use it. The experimental results in Section 4.3 about *Regenerative Breaking* give back values that are lower than those of the calculations. The explanation for this is probably that the experiments did not deliver any accurate values. The actual input power is estimated based on readings from the programmable power supply and the exact point where the input power is at the limit of being able to run the door is difficult to pinpoint to the watt. The readings from the power supply are difficult to read as the input power will drop if the voltage from the capacitor bank drops. The output voltage from the supercapacitors varies during a cycle, both due to the capacitors discharging and the ESR of the capacitors consuming some voltage during high loads.

The cost of either solution is of course an important aspect to consider when determining what power supply to use. It has been difficult to make a fair estimate of the cost that takes every aspect into account. Therefore, it is difficult to recommend one solution as superior in every aspect. However, it can be said that if cost is the most important aspect in choosing a solution batteries would most probably be the best choice. The door that is used would have to be dimensioned after the power supply and what it is able to operate but the cost would be minimized. Although, if other aspects such as the life expectancy is to also be taken into account the choice would most likely be that supercapcitors are superior as they cost more but also perform better and last longer.

5.3 Future applications

Smart buildings

Smart buildings is a concept of creating entire areas where the buildings within these areas are designed and constructed in a way that they are more intelligent with regards to new technology, environment, economy and most relevant for this thesis, energy consumption [20] [25]. One way that is used to restrict the energy consumption and reduce the strain that is put on the power grid is to keep a restricted energy budget for each building. If this is to be implemented on an entire building or neighborhood the solutions presented in this thesis would be a relevant addition if sliding doors are to be used. If the current power supply would be implemented it would require large amounts of power to be reserved in case of a door needing to be opened. As there is no energy reserve to take energy from when an opening should be done it requires this energy to be reserved in the budget instead. This may either result in difficulties to reopen a door or perform multiple consecutive openings without waiting.

However, if the solution presented previously in this report is to be implemented there is a more efficient way of conserving energy as well as a more economic use. The power reserve that is done will help reduce the sudden need for energy and make the strain on the power budget more even and therefore easier to handle.

Also another difficulty will be when internet of things becomes more prevalent and is launched to a larger market. This will require everything in a home to be connected and thus will also result in large requirement for power at all time. This does not agree completely with the current environmental goals set by the united nations. Goal number 7 is related to energy and says that the world should strive towards the use of cleaner and more environmentally friendly energy [22]. As an addition to this, reducing the energy consumption should be even better. Therefore, with the solution presented in this thesis, smart homes would be even more in line with the standard set by the united nations. Also, as this is the direction in which the world as well as technology is headed, this is what should be used in order to stay relevant and updated with the current requirements of customers.

5.4 Safety system

It is important that each solution presented as a concept is in agreement with the security standards that has been set in place to assure that a door is safe to use as well as install. These have rules regarding detecting failure in a system and should in case of error have a backup system in place.

The current solution for finding an error is to measure the voltage of the power supply. If the voltage on the input has decreased bellow a certain point the system detects an error and the backup system will be activated. The current backup is to use the battery pack that has been used previously in this thesis. These will then be used to run the door for as long as the power reserve in them last. This is, with normal usage, around one hour of time. However, ultimately the requirement is that the door should be able to perform at least one opening and then stay open until the malfunction is fixed. That the door is able to actually operate for an hour after malfunction is above the requirement.

This thesis will not present a definite and tested solution for error detection as it is outside of the scope of the project. Also, taking part of and understating the safety guidelines to the point of being able to design a proper solution would be time consuming. However, potential solutions will be presented and discussed, although not tested.

As mentioned, two error detection systems should be constructed. One for detecting error in the power supply and a second for detecting error in the backup battery, if that is in use.

Within the main power supply there can occur two types of error. Either the charger has suffered from a malfunction, or the energy buffer has suffered from one. These need to be detected individually and thus requires two separate solutions.

Detection an error in the power supply seems rather simple. If there is a diode from the power supply to the charger, there should always be a larger voltage on the side that is connected to the wall adapter. The side of the charger that is charging the capacitors of the battery should be lower due to losses in them. If this is not the case and a larger voltage is detected in the storage side than in the charging side, an error in the wall adapter has been detected and a backup system should activate.

As for detecting an error in the cell of capacitors, that is more difficult. When a capacitor breaks or the result is that they start turn into a short circuit with 0 Ω over them. Therefore, detecting an error in one capacitor in the cell would require finding the short in the collection of components. This can be done in three ways. Either by measuring the resistance over each of the supercapcitors. If one did not show a value but instead showed 0 Ω that would indicate that there is an error. Another solution would be to use a voltage measurement over each capacitor. With a short the resulting voltage would be non existing and thus indicate an error. Lastly, the current that passes through the balancing resistor could be measured. If the capacitor is broken, all current would pass through the short and the current in the resistor would go from 50 mA to 0 A.

Although, an argument against all of these is that they require multiple components as well as be costly to manufacture. However, all of them would probably work and detect an error efficiently.

There is also the possibility to check if the voltage over each capacitor is larger than zero. Most MCUs have the possibility to check if an input is high or low. With that each capacitor could be checked to see if it is working. The benefit of this type of measurement over the previous mentioned is that fewer components would be needed. Input space on a MCU would be needed anyway as the measurements need to be handled. The downside is a lack of precision in the measurements, but when checking if a value is zero it is probably not needed.

5.5 Future development

Cables

In the setup used long cables were utilized between the charging circuit and the circuit board controlling the door. Often they were long and as a result had a non-negligible resistance. This caused two main issues. The first issue caused by the cables was a power loss. Resistance in the cables was measured to a total of 0.2 Ω. When the high current used to open the doors was drawn, an approximate peak power of 10 W would be lost in the cables. These losses are not good and could be reduced by having shorter or thicker cables which would result in less line resistance. However, while cables with low resistance is good practice, 3 % of the input energy lost is not a large amount and is not enough to be considered a major issue. The other issue was the voltage drop over the cables when drawing high current. It had the same source as the first problem, but with different consequences. The voltage drop in the cables caused the system to receive 2 V lower than what was available in the energy reservoir. As a result the system would shut off due to the voltage being too low when it did not need to. A solution to this problem would be to measure the system voltage directly on the energy reservoir and also to supply the system with power before the long cables to the motor as to not drop the voltage for the rest of the system. The ESR of the supercapacitors and batteries also contributed to this issue, but are not a fixable issue, the cables on the other hand are.

Balancing circuit

The balancing circuit used was considered more inefficient than the alternatives that were also considered. As discussed in the background for balancing circuits the typical way to design is using operational amplifiers as voltage followers to balance the supercapacitors. The resulting circuit is almost lossless when balanced, which would reduce up to two watts of losses from the system.

Charging circuit

The designed charging circuit charges using a constant current. As a result the input and output power will vary linearly with the output voltage. With one of the main goals of the thesis being smoothing out power peaks this is not ideal. A more suiting solution would be to use a current power charger [13]. As described in the name, a constant power charger outputs a constant power. If the voltage drops the current rises and if the voltage increases the current drops. As a result the power supply could be run at maximum power at all times smoothing out the power peaks even further. Another resulting benefit of a constant power charger over a constant current charger is that if the voltage drops due to heavy load in the energy reserve, the constant power charger will increase the charging current instead of keeping it the same, yielding better performance than the constant current charger.

Limitations

As the thesis have been focused on finding a solution there are limitations to what has been considered during the design. Main priority has been functionality as well as that the components used need to be rated for the voltage and current used in the circuit. The current was the main concern as finding components rated for the desired voltages was fairly common. If the design was to be made into a product it also has to be EMC compliant, but as the thesis was focused on testing the concept and the fact that the circuits were built on through hole cards as opposed to printed circuit boards, PCBs, the limitations of EMC compliance were decided to be out of the scope for this thesis.

Realistic testing

The tests were performed with the door opening at high frequencies. In doors installed commercially the door will stay open for longer, not open as frequently and have more reopens. All of this affects the average power consumption and thus the size of the power supply to be used. Ideally some tests for realistic scenarios, such as lower frequency of openings during the mid day and higher during rush hour, could have been done, but no data was available to perform such tests.

What does need to be taken into account when viewing the results presented in this thesis is that all results have been found using the hardest tests. Therefore, if a test has showed that something is not possible, it may have been possible with an easier run mode or with other settings for the door. For example, it has been found that a longer hold open time or slower closing speeds will greatly impact the results with capacitors. As the time that the door is open is increased this will as a result let the energy buffer have a longer charging time and thus increase the possibility of the power being stable when the door closes. Reducing the stress for the door was considered when designing the tests, however, the conclusion was that if tests were successful for a harder test that would give better results than if the test was easier. Also if a concept was failed for a hard test that would give room to improve and allow for greater analyzing than to achieve better results from weaker and easier testing.

Another discussion worth having is if designing for the worst case is a good idea if it rarely ever happens. The tests were considered as not successful if the door was not able to run frequent openings indefinitely. The fact is that a scenario of openings like that rarely ever happen. If there is rush hour, a door is often idle in the open position. If little traffic, a door will often be idle in closed position. When the goal is to minimize power peaks perhaps a suitable solution would be to design for normal operation conditions and have the door run at reduced performance if a problem of too frequent door openings arises.

Combining supercapacitors and batteries

As mentioned there can not be made a decision of what solution is the best as there are to many parameters to consider. There can only be recommendations for what would be best in certain cases.

One thought that could possibly solve this is if there was a combination of capacitors and batteries. Large currents would be drawn from the capacitors and the regenerative breaking would charge them. However, low current continuous operations would be run from the batteries. This is a good solution that would possibly utilize the best aspects from each concept.

From an economic standpoint there may be issues however. Capacitors of the magnitude that would be required and at the voltage that is necessary are expensive regardless if they are supercapacitors or just regular lower capacitance capacitors. This can be seen from Equation 2.1. They do however, need a certain amount of capacitance in order to be able to store as much of the energy as would be needed. Therefore, this may not be a solution to the problem anyway. In aspects other than cost they would probably perform just as well as supercapacitors other than lifespan that would be dictated by how long the batteries last. Which is in most cases shorter than for capacitors. The main issue with this solution is that a larger voltage often results in a smaller capacitance and larger capacitance is often correlated to lower voltage. Therefore, regardless of the capacitors chosen, the amount would likely be rather large and therefore cost as well. A solution could be to use a cheaper variety with lower capacitance, however, then the amount would be even larger and thus the size would also increase.

5.6 Conclusion

In this thesis it has been shown that power peak reduction for automatic sliding doors is possible using either supercapacitors or batteries. For pure peak reduction purposes batteries were found to be the better option as they can store more energy but have a questionable life time and may require a lower performance. Supercapacitors offer a longer life time and higher performance at the cost of a less smooth power draw and a higher price. Although ultimate numbers for what the power rating should be reduced to are difficult to determine as they depend on many variables, such as door traffic, opening distance and many more, it can at least be concluded that the power rating to run the heaviest door could be at worst halved without any notable drop in performance using the solutions discussed in this thesis.

Bibliography

[1] *Assa abloy in brief*. https://www.assaabloy.com/en/com/about-us/assa-abloy-in-brief/. Accessed: 2019-05-06.

[2] *Assa abloy's historical timeline*. https://www.assaabloy.com/en/com/about-us/history/. Accessed: 2019-05-06.

[3] T.-T. Compounds. *Prices for heavy liquids*. https://www.heavy-liquid.com/wp-content/uploads/2019/02/Price-list-1.pdf. Accessed: 2019-04-23. 2019-03-19.

[4] M. Dummett. *The dark side of electric cars: exploitative labor practices*. https://www.amnesty.org/en/latest/news/2017/09/the-dark-side-of-electric-cars-exploitative-labor-practices/. Accessed: 2019-04-15. 2017-09-29.

[5] Elna. *Datasheet supercapacitor 1 f*. 2001. URL: https://www.elfa.se/Web/Downloads/at/_e/ymDB_dat_e.pdf.

[6] *Energy stored in capacitor*. http://www.ee.sc.edu/personal/faculty/simin/ELCT102/16%20Capacitor%20energy,%20connections,%20RC%20transients.pdf. Accessed: 2019-04-23. 2010-04-08.

[7] Epectec. *Battery cell comparasion*. https://www.epectec.com/batteries/cell-comparison.html. Accessed: 2019-04-24.

[8] *Flywheel energy storage*. http://large.stanford.edu/courses/2010/ph240/wheeler1/. Accessed: 2019-04-09. 2010-10-24.

[9] *From child's toy to the iss: flywheels hold the power*. https://www.nasa.gov/vision/earth/everydaylife/flywheel.html. Accessed: 2019-04-09. 2006-03-14.

[10] *How does a supercapacitor work?* https://batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor. Accessed: 2019-04-15. 2019-04-12.

[11] IntelliData. *Datasheet normal capacitor 1 f*. 2017. URL: https://www.elfa.se/Web/Downloads/_t/ds/ALS70A105QW025_eng_tds.pdf.

[12] Linear-Technology. *Datasheet lt1170/1171/1172*. 2012. URL: `https://www.analog.com/media/en/technical-documentation/data-sheets/117012fi.pdf`.

[13] N. K. Poon, B. M. H. Pong, and C. K. Tse. "A constant-power battery charger with inherent soft switching and power factor correction". *IEEE Transactions on Power Electronics* **18**:6 (2003), pp. 1262–1269. ISSN: 0885-8993. DOI: `10.1109/TPEL.2003.818823`.

[14] Powerstream. *Nimh battery charging basics*. `https://www.powerstream.com/NiMH.htm`. Accessed: 2019-04-16. 2018-10-08.

[15] *Pumped-storage hydropower*. `https://www.energy.gov/eere/water/pumped-storage-hydropower`. Accessed: 2019-05-06.

[16] M. Rodriguez-Achach. *Will supercapacitors ever replace batteries?* `https://hackaday.com/2017/01/19/will-supercapacitors-ever-replace-batteries/`. Accessed: 2019-04-16. 2017-01-19.

[17] C. Simpson. *Battery cell comparasion*. `http://www.ti.com/lit/an/snva533/snva533.pdf`. Accessed: 2019-04-25. 2011.

[18] A. Systems. *Datasheet li-ion battery*. 2011. URL: `https://www.elfa.se/Web/Downloads/_e/ng/ANR26650M1_2500_eng.pdf`.

[19] P. Tixador. "Superconducting magnetic energy storage: status and perspective". In: *IEEE/CSC&ESAS European superconductivity news forum*. 3. 2008.

[20] P. Tracy. *What is a smart building and how can it benefit you?* `https://www.rcrwireless.com/20160725/business/smart-building-tag31-tag99`. Accessed: 2019-04-10. 2016-07-25.

[21] F. UK. *Faac guidance notes for en16005 standard*. `https://www.faac.co.uk/productfiles/323_DataSheet_rad0A238.pdf`. Accessed: 2019-05-21.

[22] *Un sustainability goals*. `https://www.un.org/sustainabledevelopment/energy/`. Accessed: 2019-04-10. 2015-09-25.

[23] *Using a supercapacitor to manage your power*. `https://www.printedelectronicsworld.com/articles/1921/using-a-supercapacitor-to-manage-your-power`. Accessed: 2019-04-15. 2009-12-14.

[24] K. Walestrand and J. Johansson. *Energy Efficient Door Control*. Bachelor's Thesis. Lund's University, Campus Helsingborg, 2017.

[25] *What is a smart building?* `https://buildingefficiencyinitiative.org/articles/what-smart-building`. Accessed: 2019-04-10. 2011-04-05.

[26] *What's the best battery*. `https://batteryuniversity.com/learn/archive/whats_the_best_battery`. Accessed: 2019-04-24. 2017-03-21.

A

Low current charger

In Figure A.1 the schematics for the low current charger can be seen. This is a constant current charger that is able to deliver 1.3 A continuously. The circuit was described in Section 3.2 and in Section 4.2.

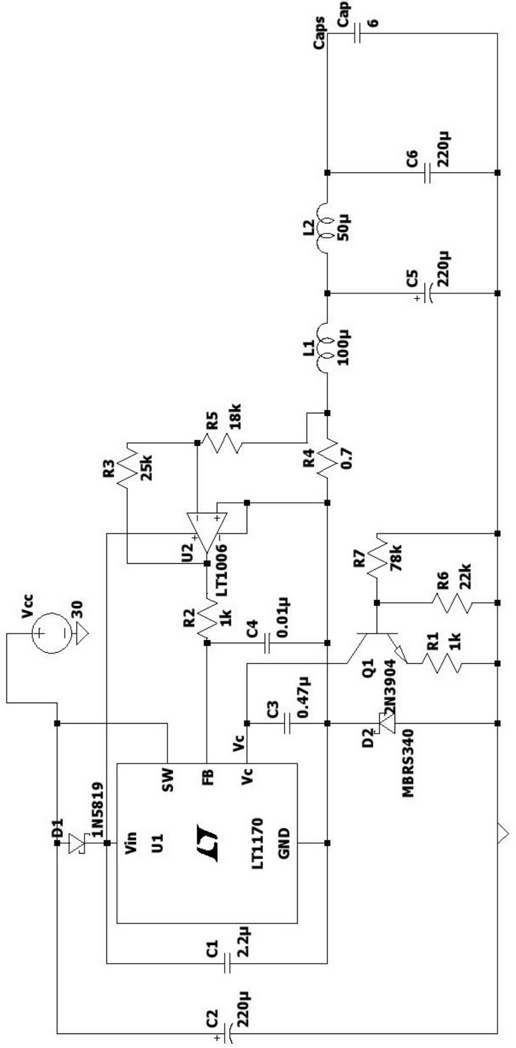


Figure A.1: Schematics for the low current charger

B

High current charger

In Figure B.1 the schematics for the high current charger can be seen. This charger has a variable resistor with range 1000 Ω to 10.000 Ω allowing it to vary the charging current and is therefore a constant current charger that is able to deliver between 0.4 A and 4 A continuously. As opposed to the low current this also utilizes a comparator in order to keep the current at 0 A when the energy source has reached 24 V. The circuit was described in Section 3.2 and in Section 4.2.

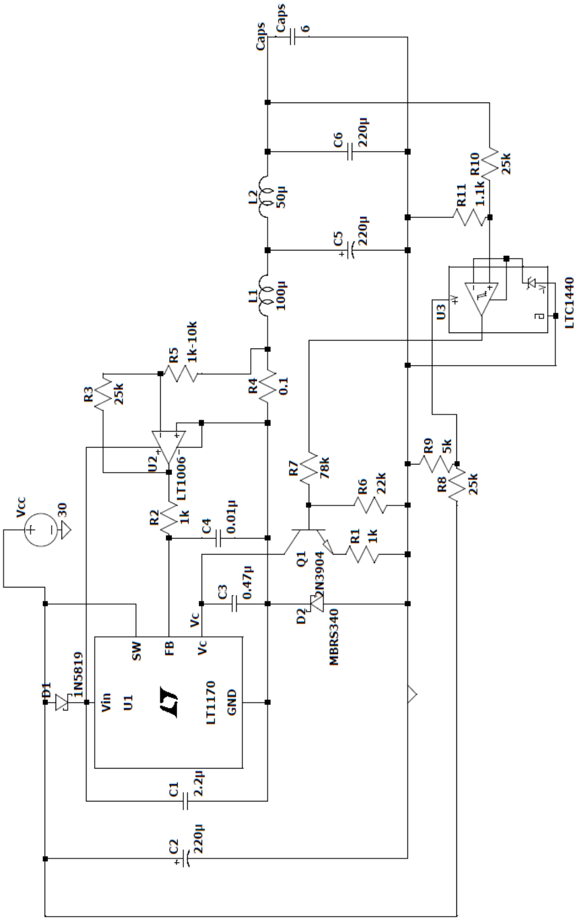


Figure B.1: Schematics for the high current charger

C

Concept grading

Table C.1 illustrates the attributes that were used in order to grade the concepts. The weights were determined with consideration to the importance that each attribute had to ASSA Abloy. There was not decided a specific score that signified that the concept would be worked on further but rather a decision was made with regards to how the concepts scored relative to each other.

Table C.1: Concept grading matrix.

Attribute	Weight	Flywheel	ScMec	Potential energy water	Potential energy weight	Supercapacitors (SC)	SC+converter	Backup battery	Extra battery	Compressed air	SC+battery	SC+backup battery	Current solution
Peak current	5	4	5	2	1	5	5	3	3	4	5	5	4
Simple mechanism	4	2	1	2	3	4	3	5	5	3	4	4	4
Losses	2	1	5	3	2	4	3	4	4	4	4	4	5
MTBF	5	5	2	3	2	4	4	3	3	5	4	4	4
Cost	5	1	1	2	2	4	4	5	4	2	3	4	2
Wh/l	3	4	4	1	2	2	2	5	5	3	4	4	3
Wh/kg	2	4	4	1	2	2	2	5	5	2	4	4	3
Power density	3	4	4	2	1	5	5	3	3	3	4	4	3
Noise	3	2	4	1	3	4	4	5	5	2	4	4	5
Regenerative energy	2	4	4	1	2	5	5	2	2	2	5	5	2
Re-energizing time	4	4	5	2	2	5	5	3	3	2	5	5	3
Run time power out	3	5	1	3	3	3	3	2	4	5	4	3	3
Environmental impact	4	4	2	4	4	3	3	3	2	4	2	3	3
Total score	-	153	137	98	98	177	171	166	163	146	178	184	152

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Abstract

When a sliding door is opened there is a sudden current peak that the electric network is subjected to. As a result of this it is difficult to design a power supply that operates the door with adequate performance while still maintaining a low power rating. In the current solution the power rating is designed for the sudden peaks and as there is no buffer of energy everything has to be taken directly from the power grid at the instance of a door opening. This thesis aims to use an energy buffer to store energy between openings and then utilize this when it needs to open. As a result of this the power grid will suffer from less sudden peaks. The power supply will also be allowed to be rated for the continuous power rather than the peaks.

Throughout different solutions to solve the energy buffer have been discussed, investigated and tested. The most prevalent and thoroughly tested was supercapacitors, which are an evolution of regular capacitors and nickel metal hydride batteries. Supercapacitors have the possibility of delivering a large current and being charged with equally large current allowing for fast charge as well as discharge. However, they do have a low voltage rating, which results in a small capacity of maintaining charge. Batteries on the other hand have a large voltage while having a lower current capacity. The differences of these have been discussed at large in the report.

The work shows that both batteries and supercapacitors are able to power the door. They are both able to offer a smoother power consumption and a lower power rating of the power supply. However, they have different capacities with regards to the door that they can power. Batteries are limited by the speed, weight and run style of the door. This limit is set by the charging current that the batteries can handle. Supercapacitors on the other hand are able to handle every scenario tested due to the large current capacity.

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