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Industrial Electrical Engineering and Automation

Evaluation of Energy Harvesting from Door Closer and Solutions for Assisted Opening

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Abstract

A door closer is a device that closes a door in a controlled manner after it has been opened. This can be beneficial for many reasons, for example security purposes, to prevent energy waste and to live up to fire regulations. This thesis project focuses on the possibilities of using a door closer that has replaced the hydraulic braking typically used in these devices with an electric generator. The goal is to have the door closer power added functionality without connecting the door to an external power source. More specifically, this thesis has studied the possibility of harvesting energy from the movements of a swing door to power assisted opening. Unlike an automated door, an assisted opening would only supply some helping opening force to users in need of assistance.

The main goal of this thesis was to study and test the energy efficiency of the electromechanical door closer. This was done through a series of tests on three different prototypes. By measuring the energy in different parts of the system, as well as the energy required to open the door, the energy efficiency of the system could be determined. Furthermore, a comparison between the results from energy harvesting tests and the results from the assisted opening tests was made. Another objective was to test and analyze the possibilities of energy harvesting during opening. After testing and analyzing the data, a test case was made for the assisted opening, including when and how much the door should assists and how the door should identify a user with the need for assistance.

It was concluded that a similar amount of energy could be harvested from all prototypes but at differing closing times. Furthermore, it was determined that powering one automatic opening required many more manual openings. It was demonstrated that while assisted opening required less energy, it was necessary for the system to be able to differentiate between users with and without need of assistance.

Based on the results, a solution for how the assisted opening should be implemented was suggested. The solution was evaluated in a user experience test. It was found that while the assistance was appreciated, one common criticism was that it was too difficult to trigger the assisted opening. While it would be optimal from a user experience perspective to have the door closer assist every time, this is not possible energy-wise with the current system. Based on the findings of this thesis, proposals for future studies and improvements were made.

Sammanfattning

En dörrstängare är en anordning som stänger en dörr på ett kontrollerat sätt efter att den har öppnats. Detta kan vara fördelaktigt av många skäl, till exempel ur en säkerhetsperspektiv, för att förhindra energislöseri och för att uppfylla brandsäkerhetskrav. Det här projektet har fokuserat på en ny dörrstängare där den hydrauliska dämpningen som vanligtvis används är ersatt med en elektrisk generator. Målet är att låta dörrstängaren driva extrafunktioner, men utan att ansluta dörren till extern strömförsörjning. Projektet har mer specifikt undersökt möjligheterna att utvinna energi från en slagdörrs rörelser för att kunna driva en assisterad öppning. En assisterad öppning skulle, till skillnad från en automatisk öppning, bara hjälpa användaren i öppningen och fortfarande kräva att användaren bidrar med viss kraft.

Det huvudsakliga målet med det här arbetet var att undersöka och testa den elektromekaniska dörrstängarens energieffektivitet. Detta gjordes genom en serie mätningar på tre olika prototyper där energin i olika delar av systemet och energin som krävs för att öppna dörren mättes. Utöver det gjordes en jämförelse mellan resultaten från mätningarna av utvunnen energi och mätningarna på assisterad öppning. Ett annat syfte med projektet var att undersöka möjligheten att utvinna energi under öppningsfasen av dörren. Efter att ha utfört testerna och analyserat denna data definierades ett användarfall som innefattade när och hur mycket dörren ska assistera, samt hur dörren ska identifiera en användare som är i behov av assistans.

Slutsatsen är att mängden energi som kunde skördas var ungefär lika stor för alla prototyperna, men vid skilda stängningstider. Vidare kunde det konstateras att det krävdes åtminstone tio gånger mer energi till att genomföra en automatiskt öppning än vad som gick att utvinna från en manuell stängning. Trots att en assisterad öppning krävde mindre energi än en automatisk, kommer alltså systemet behöva kunna skilja på användare som behöver assistans och på genomsnittliga användare.

Utifrån resultaten presenterades ett förslag på hur en assisterad öppning skulle implementeras. Lösningen utvärderades sen i form av ett användartest. Enligt svaren från testdeltagarna var assistansen uppskattad men en återkommande kritik var att det var för svårt att trigga den assisterade öppningen. Även om det hade varit optimalt ur ett användarperspektiv att dörren assisterar varje gång är det med det nuvaranda systemet inte möjligt på grund av energiåtgången. Utifrån slutsatserna från projektet lades förslag på framtida arbete och förbättringar fram.

Acknowledgments

We would like to thank the Division of Industrial Electrical Engineering and Automation and especially our supervisor Gunnar Lindstedt for his support during this process. Because of his optimism and positive energy, no challenge has seemed too hard to overcome.

In addition, we would like to express our sincere gratitude to our assisting supervisors Sara and Martin, for guiding and supporting us throughout the project. Thank you for all your help and motivation. We would also like to express our great appreciation to those who took time for us whenever we needed help. Special thanks to Daniel, Jonas, Robin, Johan and Emelie who contributed with invaluable knowledge and support and always were willing to discuss ideas with us.

Thank you!

The work for this thesis was divided equally.

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List of Acronyms

- **PWM** - Pulse-Width Modulation
- **DC** - Direct Current
- **BLDC** - Brushless Direct Current
- **ISO** - International Organization for Standardization
- **PID** - Proportional Integral Derivative
- **Kv** - Revolutions per minute a motor makes when 1 V is supplied with no load
- **RPM** - Revolutions Per Minute
- **GR** - Gear Ratio
- **IDE** - Integrated Development Environment
- **V** - Voltage
- **I** - Current
- **R** - Resistance
- **E** - Energy

1 Background

1.1 Door Closers

The door closer is a device that closes a door in a controlled manner after it has been opened [3]. This can be beneficial for many reasons, for example security reasons, to prevent energy waste and to comply with fire regulations. Some other purposes for attaching a door closer might be to suppress unwanted noise and to keep rooms free of dirt and pests. The traditional door closer consists of a spring that acts to close the door and a cylinder with hydraulic oil that dampens the closing action [25]. An example of what the product looks like when installed can be seen in Figure 1.

Figure 1: Door closer [37].

1.2 Problem Formulation

With expanding markets regarding smart buildings, there is an increasing demand on added functionality around the door such as automation [13]. However, conventional mechanical and hydraulic door closers are not usually built to be able to power any added functionality. To achieve a door with added automation, the current solution is to connect it to an external power source, which increases cost and maintenance. Furthermore, regulations surrounding accessibility are continuously increasing, which in the long term might require even more doors to be connected to external power sources.

1.3 Thesis Purpose

One possible approach to avoid powering the door with an external power source would be to harvest energy from when the door is closing. Thus, energy that would otherwise go to waste could be stored and then used to power the added functions. This could possibly be achieved by replacing the hydraulic braking typically used in door closers with an electric generator that is controlled to create a door closing action with the desired behavior. By using the generator as a motor, driven by stored energy from previous cycles of opening and closing the door, extra opening functionality can possibly be added. Although the amount of energy that can be harvested from a closing will not be sufficient to power an *automatic opening*, it might be enough to perform an *assisted opening*. As the name suggests, an assisted opening would only aid the user in opening the door instead of swinging it open without any added force from the user. However, with the same door closer mechanism being used for both harvesting and opening, the preferred solutions for the two cases might differ.

This thesis project focuses on a new generation door closer, moving away from a standard mechanical and hydraulic solution. Specifically, this thesis focuses on energy harvesting to enable what is referred to as "assisted opening" to supply some helping opening force to users in need of assistance.

The purpose was to:

- Study and test the energy efficiency of the electromechanical system.
- Compare the results of the energy harvesting tests with the results of the assisted opening tests. Make an analysis between the two cases including trade-offs.
- Test and analyze the possibilities to harvest energy during opening.
- Investigate solutions around controlled assisted opening of a door given the conditions set by the harvesting.
- Write a test case for the assisted opening including when and how much the door should assists and how the door can identify a user with the need for assisted opening.

1.4 Methodology

The project was started by studying former research to gain an understanding of the problem. An electrical system that was capable of energy harvesting had already been designed and was thoroughly studied before being assembled. Initial tests had been performed on the mechanical system and three prototypes had been selected as promising prototypes.

This thesis project was carried out using both a quantitative and a qualitative methodology. The quantitative part of this project consisted of data acquisition through testing the energy efficiency of the system. It was also studied how the door closer behavior depended on a number of different variables. Furthermore, energy harvesting during opening instead of closing was tested as well as required energy for performing an assisted or automated opening. The aim of the quantitative work was to give a broad representation of the system capabilities and was not meant to have statistical significance. The test results were analyzed and the prototypes compared. Based on the test results, a test case for how the door should behave was created and then implemented on the prototype's firmware.

The qualitative part consisted of an initial user experience test that was performed to evaluate the prototype and the test case.

1.5 Limitations

The scope of this project was not to provide a fully functional product, but rather to investigate the technical possibilities of a product capable of energy harvesting and assisted opening. Thus, regulations and standards were taken into some consideration but were not strictly followed. Also, since this thesis work focused on pre-product development, the tests that were performed on the prototypes were not meant to be extensive and statistically significant, but more focused on giving an overall picture of the possibilities and limitations of the project.

It was also out of scope to find the optimal solution taking all parts of the project (electronics, mechanics, software) into account but rather to continue the development of the existing prototype and give suggestions that could be iterated upon. The project in large aimed for a global solution with low cost and high volumes, and the choices of components were somewhat affected by this. Some basic tests on mechanical setups had been made before the start of this work, and these results were used to determine which components seemed suitable for more extensive testing. Much of the electronics of the prototype were already designed and only changes necessary for basic functionality, safety and testing were made to it.

2 Theory

2.1 Door Closers

2.1.1 Working Principles

As previously described, a door closer is a device that closes a door in a controlled manner after it has been opened. Typically, only one is needed per door leaf. The predominant type of door closer is a hydraulic-mechanical solution, which typically includes a spring, some hydraulic fluid, stops, valves and a surface mounted arm to connect the door to the side of a swing door. A swing door is a door with hinges on one side that is opened by rotating the door around the hinge. An example of the composition of a conventional door closer is demonstrated in Figure 2. The internal components are usually covered by a metal or plastic cover. [26]

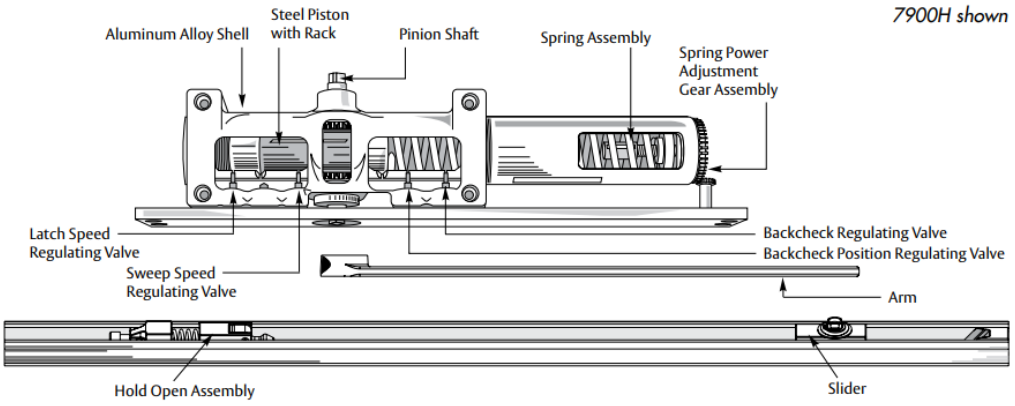


Figure 2: Door closer mechanism [1].

When the door is opened, the spring is elongated and the force from the spring acts on the door to close it again. This motion is dampened by the hydraulic fluid to create a soft closing motion. By opening and closing the different valves, the motion can be controlled by setting the speed at different angles. By adjusting the spring tension, the closing force can be adjusted. These settings are used to create a customized solution with alternatives such as holding the door open for some time before starting to close or closing at a certain angle velocity. To ensure latching, the torque acting on the door increases when it is near closing, see Figure 3. This is achieved by having a decreasing radius of the cylinder attached to the spring. Usually, the acting torque becomes higher in the interval of 0-20 degrees. Naturally, the force required to open the door will then also be the highest from 0-20 degrees. For other angles, the acting torque is relatively constant. Furthermore, the torque acting on the door during closing is lower than during opening. That is mainly due to hysteresis in the spring, resulting in a loss of mechanical energy, see Figure 4 [12]. In the figure, the lines describing the actual forces acting on the spring during compression and release can be seen, as well as the approximated linear relationship between force and deflection for different stages. While normally assuming that a spring can be described in terms of a constant, the large deflection of springs in door closers makes it necessary to also take the difference in force between compression and release into account. The cause of this difference stems from that during cyclic loading and unloading of any spring, there will be some losses due to the ends rotating when the spring is compressed, which leads to friction. As a result of that, the energy required to elongate the spring is greater than the energy released when the spring is contracted [34]. The difference between the curves is further expanded by friction in the mechanical system, which increases the torque needed to open the door while working against the closing motion, which means a lower torque operates on the door during closing. The efficiency of a door closer can be calculated using Equation 1.

$$\eta = \frac{\tau_{closing}}{\tau_{opening}} \tag{1}$$

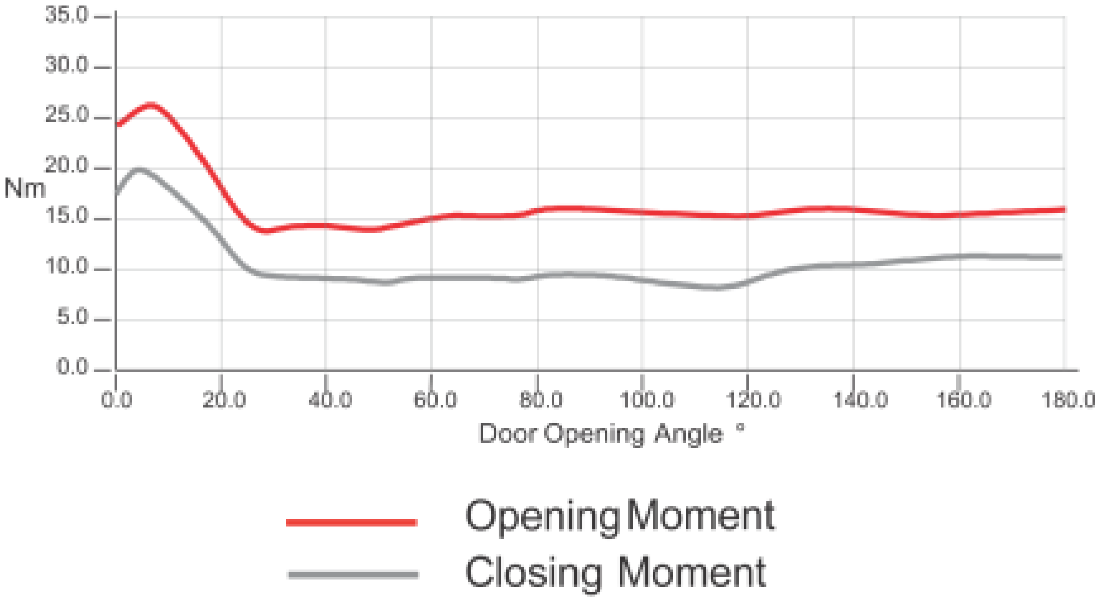


Figure 3: Example of a power curve [8].

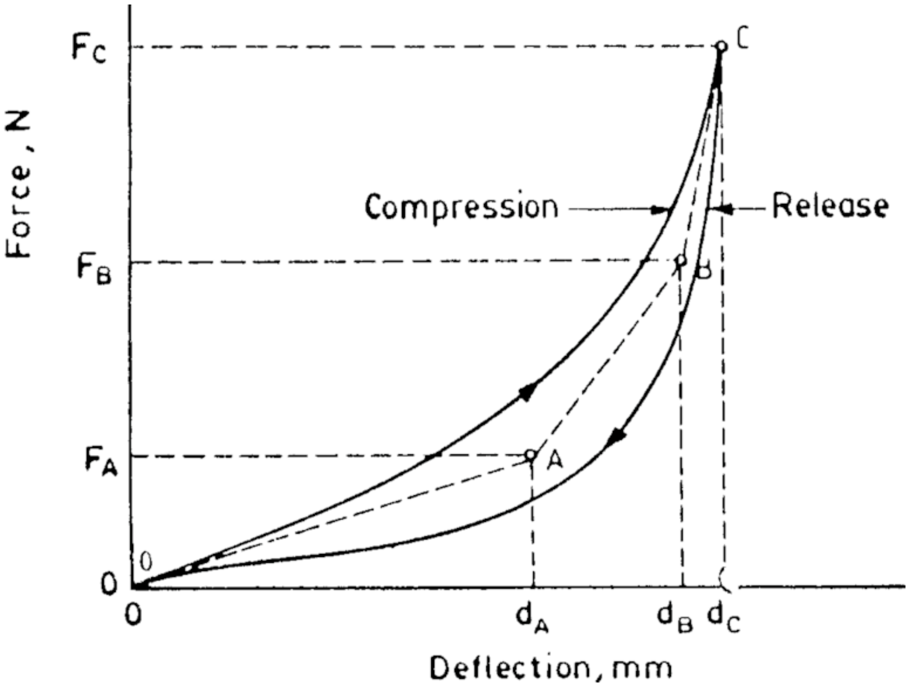


Figure 4: Hysteresis in a spring [34].

2.1.2 Automatic Opening

A door closer can also perform more actions than just simply braking the closing motion of the door. For example, the door closer can be connected to the fire alarm system or allow accessible opening for elderly and disabled people. A door closer that can automatically open a door is sometimes referred to as a door opener. This usually requires the door to be externally powered and with some added components such as timers, motion sensors and actuators. Automatic door openers will also include a motor and a gearbox connected to the pinion shaft of the door. Usually, it will be a direct current motor specified for a maximum power consumption around a few hundred watts [4]. Automatic opening can be activated in multiple different ways. Some of the most common are buttons, pressure sensors, motion-detection sensors, or access control systems. When the automatic opening is activated, the motor starts to rotate the door which swings open to allow passage. Depending on where the door is located and the normal use, the automatic opening can vary in speed, opening degrees and delay time before starting to close again [7].

2.1.3 Assisted Opening

In some cases, fully automated doors might be unnecessary. For example, completely opening a door every time someone passes can lead to heat leaking in or out of a room, especially if the door is automatically being held open for a longer period of time [42]. Another limitation in automated doors is that they can be complicated to interact with, for example by being too slow or fast, or being difficult to trigger [17]. Efforts have been made to solve this, for example, it has been investigated how to make the door-opening action easier for wheelchair users. One study suggests using a vision-based assist controller to control the relative velocity between the door and wheelchair user [18]. In some scenarios, the need for automatic opening can be shifting. For example, one study on passenger car doors proposed a solution that compensated for the effort of the passenger when the force applied to the door was unusually low by supplying additional force [16]. An additional study suggested that depending on the roll and pitch angle of the vehicle, the gravity acting against the passengers movements would be compensated for [30]. If a car is parked in an angle and the passenger needs to ”push up” the door, they will then be assisted by a motor and clutch but if it is parked on a flat surface, the opening will be manual. Although this thesis focuses on fixed swing doors, the idea of assisting only when necessary can still be translated into this project. However, it will be a matter of identifying which users need assisting rather than identifying which environment would be cause for assistance. In the case of a swing door, assisted opening could mean that the door closer aids in opening the door fully or partly, but that a user is still required to add some force. It could also mean that the assisting force from the motor can vary depending on how much help the user needs.

Four main test cases with varying degrees of assistance during opening were identified for swing doors.

Fully automated opening for users in need of assistance would mean that the door would swing open to 90 degrees whenever a user in need of assistance was identified. This case would require the system to identify which users are in need of assistance. If the user needs assistance, the motor would be turned on and set to a constant opening speed to automatically open the door. When reaching 90 degrees, the motor would be turned off and the door would start to close, enabling the energy harvesting mode, which continues until the door is closed and latched. If, on the other hand, the users are identified as being capable of opening the door themselves, the system would work as a conventional door closer. When the user lets go of the door and it starts to close, energy harvesting would be enabled until the door is latched.

Semi-automatic opening would follow the same logic as the fully automated door closer but would swing open to an angle less than 90 degrees after detecting a user in need of assistance. This would require less energy than the fully automated door.

Assisted opening during entire opening would make the opening less heavy by letting the motor provide some extra torque to decrease the force needed from the user to push open the door, see Figure 5. The user would still need to contribute to the opening, similarly to the car door previously described. This would require less energy than the fully automated opening since the contribution from the motor could be adapted depending on how much force the user adds. The door closer would only assist as long as the user is actively contributing with force and would harvest energy during closing.

Assisted opening to overcome initial torque could be described as a mixture between a semi-automatic opening and assisted opening. The motor would contribute with some torque to ”even out” the power curve the first 20 degrees and then the user would have to manually open the door the rest of the way. Similarly to a semi-automatic door, this test case would make the first part of the opening less heavy while using less energy than having assistance during the entire opening. Unlike the semi-automatic door, this would still require that the user applies some force during the first 20 degrees, which could possibly make it smoother to go from being assisted the first 20 degrees to opening manually with no assist after 20 degrees.

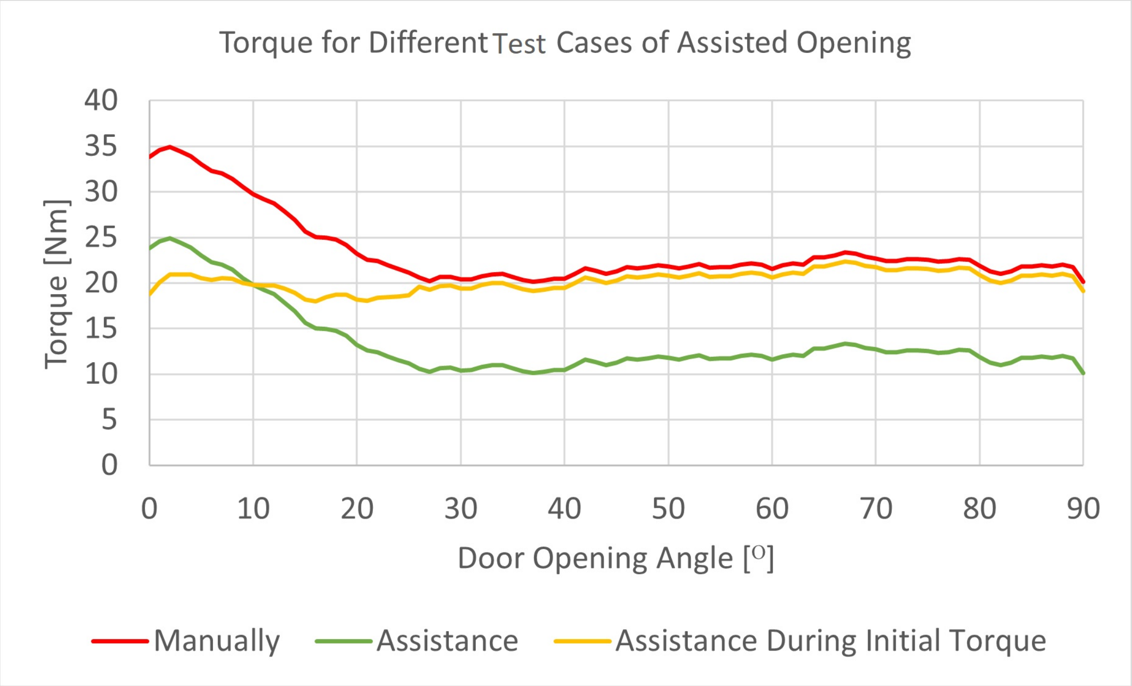


Figure 5: Conceived power curve from a user perspective during assisted opening.

2.2 Energy Harvesting

Energy harvesting is the practice of capturing energy from external sources such as solar power, heat, motion or radio signals. With an increasing demand for clean energy, research into harvesting energy from everyday appliances has been expanding. One reason for wanting to use energy harvesting is to eliminate the need for batteries in products, such as digital locks [2]. Another reason could be to avoid relying on power from the grid. Numerous attempts have been made in the past years to harvest energy from door movements. Studies on energy harvesting from doors have focused mainly on low power applications [41]. It has been estimated that around 10 J could be expected from a single action on a swing door while a revolving door could result in about 40 J from one use [22]. Some attempts have also been made to design commercial door closers that are simple and cheap to manufacture and can power low-energy appliances [38]. A generator and a converter can be used to harvest the energy and prepare it for storing. However, not all the energy acquired from the closing motion of the door can be used due to energy losses, see Figure 6. Ultimately, neither the mechanical parts (spring, gear box) nor the electronic parts (motor, harvesting circuit) have 100 % efficiency and the actual amount of energy that can be used to add features will be drastically lower than the theoretical amount. Naturally, this also works in reverse so that friction increases the amount of energy needed to open the door. To maximize the energy that can be harvested, and minimize the required energy to open, it is necessary to design a system that limits the energy losses due to friction as much as possible.

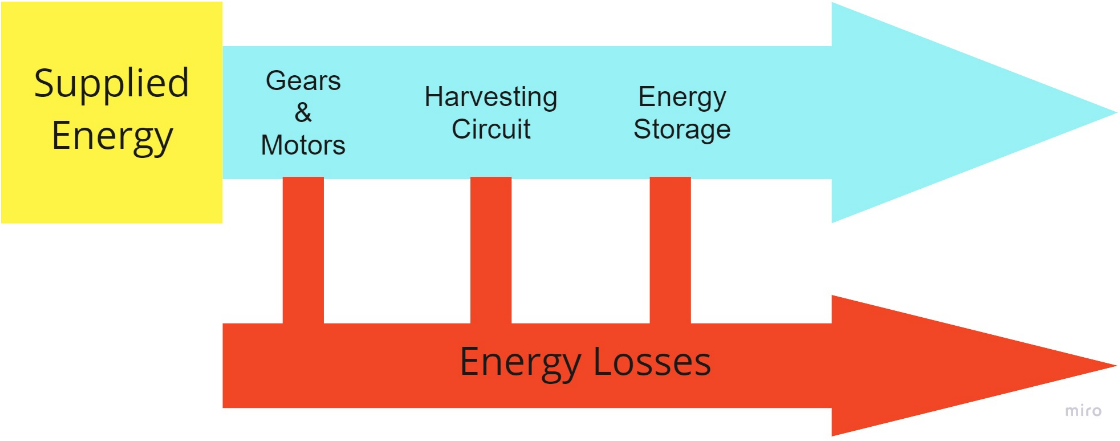


Figure 6: Energy losses in the system.

The previously mentioned studies, have mainly focused on harvesting during the closing movement of a swing door. A door closer that harvests during closing will behave similarly to how a conventional door would behave. However, there is also the option of harvesting energy during the opening. Since this would add resistance to the door it would require more force from the user when pushing or pulling the door open.

2.2.1 Energy Generation Using BLDC Motor and Gear Box

To be able to harvest the mechanical energy in the movement of a door, it is first necessary to transform it to electrical energy. For this project, brushless direct current motors (BLDC motors) were used. BLDC motors are relatively high-efficiency synchronous motors that can deliver a relatively high torque compared to their size.

Using the motor as a generator, electrical energy can be generated from mechanical energy, which in this case will be the rotating motion of the door. When the door moves, the permanent magnets on the rotor rotates inside of the stator and moves the magnetic field which will induce a flow of electric current in the windings. This current can then be harvested [39]. Using the same principle backwards, the motor can be used to create a torque that opens the door automatically. Since the amount of energy that can be used is limited, a type of BLDC motor called gimbal motor was used. Gimbal motors require a smaller current to produce torque than other brushless motors. This stems from that the stators of gimbal motors are wound many turns and thus have higher resistance and inductance. To simplify the transmission of the motor's rotations to that of the door and increase the torque on the door, a gearbox was added.

The maximum velocity of the motor is dependant on the constant velocity (Kv) rating of the motor and the supplied voltage, see Equation 2. The supplied voltage can be varied while the constant velocity is an inherent property of the motor that could be read from its data sheet. The Kv rating describes the revolutions per minute (RPM) the motors makes when 1 V is applied with no load. [5]

$$v_{max,motor} = Kv * U_{supplied} \tag{2}$$

However, since the motor also needs to drive a load, its actual speed will be lower than the maximum velocity. The total opening time of the door can then be calculated from the motor's actual speed if the gear ratio (GR) of the gear box is known. Assuming that the door will open to 90 degrees and that the motor's velocity is constant the opening time is derived in Equation 3.

$$t_{open} = \frac{\frac{\pi}{2}}{v_{motor}} * GR \tag{3}$$

2.2.2 Flyback Converter

One method that can be used to multiply voltage ratios while at the same time isolating the system when harvesting energy is a flyback converter, see Figure 7. The flyback converter has been used previously for these types of implementations, for example, in a study where energy was harvested during walking or jogging [40].

A flyback controller shifts between storing and releasing energy depending on whether a switch is open or closed. While the switch remains closed, the primary side of the transformer is connected to the input voltage source. In this state, the current and magnetic flux in the transformer increase, and energy starts to be stored in the transformer. Since the voltage induced is negative, the diode becomes reversed biased. This leads to the output capacitor supplying energy to the output load. After the switch is opened, the current and magnetic flux starts to drop. The voltage becomes positive, which allows the current to flow from the transformer through the diode, which recharges the capacitor that supplies the load. The switch that determines the modes in the flyback converter is essentially controlled by a pulse-width modulation (PWM) signal. The PWM signal will be set to a certain frequency and duty cycle. The frequency regulates the rate of one "store and release"-cycle while the duty cycle determines the time proportions of each segment. PWM signals operating at the same frequency with duty cycles at 50, 75 and 25 %, respectively, are demonstrated in Figure 8. [31]

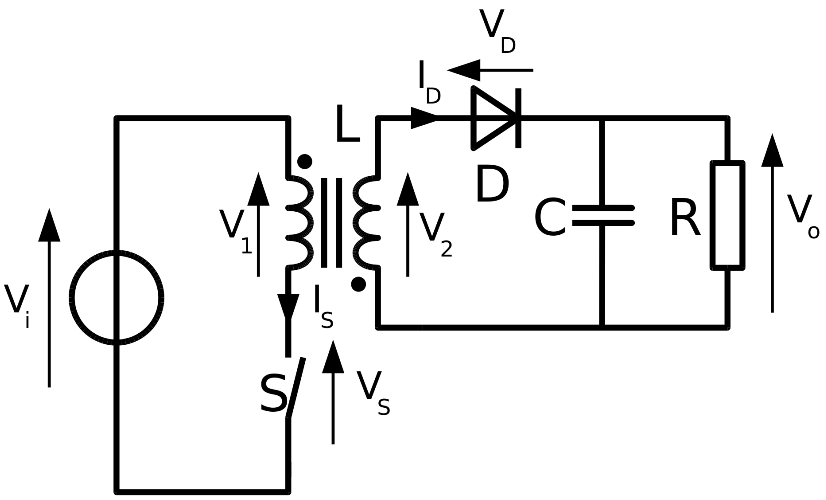


Figure 7: Schematic of flyback converter [6].

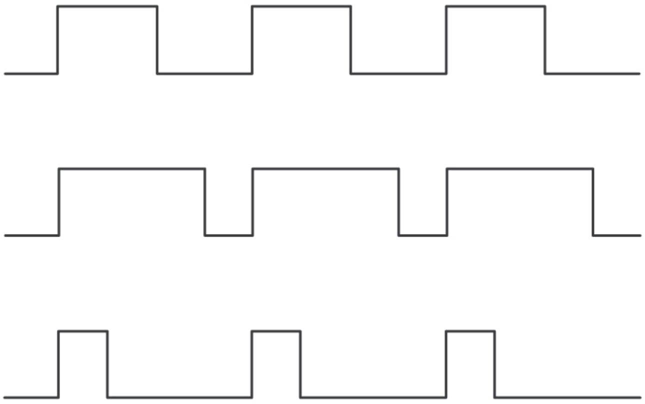


Figure 8: Pulse-width modulation signals with 50 %, 75 % and 25 % duty cycle [36].

2.2.3 Energy Storage

The energy that can be transferred to the capacitor in the flyback converter will discharge over time, at differing rates depending on the material, quality, and age of the capacitor [35]. In this project, an aluminum electrolytic capacitor was used [19]. As the regularity of a door being open and closed can be lacking, it is necessary to store the energy in a separate device, such as a battery.

2.3 ISO standards

There are many regulations regarding the functionality of a door closer defined by the International Organization for Standardization (ISO). The regulations set by ISO are often recognized by national entities as well, for example by the Swedish Institute of Standards (SIS). The ISO standard SS-EN 1154 determines the allowed torque to be used when manually opening or closing a door at certain angles [32]. This is both to ensure that it is possible to open the door and to prevent the door from slamming shut in case of for example wind. Depending on the size and weight of the door, the required force varies. The standard also states that the closing time from 90 degrees to the end zone should be less than 20 seconds at room temperature. For door closers that automatically open or are used as fire/smoke doors, ISO SS-

EN16005 applies. It regulates the safety of power-operated doors for pedestrians for both normal use and use in escape routes. It applies to electromechanical doors as well as electrohydraulic and pneumatic doors [33]. For some geographical regions, additional standards also apply and need to be taken into consideration.

2.4 Initial Door Closer Prototype

By combining the concepts of a conventional door closer, energy harvesting, and assisted opening, the initial prototype including both mechanics and electrical parts had already been developed. The prototype can be seen in Figure 9.

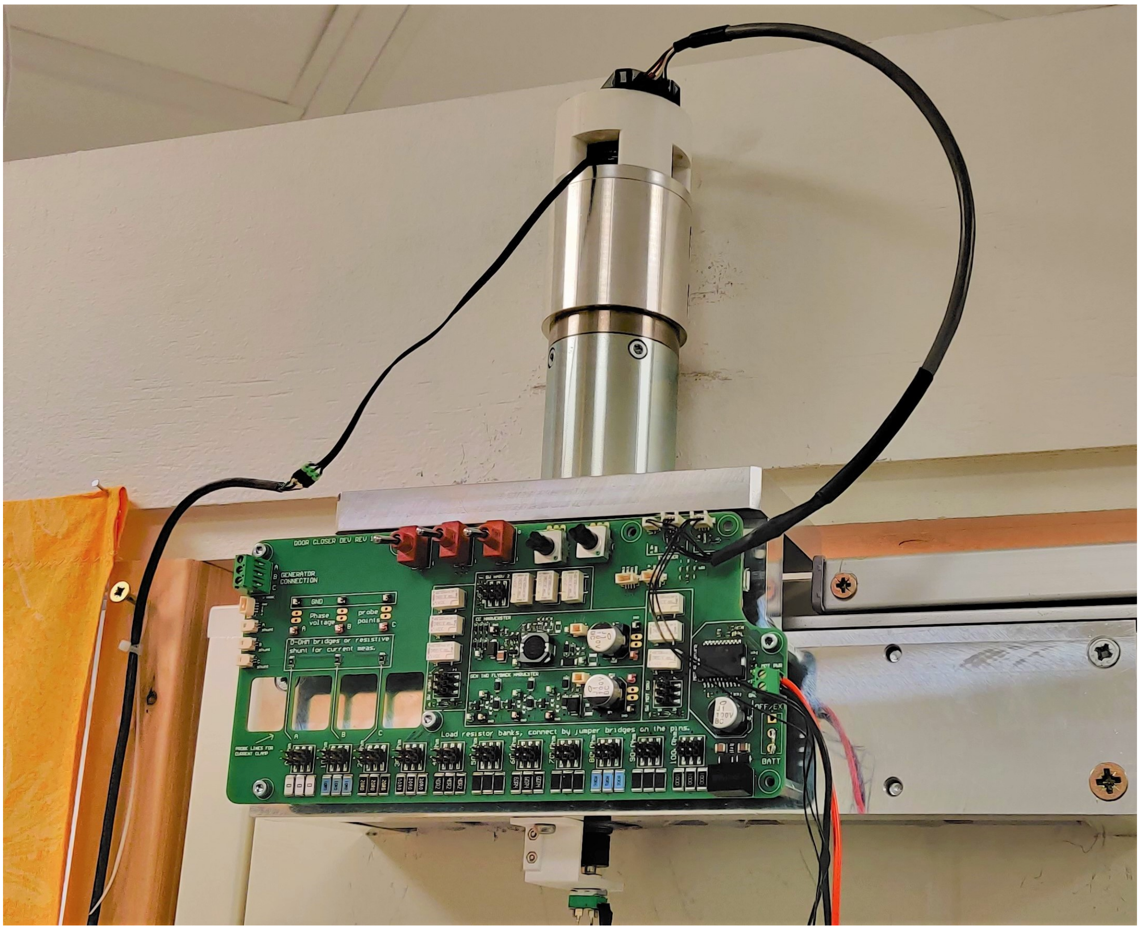


Figure 9: The initial door closer prototype.

2.4.1 Mechanical Design

The design originated from a standard hydraulic door closer and included a spring but no hydraulic oil to dampen the closing of the door. Instead, the door opening lever was attached to a brushless DC motor with an added gearbox to allow controlled closing motion. The door closer was designed to be mounted on a swing door. An external encoder needed to be connected to the motor to read and control its position. Based on the preferred type of motor and the Kv-value of different motors, two motors were chosen as promising candidates; EMAX GB2808 [10] and EMAX GB4114 [11]. A comparison between the two is demonstrated in Table 1. Gear boxes were chosen to follow ISO standards regarding torque and closing time and to allow for a timely opening based on Equation 3. Two of the gear boxes with

1:150 and 1:200 gearings were from Panasonic [21], while the one with the highest gearing, 1:225, was from Dunkermotoren [9]. Initial tests on the motors combined with spur gear boxes ruled out some combinations that did not meet the criteria on maximum torque specified by the ISO standards. The ones that met the technical specification and seemed promising to test for energy harvesting were further evaluated in this project.

Motor	GB2808	GB4114
Kv [rpm/V]	70	42
Weight [g]	64	143
Dim [mm]	∅ 35 x 22.3	∅ 46 x 31.4

Table 1: Comparison motors.

2.4.2 Electronics Design

In addition to mechanical parts, the prototype contained a circuit board for controlling the motor and the harvesting. The previously described principle of the flyback converter was used to allow energy harvesting with an added possibility to connect a battery. However, a DC power supply was used instead of a battery to power the system in the initial product development phase. The system was controlled using a RP2040 SoC on a Rasberry Pi Pico [24], and was in addition to that used to sample data from the circuit, such as encoder values, toggle switch values, and potentiometer values. The potentiometer was used to get feedback on the angular position of the door. A linear taper potentiometer was used, consisting of a resistive element with a constant cross section. This meant that the resistance was proportional to the distance between the contact and the end terminal. Consequently, in this application the potentiometer readings were assumed to be proportional to the angle of rotation of the door shaft.

2.4.3 Programming and Control Theory

As mentioned previously, the actions of the door closer and motor were controlled using a micro controller mounted on the Rasberry Pi Pico. All code was developed using the Visual Studio Code integrated development environment (IDE) with an Arduino extension to be able to use the built-in serial monitor in the Arduino IDE. To regulate the motor, an open source field oriented control library was used to send signals to a motor driver (BLDC driver) [27]. The library was chosen partly because it could be used with the gimbal motors in the project, and partly because it was straightforward to implement but could still be used in a more advanced way to optimize the hardware functionality in the future. The library was mainly used to read the position of the motor's rotor and calculate the appropriate phase voltages. This was achieved through a low-level control algorithm that calculated the phase voltages u_a, u_b and u_c needed to create a magnetic field, which was 90 degrees offset the rotor's permanent magnetic field. The desired phase voltages were then sent as control signals to the motor driver mounted on the board, which in turn controlled the motor [28]. The low-level control loop for the system is described in Figure 10.

The library also includes a PID (proportional, integral, derivative) controller to keep the motor at constant velocity or torque during operation [29]. A PID controller uses feedback to calculate an error value, which is the difference between

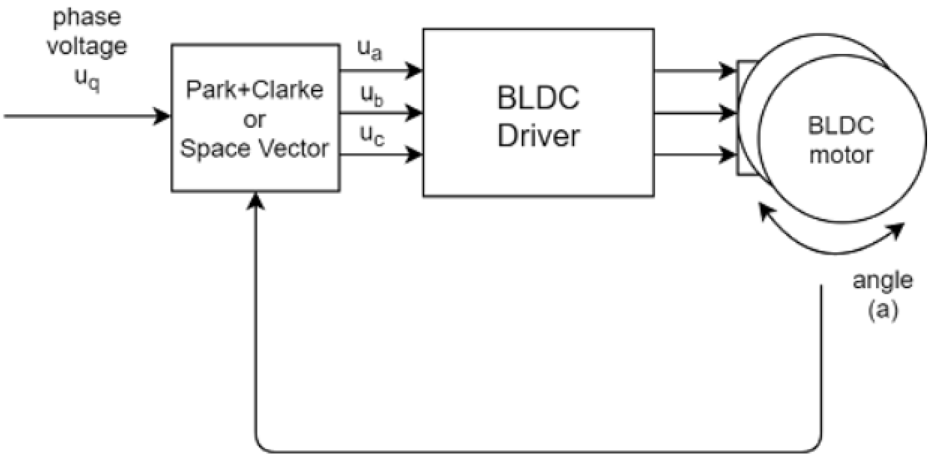


Figure 10: Field oriented control loop [28].

a desired set point and a measured variable. In this system, feedback from the encoder attached to the motor was sent back to the controller, which calculated the error between the desired and actual angle velocity; see Equation 4. In the default setup, a torque control loop was used, and the control signal would be the target voltage, see Figure 11. If instead implementing the velocity control loop, the error will translate to a target current. This was desirable since the supplied voltage was set to be constant, while the supplied current could vary. The target current was initially set to zero. If the desired velocity was set to anything above zero when the door was still, the target current would start increasing until the power to the motor was sufficient to make it run at the desired velocity. Then, the system would continue to increase or decrease the current to stay at the desired velocity. The current setpoint was calculated using Equation 5.

$$e(t) = \omega_{desired} - \omega_{actual} \tag{4}$$

$$i_{target} = K_P * e + K_I * \int_o^t e(\tau) d\tau \tag{5}$$

In the library, there was also an option to set a maximum value for the allowed current, voltage and other parameters. Since the electronics of the system had been designed to allow 1 A, this was set as the maximum current allowed in the control loop to match the actual conditions. Likewise, the desired velocity should be set in the range possible to achieve by the motor described in Section 2.2.1 if the goal is to have the motor run at that velocity. This means that if the target velocity is set higher than the motor can spin according to Equation 2, the target current and voltage will supply the maximum amount of power until the door is fully open and starts closing. Furthermore, the derivative part of the PID-controller was not used and the other parameters were set to $K_P = 0.2$ and $K_I = 20/s$, which were the default values. A digital low-pass filter was also set up with the default settings to remove any outlier values from the encoder.

The first version of the code only supported energy harvesting during closing, but was developed to be able to test energy harvesting during the opening phase as well. Furthermore, only automatic opening was at first implemented, and the code was therefore developed to also support a simple implementation of assisted

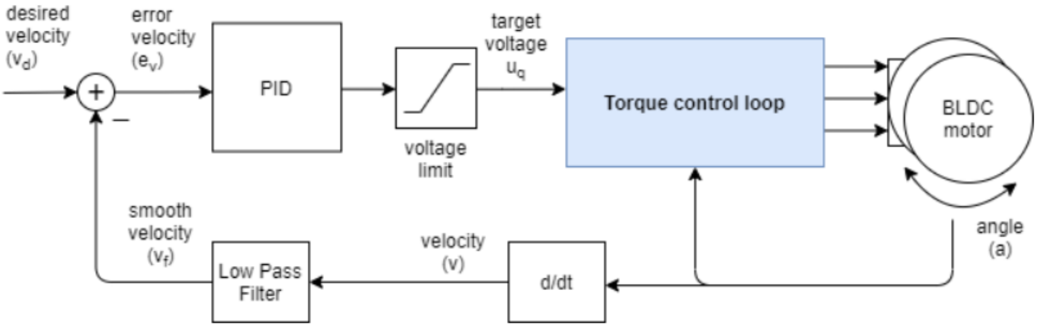


Figure 11: PID controller [29].

opening that could be tested. On a high level, the original software read door angle values from the potentiometer with the highest frequency possible. If the door angle surpassed a low angle, for example 2 degrees, an automatic opening would begin where the motor was set to a target velocity that could not be overridden by the user. It would open to a set degree, specified as 90 degrees and then start to close while simultaneously harvesting energy until closed. While the PID controller was a suitable control algorithm to use when the door was operating automatically, any interference with the opening would affect the motor's behavior. If, for example, the motor was set to open the door at a certain speed and a user tried to pull the door open at an even faster speed, the motor would start braking the motion.

3 Tests and Data Acquisition

To get an idea of the total amount of energy in the system and where energy losses occurred, a test rig was set up to measure the amount of generated energy that were available in different parts of the system. Tests were also conducted to measure the energy required to perform an automated door opening to be able to make a comparison. The behavior of the door during the tests was also studied to map out boundary values for different parameters and to find out under what circumstances the door was able to operate correctly and within the specifications.

3.1 Test Rig

All tests were performed in a combined electronics and user experience lab. The door closer system was mounted on a wooden door with a width of 0.85 m. All tests were carried out at room temperature (18-20°) using calibrated equipment. Instead of connecting an energy storage solution to the capacitor in the harvesting circuit, power was supplied through an external DC power supply. This eliminated the effects that a non-optimal storage solution might have had on the test results. The different door closer prototypes presented in Table 2 were tested and compared.

Motor Gear	GB2808	GB4114
1:150		x
1:200		x
1:225	x	

Table 2: Tested prototypes.

The prototypes were tested with three spring settings each, 1, 3 and 5, according to the ISO standard SS-EN 1154 [32]. The spring was set to meet the torque requirements for the closing moment between 0° and 4° in accordance with the standard, which is further described in Appendix C. Normally, the spring tension would be selected based on the weight of the door but in these tests the spring settings instead ”simulated” different door sizes. Hereafter, these tested spring settings will be referred to as ”iso 1”, ”iso 3” and ”iso 5” and should not be interpreted as referring to an ISO standard in any other way than has been outlined above and in Appendix C. Since one of the main goals of the tests was to determine where energy losses occurred it was important to minimize sources of errors by mounting and dismounting the prototypes more than necessary. Therefore, all relevant tests were performed on one prototype at a time before switching it to the next. This meant that all three spring settings were tested on one prototype before changing it out for the next. As a consequence, the spring settings were not identical between the prototypes.

3.1.1 Sensors

Mainly two sensors were used to receive feedback from the system, the encoder attached to the motor and a potentiometer. The encoder was used to gather data on the motor's angle and angle velocity, while the potentiometer gave feedback on the door shaft angle, i.e. the opening angle of the door.

3.1.2 Calibrations

To accurately control the behavior of the door while testing the closing and opening, it was necessary to get accurate angle readings from the attached potentiometer. Firstly, a calibration was done noting the potentiometer readings for 0 degrees and 90 degrees. The relation between the door angle and the potentiometer values was assumed to be linear. Secondly, an analog low-pass filter was added to the circuit to filter out inaccurate values.

3.1.3 Alterations to Electronic board

Before and during testing, issues with transient protection were identified. The first prototype included a diode that would lead away excess voltage if the voltage to the motor surpassed 20 V. However, with the higher spring settings, it was discovered that a voltage above 20 V was required to open the door. Therefore, the diode was exchanged for one with a maximum capacity of 30 V. Furthermore, several diodes were connected to the input power to lead away excess voltage if the power supplied to the voltage regulator spiked.

3.1.4 Test Program

While performing the energy tests, a test program was used to get digital readings of the door shaft angle from the potentiometer and the motor angle and angle velocity from the encoder connected to the motor. The test program was uploaded to the Raspberry Pi Pico and the values together with a timestamp was reported back to the computer using serial communication through a USB cable.

3.2 Energy Tests

3.2.1 Force Measurements

To validate that the mechanical parts work properly and to investigate mechanical energy in the system, force measurements were made. The estimated mechanical energy could be used to determine the potential amount of energy in the system, while also showing whether the prototype followed the mandatory regulations specified in the ISO standards. A Sauter FL100 force gauge [14] was used to measure torque during different opening and closing stages. The hook attached to the force gauge was hooked to a cable tie, that in turn was fastened to the door handle. To be able to sample continuously, a program was written in Python. The original test program was running on the Raspberry Pi and therefore it was possible to use serial communication to retrieve data from both the Raspberry Pi and the force gauge while they were connected to the computer through USB. The Python program retrieved data approximately 200 times per second, which seemingly allowed simultaneous sampling of the door angle and forces. The test setup can be seen in Figure 12.

For every prototype-spring setting combination, the door was manually opened five times from 0 to 90 degrees and then slowly closed. This was done to reduce the errors that could appear from manual handling of the force gauge. Using the average values from these measurements and the door's geometry, the torque could be calculated using Equation 6.

$$\tau = Fr \tag{6}$$

From this, the accumulated mechanical energy required to open the door 90 degrees as well as the mechanical energy that could potentially be harvested for each prototype could be calculated, see Equation 7.

$$E = \int_0^{\pi/2} \tau * d\theta \tag{7}$$

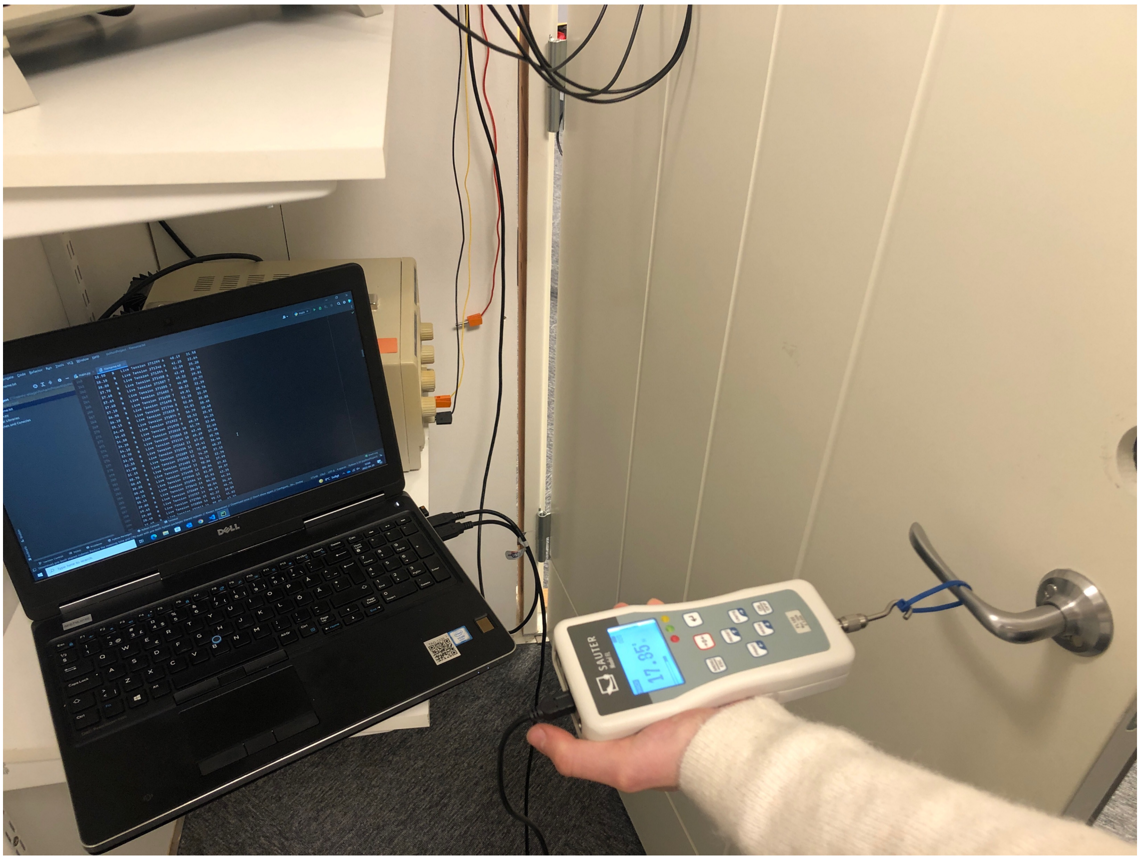


Figure 12: Setup to measure the torque of the door during opening and closing.

3.2.2 Raw Electrical Energy from Closing

To determine the total amount of raw electrical energy that could be generated during the door closing, resistances in the range 0-100 Ω were added as load to the motor. The added loads corresponded to varying closing speeds and were tested using approximately 10 Ω steps; see the exact values measured by a multimeter in Table 3. Thus, 10 measurements were taken for every prototype-spring combination. To measure the energy, an oscilloscope was used. Three probes were connected to the board's three phases and one was connected to the potentiometer for door angle readings, see Figure 13. By integrating the voltages over time, the energy generated within each phase could be calculated. The total raw energy was calculated using Equation 8.

R (Ω)	0.7	11.1	20.5	30.6	40.7	49.1	60.8	71.9	81.1	91.2	101.5

Table 3: Tested resistances.

$$E_{tot} = \int \frac{V_1^2 + V_2^2 + V_3^2}{R} dt \tag{8}$$

The test was performed by releasing the door from a 90 degree angle and measuring until it was still while supplying the motor with a voltage of 20 V and maximum current of 1 A from a DC power supply. The oscilloscope was set to note the voltages at a frequency of 100 000 times/s while the test program noted angles and velocities approximately once every 30 milliseconds.

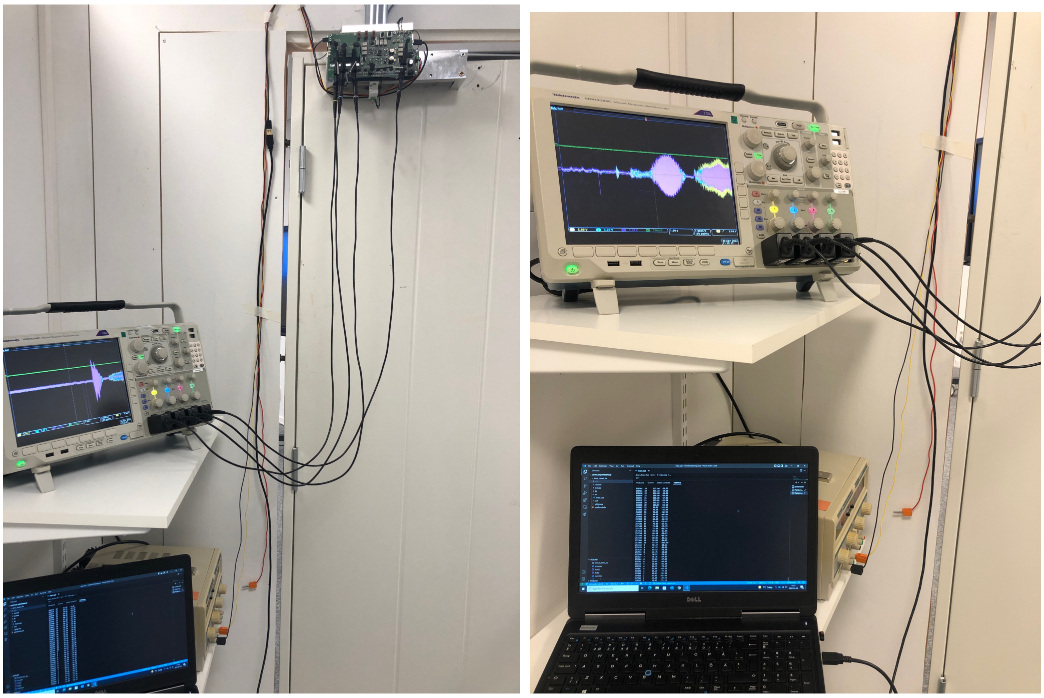


Figure 13: Setup to measure raw energy.

3.2.3 Harvested Electrical Energy from Closing

To determine the harvested energy that would go into an energy storage device, the voltage and current over the capacitor in the flyback converter were measured using a DC power analyzer, Keysight N6705B [15], see Figure 14. In this setup, load was added to the motor through the PWM signal generated from the Rasberry Pi going into the flyback harvester. The duty cycle of the PWM signal was varied from 0 to 100 %, with 10 % increment steps during testing.

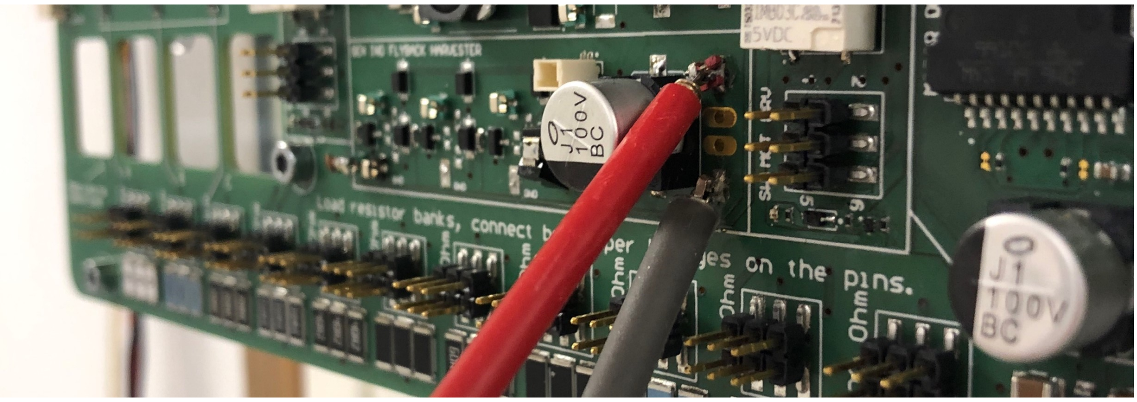


Figure 14: Probes to measure harvested electrical energy.

As an initial test, different frequencies were also tested: 1 kHz, 10 kHz, 20 kHz, 100 kHz and 1 MHz. Because of similar behavior for all frequencies above

10 kHz, a frequency of 20 kHz was chosen to perform the rest of the tests since anything below this is audible to the human ear [23]. As in the test described in 3.2.2, power was supplied from a DC power supply but three different voltages were tested initially: 15 V, 20 V and 24 V. The maximum current was constantly set at 3 A, as to not initiate over-voltage protection in the power supply if the current momentarily exceeded 1 A. These variations showed similar behaviors as could be seen with varying frequencies and therefore only 20 V supplied voltage was used to test the prototypes onwards.

The test was performed by releasing the door from a 90 degree angle and measuring until it was still. The power analyzer continuously measured the voltage and current while the test program noted angles and velocities approximately once every 30 milliseconds.

3.2.4 Energy Required for Automatic Opening

The energy required for automatic opening was tested by varying the voltage supplied to the motor from the DC power supply. The current and voltage that go directly from the circuit to the motor were probed and measured with an oscilloscope and then integrated over time to calculate the total energy, see Equation 9. The test setup can be seen in Figure 15.

$$E = \int VIdt \tag{9}$$

During testing, the voltage was varied from 28 V to the lowest possible voltage where the door would still swing open to 90 degrees. The maximum limit of 28 V was due to the maximum operating voltage of some electrical components. The voltage was then lowered after each successful opening using 1 V decrements. The maximum allowed current was set to 3 A. To create a safe testing environment, the door needed to be manually opened 2 degrees before automatically trying to open to ensure that the door does not swing open when not expected to. In this setup, the test program could not be used since serial communication interrupted the signals to the motor.

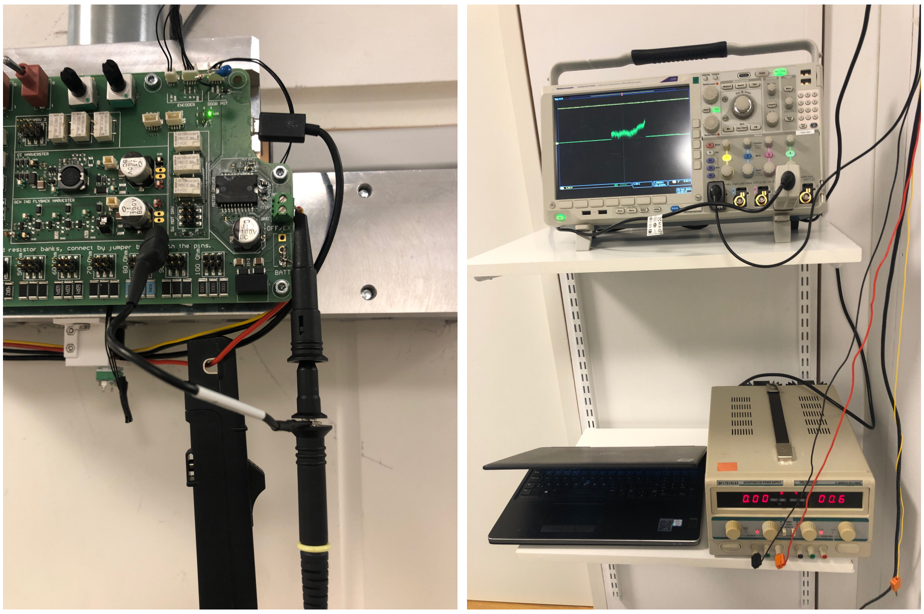


Figure 15: Setup to measure energy required for automatic opening.

3.2.5 Energy Harvesting during Opening

The potential of harvesting energy during the opening of the door was also evaluated. Identically to when harvesting during closing was tested, the flyback converter was used with a PWM signal as input. Initially, all duty cycles were evaluated. However, the higher ones required a torque much higher than the maximum allowed one according to the ISO standards to open, and were thus disregarded. Instead of using the Keysight N6705B DC power analyzer, a specifically designed load was added, see Figure 16. The load had several diodes attached to it to protect the circuit from spikes in power.

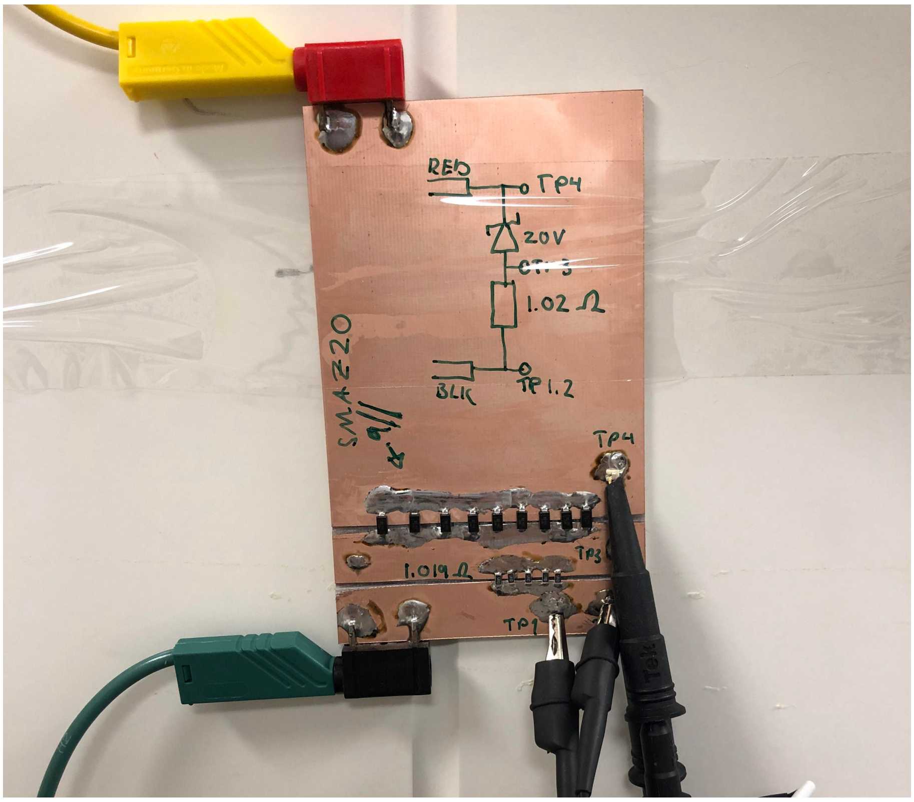


Figure 16: Load for energy harvesting during opening.

The tests were made on the motor gearbox-combination thought to be the heaviest to open seeing as the most energy could be harvested from that one. Previous tests had confirmed that the GB4114 1:200 prototype would be the most suitable and was set to an iso 3 spring setting. Data from previous tests had indicated that the maximum energy could be harvested using a PWM signal with a duty cycle of 53.47 % and a frequency of 20 kHz. The supplied voltage was set to 20 V with a maximum current of 3 A.

In the first session, five opening and closing cycles were made, with an oscilloscope probed over the capacitor. Both the energy harvested during the opening and the closing phase was recorded. The door was opened approximately 90 degrees and the opening was attempted to be at constant velocity.

A second test session was conducted using the test program noting door angle and motor angle velocity and the Keysight N6705B DC power analyzer concurrently.

3.2.6 Required Energy for Assisted Opening

The same setup was used as in the test of required energy for automatic opening; see Section 4.1.4. However, this test was only performed on GB2808 1:225 iso 3. The door was opened ten times to 90 degrees with a supplied voltage of 20 V. To perform this test, the firmware that had previously been uploaded to the Rasberry Pi was exchanged for one that executed assisted opening instead of automatic opening.

4 Test Results and Analysis

As mentioned in Section 3.1, all results were not completely comparable since the spring settings slightly varied between the prototypes. However, the tests were conducted only to give an indication of the performance of the prototypes and were not extensive. Therefore the difference in spring settings was considered negligible in some of the analyses.

The raw data is visualized using diagrams of which some only include marks, while some also include linear interpolations between the marks. The marks represent data points and the lines are only added to better visualize the data. Some diagrams only include lines since the number of data points was considered sufficient to support only using trend lines.

4.1 Energy Tests

4.1.1 Force Measurements

The results from the force measurements is demonstrated in Figure 18 where the average torques during opening and closing are plotted for the prototypes with iso 3 settings. As expected, it can be seen that the torque is higher for the first 20 degrees and is then quite similar for the rest of the opening. The closing force follows the same curve as the opening, but requires a lower torque, which follows the theory explained in Section 2.1.1.

As expected, higher spring tensions result in more energy in the system, see Figure 17 where this is demonstrated for GB4114 1:150. It can also be seen that the efficiency remains the same regardless of spring setting.

When comparing the curves between prototypes, it can be seen that GB4114 1:200 has a higher deviation between the opening and closing forces, meaning that it appears to be less efficient than the other systems.

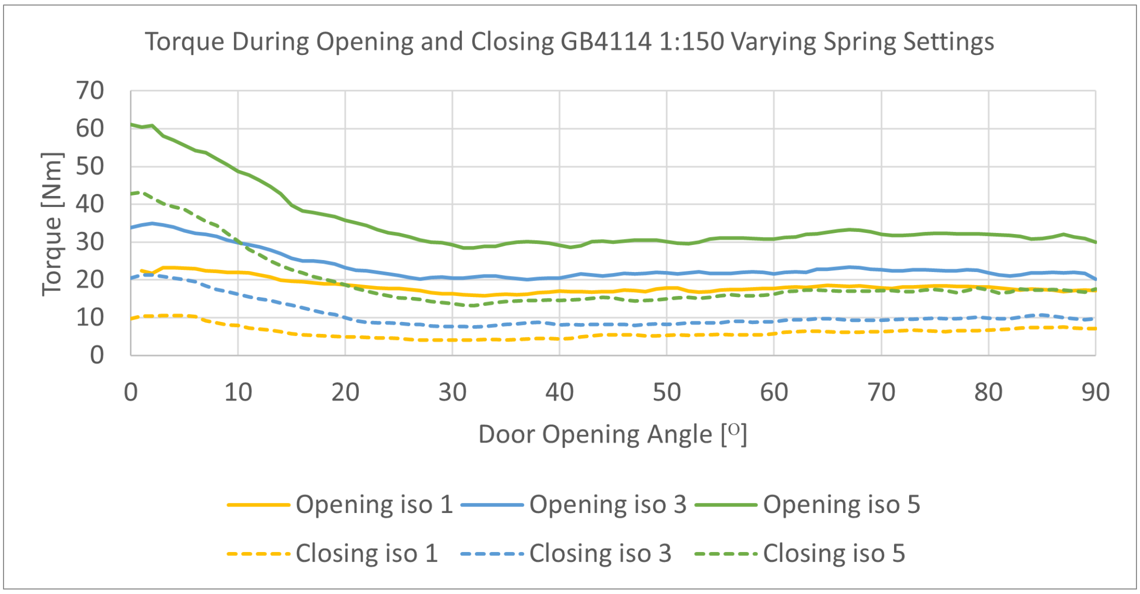
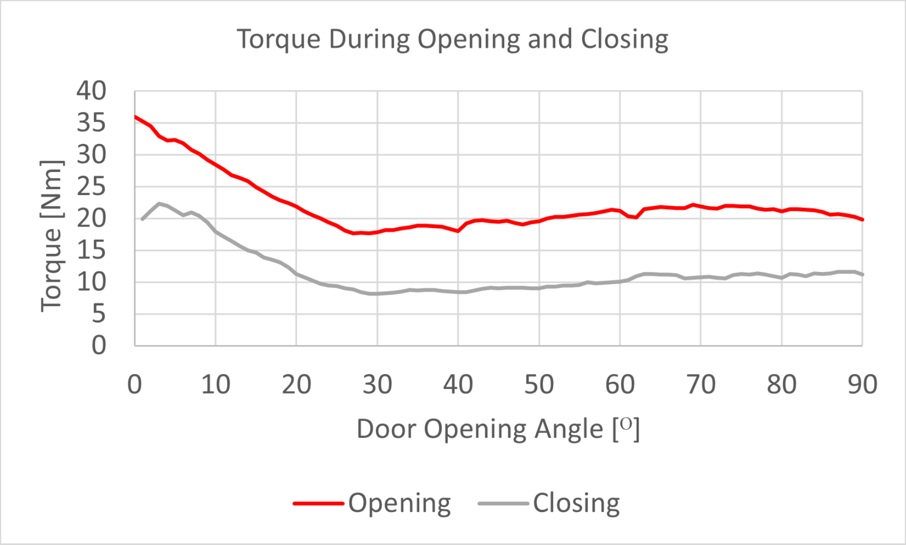
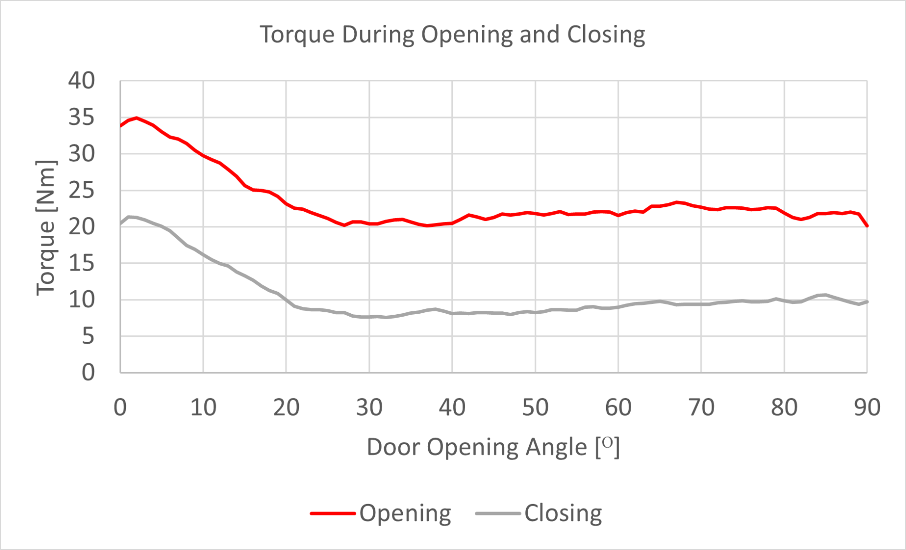


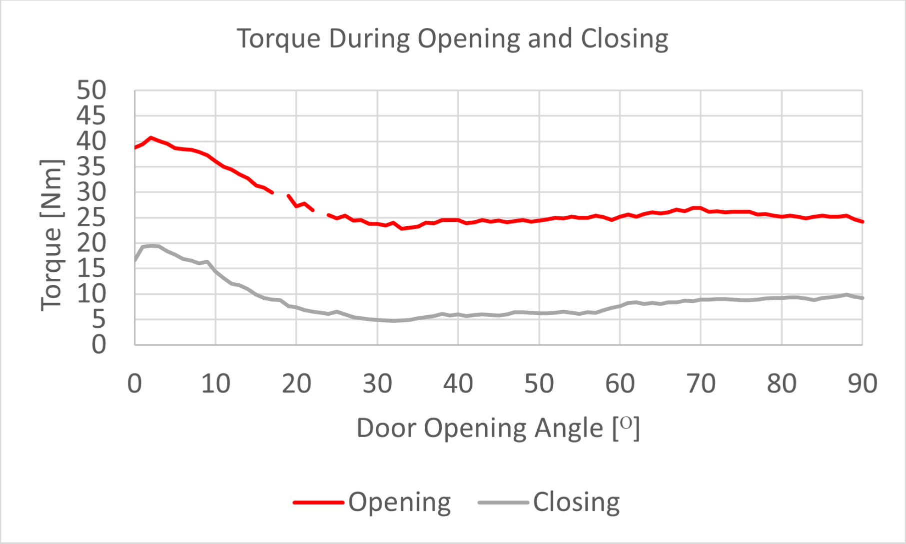
Figure 17: Torque with varying spring settings in GB4114 1:150.



(a) GB2808 1:225 iso 3



(b) GB4114 1:150 iso 3



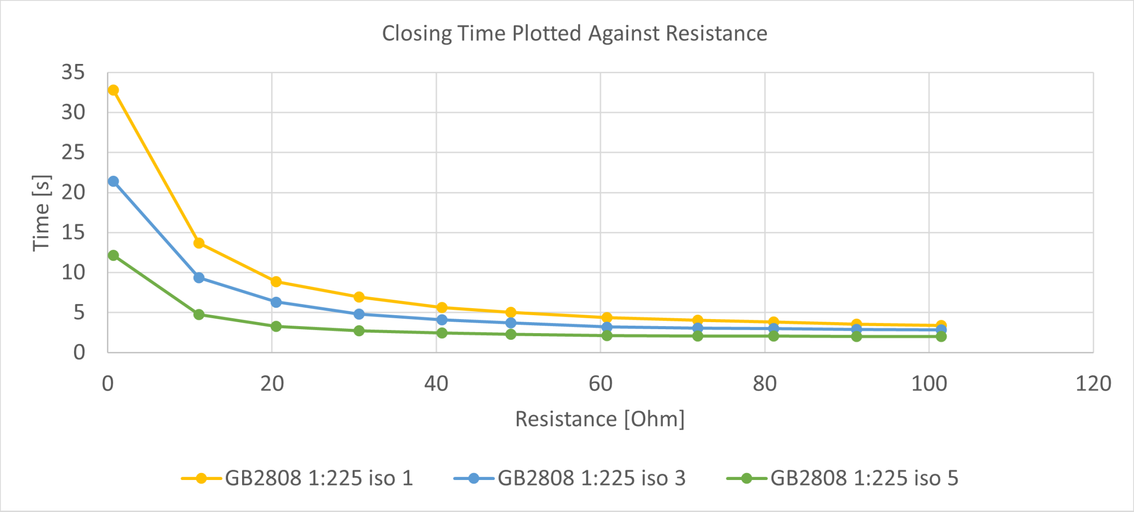
(c) GB4114 1:200 iso 3

Figure 18: Torque during opening and closing iso 3.

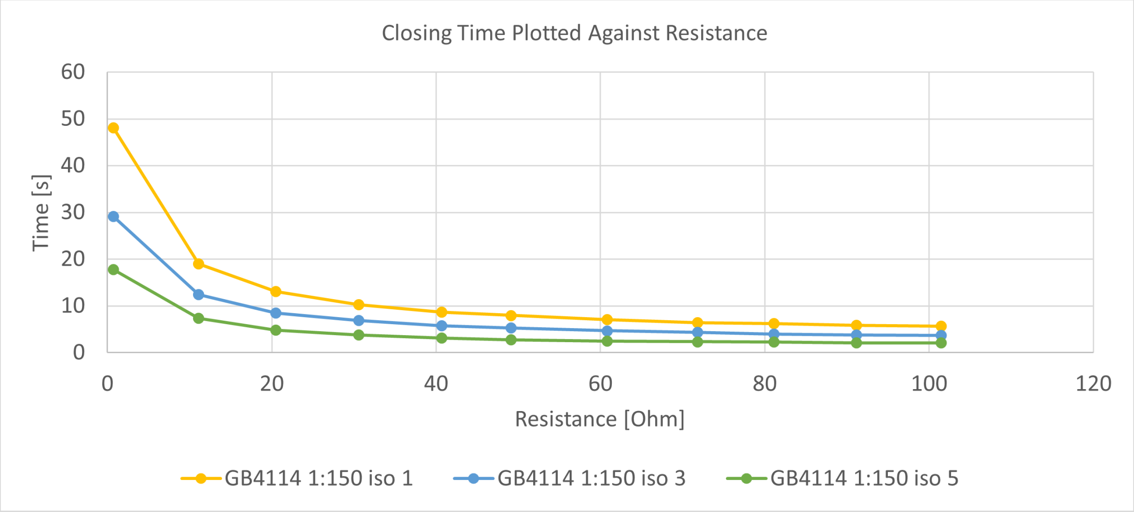
4.1.2 Raw Electrical Energy from Closing

The raw data from the test can be found in Appendix A. From the tests it could be seen that different resistances affected the closing times and the amount of generated energy, see Figure 19 and 20. Furthermore, when comparing the data between the spring settings, it could be seen that a higher spring tension resulted in shorter closing times and more generated energy.

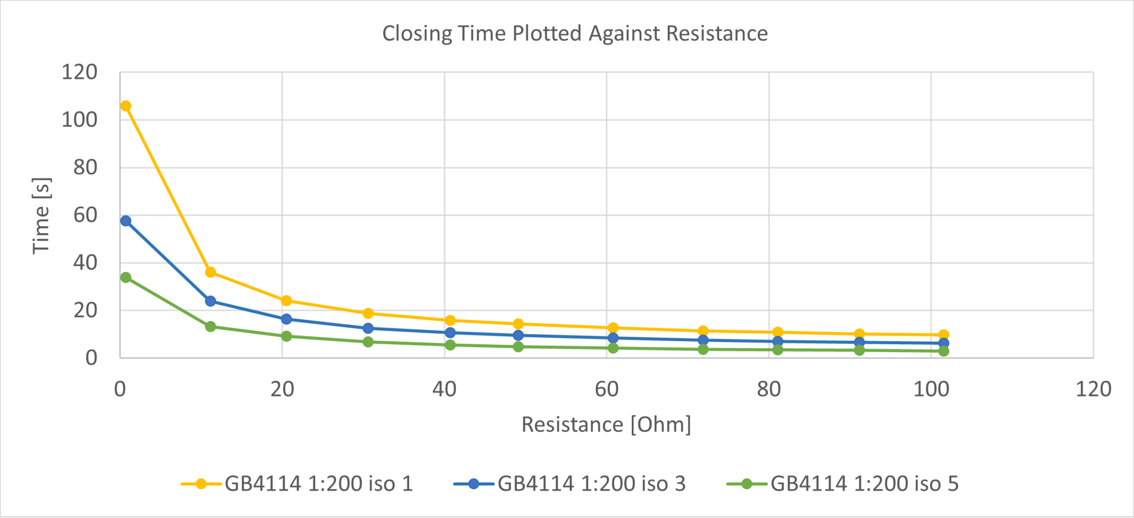
The prototypes all showed similar behaviors, see Figure 21. Specifically, the gearing and motor did not clearly affect the magnitude of energy that was generated, see Figure 22. However, the peak in energy appeared at different closing times, which is demonstrated in the same figure.



(a) GB2808 1:225

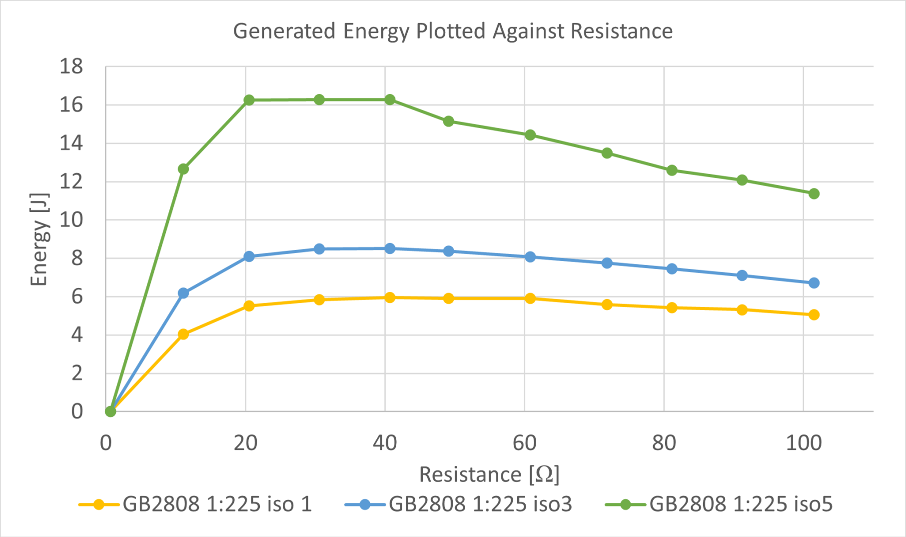


(b) GB4114 1:150

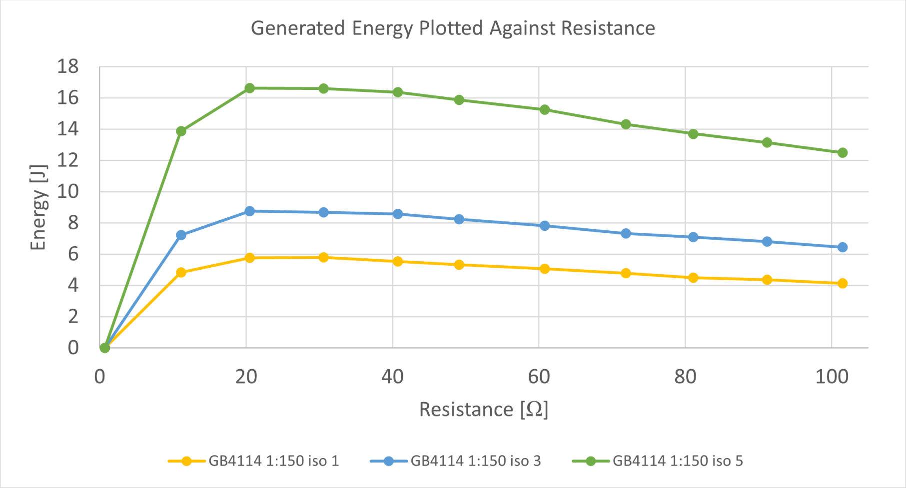


(c) GB4114 1:200

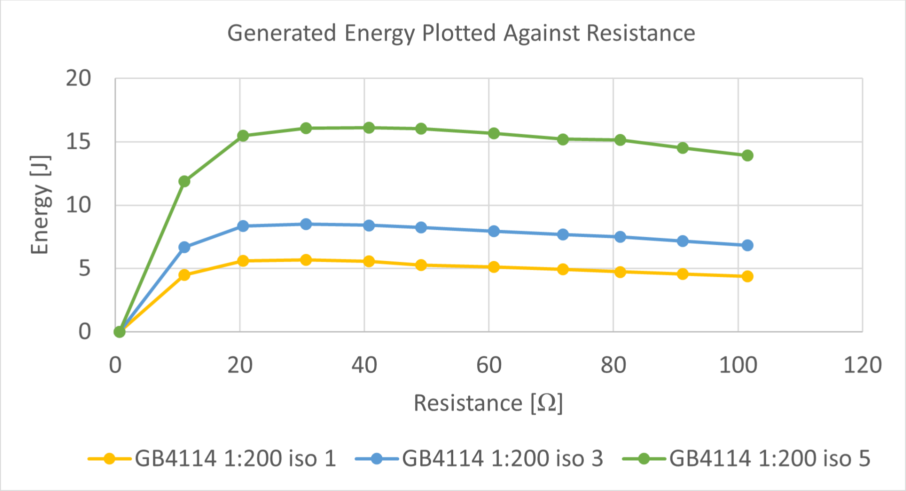
Figure 19: Closing times for different resistances depending on load.



(a) GB2808 1:225

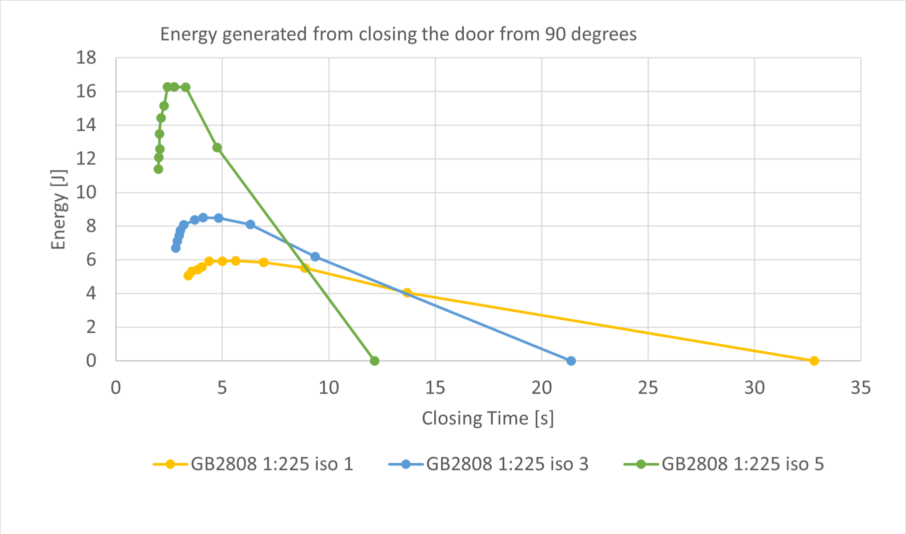


(b) GB4114 1:150

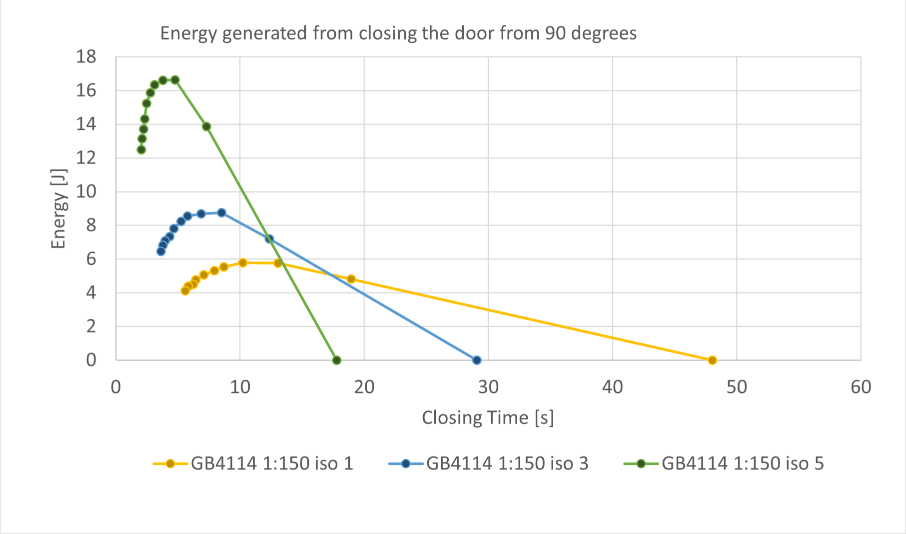


(c) GB4114 1:200

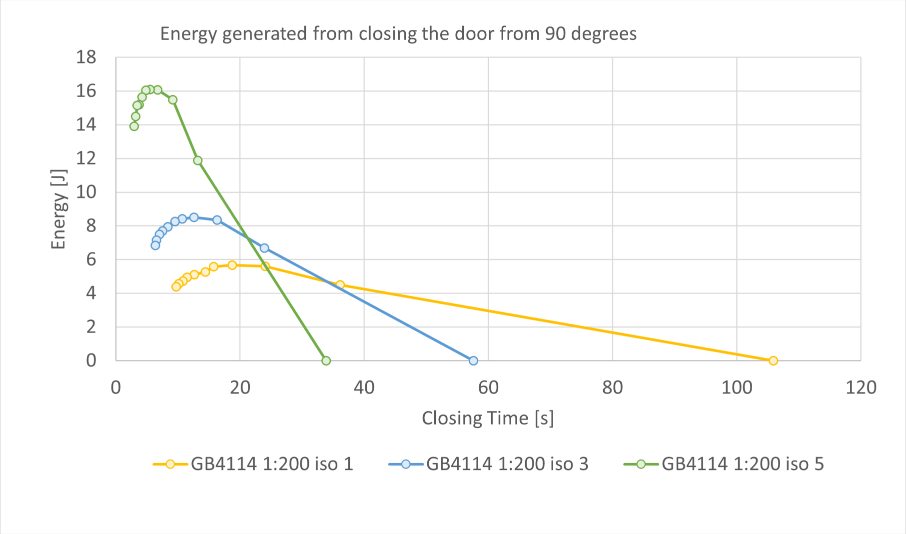
Figure 20: Generated raw energy depending on load.



(a) GB2808 1:225



(b) GB4114 1:150



(c) GB4114 1:200

Figure 21: Generated raw energy depending on total closing time.

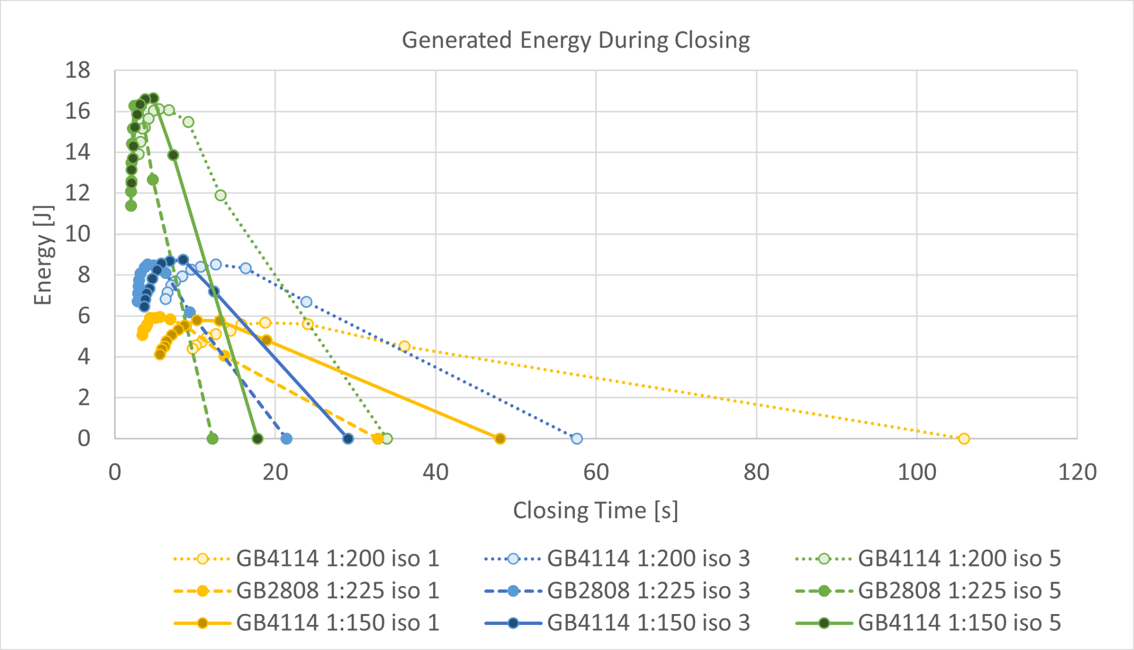
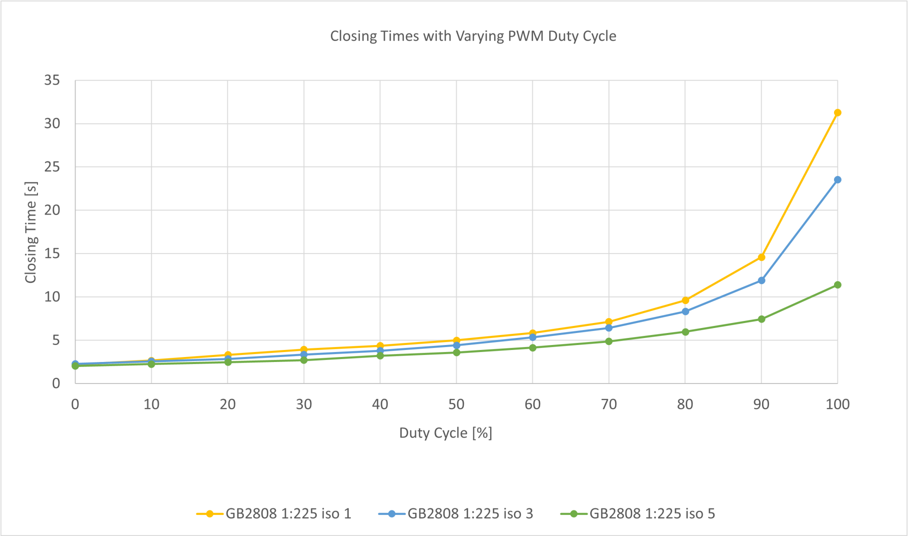


Figure 22: Comparison between prototypes and spring settings.

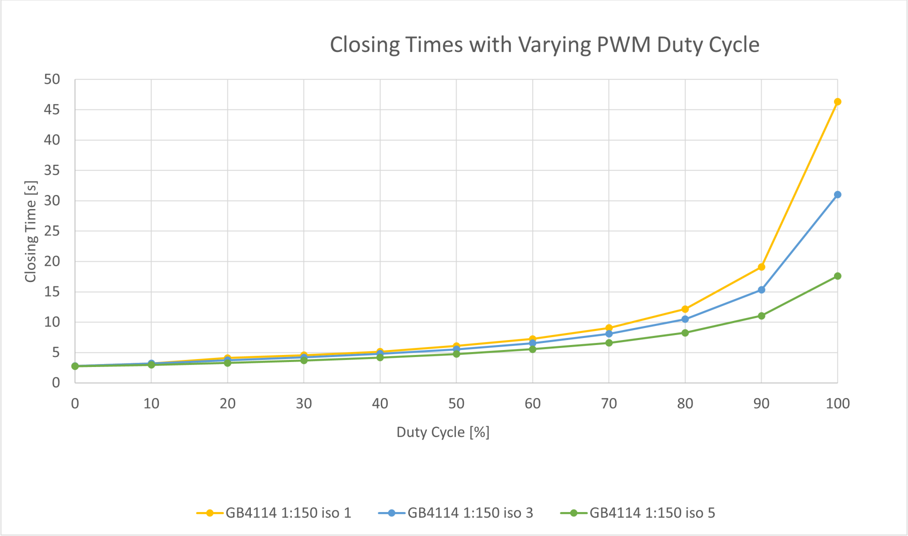
4.1.3 Harvested Electrical Energy from Closing

The raw data from the test can be found in Appendix B. The results from the energy harvesting tests reflected those from the raw energy tests quite well. The spring tension affected the closing time in the same manner with higher spring tension resulting in shorter closing times, see Figure 23. As expected, the measured amount of energy was often lower compared to the raw energy generated at the same closing time, which would be due to energy losses. However, this was not always the case and further analyzed in the discussion.

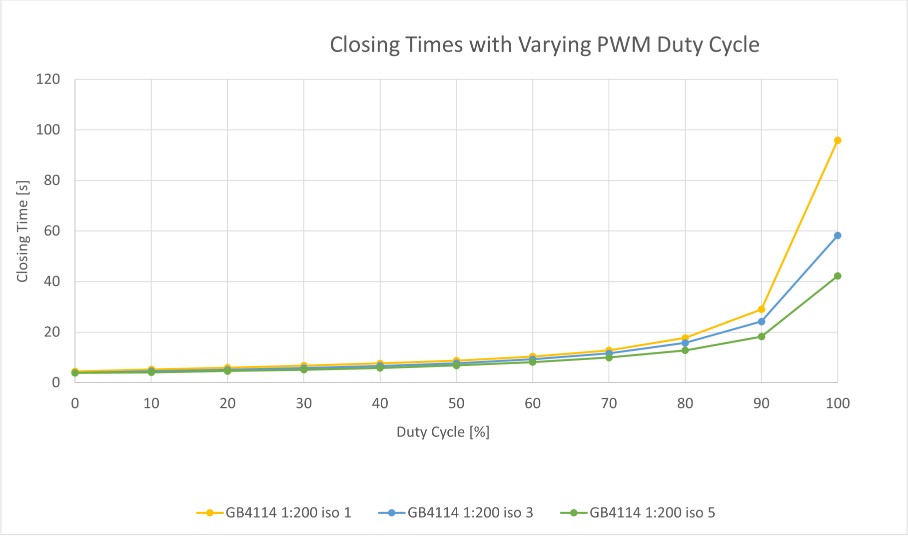
When comparing the results for different spring tensions for each prototype, it could be seen that a higher spring tension resulted in more harvested energy and that all prototypes showed similar behavior, see Figure 24. Similarly to the raw energy, the amount of harvested energy did not appear to be clearly affected by the gearing and motor as can be seen in Figure 25. However, the peak in harvested energy appears at different closing times and varies between the prototypes.



(a) GB2808 1:225

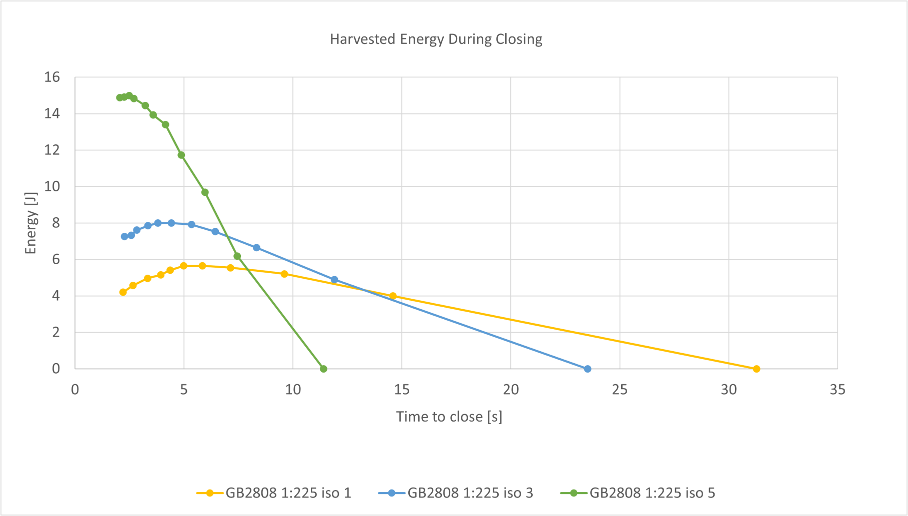


(b) GB4114 1:150

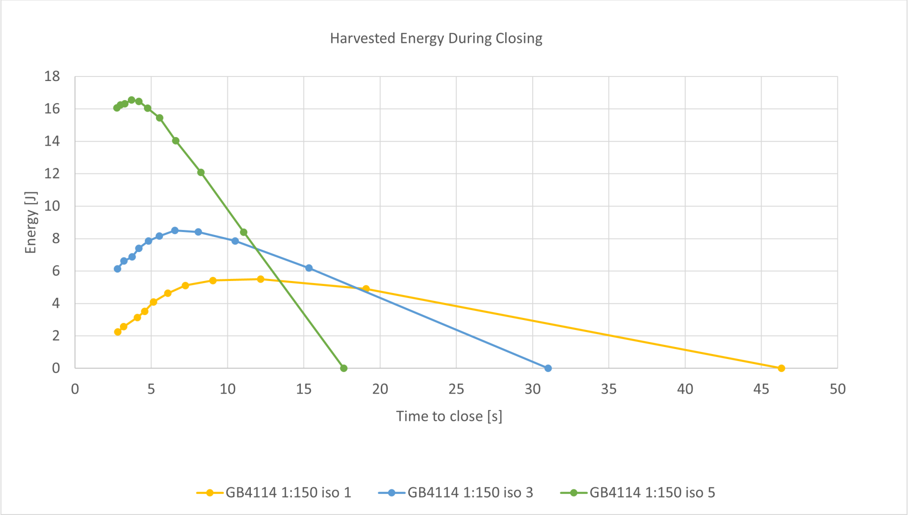


(c) GB4114 1:200

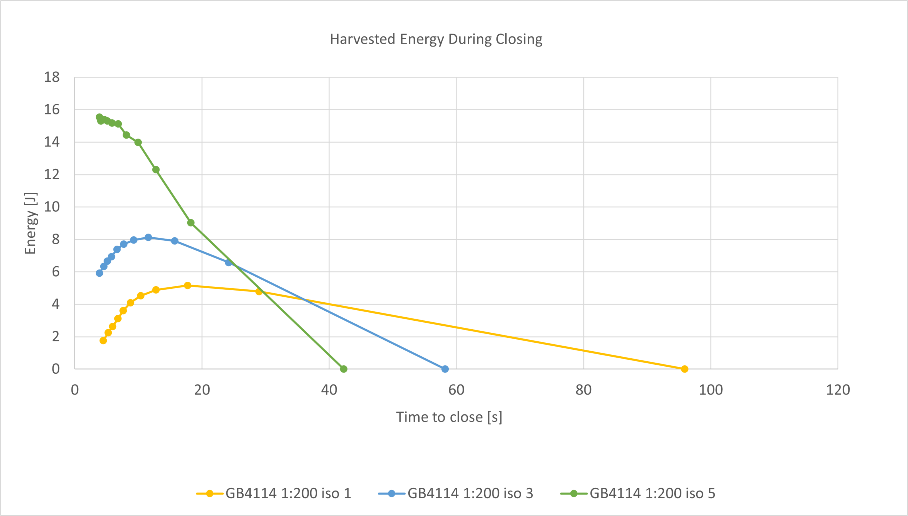
Figure 23: Closing times for different duty cycles depending on load.



(a) GB2808 1:225



(b) GB4114 1:150



(c) GB4114 1:200

Figure 24: Harvested energy for different closing times.

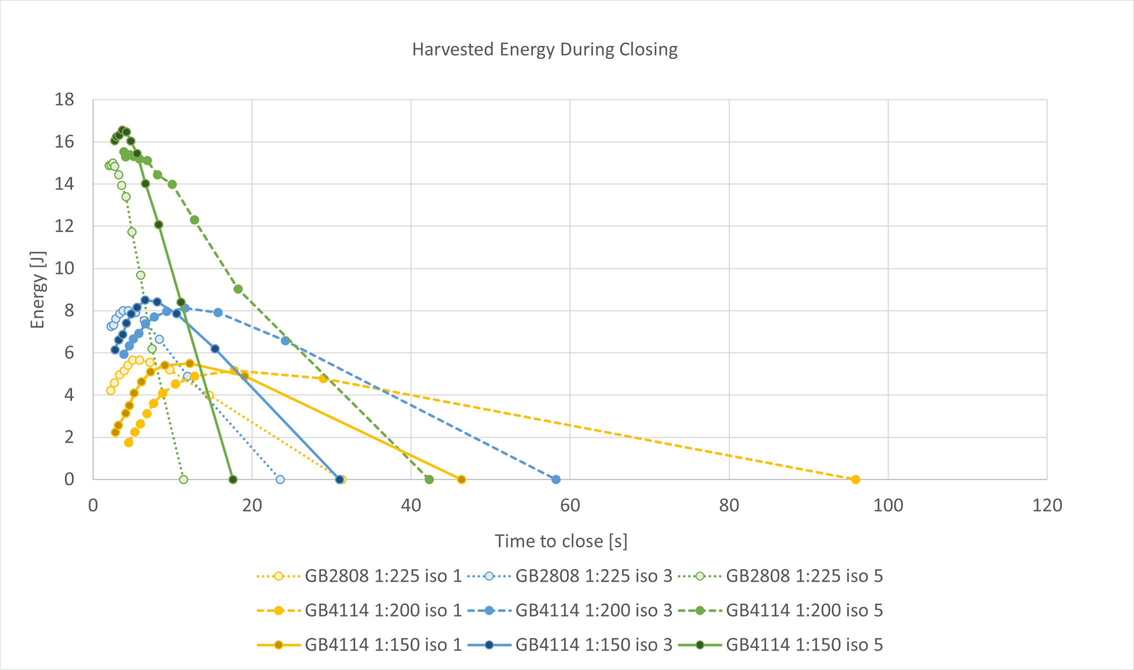


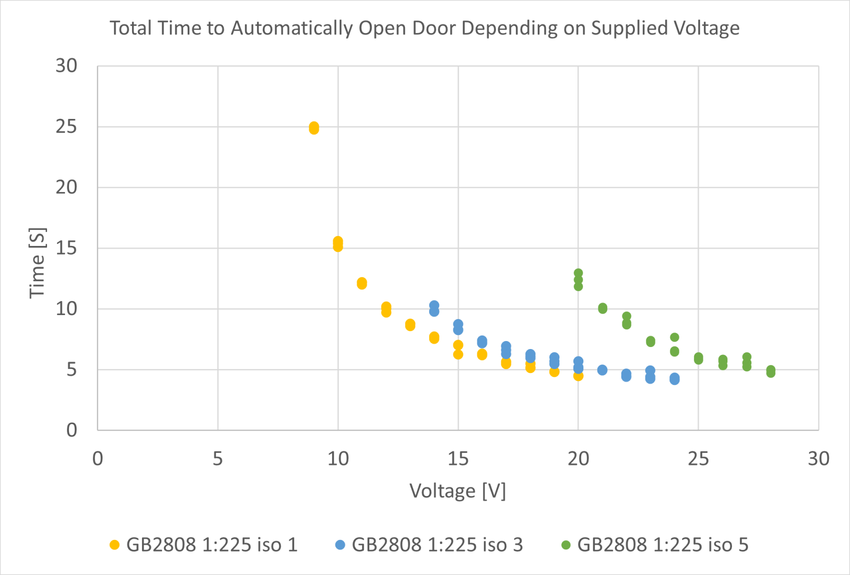
Figure 25: Comparison of harvested energy between prototypes and spring settings.

4.1.4 Energy Required for Automatic Opening

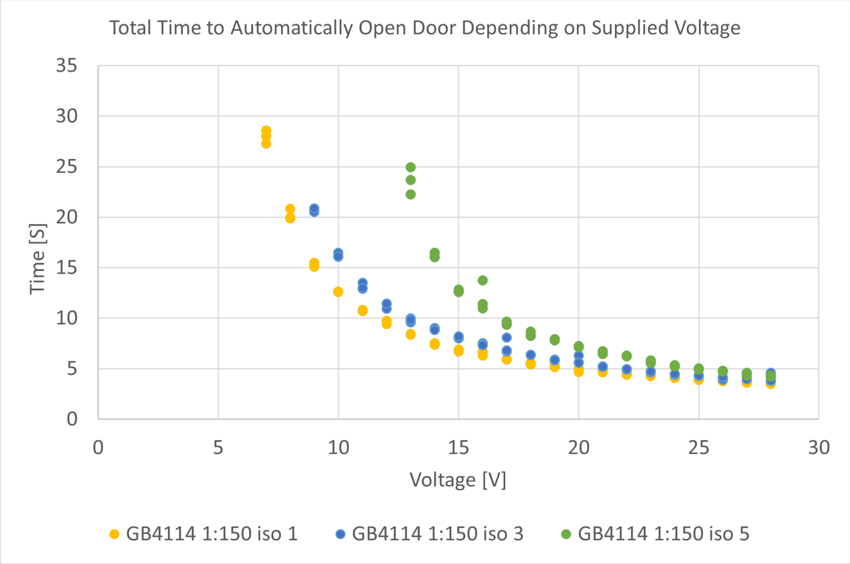
When using supplied voltage to automatically open the door to 90 degrees, it could be seen that a higher supplied voltage resulted in a shorter opening time, see Figure 26. In the same figure, it can be seen that the curve flattens out for higher voltages and seems to reach a minimum value. Both the value and the time at which this occurs differ between the prototypes and the spring tensions. In Figure 27, the amount of energy required to open the door for each voltage level is shown. It can be seen that the for the lowest voltages, the required energy is relatively high. With increasing voltages, the energy decreases up until a certain point after which the energy either stays constant or starts to increase slightly.

The energy required to open the door was in general lower for shorter opening times. For some combinations it could be seen that the required energy decreased to a certain limit but then started to increase again for the fastest openings, see Figure 28. Although this could not be seen for all setups, it is reasonable to assume that all prototypes would follow this trend when the opening times approaches zero seconds.

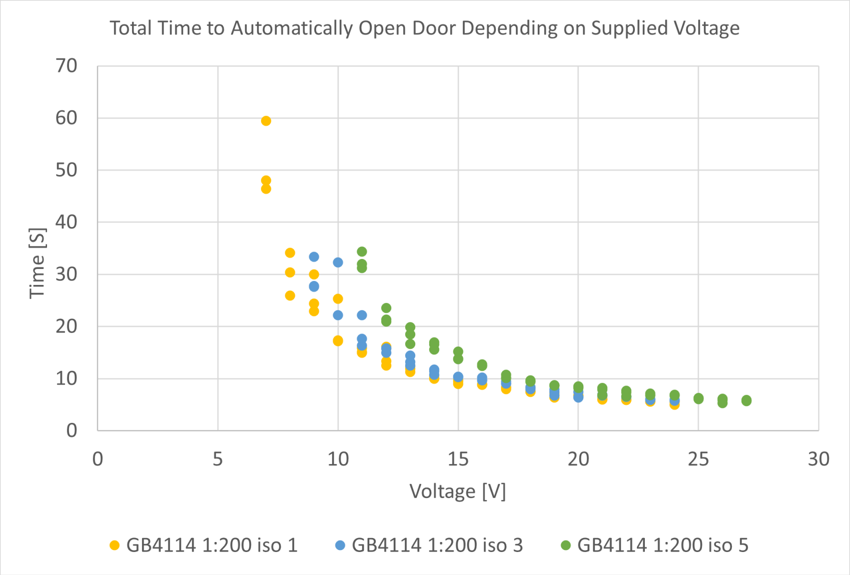
The opening times differed between the prototypes when the same voltage was supplied, see Table 4. While GB2808 1:225 and GB4114 1:150 followed approximately the same pattern, GB4114 1:200 consistently had a slower opening time.



(a) GB2808 1:225

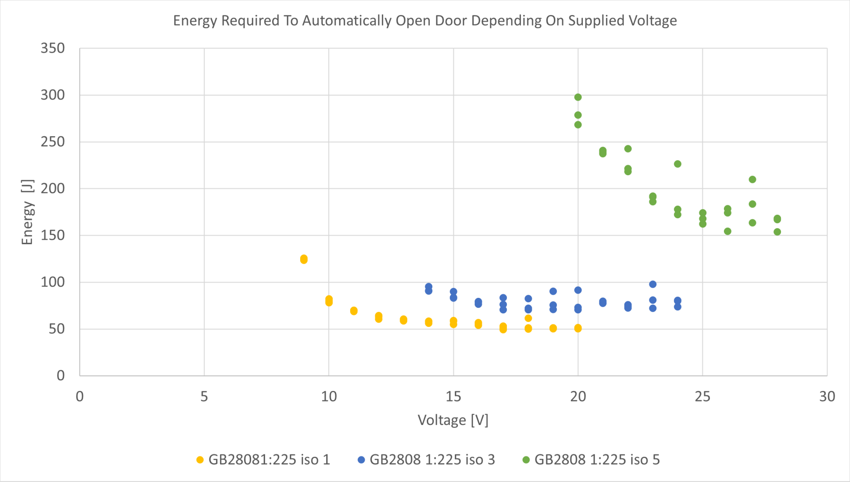


(b) GB4114 1:150

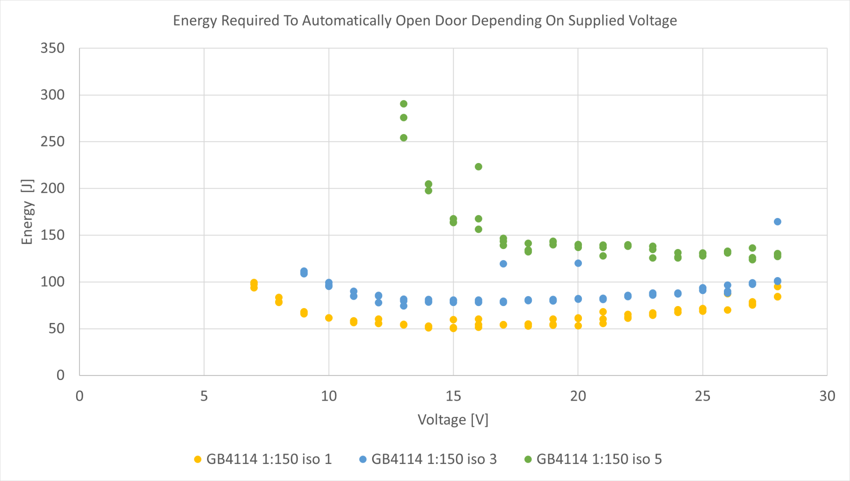


(c) GB4114 1:200

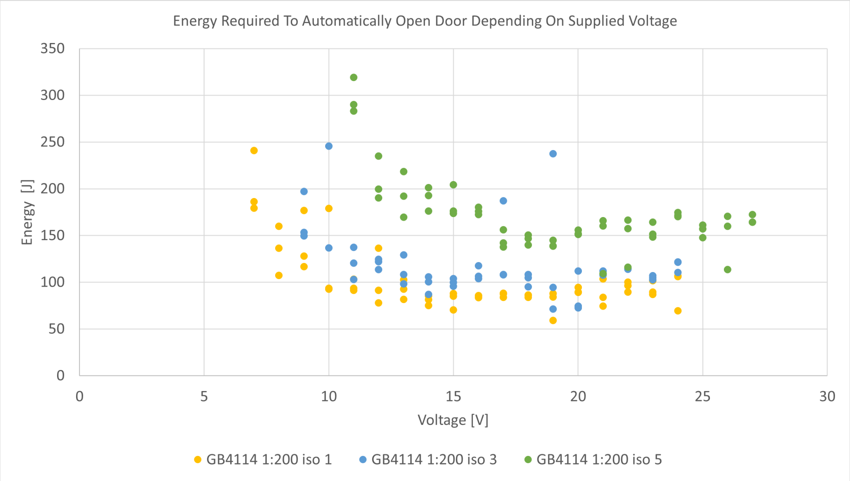
Figure 26: Total opening time depending on voltage.



(a) GB2808 1:225



(b) GB4114 1:150



(c) GB4114 1:200

Figure 27: Energy required to open door depending on voltage.

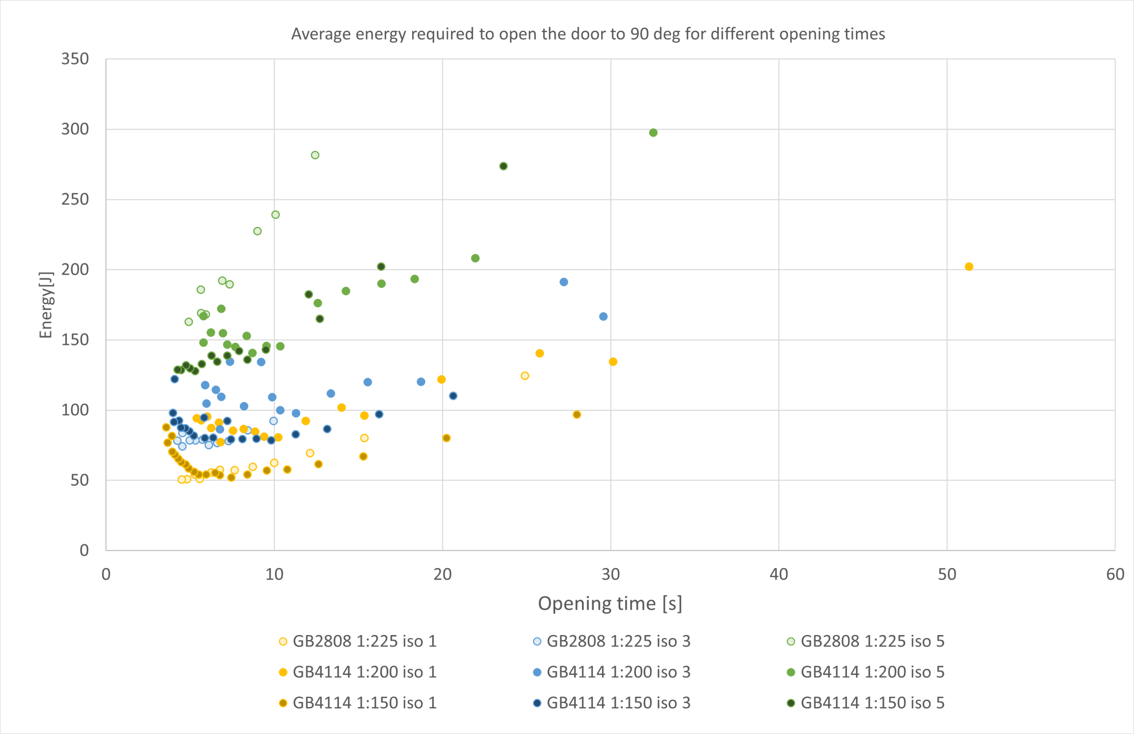


Figure 28: Results from testing the harvested electrical energy.

Voltage	GB2808 1:225	GB4114 1:200	GB4114 1:150
16 V	7.17-7.39 s	9.7-10.18 s	7.35-7.53 s
20 V	5.07-5.69 s	6.4-7.46 s	5.59-6.31 s
24 V	4.15-4.35 s	5.77-5.96 s	4.43-4.49 s

Table 4: Opening times for the prototypes set to iso 3 spring setting.

4.1.5 Energy Harvesting during Opening

When opening the door to 90 degrees with constant velocity during the full opening, it could be seen that a faster velocity resulted in more harvested energy. The maximum harvested energy during an opening is 38 J according to Figure 29 which is approximately four times higher than the maximum harvested energy from a closing. In these test, the harvested energy increased with shorter opening times.

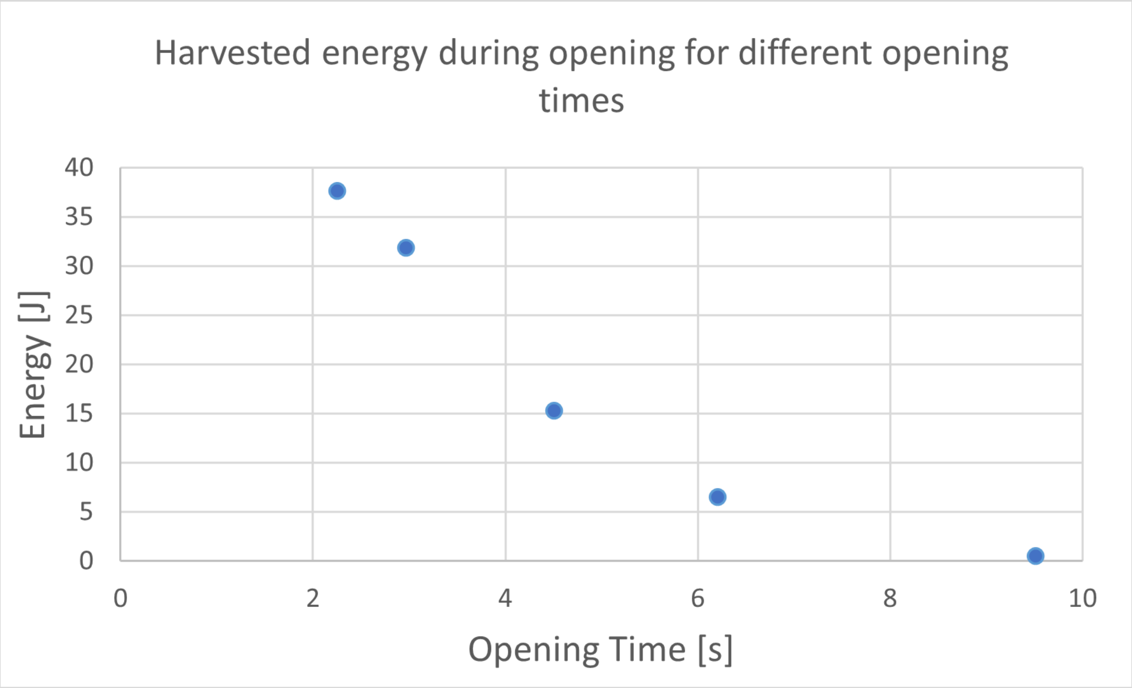


Figure 29: Results from harvesting energy during opening.

When also collecting data from the test program, it could be seen that the generated power seemed to increase with an increase in the motor's angle velocity, see Figure 30. Given the results from this, together with the data from Figure 29, it seems like a higher opening speed could generate more energy when harvesting during opening.

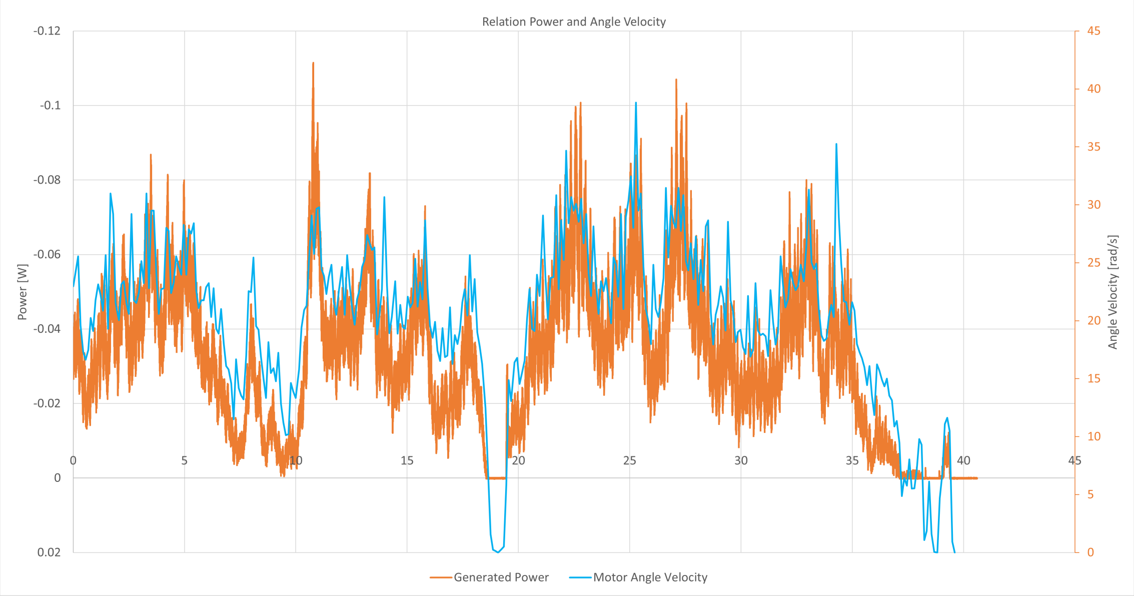


Figure 30: Relation between generated power and motor angle velocity.

4.1.6 Assisted Opening

The energy required to open the door with assisted opening using the GB2808 1:225 iso 3 prototype with different opening times, is demonstrated in Figure 31. In the same figure, the corresponding values for automatic opening can also be seen. Although not many data points were recorded during the test, it seems like less energy is needed for an assisted opening. There also seems to be an almost linear relation between the required energy and the opening time.

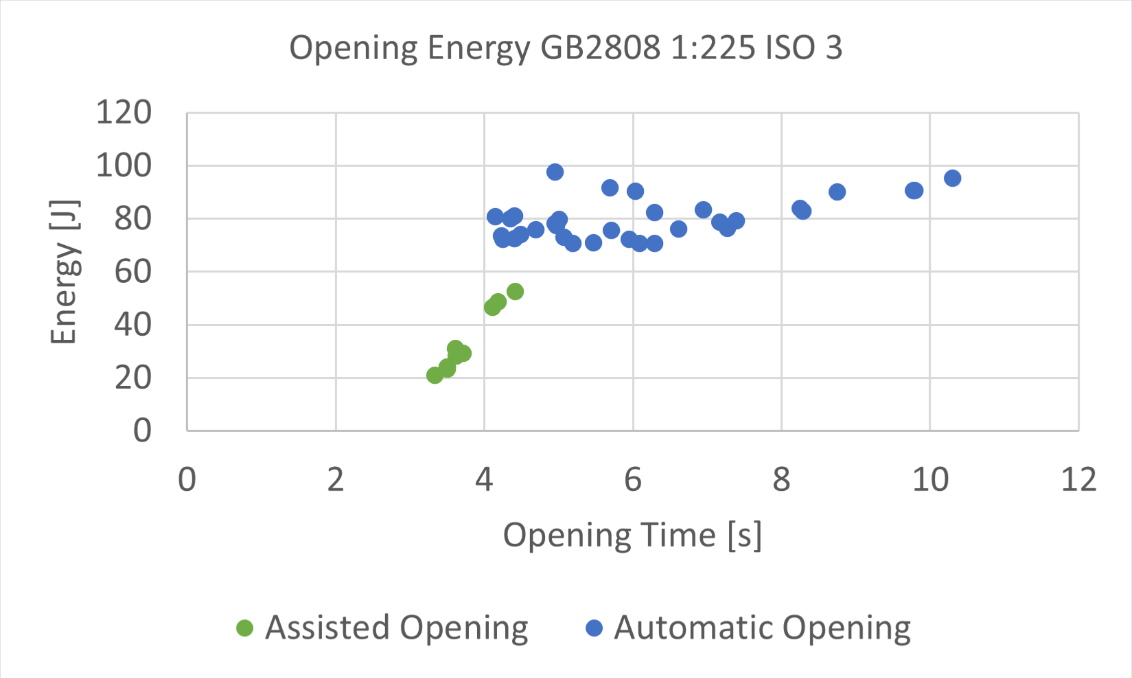


Figure 31: A comparison of the results between assisted opening and automatic opening for GB2808 1:225 iso 3.

4.1.7 Summary Test Results

From the data gathered in the energy tests it can be concluded that:

- More energy exists in the system with increasing spring tension.
- Approximately the same amount of energy can be harvested regardless of which motor-gear-box combination is mounted on the door.
- The optimal closing time to be able to harvest the maximum amount of energy does, however, vary between the motor-gear-box combinations.
- The energy required to automatically open the door seems to decrease with more rapid openings up to a certain point.
- There is, however, a considerable variance in the results when testing automatic opening.
- The motor-gear box combination GB4114 1:200 appears to be less efficient than the other two.

4.2 Analysis

4.2.1 Energy Losses

With the results from the energy tests it was possible to analyze where energy losses occurred in the system, see Table 5. The values varied slightly between the different prototypes but generally it can be said that energy losses seemed to be most evident in the mechanical system (gears, motor). It should be noted that some of the values are not completely coherent, such as the generator efficiency for GB4114 with gearing 1:150 and 1:200. The harvesting efficiency is also notably high but varies between the tests, which means that there is probably some uncertainty in the results. This uncertainty could come from, for example, the handling of the door during the tests or malfunctioning components and will be further analyzed in the discussion. Comparing the efficiencies between the prototypes therefore does not give any clear advantage to any motor-gear box combination over another but rather suggests that improvements in the mechanical systems can have the most impact.

Subsystem	GB2808 1:225	GB4114 1:150	GB4114 1:200	Source
Mech. closing energy	18.06 J	16.63 J	13.67 J	Measured
Gear box efficiency	66 %	70 %	70 %	Data sheet
Mech. energy to gen.	11.92 J	11.64 J	9.57 J	Calculated
Gen. efficiency	71 %	74 %	88 %	Calculated
Raw elec. energy	8.51 J	8.64 J	8.46 J	Measured
Harv. efficiency	94 %	98 %	96 %	Calculated
Harv. energy	8 J	8.5 J	8.12 J	Measured

Table 5: Energy losses and efficiency for harvesting in prototypes iso 3.

The same analysis can also be made for energy losses during automatic opening, see Table 6. Combined these tables show the efficiency of the system as a whole.

Subsystem	GB2808 1:225	GB4114 1:150	GB4114 1:200	Source
Mech. opening energy	34.34 J	36.85 J	42.97 J	Measured
Gear box efficiency	66 %	70 %	70 %	Data sheet
Mech. energy fr. motor	52.03 J	52.65 J	61.39 J	Calculated
Motor efficiency.	65 %	66 %	59 %	Calculated
Elec. energy to motor	80.04 J	80 J	104.2 J	Measured

Table 6: Energy losses and efficiency during automatic opening in prototypes iso 3.

4.2.2 System Efficiency

Based on the results in Section 4.1.3 and Section 4.1.4, the number of door closings with energy harvesting required to once open it automatically to 90 degrees could be calculated. To do this, the energy required for one automatic opening was divided with the harvested energy from one opening, see Equation 10. The harvested energy was set to the maximum found when letting go of the door from 90 degrees. It should however be noted that the actual energy that can be used to power the door would be lower since there will also be losses from energy storage. The required opening energy was set to be an average of all automatic openings with an opening time between 5-10 s, except for a few measurement points that were obvious outlier values, shown in Figure 27. The reason for choosing this time frame was that 10 s is a relatively slow opening and any opening times above that was not considered interesting. The lower limit stemmed from the fact that either the prototypes were unable to open the door faster than that or more energy was required beyond that point. Furthermore, the energy to open the door automatically was assumed to be proportional to the accumulated energy calculated from the force measurements in Section 4.1.1. Based on this assumption, it was possible to calculate the number of manual cycles of openings and closings required to once open the door automatically to *any* degree.

$$cycles = \frac{E_{opening}}{E_{harvested}} \tag{10}$$

For GB4114 1:150, the difference between the spring settings was compared, which is demonstrated in Figure 32. As expected, the number of closings is increasing at a steeper rate the first 20 degrees to overcome the high acting torque that ensures latching. While the results are similar to around the first 20 degrees, it appears as if a spring with higher tension might potentially be more effective under some circumstances.

It can also be seen that one automatic opening requires many more manual openings to be powered. Even with assisted opening, which requires less energy, one closing will not generate enough energy to power one assisted opening.

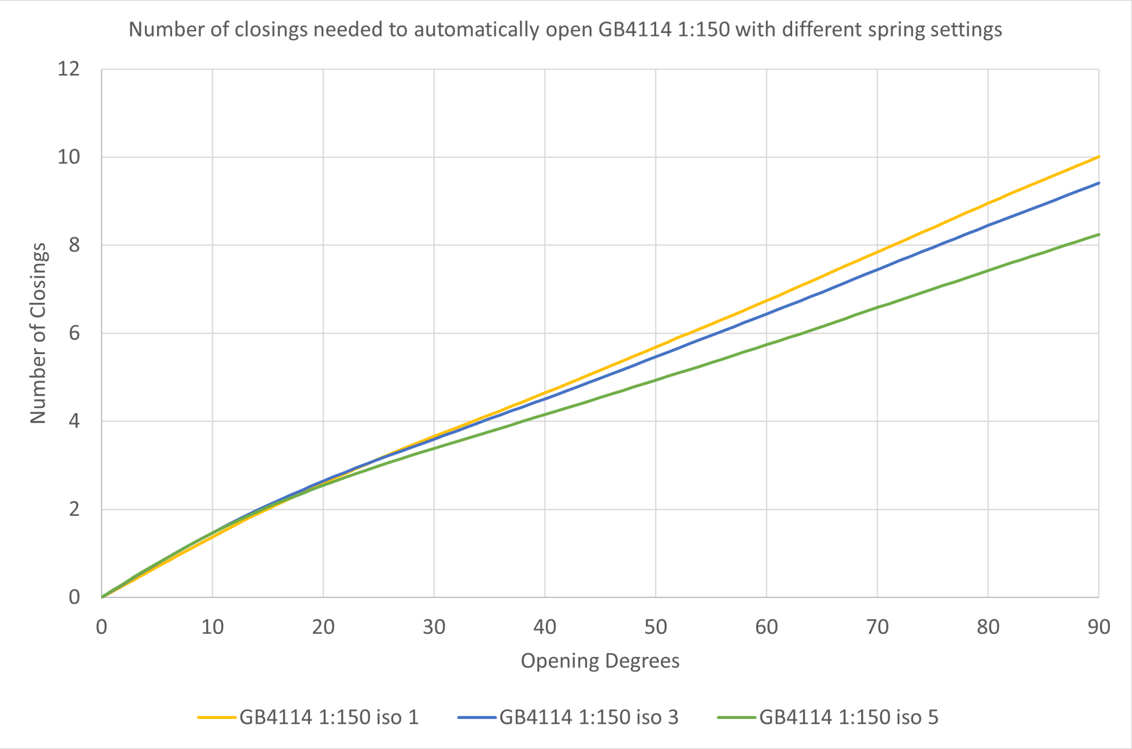


Figure 32: Efficiency comparison between different spring tensions for GB4114 1:150.

4.2.3 System Limitations

While varying the different parameters during testing, some limitations in the system were discovered. Using Equations 2 and 3 together with the results of 4.1.4, it could be determined that with 20 V supplied, the actual motor speed ended up being in the region of 40-70 % of the theoretical maximum speed due to the added load.

From the results from testing energy harvesting during opening, it seems like harvesting during opening can be an important source of energy with the potential of harvesting much more energy than a closing. However, the door was perceived to be very heavy compared to a standard door when harvesting during opening.

4.2.4 Test Case Feasibility

The test results provided some indication on which of the test cases would be more suitable to further investigate. One test case was the **fully automated opening** where harvesting was enabled during closing and then this energy was used to automatically open the door 90 degrees when a user in need of assistance needed to pass through. Based on the results of this project, this implementation would require at least 10 cycles of manually opening the door to 90 degrees and the door fully closing for one automatic opening. This was considered too inefficient and therefore this solution was deemed infeasible. A second, less energy draining test case was the **semi-automatic opening** where the door would be automatically opened to an angle less than 90 degrees after detecting a user in need of assistance. According to the test data, at least three manual openings to 90 degrees would be required to automatically open the door to 25 degrees (using the GB4114 1:150 prototype), thus sparing the user of the heaviest part of the opening phase. However, this is without taking energy losses from the storage into account. This was considered a more reasonable ratio between manual and automatic openings. The third test case was **assisted opening**. According to the test results, this could possibly require less than half the energy that an automated opening would need. Furthermore, if combined with energy harvesting during opening, energy harvesting could start if more energy than deemed necessary was added, while if less energy than needed to open the door was contributed, the door closer would aid in opening through the motor. Assisted opening was therefore also considered interesting to test further. The fourth option, **assisted opening to overcome initial torque** was not possible to test due to the control of the motor not being smooth enough for this test case, but it should require the least amount of energy seeing as assisted opening required less energy than automated, and semi-automatic required less than automatic.

5 Suggested Design

5.1 Suggested Prototype

Based on the energy efficiency tests there is no single answer as to which prototype would have been the most suitable for either energy harvesting or automatic opening. The motor gearbox combination GB4114 1:200 appeared to be the least efficient of the prototypes based on torque measurements and might therefore be less suitable to use. It was also the prototype which required the highest supplied voltage to open, which was a limitation since the system was designed to use 20 V. Furthermore, for this prototype, with the lower springs setting iso 1, the closing time when the maximum amount of energy could be harvested was close to 20 seconds, which is outside of what is acceptable according to ISO standards. The closing times with peak energies for the prototypes are demonstrated in Figure 33. Therefore, GB2808 1:225 and GB4114 1:150 appear to be better choices for this application.

With rather similar opening times, GB2808 1:225 and GB4114 1:150 both seem like reasonable choices if only taking the opening times into account. When it comes to harvesting during closing, GB2808 1:225 has its peak amount of harvested energy during a faster closing than GB4114 1:150.

Thus, GB2808 1:225 and GB4114 1:150 seem like the better options, both harvesting energy from closings and when using them for assisted opening. Both appear to be able to fulfill the ISO standards, so depending on the preferred opening and closing times, both of them would be qualified options.

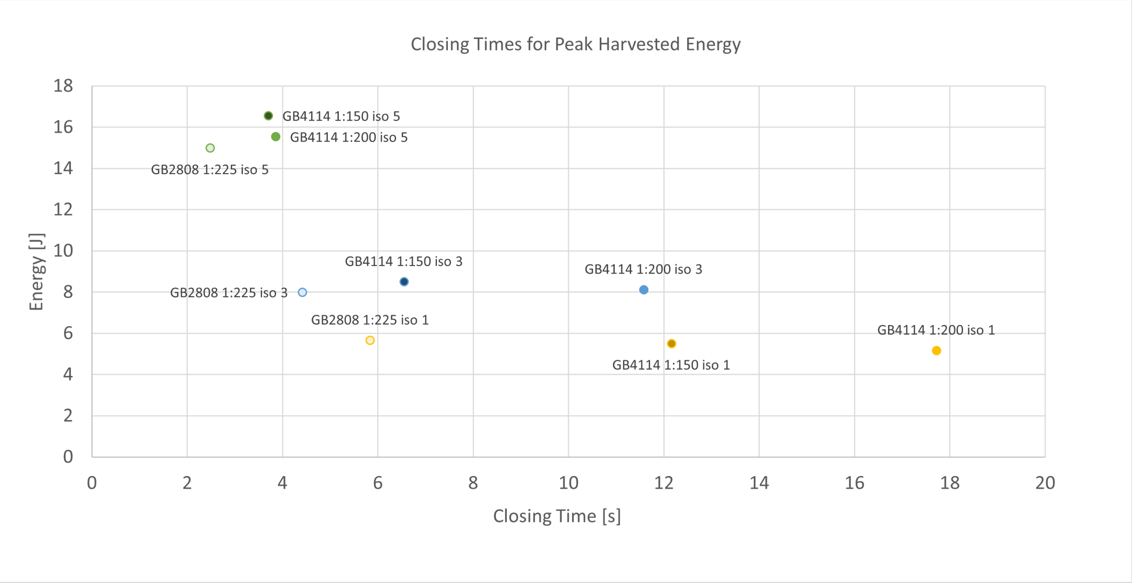


Figure 33: Closing times for peak harvested energy.

5.2 Suggested test case

After taking the system efficiency and future development possibilities into account, the proposed test case to look further into was the assisted opening. The tests made on assisted opening demonstrate that this solution might be energy efficient enough to be feasible. However, even with the lower energy consumption than some of the other test cases, the future product will need to be able to differentiate between users in need of assisted opening and those capable of opening the door themselves.

The idea was to implement a state-machine which would shift between five different "modes", see Figure 34. Firstly, the door is closed and the motor is turned off. As soon as the sensors detect that the door is moving, the idea was to try and identify users in need of assistance using the available sensors, which will be further described in Section 5.2.2. If the user is in need of assistance, the motor will go into "assisted opening" mode, which is further described below. After the user lets go of the door it will start to close behind them while harvesting energy. When the door is closed and latched, the energy harvesting will stop and the motor will be turned off. If, on the other hand, the user is identified as being capable of opening the door themselves, the door closer will work as a conventional one, however with energy harvesting during closing.

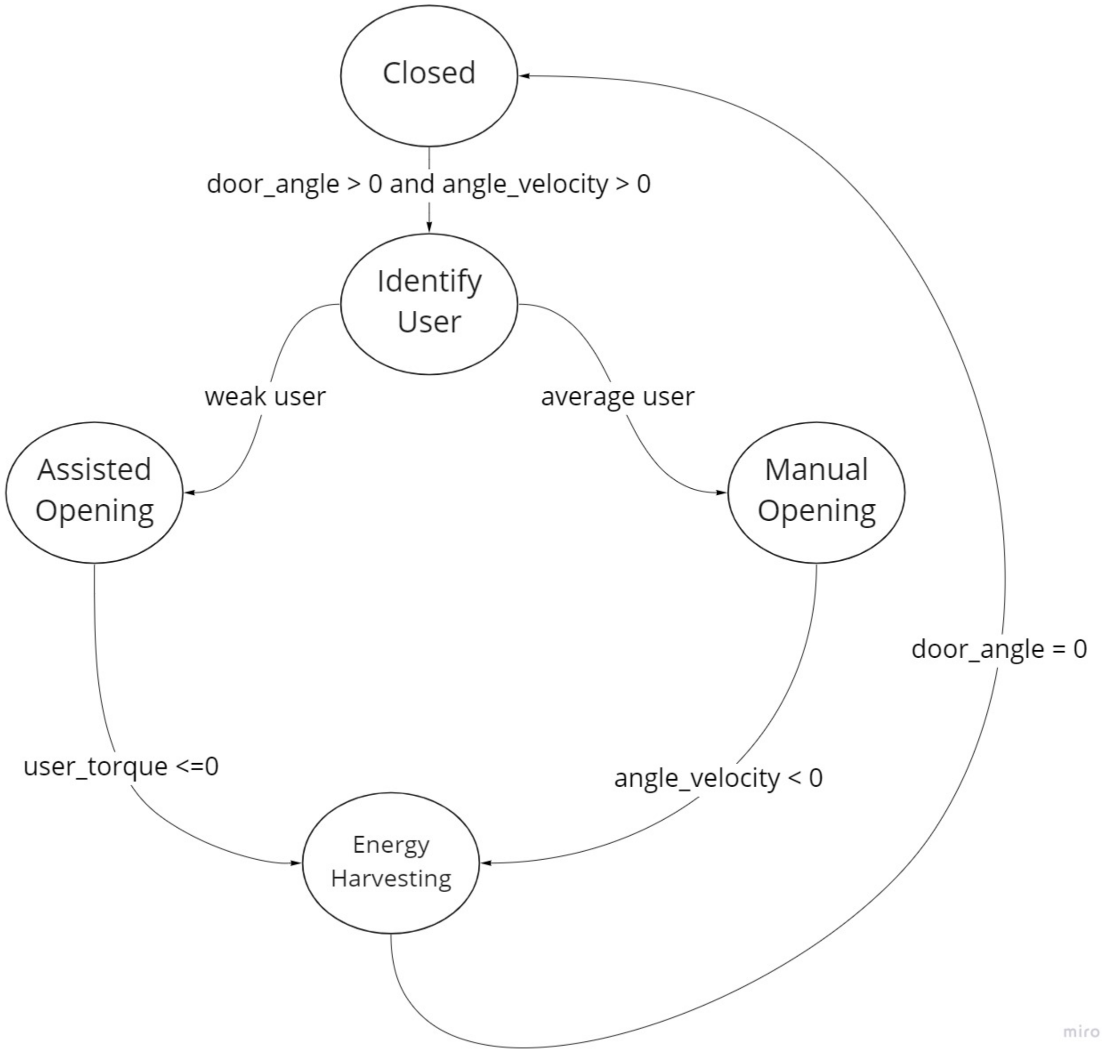


Figure 34: Flow chart of the opening and closing process.

5.2.1 Implemented Assisted Opening Algorithm

The proposed solution would be to implement assisted opening during the entire opening phase as an initial step to test the users' experience of this. The motor was controlled by a simple high-level algorithm stating that if the angle velocity became higher than the motor's own maximum angle velocity, then the new target velocity would be set to the actual one, see Algorithm 1. This was done to prevent the PID-controller controlling the motor from trying to brake the motion. After the door has closed and the system has returned to ”closed mode”, the target velocity would be reset to its initial value. While the algorithm proved to be sufficient to achieve an assisted opening, it could be developed to be more adaptable and energy efficient.

Algorithm 1 High-level control of motor velocity

```
$v_{target} \leftarrow v_{max,motor}$
if $v_{actual} \geq v_{target}$ then
    $v_{target} \leftarrow v_{actual}$
end if
```

To be able to detect when the user lets go of the door was a more complex task since the sensors could not differentiate between the torque/velocity coming from the motor and the torque/velocity added by the user. A temporary solution was developed, where the motor would stop to assist whenever the angle velocity dropped to a certain level at the same time as the control signal from the PID-controller was high. However, this resulted in some delay between the user letting go of the door and the motor turning off. To achieve a quick transition between assisted opening and energy harvesting in the state-machine, a better way to differentiate between the torque added from the user and the motor would be required, for example by measuring the torque in the motor.

5.2.2 Identifying Users in Need of Assistance

With the prototypes tested in this project, it is clear that the door closer will be unable to assist every user that wants to go through the door unless energy harvesting is also widely used during the opening phase. The second option would be to only allow assisted opening whenever a user in need of assistance is detected. With the current setup, the sensors that could be used to identify users was limited. The only input to the controller was the door angle, encoder angle, angle velocity, and time. For this test case, the angle velocity was used to identify the users. If a user opens the first degrees of the door slower than a selected time, the user is assumed to be a user in need of assistance. With the current setup, only integer values from the potentiometer was used to determine the door angle. This meant that the door needed to be opened one degree for the state machine to initiate the ”identify user” mode. Then, at least one degree was needed for the identification. Consequently, this required the user to be able to open the door at least two degrees without assistance. The solution also relies on the assumption that a user in need of assistance is also a slow user, which might not be the case. To have a more robust identification, it is suggested that additional sensors are used, for example a pressure sensor in the door handle. Another less robust solution would be to at least have a potentiometer capable of communicating the door angle in decimals.

5.2.3 Decreasing Energy Consumption through Improved Control

With the implemented version of assisted opening, the PID controller is not especially optimized and the system does not act in an energy efficient way. As soon as the actual velocity exceeds the motor’s maximum velocity, the target velocity will remain unattainable for the motor without the added force from the user. This means that if the user then starts to contribute with less energy, the control signal, or supplied current, will be set to its maximum value in order to attain the correct speed. This waste of energy could easily be eliminated, without noticeably changing the behavior of the door closer. If instead, the target velocity is continuously adjusted to follow the user's velocity, the energy consumption would decrease since the control signal would not "max out". A suggestion for this implementation is demonstrated in Algorithm 2. Another solution for optimizing the energy consumption of the system would be to use a different controller than the PID, seeing as it is only reactive and is unable to predict how the torque acting on the door might change. Model predictive control can for example be used to optimize a current time-slot while keeping future ones in mind. With any of these solution, it might even be unnecessary to separate users in need of assistance from users without need of assistance. However, due to time constraints, this suggestion was never tested.

Algorithm 2 High-level adaptive control of motor velocity

```
$v_{target} \leftarrow v_{max,motor}$
while $\tau_{user} > 0$ do
    $v_{target} \leftarrow v_{user}$
end while
```

6 User Experience Test

With the prototype set up to follow the processes outlined in Figure 34, user input was considered through a minor user experience test. The purpose of this test was to gather some data that could be used for further development of the system and functionality.

6.1 Methodology

The test was carried out with ten test subjects without any prior knowledge about the prototype. The number of test subjects was decided based on findings that most usability problems can be found when having between five and 15 subjects in a study [20]. Normally, none of the test subjects would be considered users in need of assistance, so to be able to test the automatic door opener, the test subjects were instructed to carry a large box. Each subject was given a brief introduction to the test and was then asked to walk through the door a couple of times from alternating directions. Five subjects began the test carrying the boxes and were then asked to repeat the test without boxes, while the other five began the test without boxes and were then asked to repeat the test carrying boxes. If no assistance were needed even with the boxes, an additional item for them to carry was added and the test was repeated. After the practical part of the test was completed, an interview was conducted in which the test subject was asked a number of questions about the experience. The results were then used to suggest future improvements.

6.2 Result

The answers from the test subjects could be summarized in the following list of opinions, each mentioned by at least one test subject:

- The door is unpredictable and it is difficult to comprehend how the assisted opening can be activated.
- The sound of the door is loud and unpleasant.
- It would have been desirable to also receive assistance during the first degrees of opening when the box was carried.
- The door is slightly heavy to open.
- Opening the door manually and without boxes works well.
- It should be possible to close the door manually immediately after walking through it.

Apart from that, the following was concluded from observing the tests:

- All test subjects were able to get through the door in every test.
- It seemed to be easier to use the door when pushing it open rather than pulling it open.

7 Discussion and Conclusions

7.1 Sources of Error

Various sources of errors affected the test results in this study, some of which are presented below.

7.1.1 Component Breakage

A few times during testing, an electronic component would become overheated and break. This was mainly due to the lack of over voltage protection in some stages of the testing and because some components were only suitable to use at maximum 20 V. The lack of protection was subsequently resolved but it is likely that components did not work as expected right before the breakage, which would then be a source of error in the results.

7.1.2 Prototype Assembly

When assembling the motor, encoder and gearbox, it was unavoidable to get unwanted friction between the parts, especially since the mechanical parts were not from the same brand and had to be attached using 3D-printed connections. It was also difficult to perfectly align all the vertical axes of the system. Therefore, it might be misleading to compare the prototypes with each other.

7.1.3 Test Methodology

With the current setup, it was not possible to measure the energy losses in different parts of the system during the same closing. This means that it cannot be guaranteed that the test environment and test setup were exactly the same for the different tests, which can lead to differences in the results. Factors such as temperature of the motor and electric components can affect the result and disturbances and wear of the mechanics can change between tests. The measurement tools could also potentially influence the results. To get more accurate results, the number of samples could be increased and the harvested energy could be tested immediately before and after the raw energy test to limit the differences. Furthermore, the results from the automatic opening tests are not fully comparable since the entire voltage span could not be tested on all prototypes and spring settings. For example, GB2808 1:225 was only tested up until 24 V when a diode broke. It was then exchanged for a diode capable of withstanding 30 V, which subsequently meant that higher voltages could be tested on the remaining prototypes. The consequence of this is that it was not possible to establish a perfect relationship between opening times and energy consumption.

7.1.4 Test Repeatability

The energy harvesting during opening test was carried out by manually opening the door and could not be conducted repeatedly in a controlled manner with the available equipment. This was largely due to the fact that the amount of energy possible to harvest would vary depending on, for example, the speed and force of the opening. The test was performed by attempting to open the door with a constant velocity, but it was not possible to keep the velocity completely constant during all stages of the opening when opening by hand. Furthermore, the opening in a real scenario would very likely not be near constant but rather have a large acceleration in the beginning of the opening and a lower velocity towards the end of the opening. By testing a number of different velocities that were assumed to cover the minimum and maximum velocity from a real scenario opening, the results gave an idea about how much energy could be harvested during an opening. Correspondingly, the test result of the required energy for assisted opening would depend on the force that the user added during the opening and could not be carried out reliably with the available equipment.

7.1.5 User Experience Test

Firstly, the user experience test was performed on a very small scale, which limited the amount of feedback received. Secondly, it proved to be more difficult than expected to make the test persons temporarily in need of assistance. The test was conducted by temporarily giving them boxes to carry. This did indeed put them in a situation where they needed assistance to open the door, however, their biggest problem was how to grasp the handle and unlatch the door. This was not the problem that was aimed at being solved in this project and would probably be easier solved with an automatic door triggered by a push button. This test case was instead aimed to solve the problem for users who struggle to use enough force to open the door but have their hands free to use the handle, for example, elderly people. This resulted in some test subjects not finding the assisted door opener very helpful when carrying the boxes. Even if the intended function was not fully tested in this test, the test was very useful to verify the manual opening, which operated as expected.

7.2 Conclusions

One of the goals with the project was to study and test the energy efficiency for the electromechanical system and motor drive. The energy efficiency of the motor drive and the harvesting circuit was tested for three different motor gearbox combinations. Several different variables that were believed to possibly affect the efficiency were also tested. From the results, it could be concluded that most energy losses occurred in the mechanical system and that this is where there is most room from improvement. It was also concluded that the ratio between the manual openings needed for one automatic opening was around 1:10 for all prototypes, not taking losses from energy storage into account.

Another goal was to compare the results from energy harvesting tests to results from assisted opening tests. Since the results from the automatic opening test were considered to be more reliable than those for assisted opening due to the larger number of data points and repeatability of the test, the most relevant comparison was made between the energy harvesting test and the automatic opening tests. From the results, it could be observed that it was possible to harvest approximately the same amount of energy from all prototypes. However, the peak in possible energy to harvest occurred at different closing times. The same principle was applicable to the energy required to automatically open the door with the different prototypes. However, in this case, the voltage needed to open the door at a certain time showed that GB2808 1:225 and GB4114 1:150 were more suitable. The results from assisted opening were also considered and analyzed. An analysis including trade-offs was made according to the goal, and based on it, recommendations for future work was made.

The third goal was to test and analyze the possibilities to harvest energy during opening. After some initial tests, it was concluded that it might be possible to harvest more energy from an opening than from a closing. However, seeing as the door opener is perceived as rather heavy according to the user experience test, even without the added load from energy harvesting, this has to be implemented carefully.

The last goal was to investigate solutions regarding controlled assisted opening and then create a test case for that assisted opening. Four different test cases were made for assisted and automated opening. Two of them were implemented and tested with regard to energy efficiency and one of them was used in a user experience test. The possibility of identifying a user in need of assistance was investigated and discussed. From an energy budget perspective, it could be concluded that the system would probably still need to be able to differentiate between users with and without need of assistance, since the energy from one closing would not be sufficient to support one assisted opening in the current implementation. However, with more sophisticated algorithms and possibly energy harvesting during opening, there is potential for a door closer that can assist every user during some phase of the opening. From the user experience test it could also be concluded that while the functionality of an assisted opening was appreciated, any future implementation needs to be more predictable. One criticism that was common amongst all test subjects was that it was too difficult to trigger the assisted opening. While it would be optimal from a user experience perspective to have the door closer assist every time, this is not possible energy-wise with the current system.

7.3 Future work

Efforts to replace the hydraulic-mechanical door closer with an electric one that can harvest energy has only just started. Therefore, following this report, there are multiple areas of interest that could be further explored. An area that plays a crucial role in a door closer capable of energy harvesting is energy storage. This needs to be further investigated to determine how feasible any added functionality actually would be. Different storage methods should be investigated, and the energy efficiency of the chosen solution should be tested to see how it affects the overall energy efficiency of the system. It would give valuable insight to test the system as a whole and evaluating its performance. Apart from the energy efficiency, important criteria for a storing solution would be size and what voltage would be suitable to power assisted opening.

Apart from completing the design of the product, some issues where discovered with the system in general. Based on the feedback from the user testings in Section 6, one important area for future work is the sound, which was found to be loud. Another conclusion from the user tests is that the door is perceived to be slightly heavier than other doors. The current ISO standards for door closers are specifically designed for hydraulic door closers and thus not fully applicable to this prototype. Future work would need to include investigating what ISO standards apply and suitable adjustment would have to be made to the prototype.

In this project, no cost analysis was made and at a later stage of this project, a thorough cost analysis should be performed. Furthermore, the suggested test case presented in this thesis should be iterated upon. The algorithms developed to identify users in need of assistance and to control the motor only consist of basic functionality and in a commercialized product, the assisted opening should both be more adaptable and predictable. While the current system and algorithms does not support assisting every person that wants to pass through the door, it would be interesting for future studies to see if such an implementation is possible to achieve.

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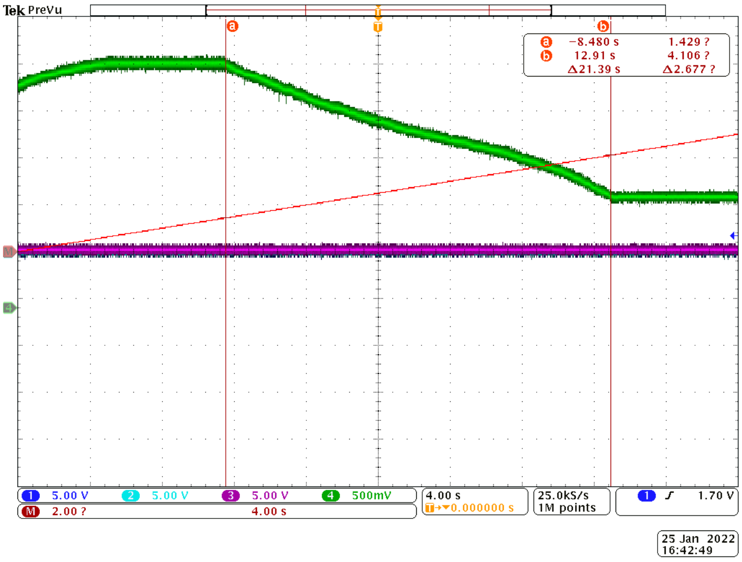
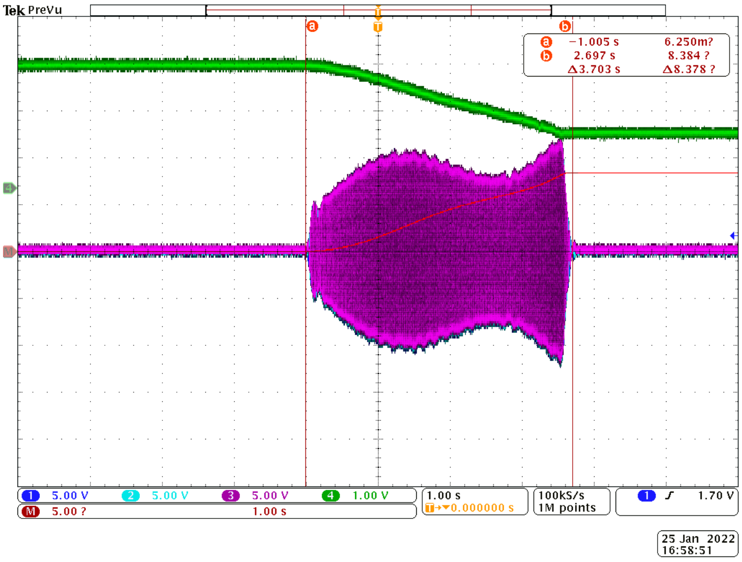
Appendix A

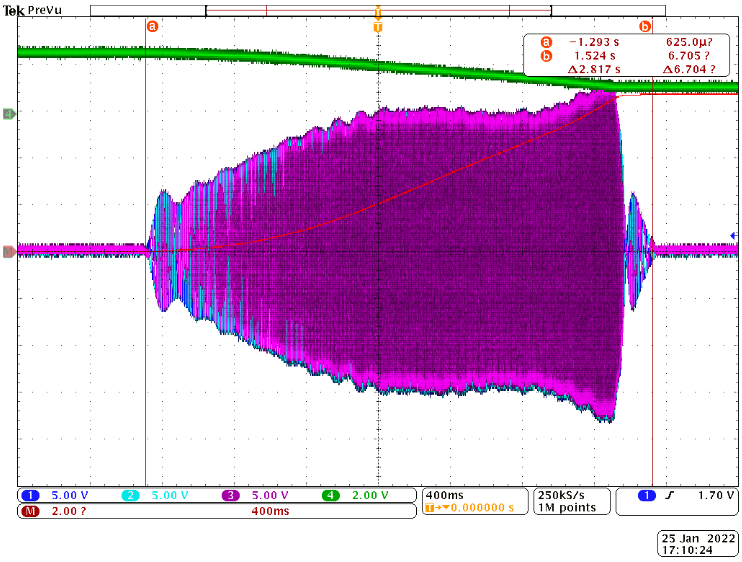
The figures in this Section are supplementary to Section 4.1.2. The raw oscilloscope readings from the test on all prototypes and spring settings are demonstrated. The results are shown for resistances 0.7, 49.1 and 101.5 Ω. Values in between follow the general trend demonstrated by those resistances. Note that the magnitudes of the axes are changing between some of the graphs to fit all data in the same window. The (in most windows) green line shows the potentiometer output, i.e. the angle of the door. The door starts at 90 degrees and then closes at 0 degrees. The visibly purple graph (in most windows) shows the voltage over the three phases connected to the motor (blue, cyan and purple curves). The vertical lines a and b enclose the closing period. The red line represents the calculations in Equation 8 and the final results can be seen in the upper, right window in the figures. The value for the total energy is found in the lower, right corner of the window. As can be seen in Figure 36a, no energy is generated without a load. However, due to integration errors in the oscilloscope the results still show up as $E > 0$, which is neglected in the rest of the presentation of the results.



(a) $R = 0.7\ \Omega$

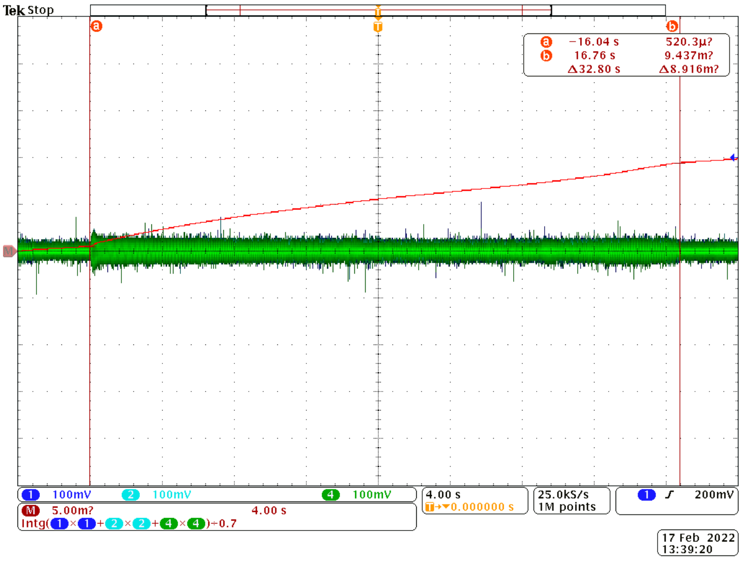


(b) $R = 49.1\ \Omega$

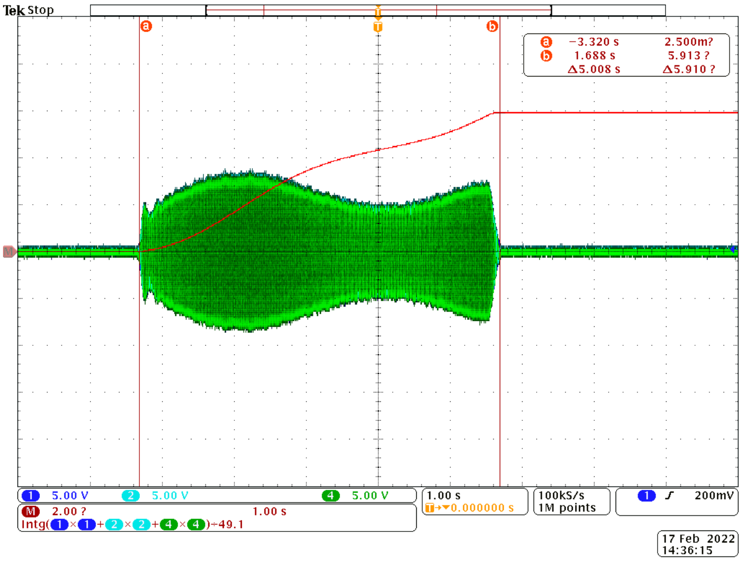


(c) $R = 101.5\ \Omega$

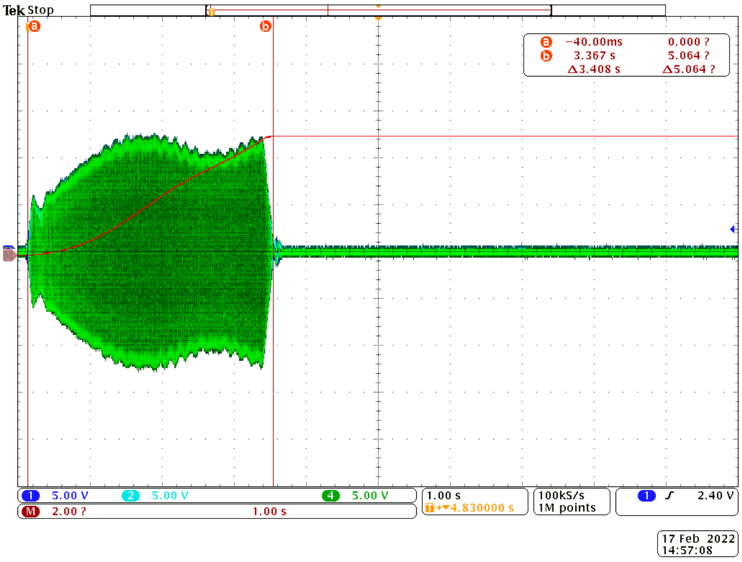
Figure 36: Oscilloscope readings of raw energy GB2808 1:225 iso 3.



(a) $R = 0.7\ \Omega$

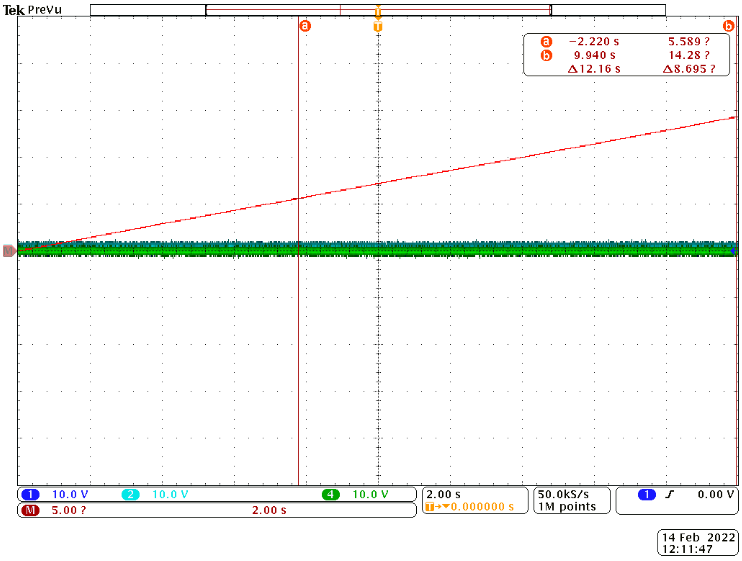


(b) $R = 49.1\ \Omega$

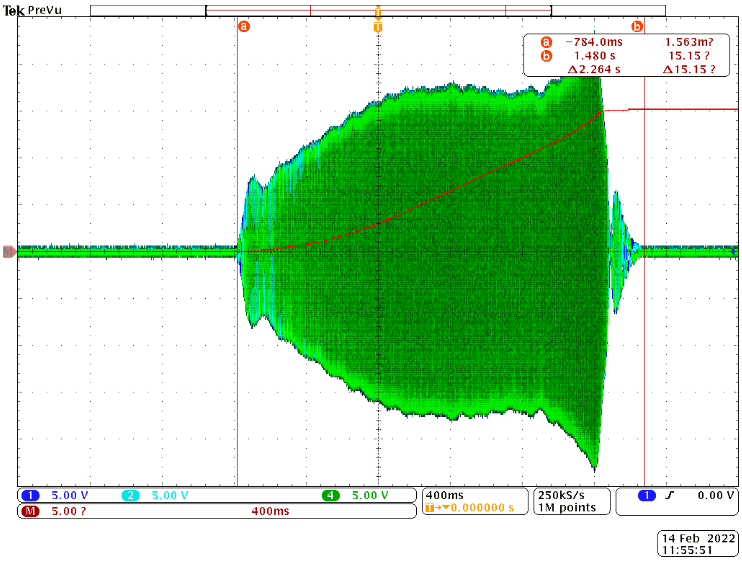


(c) $R = 101.5\ \Omega$

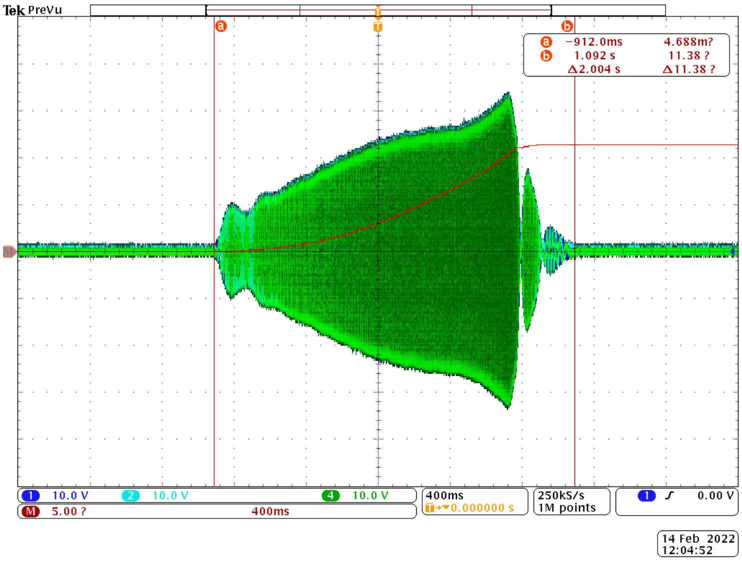
Figure 35: Oscilloscope readings of raw energy GB2808 1:225 iso 1.



(a) $R = 0.7\ \Omega$

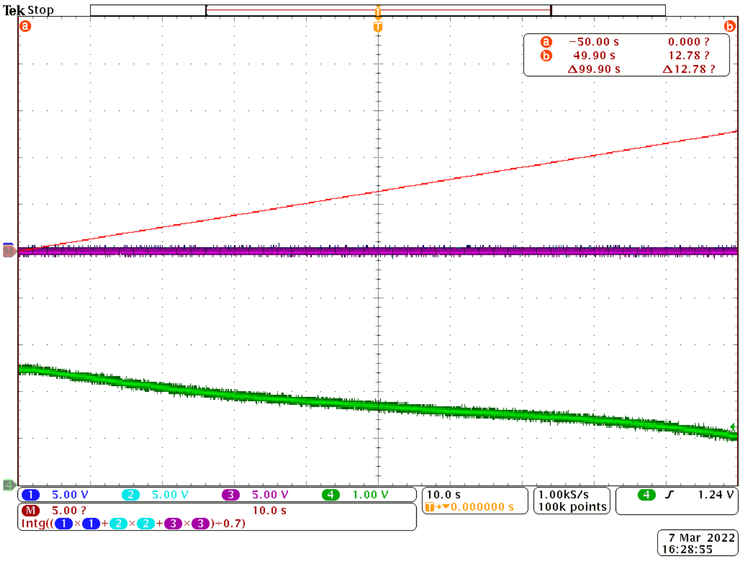


(b) $R = 49.1\ \Omega$

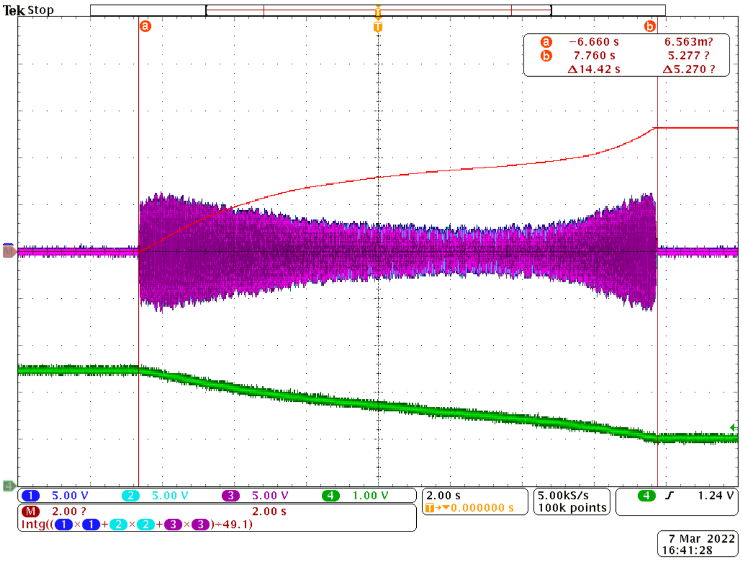


(c) $R = 101.5\ \Omega$

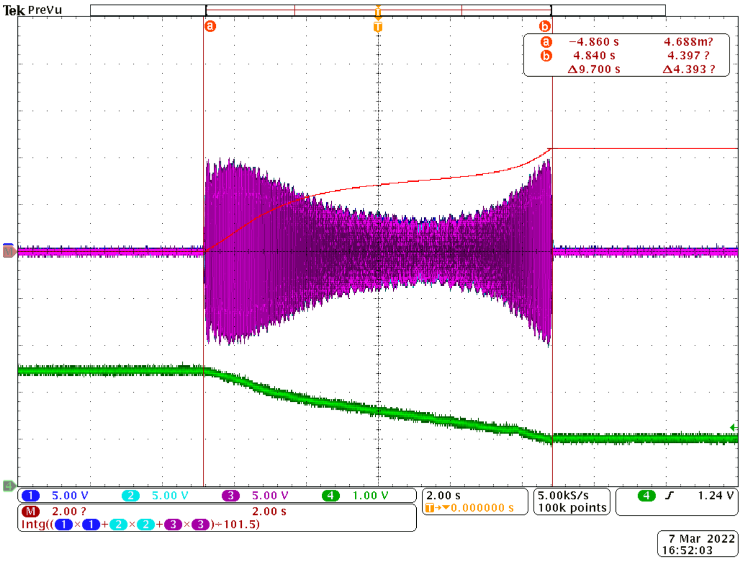
Figure 37: Oscilloscope readings of raw energy GB2808 1:225 iso 5.



(a) $R = 0.7\ \Omega$

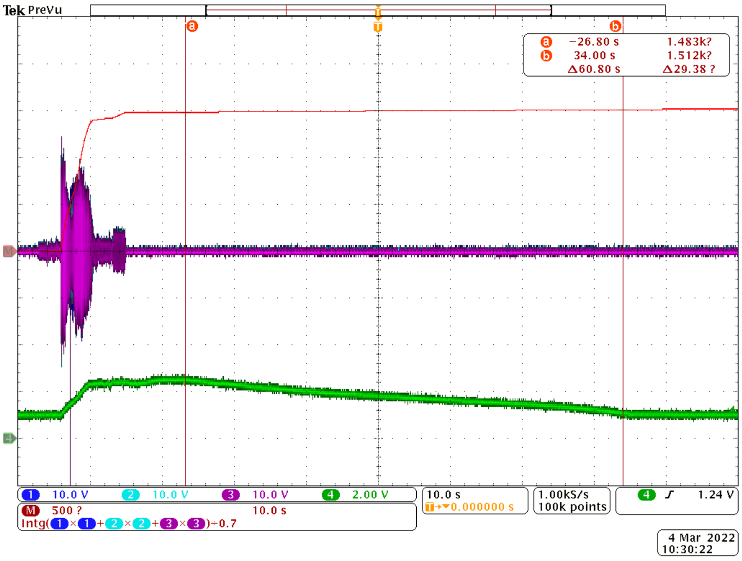


(b) $R = 49.1\ \Omega$

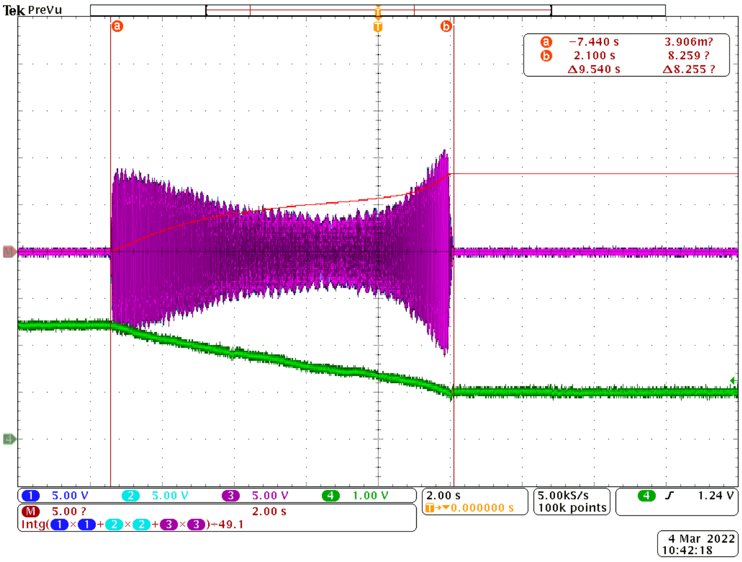


(c) $R = 101.5\ \Omega$

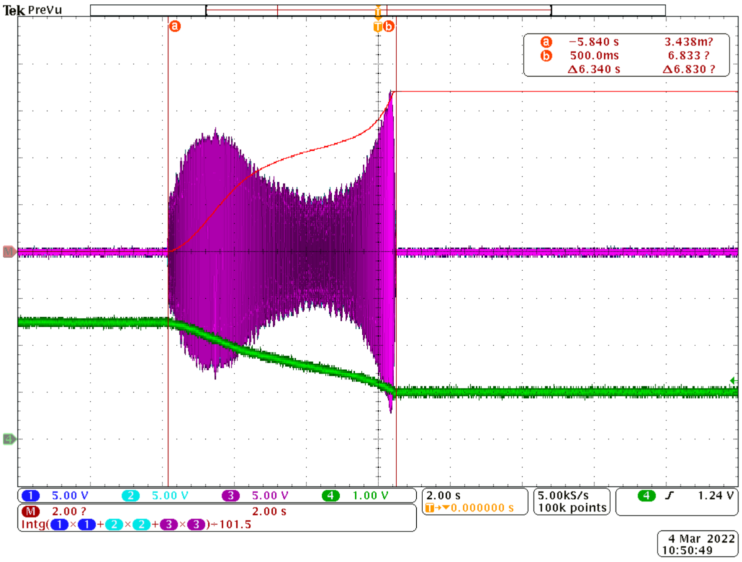
Figure 38: Oscilloscope readings of raw energy GB4114 1:200 iso 1.



(a) $R = 0.7\ \Omega$

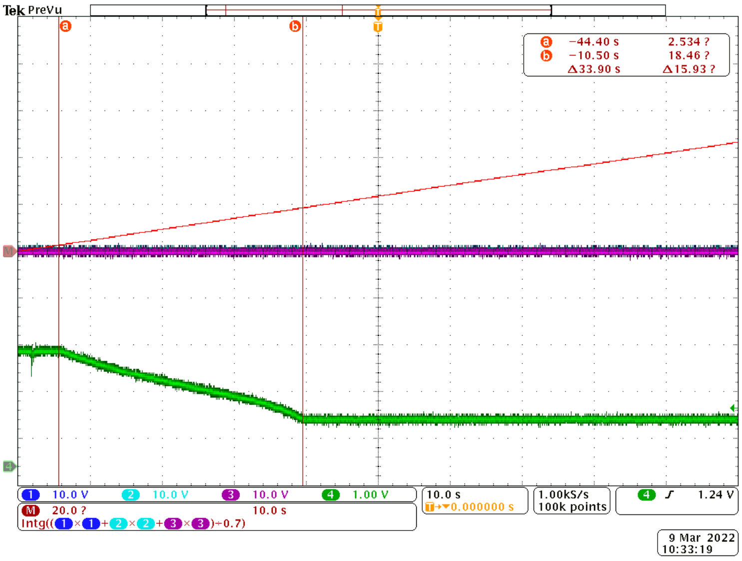


(b) $R = 49.1\ \Omega$

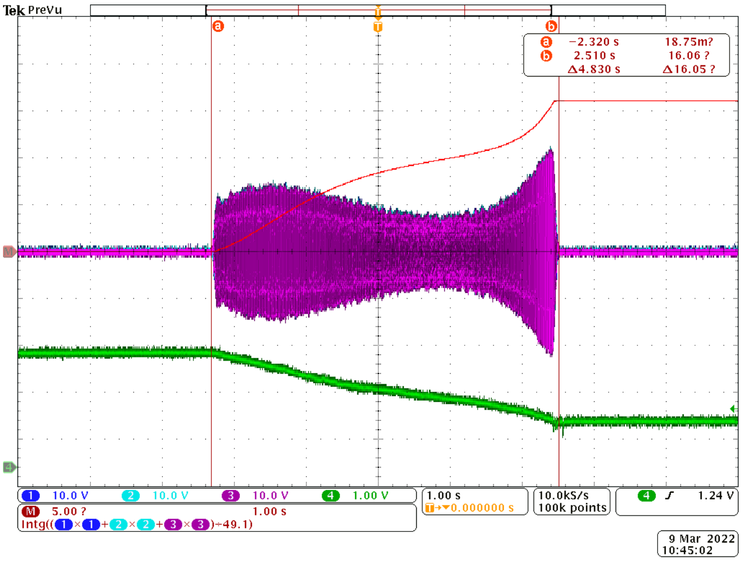


(c) $R = 101.5\ \Omega$

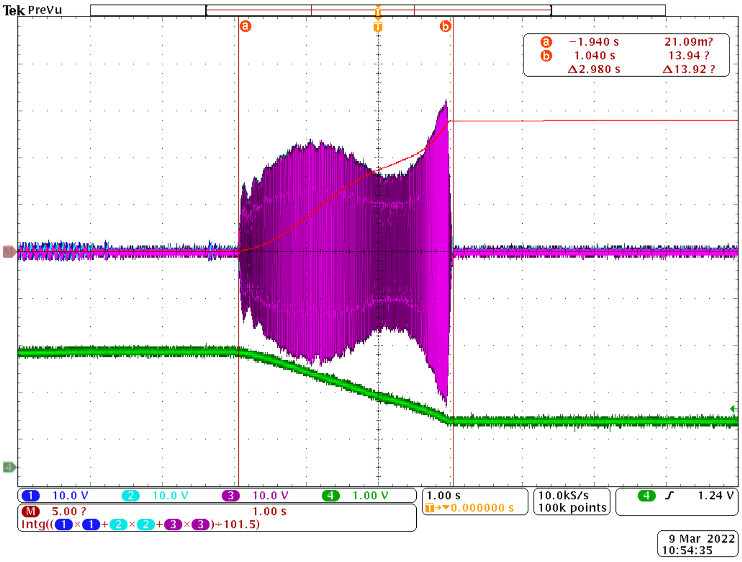
Figure 39: Oscilloscope readings of raw energy GB4114 1:200 iso 3.



(a) $R = 0.7\ \Omega$

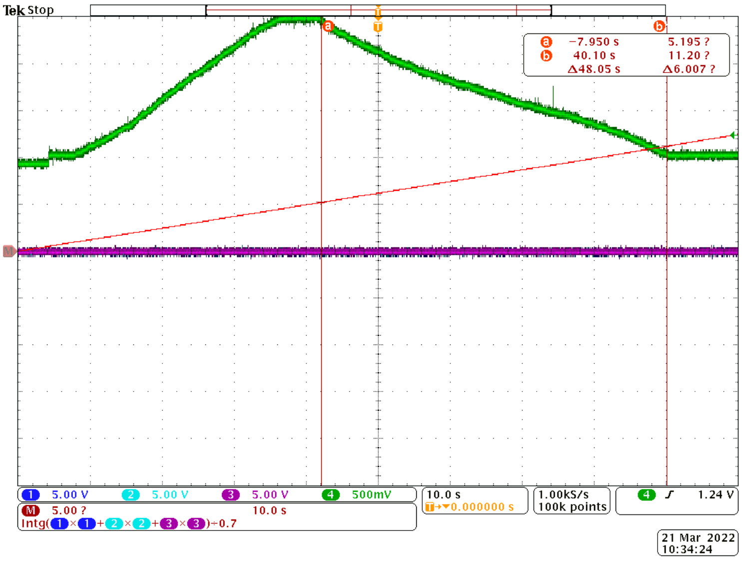


(b) $R = 49.1\ \Omega$

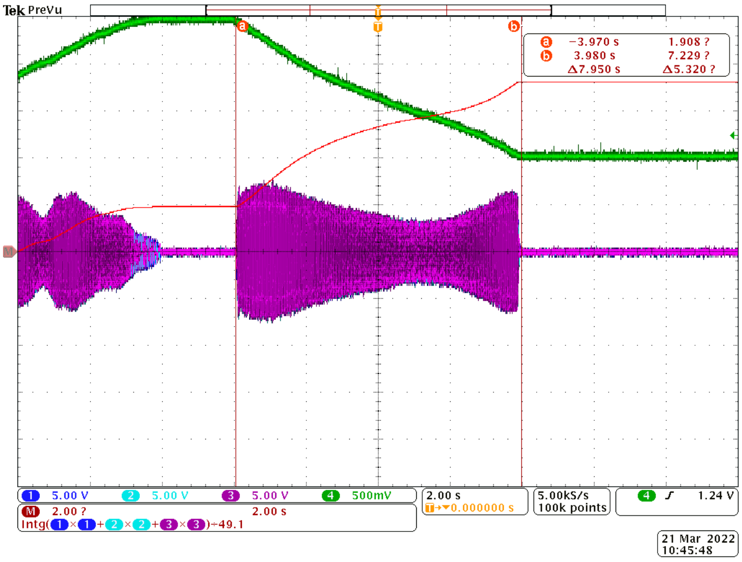


(c) $R = 101.5\ \Omega$

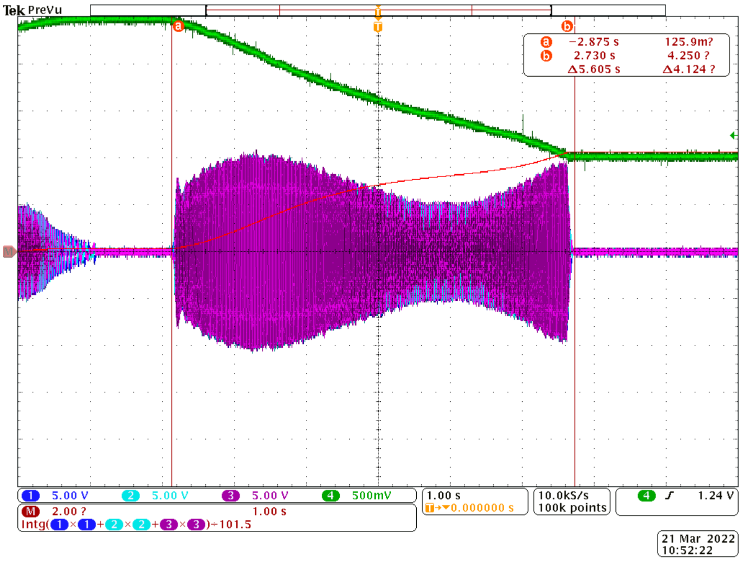
Figure 40: Oscilloscope readings of raw energy GB4114 1:200 iso 5.



(a) $R = 0.7\ \Omega$

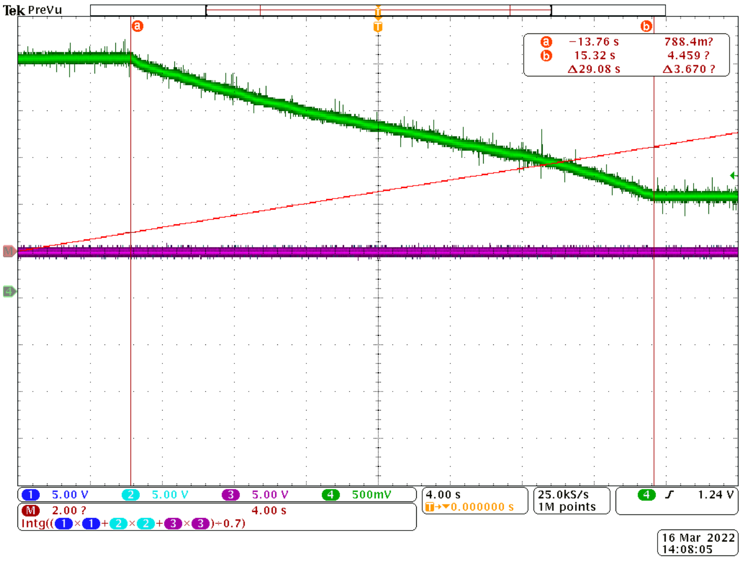


(b) $R = 49.1\ \Omega$

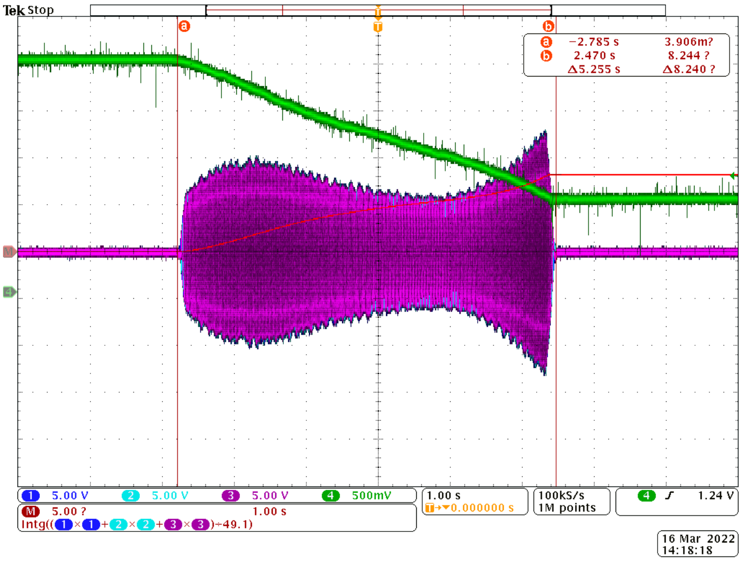


(c) $R = 101.5\ \Omega$

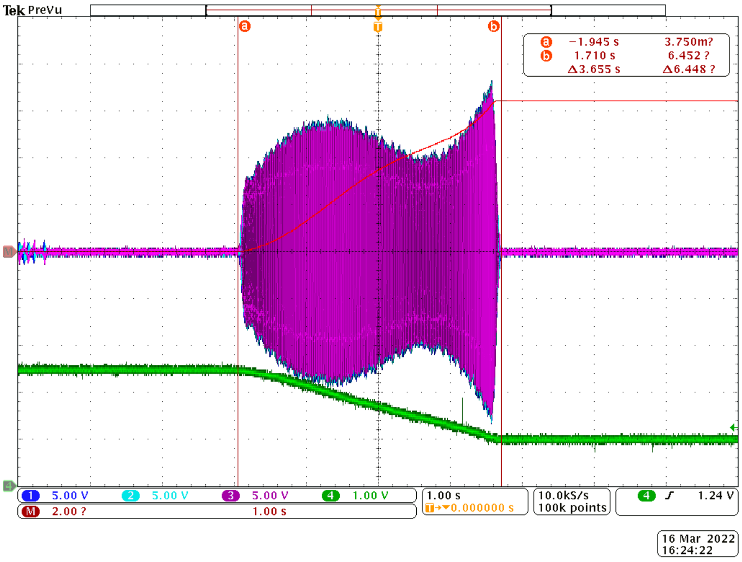
Figure 41: Oscilloscope readings of raw energy GB4114 1:150 iso 1.



(a) $R = 0.7\ \Omega$

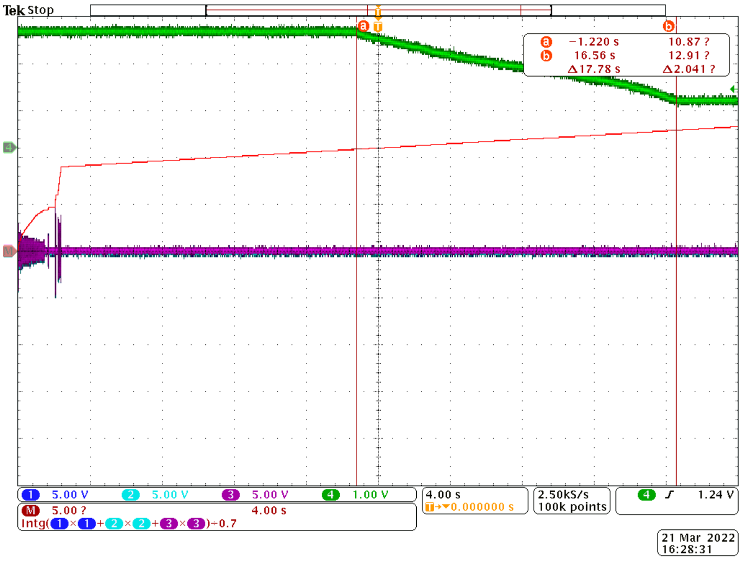


(b) $R = 49.1\ \Omega$

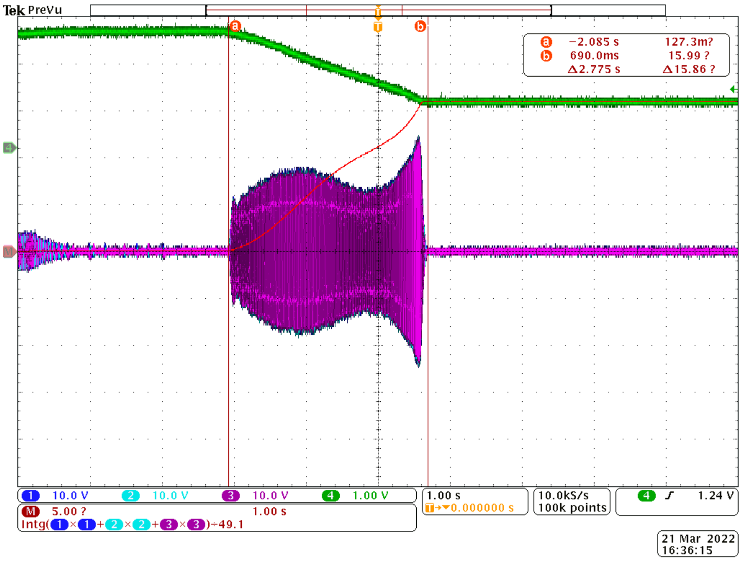


(c) $R = 101.5\ \Omega$

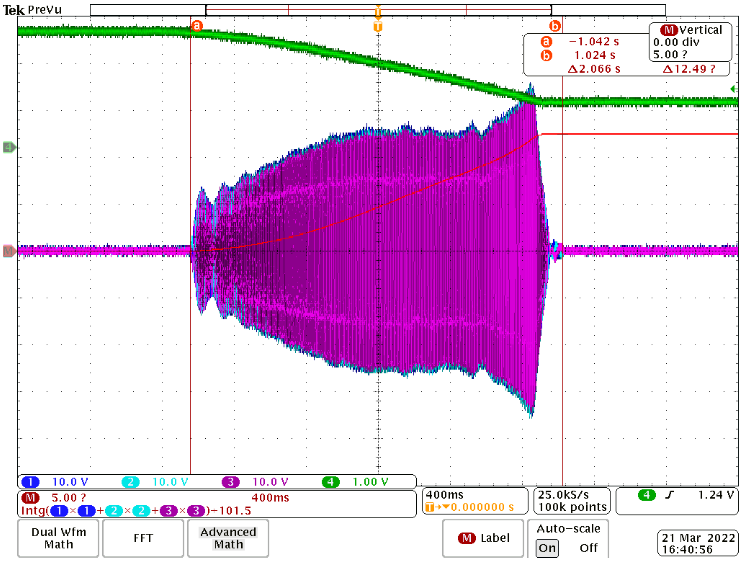
Figure 42: Oscilloscope readings of raw energy GB4114 1:150 iso 3.



(a) $R = 0.7\ \Omega$



(b) $R = 49.1\ \Omega$



(c) $R = 101.5\ \Omega$

Figure 43: Oscilloscope readings of raw energy GB4114 1:150 iso 5.

Appendix B

The figures in this section are supplementary to Section 4.1.3. The raw DC power analyzer readings for the test on all prototypes and spring settings are demonstrated. The results are shown for duty cycles 0, 50 and 100 %. Values in between follow the general trend demonstrated by those duty cycles. The yellow line shows the current, the upper orange line shows the voltage and the lower orange line shows the power. The markers 1 and 2 enclose the closing period. The closing time can be read from the delta time between the markers under "Measurements Between Markers" in the bottom of the window. The amount of harvested energy can be seen under Charge/Energy for A-P1 in the bottom right corner of the window, and is an integration of the power over the given time.

	Marker 1	Measurements Between Markers						Marker 2
Time	4,810875 s	Δ = 2,201723 s Freq = 454 mHz						7,012598 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000355721 V	19,999103546 V	20,000326421 V	20,001535416 V	2,43187 mV	---	---	20,000343323 V
A-I1	-1,595414 mA	-180,615664 mA	-95,713172 mA	-87,958 µA	180,527706 mA	-58,537 µA h	-210,733881 mC	-117,572 µA
A-P1	-31,908839 mW	-3,612486897 W	-1,91429527 W	-1,759186 mW	3,610727711 W	-1,170763 mW h	-4,214747696 J	-2,351477 mW

1 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata352.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\spring 1\20kHz90deg\0.csv success.

V1 1 mV / I1 100 mA / P1 2 W / F1 1 V / F2 1 V / F3 1 V /

(a) dt = 0 %

	Marker 1	Measurements Between Markers						Marker 2
Time	4,108411 s	Δ = 4,991508 s Freq = 200 mHz						9,099919 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000291824 V	19,999412537 V	20,000303851 V	20,001178741 V	1,766205 mV	---	---	20,000466347 V
A-I1	-243,421 µA	-115,786843 mA	-56,555 mA	4,978 µA	115,791821 mA	-78,415 µA h	-282,294763 mC	-887 nA
A-P1	-4,8685 mW	-2,315809297 W	-1,131118189 W	99,568 µW	2,315908866 W	-1,568329 mW h	-5,645986031 J	-17,741 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata357.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\spring 1\20kHz90deg\50.csv success.

V1 1 mV / I1 50 mA / P1 1 W / F1 1 V / F2 1 V / F3 1 V /

(b) dt = 50 %

	Marker 1	Measurements Between Markers						Marker 2
Time	-46,162 ms	Δ = 30,007255 s						29,961093 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1		19,999998093 V	20,000398221 V	20,000799179 V	801,086 µV	---	---	20,000436783 V
A-I1		-8,712 µA	205 nA	9,603 µA	18,315 µA	2 nA h	6,134 µC	-87 nA
A-P1		-174,245 µW	4,094 µW	192,058 µW	366,303 µW	34 nW h	122,675 µJ	-1,744 µW

5 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata363.dlg Trigger Data Log Run Button Source 14585A

ACTIVE - datalogdata363

V1 500 µV / I1 10 µA / P1 200 µW / F1 1 V / F2 1 V / F3 1 V /

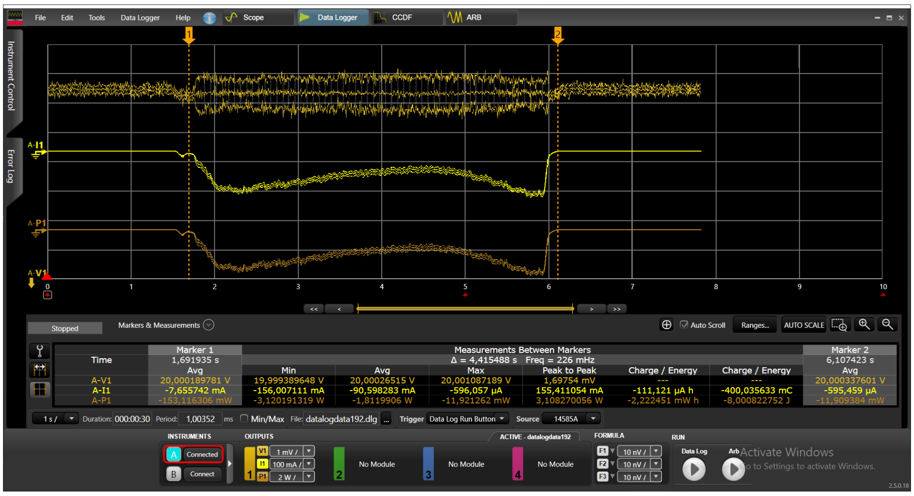
(c) dt = 100 %

Figure 44: DC power analyzer readings of harvested energy GB2808 1:225 iso 1.

	Marker 1	Measurements Between Markers						Marker 2
Time	1,675878 s	Δ = 2,577039 s Freq = 388 mHz						4,252918 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000170708 V	19,999399185 V	20,000296707 V	20,001260757 V	1,861572 mV	---	---	20,000309944 V
A-I1	-2,656312 mA	-260,302603 mA	-142,089678 mA	-689,898 µA	259,612705 mA	-101,714 µA h	-366,170692 mC	-514,306 µA
A-P1	-53,126702 mW	-5,206247681 W	-2,841837302 W	-13,79812 mW	5,192449561 W	-2,034313 mW h	-7,323526582 J	-10,286272 mW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata188.dlg Trigger Data Log Run Button Source 14585A

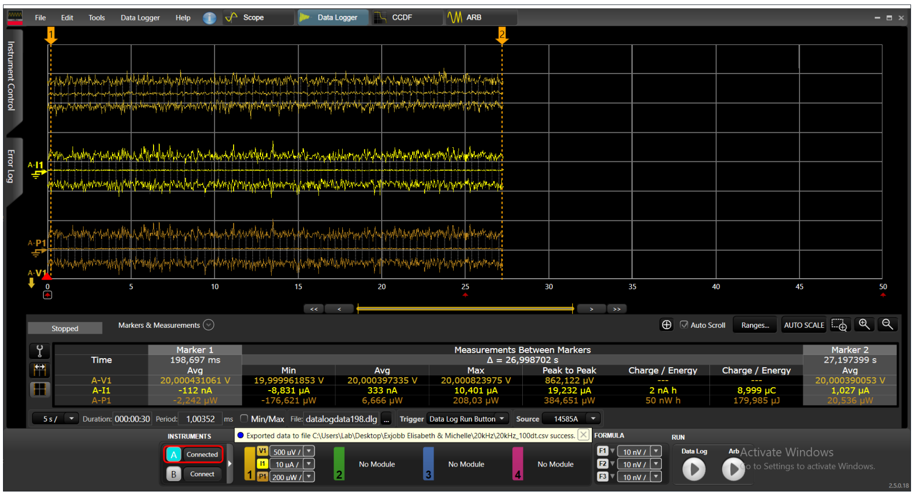
(a) 10 dt



	Marker 1	Measurements Between Markers						Marker 2
Time	1,691935 s	Δ = 4,415488 s Freq = 226 mHz						6,107423 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000189781 V	19,999389648 V	20,00026515 V	20,001087189 V	1,69754 mV	---	---	20,000337601 V
A-I1	-7,655742 mA	-156,007111 mA	-90,598283 mA	-596,057 µA	155,411054 mA	-111,121 µA h	-400,035633 mC	-595,459 µA
A-P1	-153,116306 mW	-3,120191319 W	-1,8119906 W	-11,921262 mW	3,108270056 W	-2,222451 mW h	-8,000822752 J	-11,909384 mW

1 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata192.dlg Trigger Data Log Run Button Source 14585A

(b) 50 dt



	Marker 1	Measurements Between Markers						Marker 2
Time	198,697 ms	Δ = 26,998702 s						27,197399 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000431061 V	19,999961853 V	20,000397335 V	20,000823975 V	862,122 µV	---	---	20,000390053 V
A-I1	-112 nA	-8,831 µA	333 nA	10,401 µA	19,232 µA	2 nA h	8,999 µC	1,027 µA
A-P1	-2,242 µW	-176,621 µW	6,666 µW	208,03 µW	384,651 µW	50 nW h	179,985 µJ	20,536 µW

5 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata198.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\20kHz\20kHz_100dt.csv success.

(c) 100 dt

Figure 45: DC power analyzer readings of harvested energy GB2808 1:225 iso 3.

	Marker 1	Measurements Between Markers						Marker 2
Time	4,832952 s	Δ = 2,053202 s Freq = 487 mHz						6,886154 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000317574 V	19,998807907 V	20,000336375 V	20,00170517 V	2,897263 mV	---	---	20,00026226 V
A-I1	824 nA	-733,686924 mA	-362,298609 mA	3,908 µA	733,690832 mA	-206,631 µA h	-743,872199 mC	-713,021 µA
A-P1	16,47 µW	-14,674186287 W	-7,246096578 W	78,165 µW	14,674264452 W	-4,132694 mW h	-14,877699407 J	-14,260611 mW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata311.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\Spring 5\20kHz90deg\0.csv success.

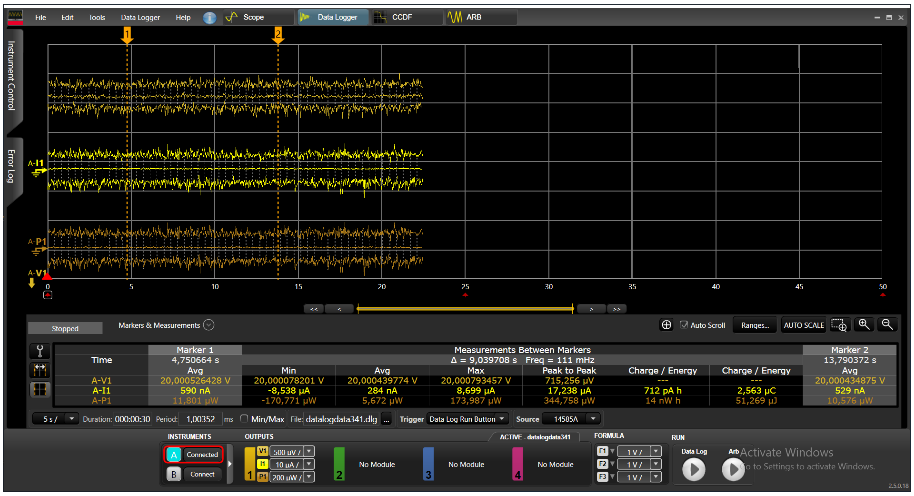
(a) dt = 0 %

	Marker 1	Measurements Between Markers						Marker 2
Time	5,134008 s	Δ = 3,592602 s Freq = 278 mHz						8,72661 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000332832 V	19,993976593 V	20,000430804 V	20,001438141 V	7,461548 mV	---	---	20,00032711 V
A-I1	1,981 µA	-390,596688 mA	-193,935097 mA	3,057 µA	390,599744 mA	-193,537 µA h	-696,731539 mC	881 nA
A-P1	39,628 µW	-7,812016451 W	-3,878789463 W	61,134 µW	7,812077585 W	-3,870818 mW h	-13,934945229 J	17,615 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata316.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\Spring 5\20kHz90deg\50.csv success.

(b) dt = 50 %



	Marker 1	Measurements Between Markers						Marker 2
Time	4,750664 s	Δ = 9,039708 s Freq = 111 mHz						13,790372 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000526428 V	20,000078201 V	20,000439774 V	20,000793457 V	715,256 µV	---	---	20,000434875 V
A-I1	590 nA	-8,538 µA	284 nA	8,699 µA	17,238 µA	712 pA h	2,563 µC	529 nA
A-P1	11,801 µW	-170,771 µW	5,672 µW	173,987 µW	344,758 µW	14 nW h	51,269 µJ	10,576 µW

5 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata341.dlg Trigger Data Log Run Button Source 14585A

(c) dt = 100 %

Figure 46: DC power analyzer readings of harvested energy GB2808 1:225 iso 5.

	Marker 1	Measurements Between Markers						Marker 2
Time	2,286019 s	Δ = 2,797814 s Freq = 357 mHz						5,083832 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000475883 V	19,998857498 V	20,000296297 V	20,001693726 V	2,836227 mV	---	---	20,000343323 V
A-I1	-16,006 µA	-126,890406 mA	-40,067608 mA	2,826 µA	126,893232 mA	-31,139 µA h	-112,101706 mC	-3,533 µA
A-P1	-320,132 µW	-2,537817559 W	-801,364986 mW	56,518 µW	2,537874077 W	-622,797 µW h	-2,242069983 J	-70,666 µW

1 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata472.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\GB4114 150\20 kHz iso 1\0.csv success.

V1 2 mV / I1 100 mA / P1 2 W /

F1 334 mV / F2 334 mV / F3 334 mV /

Activate Windows
Go to Settings to activate Windows.

(a) dt = 0 %

	Marker 1	Measurements Between Markers						Marker 2
Time	2,643272 s	Δ = 6,079324 s Freq = 164 mHz						8,722596 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,00045681 V	19,999202728 V	20,000249321 V	20,001523972 V	2,321243 mV	---	---	20,000305176 V
A-I1	898 nA	-104,205884 mA	-38,047837 mA	4,449 µA	104,210333 mA	-64,251 µA h	-231,305134 mC	1,64 µA
A-P1	17,953 µW	-2,084145109 W	-760,967245 mW	88,984 µW	2,084234093 W	-1,285046 mW h	-4,626166558 J	32,809 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata478.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\GB4114 150\20 kHz iso 1\50.csv success.

V1 1 mV / I1 50 mA / P1 1 W /

F1 334 mV / F2 334 mV / F3 334 mV /

Activate Windows
Go to Settings to activate Windows.

(b) dt = 50 %

	Marker 1	Measurements Between Markers						Marker 2
Time	1,994998 s	Δ = 46,085652 s						48,08065 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000324249 V	20 V	20,000410745 V	20,000812531 V	812,531 µV	---	---	20,000314713 V
A-I1	210 nA	-10,62 µA	229 nA	10,081 µA	20,701 µA	3 nA h	10,532 µC	1,183 µA
A-P1	4,205 µW	-212,402 µW	4,571 µW	201,62 µW	414,022 µW	59 nW h	210,643 µJ	23,668 µW

5 s / Duration: 000:01:00 Period: 1,00352 ms ☐ Min/Max File: datalogdata483.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\GB4114 150\20 kHz iso 1\100.csv success.

V1 500 uV / I1 10 µA / P1 200 µW /

F1 334 mV / F2 334 mV / F3 334 mV /

Activate Windows
Go to Settings to activate Windows.

(c) dt = 100 %

Figure 47: DC power analyzer readings of harvested energy GB4114 1:150 iso 1.

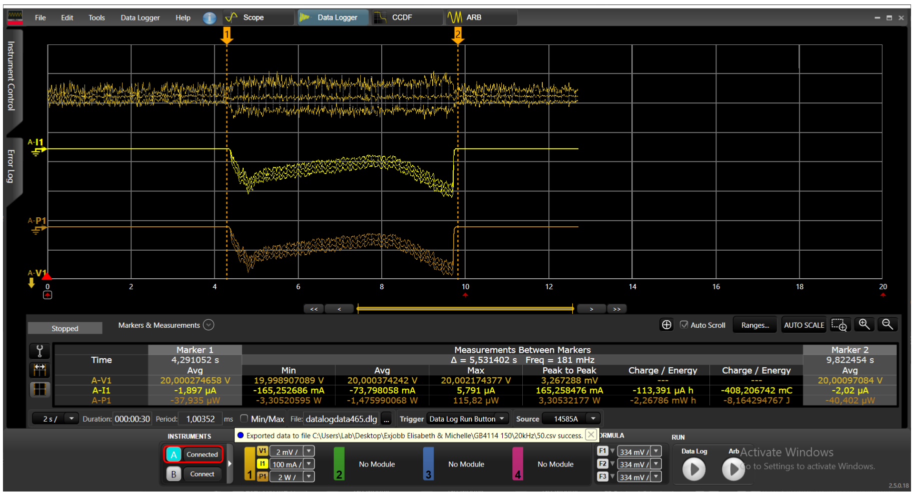
	Marker 1	Measurements Between Markers						Marker 2
Time	8,688476 s	Δ = 2,781757 s Freq = 359 mHz						11,470234 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000502586 V	19,998186111 V	20,000359546 V	20,001899719 V	3,713608 mV	---	---	20,000364304 V
A-I1	-306,997 µA	-299,645901 mA	-110,319834 mA	-103 nA	299,645798 mA	-85,245 µA h	-306,88302 mC	-3,805 µA
A-P1	-6,140067 mW	-5,993394098 W	-2,206437124 W	-2,054 µW	5,993392045 W	-1,704937 mW h	-6,137772884 J	-76,097 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata459.dlg ... Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\GB4114 150\20kHz\0.csv success.

V1 2 mV / I1 200 mA / P1 5 W / F1 334 mV / F2 334 mV / F3 334 mV /

(a) dt = 0 %



	Marker 1	Measurements Between Markers						Marker 2
Time	4,291052 s	Δ = 5,531402 s Freq = 181 mHz						9,822454 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000274658 V	19,998907089 V	20,000374242 V	20,002174377 V	3,267288 mV	---	---	20,00097084 V
A-I1	-1,897 µA	-165,252686 mA	-73,798058 mA	5,791 µA	165,258476 mA	-113,391 µA h	-408,206742 mC	-2,02 µA
A-P1	-37,935 µW	-3,30520595 W	-1,475990068 W	115,82 µW	3,30532177 W	-2,26786 mW h	-8,164294767 J	-40,402 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata465.dlg ... Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\GB4114 150\20kHz\50.csv success.

V1 2 mV / I1 100 mA / P1 2 W / F1 334 mV / F2 334 mV / F3 334 mV /

(b) dt = 50 %

	Marker 1	Measurements Between Markers						Marker 2
Time	4,501791 s	Δ = 30,448804 s						34,950595 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000318527 V	20,000074387 V	20,000456403 V	20,000854492 V	780,106 µV	---	---	20,000535965 V
A-I1	-66 nA	-8,629 µA	184 nA	10,147 µA	18,777 µA	2 nA h	5,616 µC	1,297 µA
A-P1	-1,313 µW	-172,589 µW	3,689 µW	202,95 µW	375,538 µW	31 nW h	112,317 µJ	25,941 µW

5 s / Duration: 000:01:00 Period: 1,00352 ms ☐ Min/Max File: datalogdata470.dlg ... Trigger Data Log Run Button Source 14585A

V1 500 uV / I1 10 uA / P1 200 uW / F1 334 mV / F2 334 mV / F3 334 mV /

(c) dt = 100 %

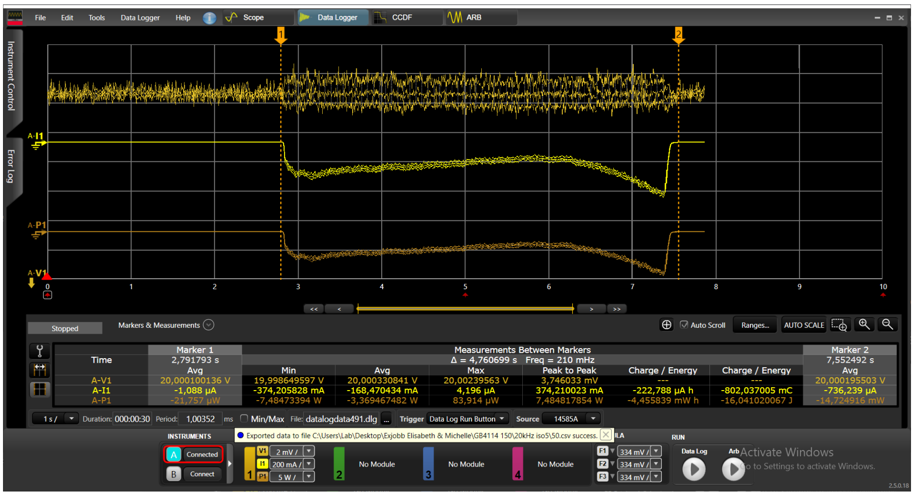
Figure 48: DC power analyzer readings of harvested energy GB4114 1:150 iso 3.

Time	Marker 1	Measurements Between Markers						Marker 2
	1,760174 s	Δ = 2,735596 s Freq = 366 mHz						4,49577 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000388145 V	19,99691391 V	20,000278744 V	20,003204346 V	6,290436 mV	---	---	20,000266075 V
A-I1	65 nA	-699,485064 mA	-293,546855 mA	5,582 µA	699,490646 mA	-223,063 µA h	-803,02546 mC	-20,3 µA
A-P1	1,293 µW	-13,990703227 W	-5,871022088 W	111,647 µW	13,990814873 W	-4,461317 mW h	-16,060741723 J	-406,004 µW

1 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata486.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\GB4114 150\20kHz iso5\0.csv success.

(a) dt = 0 %

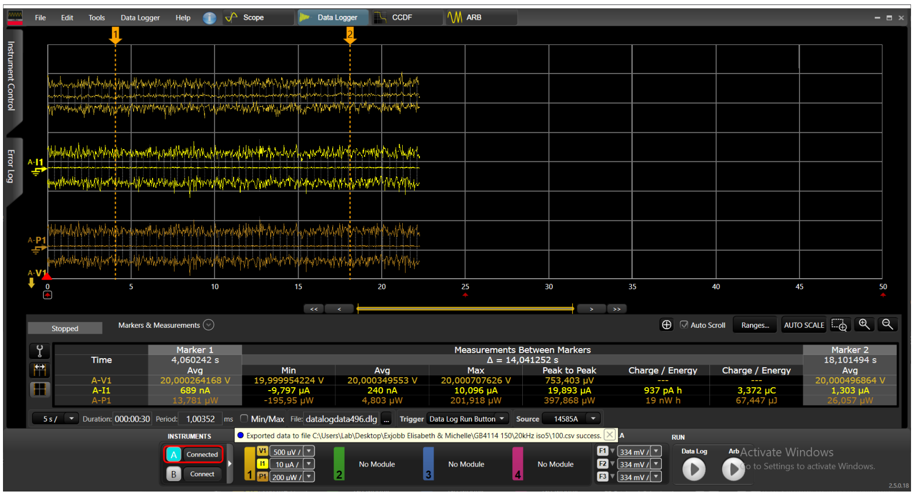


Time	Marker 1	Measurements Between Markers						Marker 2
	2,791793 s	Δ = 4,760699 s Freq = 210 mHz						7,552492 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000100136 V	19,998649597 V	20,000330841 V	20,00239563 V	3,746033 mV	---	---	20,000195503 V
A-I1	-1,088 µA	-374,205828 mA	-168,470434 mA	4,196 µA	374,210023 mA	-222,788 µA h	-802,037005 mC	-736,239 µA
A-P1	-21,757 µW	-7,48473394 W	-3,369467482 W	83,914 µW	7,484817854 W	-4,455839 mW h	-16,041020067 J	-14,724916 mW

1 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata491.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\GB4114 150\20kHz iso5\50.csv success.

(b) dt = 50 %



Time	Marker 1	Measurements Between Markers						Marker 2
	4,060242 s	Δ = 14,041252 s						18,101494 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000264168 V	19,999954224 V	20,000349553 V	20,000707626 V	753,403 µV	---	---	20,000496864 V
A-I1	689 nA	-9,797 µA	240 nA	10,096 µA	19,893 µA	937 pA h	3,372 µC	1,303 µA
A-P1	13,781 µW	-195,95 µW	4,803 µW	201,918 µW	397,868 µW	19 nW h	67,447 µJ	26,057 µW

5 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata496.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\GB4114 150\20kHz iso5\100.csv success.

(c) dt = 100 %

Figure 49: DC power analyzer readings of harvested energy GB4114 1:150 iso 5.

	Marker 1	Measurements Between Markers						Marker 2
Time	5,107917 s	Δ = 4,469678 s Freq = 224 mHz						9,577595 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000349998 V	19,998437881 V	20,000349764 V	20,001689911 V	3,252029 mV	---	---	20,00036335 V
A-I1	289 nA	-276,711375 mA	-19,668516 mA	7,835 µA	276,71921 mA	-24,42 µA h	-87,911935 mC	444 nA
A-P1	5,778 µW	-5,53413935 W	-393,376407 mW	156,71 µW	5,53429606 W	-488,407 µW h	-1,758265902 J	8,888 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata384.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\prototype 2\20kHziso1\0.csv success.

(a) dt = 0 %

	Marker 1	Measurements Between Markers						Marker 2
Time	4,582072 s	Δ = 8,742666 s Freq = 114 mHz						13,324739 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000426292 V	19,999202728 V	20,000193795 V	20,001405716 V	2,202988 mV	---	---	20,000494957 V
A-I1	-990 nA	-87,116174 mA	-23,462376 mA	5,776 µA	87,121951 mA	-56,979 µA h	-205,123725 mC	-43 nA
A-P1	-19,793 µW	-1,742365361 W	-469,252913 mW	115,529 µW	1,74248089 W	-1,139589 mW h	-4,102521599 J	-868 nW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata389.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\prototype 2\20kHziso1\50.csv success.

(b) dt = 50 %

	Marker 1	Measurements Between Markers						Marker 2
Time	1,1119 s	Δ = 01:55,214131						01:56,326031
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000294685 V	19,999927521 V	20,00034495 V	20,000759125 V	831,604 µV	---	---	20,000332832 V
A-I1	967 nA	-9,869 µA	228 nA	10,023 µA	19,892 µA	7 nA h	26,281 µC	745 nA
A-P1	19,335 µW	-197,383 µW	4,562 µW	200,46 µW	397,843 µW	146 nW h	525,636 µJ	14,906 µW

20 s / Duration: 000:02:00 Period: 1,00352 ms ☐ Min/Max File: datalogdata396.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\prototype 2\20kHziso1\100.csv success.

(c) dt = 100 %

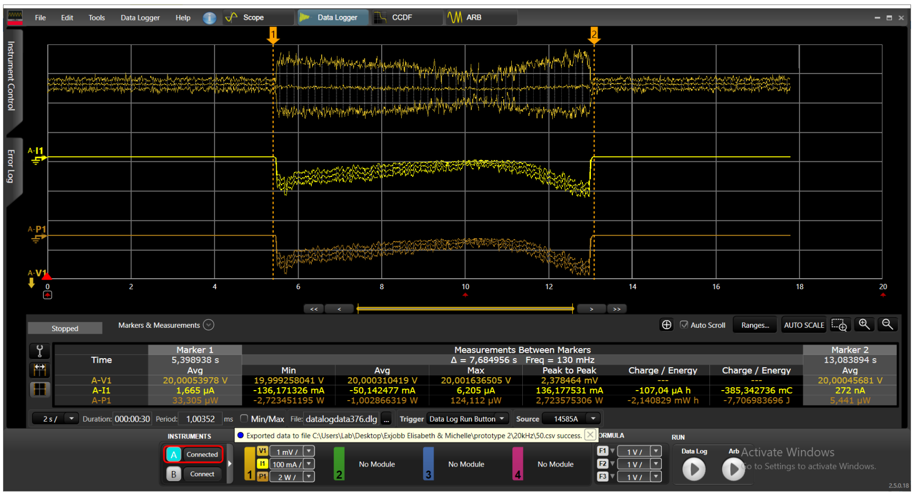
Figure 50: DC power analyzer readings of harvested energy GB4114 1:200 iso 1.

	Marker 1	Measurements Between Markers						Marker 2
Time	4,28503 s	Δ = 3,889644 s Freq = 257 mHz						8,174674 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000264168 V	19,998304367 V	20,000308893 V	20,001699448 V	3,395081 mV	---	---	20,000490189 V
A-I1	-2,545844 mA	-234,172314 mA	-76,244078 mA	1,197 µA	234,173511 mA	-82,378 µA h	-296,562283 mC	-2,61 µA
A-P1	-50,917444 mW	-4,683694625 W	-1,524906631 W	23,932 µW	4,683718557 W	-1,647595 mW h	-5,931343198 J	-52,206 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata370.dlg Trigger Data Log Run Button Source 14585A

A Connected
B Connect
1 V1 2 mV / I1 100 mA / P1 2 W /
F1 1 V / F2 1 V / F3 1 V /

(a) dt = 0 %



	Marker 1	Measurements Between Markers						Marker 2
Time	5,398938 s	Δ = 7,684956 s Freq = 130 mHz						13,083894 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,00053978 V	19,999258041 V	20,000310419 V	20,001636505 V	2,378464 mV	---	---	20,00045681 V
A-I1	1,665 µA	-136,171326 mA	-50,142477 mA	6,205 µA	136,177531 mA	-107,04 µA h	-385,342736 mC	272 nA
A-P1	33,305 µW	-2,723451195 W	-1,002866319 W	124,112 µW	2,723575306 W	-2,140829 mW h	-7,706983696 J	5,441 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata376.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\prototype 2\20kHz\50.csv success.

A Connected
B Connect
1 V1 1 mV / I1 100 mA / P1 2 W /
F1 1 V / F2 1 V / F3 1 V /

(b) dt = 50 %

	Marker 1	Measurements Between Markers						Marker 2
Time	52,183 ms	Δ = 30,027325 s						30,079508 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,00037384 V	19,999998093 V	20,000418377 V	20,000780106 V	782,013 µV	---	---	
A-I1	-789 nA	-9,248 µA	214 nA	9,196 µA	18,444 µA	2 nA h	6,42 µC	
A-P1	-15,777 µW	-184,966 µW	4,288 µW	183,917 µW	368,883 µW	36 nW h	128,403 µJ	

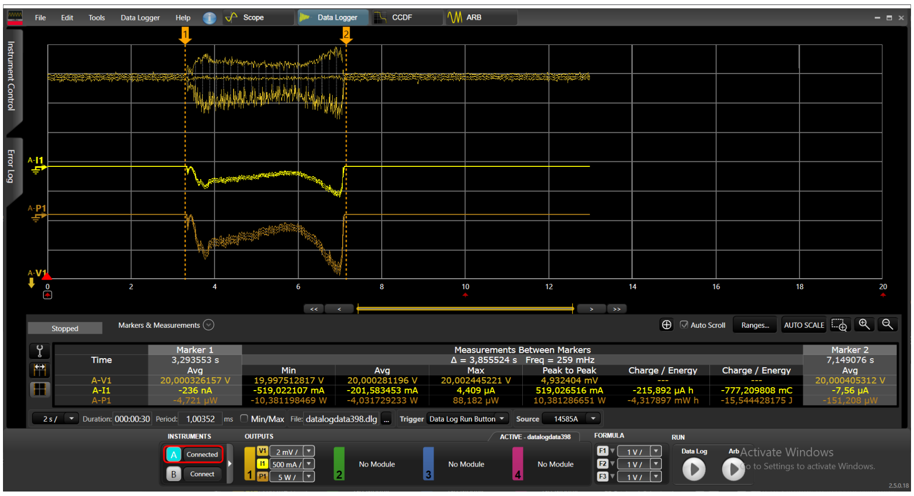
5 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata382.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\prototype 2\20kHz\100.csv success.

A Connected
B Connect
1 V1 500 uV / I1 10 uA / P1 200 uW /
F1 1 V / F2 1 V / F3 1 V /

(c) dt = 100 %

Figure 51: DC power analyzer readings of harvested energy GB4114 1:200 iso 3.



Time	Marker 1	Measurements Between Markers						Marker 2
	3,293553 s	Δ = 3,855524 s Freq = 259 mHz						7,149076 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000326157 V	19,997512817 V	20,000281196 V	20,002445221 V	4,932404 mV	---	---	20,000405312 V
A-I1	-236 nA	-519,022107 mA	-201,583453 mA	4,409 µA	519,026516 mA	-215,892 µA h	-777,209808 mC	-7,56 µA
A-P1	-4,721 µW	-10,381198469 W	-4,031729233 W	88,182 µW	10,381286651 W	-4,317897 mW h	-15,544428175 J	-151,208 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata398.dlg Trigger Data Log Run Button Source 14585A

ACTIVE - datalogdata398

V1 2 mV / I1 500 mA / P1 5 W /

(a) dt = 0 %

Time	Marker 1	Measurements Between Markers						Marker 2
	1,724047 s	Δ = 6,799852 s Freq = 147 mHz						8,523899 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000160217 V	19,998977661 V	20,000251572 V	20,001724243 V	2,746582 mV	---	---	20,000263214 V
A-I1	-2,02 µA	-282,571226 mA	-111,2034 mA	8,039 µA	282,579265 mA	-210,046 µA h	-756,166608 mC	-1,858 µA
A-P1	-40,405 µW	-5,651544716 W	-2,224097376 W	160,783 µW	5,651705499 W	-4,200981 mW h	-15,123531924 J	-37,153 µW

2 s / Duration: 000:00:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata404.dlg Trigger Data Log Run Button Source 14585A

ACTIVE - datalogdata404

V1 2 mV / I1 200 mA / P1 5 W /

(b) dt = 50 %

Time	Marker 1	Measurements Between Markers						Marker 2
	2,801828 s	Δ = 32,407675 s						35,209503 s
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
A-V1	20,000254631 V	19,999925613 V	20,000319797 V	20,000722885 V	797,272 µV	---	---	20,000384331 V
A-I1	523 nA	-8,564 µA	224 nA	9,549 µA	18,113 µA	2 nA h	7,252 µC	-432 nA
A-P1	10,464 µW	-171,283 µW	4,476 µW	190,991 µW	362,274 µW	40 nW h	145,048 µJ	-8,643 µW

5 s / Duration: 000:01:30 Period: 1,00352 ms ☐ Min/Max File: datalogdata409.dlg Trigger Data Log Run Button Source 14585A

Exported data to file C:\Users\Lab\Desktop\Exjobb Elisabeth & Michelle\prototype 2\20kHziso3\100.csv success.

V1 500 uV / I1 10 µA / P1 200 uW /

(c) dt = 100 %

Figure 52: DC power analyzer readings of harvested energy GB4114 1:200 iso 5.

Appendix C

The figure in this section is supplementary to Section 3.1. The spring tensions were adjusted to fulfill the requirements in column 4 and 5 in Figure 53 for door closer power sizes 1, 3 and 5.

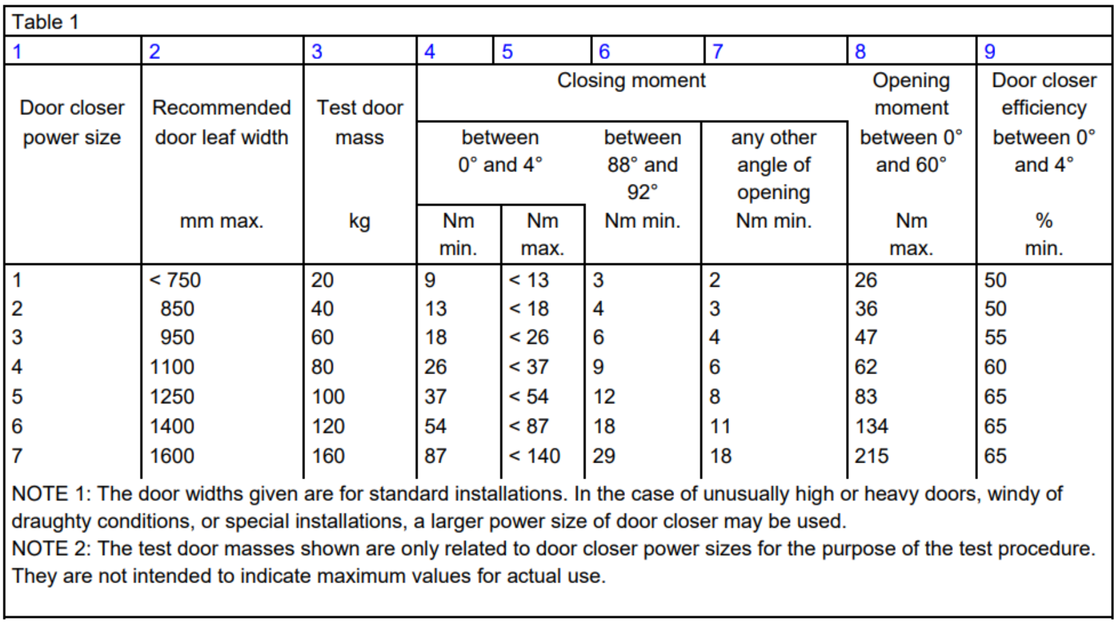


Table 1

1	2	3	4	5	6	7	8	9
Door closer power size	Recommended door leaf width	Test door mass	Closing moment				Opening moment	Door closer efficiency
			between 0° and 4°		between 88° and 92°	any other angle of opening	between 0° and 60°	between 0° and 4°
	mm max.	kg	Nm min.	Nm max.	Nm min.	Nm min.	Nm max.	% min.
1	< 750	20	9	< 13	3	2	26	50
2	850	40	13	< 18	4	3	36	50
3	950	60	18	< 26	6	4	47	55
4	1100	80	26	< 37	9	6	62	60
5	1250	100	37	< 54	12	8	83	65
6	1400	120	54	< 87	18	11	134	65
7	1600	160	87	< 140	29	18	215	65

NOTE 1: The door widths given are for standard installations. In the case of unusually high or heavy doors, windy of draughty conditions, or special installations, a larger power size of door closer may be used.

NOTE 2: The test door masses shown are only related to door closer power sizes for the purpose of the test procedure. They are not intended to indicate maximum values for actual use.

Figure 53: Range of door closer power sizes and related parameters according to SS-EN 1154 [32].