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EDUCATIONAL BATTERY MEASUREMENT SYSTEM USING LABVIEW SOFTWARE

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Akkuteknologialla ja sen kehittymisellä on merkittävä rooli tulevaisuuden energiahaasteiden ratkaisemisessa. Tutkimuksen tavoitteena on rakentaa mittausjärjestelmä litiumioniakuille hyödyntäen LabVIEW-ohjelmaa. Valmiita sovelluksia sekä rakennettua mittausjärjestelmää tullaan hyödyntämään opetustarkoitukseen Technobothnia-laboratoriossa Vaasassa.

Tutkimuksen teoriaosuudessa käsitellään akkujen historiaa, lataamisen toimintaperiaatteita sekä perehdytään eri kytkentöihin ja niiden ongelmiin. Lopuksi esitellään erilaisia käytössä olevia akkuteknologioita sekä potentiaalisia tulevaisuuden ratkaisuja.

Tutkimus havainnollistaa akkujen lataamiseen vaikuttavia tekijöitä sekä mahdollistaa joustavan ja siirrettävän laitteiston, jota voidaan hyödyntää useissa eri käyttökohteissa. Työn päätehtävänä on mahdollistaa järjestelmä, jolla yksittäisten akkujen kapasiteettierot sekä niiden vaihteluiden aiheuttamat seuraukset pystytään havainnoimaan käytännössä. Tutkimuksen lopputuloksena saavutettiin viisi erilaista LabVIEW-ohjelmaa viidelle erilaiselle kytkentätyypille sekä laadittiin niihin liittyvät havainnollistavat kytkentäkaaviot ja opetusmateriaalit.

Avainsanat litiumioniakut, labview, lataus

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ABSTRACT

Author	Jaakko Yli-Sorvari
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Battery technology has a significant role in resolving the challenges concerning the production and storing of energy. The aim of this study was to build a measurement system for lithium-ion batteries using LabVIEW program. The finished applications and the constructed measurement system will be used for educational purposes in the Technobothnia laboratory unit in Vaasa.

The theoretical section of the study discusses the development of batteries, the operating principle of charging and the different connections and the problems they cause. At the end of the theoretic segment, various battery technologies and potential future solutions are introduced.

The study illustrates the elements which will have an impact on the charging process. The constructed system enables a flexible and portable hardware configuration which can be utilized in different applications. The main purpose of the study was to implement a system which practically expresses the consequences caused by the fluctuations in battery capacity. As an outcome of the study, five different LabVIEW programs for five different charging scenarios, in conjunction with illustrative wiring diagrams and educational materials, were accomplished.

Keywords Lithium-ion batteries, LabVIEW, charging

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1 INTRODUCTION

1.1 Project Background

Atmospheric pollution and climate change have modified the way we produce and consume energy. Due to the detrimental consequences caused by the utilization of fossil fuels, renewable energy sources, such as wind and solar power have become more common phenomena everywhere around the world. The quick and extensive global technological development leads to a remarkable economic growth worldwide. This economic progression is significantly coupled with an increased demand for energy and electricity. /1/

Even though wind and solar power, in addition to other renewable energy sources, act as excellent alternatives for fossil fuels, the complexity lies within the storing process. The amount of produced energy cannot be controlled efficiently, thus seasonal fluctuations will cause inconveniences and a shortage of electricity during the peak consumption periods. /1/

Electrochemical storage systems and batteries are the key elements to utilize the full potential of the renewables. Upcoming inventions within the battery industry will have a comprehensive potential regarding their capacity, efficiency, reliability, and recyclability. /1/

To utilize batteries as an efficient future solution, their technologies and operating principles are extremely important to comprehend. An interest and understanding of the topic accompanied with an informative education enable remarkable future discoveries and inventions.

1.2 Aims and Objectives

The aim of the study is to produce an educational and practical battery measurement system for charging, discharging, and measuring lithium-ion batteries. The measurements will be recorded in LabVIEW software using a data acquisition device and a computer. In an ideal situation, the charging and discharging processes can be completely remotely controlled with a programmable laboratory power source in addition to a functional program created with LabVIEW.

The completed project will be utilized for educational purposes as a laboratory exercise for corresponding courses and as a source of information on how battery cells operate during the charge and discharge process.

2 ANALYZING BATTERIES

2.1 Battery as an Energy Storage

A battery is an essential link between producing and storing energy. Despite numerous ways of generating electricity, it cannot be stored directly in a cost-efficient way. Thus, an alternative form of storage becomes useful, and the electrical energy needs to be converted to kinetic, potential, thermal or chemical energy. Battery, a chemical device, has several different shapes, forms, and advantages. Some major benefits of batteries are their multidimensionality in different sizes and an ability to be manufactured and combined in bundles. Unlike some energy sources, batteries can supply electrical power instantly and portability makes them unbeatable in many circumstances. /2/

Battery systems can be categorized in two vast classes: primary batteries and secondary batteries. Primary batteries are also known as non-rechargeable batteries. Most of the primary batteries are relatively small, consisting of single cells /2/. Even though secondary batteries tend to get better attention, primary batteries are crucial in various occasions. When charging is impractical or unattainable, primaries can be utilized. A few examples of vitally important usage are rescue missions, military conflicts, pacemakers in heart patients, distant lighthouses and tracking animals and objects. /3/

Secondary batteries can be utilized several times due to their charging capabilities. Battery charging is a specialized system of electrolytic processes. The charging process demands comprehension of electricity and transformation of chemicals back into their primordial shape so that further discharge can be accomplished. /2/

2.2 Primitive Evolution

Batteries can be classified as relatively new inventions. Approximately 200 years ago, Alessandro Volta (1745-1827) conducted an experiment where a heap of silver and zinc discs were separated by a bit of cloth infused with brine. When the silver and zinc piles were connected by a wire conductor, a continual current of electricity was generated. /2/

John Daniell (1790-1845) took a next important leap in development of batteries by designing the Daniell cell. The cell was a first functional galvanic cell that was able to produce a lasting current with a practical width. In the 1850s, Daniell cells were widely utilized in telegraphic systems. /2/

The first secondary and rechargeable cell was introduced in 1859 by French chemist Gaston Planté (1834-1889). The cell was formed of two spirals of lead layer which were detached by an absorptive cloth. The system was submerged in a mild sulfuric acid within a cylindrical glass tank. /2/

Later, between the 19th and 20th century, first alkaline inventions were demonstrated. Swedish Waldemar Jungner (1869-1924) introduced an early rendition of nickel-cadmium battery and Thomas Edison (1847-1931) patented a nickel-iron battery in the USA. /2/

During the 20th century, technologies and science developed rapidly around the battery industry. Advancements in cell design and materials have reformed the performance of lead-acid batteries. Lithium-ion and nickel-metal-hydride batteries are also some examples of newer products that impressed industry /2/. Different types of batteries will be addressed later in Chapters 2.7 and 2.8.

2.3 Battery Operation Principle

As stated in Chapter 2.1, a battery is an instrument that can store electrical energy in terms of chemical energy and then convert the energy into electricity. The electricity is generated with an electrochemical cell that consists of a positive electrode (cathode) and a negative electrode (anode). The electrodes are differentiated by an electrolyte which conducts ions between the two different points. The process will only function if the electrolyte acts also as an electronic insulator. When the electrolyte works as an insulator, self-discharge and internal short-circuit can be avoided. The electrolytes are usually enriched aquatic lotions of salts, alkalis, or acids. /2/

A term battery can be used when two or more cells are mounted together electrically, in series or in series-parallel way. However, numerous single cells are also called batteries, especially primary cells. /2/

In addition to a positive electrode, a negative electrode and an electrolyte, other essential constituents for an electrolytic cell are a separator and a housing. In order to maintain lowest possible internal resistance, electrodes have to be as close to each other as possible. When the distance between the electrodes is kept around 1 millimeter, a resistance remains in the realm of milliohms (mΩ). /2/

The separator is a thin, cellular, and insulating material that prevents the two electrodes from touching each other. The separator pores are loaded with electrolyte and consequently, the ionic current can be transmitted. /2/

The chemical reactions needed for generating electricity occur at the two electrodes. Both electrodes go through a half-cell reaction. The chemicals in an electrode attending to the reaction are known as active material. This material or mass is connected to a metal component which acts as a current collector. An electrolytic cell which provides a current is a galvanic cell. /2/

Quintessential metals which create a negative active mass are cadmium (Cd), zinc (Zn), lithium (Li) and lead (Pb). A positive active mass usually consists of an oxide of manganese (MnO_2), lead (PbO_2) or nickel ($NiOOH$). /2/

The chemistry behind the cell reactions can be presented as:

At the negative electrode:

$$M \rightarrow M^{n+} + ne^- \qquad (1)$$

At the positive electrode:

$$nX + ne^- \rightarrow nX^- \qquad (2)$$

where:

$M\ is\ a\ metal,$
$X\ is\ an\ oxidizing\ agent$
$e^- is\ an\ electron$

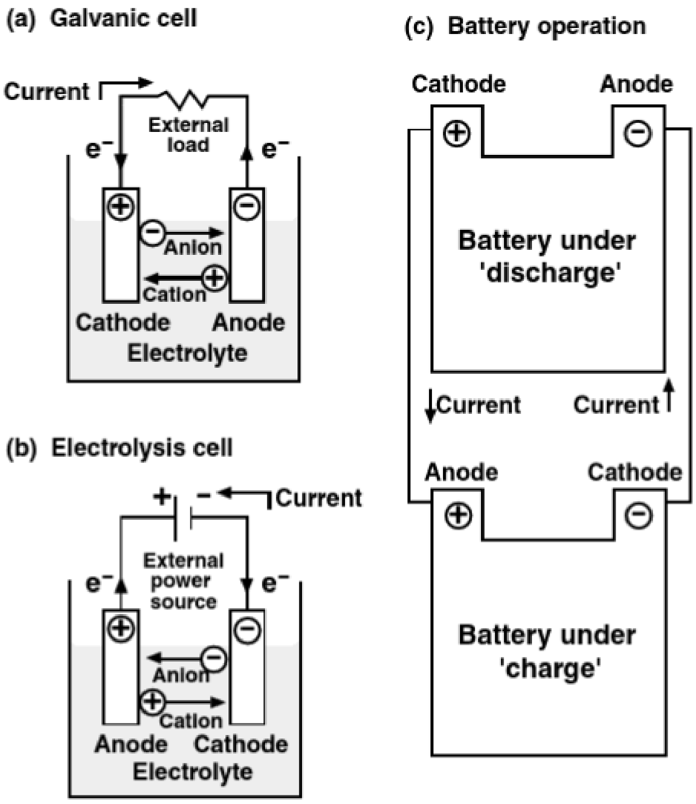


Figure 1. Schematic representation of the operation of electrochemical cells and batteries /2/.

2.4 Battery Cell Discharge

When discharging, negative ions (anions) travel towards the negative electrode and positive ions (cations) towards the positive electrode. The process is opposite during the charging process as visualized in **Figure 1** (b). In discharging state, the reaction at the negative electrode is an oxidation (anodic) reaction where electrons are emancipated. On the other side, a reduction (cathodic) reaction occurs at the positive electrode where electrons are absorbed. Batteries are commonly regarded to act in the discharge condition; therefore, the negative electrode is known as an anode and the positive electrode as a cathode. /2/

2.4.1 Capacity and C-rate

Battery capacity is measured in milliamps x hours (mAh). It is specified as an outcome of the current that is coming from the battery whilst the battery can feed the load until its voltage is dropped lower than the manufactured value for each cell. /4/

The charge and discharge raters of a battery are controlled by C-rates. The capacity is usually classified as 1 C. This term indicates that an entirely charged battery categorized at 1 Ah should supply 1 A for one hour. If the battery discharges at 0.5 C, it will give 500 mA for two hours. A C-rate of 1 C indicates also a one-hour discharge while a C-rate of 0.5 C would mean a discharge of two hours. /5/ **Table 1** demonstrates distinctive times at different C-rates.

Table 1. C-rate values and operating times when charging and discharging a battery of 1 Ah /5/.

C-rate	Time
5 C	12 min
2 C	30 min
1 C	1 h
0.5 C	2 h

0.2 C	5 h
0.1 C	10 h
0.05 C	20 h

2.4.2 State of Health

State of Health (SOH) is a definition that elucidates a common condition of a battery and its performance compared to a new battery. State of Health consists of an internal resistance, charge acceptation, voltage, and self-discharge. The performance ratio and health of the battery will slowly get worse due to inevitable chemical and physical changes inside the battery. Manufacturers do not define State of Health because the supplied batteries are new. State of Health is also a problematic concept because it cannot be measured accurately being just a subjective measurement with different values from different estimators. /6/

2.4.3 State of Charge

State of Charge (SOC) is equivalent for batteries what fuel tank is for vehicles. It indicates how long the battery will be able to operate before it needs to be charged. A reference value for State of Charge should be the rated capacity of a new battery rather than the existing capacity of the cell due to natural cell capacity reduction over time. Multiple methods can be utilized to estimate and specify the State of Charge. /7/

A direct measurement is based on the knowledge that the charge is equal to the current multiplied by time. However, this measurement becomes problematic when the battery is not discharged at a constant rate. Voltage Based State of Charge Estimation uses voltage for calculating the charge. In order to achieve sufficient precision, temperature, discharge rate and the age of the cell need to be considered. /7/

Another way of defining the State of Charge is to use Current Based Estimation which is commonly known as Coulomb Counting. The energy included in an electric charge is measured in Coulombs and is equal to the integral over time of the current which distributed the charge. The remaining capacity can be calculated by measuring the entering or leaving current and then integrating it over time. Coulomb counting enables a high accuracy compared to other State of Charge measurement customs, but it still needs a compensation as with the voltage-based methods. /7/

2.4.4 State of Energy

A real-time evaluation of the available energy of the battery is beneficial and vitally important especially in electric vehicle applications. The State of Energy (SOE) mirrors the remaining energy of the battery and it consists of the ratio of the remaining energy to the total energy. The State of Energy takes for example temperature and the age of the cell into account, but it will not give sufficiently reliable estimation of the battery's state on its own. /7/

2.4.5 Depth of Discharge

When comparing an electrochemical battery for other types of energy storage systems, it has many benefits. The energy that battery delivers stays consistent and high during most of the charge time and then drops suddenly when the charge drains. /9/

According to Dell (Understanding Batteries 2001) the Depth of Discharge (DOD) can be described as the amount of charge (capacity) withdrawn compared with the total amount which is available at the same discharge rate. The DOD-value is usually denoted as a percentage and indicates that the State of Charge (SOC) of a battery is the portion of the full capacity that is still obtainable for further discharge.

$$State\ of\ Charge = (100\ \% - Depth\ of\ Discharge\ [\%]\ ) \qquad (3)$$

For reference, lead-acid batteries discharge to $1.75\ \frac{V}{cell}$, nickel-based systems to $1.0\ \frac{V}{cell}$ and most of lithium-ion batteries to $3.0\ \frac{V}{cell}$. With these standards, approximately 95 percent of the energy is spent, and the voltage would face a prompt decrease if the discharging process were continued further. Over-discharging is inevitable without preventing the batteries to operate beyond the typical end-of-discharge voltage. Since batteries are rarely fully discharged, an 80 percent Depth of Discharge formula is often used to rate a battery by manufacturers. This indicates that 20 percent of the available energy devolves into storage while 80 percent of the energy is utilized from the capacity. /9/

2.4.6 Battery Lifetime

An electrochemical battery can have a short lifetime compared to many electrical products itself. Depending on their chemistry, battery cells can deteriorate proportionately quickly particularly with an increased usage. One of the major dilemmas for manufacturers has been to develop batteries the lifetime of which matches with the lifetime of the entire product. /10/

Numerous different factors will affect the lifetime of a battery. Too high a cell voltage might lead to disintegration of the electrolyte or augmented impact of contaminants. All the adverse effects will increase the inner resistance, downgrade the overall capacity, and reduce cycles and lifetime. High temperatures also have a negative effect for the lifetime of a battery. In some parts of the world, a utilization of batteries is extremely difficult due to temperatures of 40 °C or higher. On the other hand, too low a temperature can also turn out to be problematic in many cases. If a product is designed to be used in cold temperatures, manufacturers will propose battery heaters in order that sufficient performance is confirmed. /10/

Different batteries with distinct chemistries will have a lot of variation in their performance and durability in various circumstances. Even though two different batteries will have the same chemical constitution, their performance ratio can be vastly different from each other. Therefore, accurate comparisons of various parameters for different battery systems are hard to implement. /2/

2.5 Battery Charging

To turn the discharging process over, the charging of a secondary battery requires passing direct current (D.C.) electricity through it. The charging of a battery is an electrolytic process. At the negative electrode, an electrochemical reduction reaction occurs and commonly results in development of a metal. On the other hand, at the positive electrode, an active material undergoes an electrochemical oxidation. When discussing the battery lifetime and conditions affecting it, a first thing is usually to evaluate how it has been discharged and under which conditions. However, the situations under which a secondary battery is charged are equally important or even more crucial when calculating the battery lifetime and performance. /2/

Overcharging occurs when the current keeps on flowing after the recharge is finished. As in overcharged phase, the active material of the other electrode is entirely transformed into the charged state. The possibly overcharged electrode is determined already during the manufacturing process since batteries can be built with a surplus of negative or positive material. For instance, when the battery has an excess amount of negative material (positive-limited), the positive material will be the first to achieve a total conversion. /2/

The overcharging is detrimental because electrolyte will scatter electrochemically due to burden caused by overcharging. Batteries which are manufactured to work on aqueous electrolytes will face a development of hydrogen and oxygen due to a decomposition. The development of excessive gasses results in various disorders. The accumulation of gas undermines the substance of the active material, more recurring maintenance is needed due to a loss of water and numerous safety hazards might occur. All these adverse effects will reduce the cycle-life of the battery significantly. The simplest way to avoid overcharging is to control the charging voltage. Thus, most charging circuits will have a voltage regulator adjusting the highest voltage suitable for the battery being used depending on different circumstances and temperatures. /2/

2.5.1 Constant-current Charging

The charging of a secondary battery can be accomplished with four different basic systems. Firstly, constant-current charging keeps the current immutable throughout the whole charging process. Constant-current charging can be achieved with affordable and trustworthy equipment, but the correct current value needs to be selected carefully. Too low current makes the charging process last for an excessively long time, but overly high set value will increase the gassing at top-of-charge (**Figure 2**). /2/

More advanced charging convention is to utilize the two-step constant-current charging. Ideally, a high current is applied in the first half of the charging process while a smaller current is more useful in the later and final stages of the charging (**Figure 2**). One major advantage of using a small charge when the battery is almost full is that it enables a long series-connected battery chain to rebalance at the top-of-charge without resulting in issues for batteries and cells which are already fully charged. However, constant-current charging is the most convenient way of charging for long-lasting or overnight use. /2/

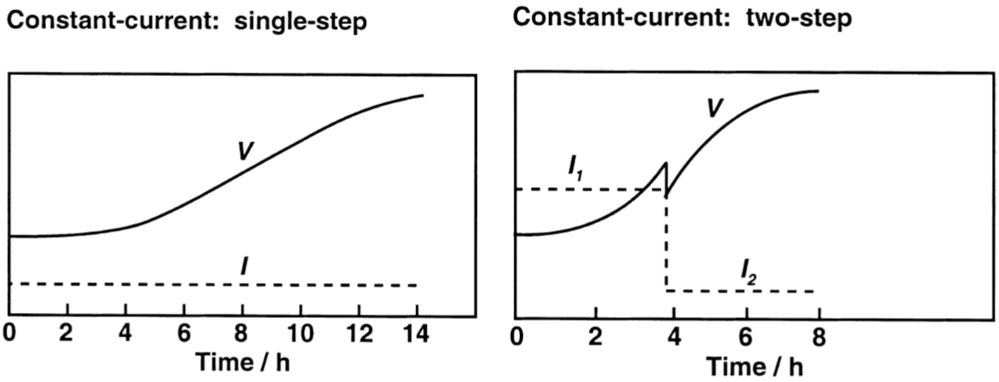


Figure 2. Constant-current charging /2/.

2.5.2 Constant-voltage Charging

In constant-voltage charging, the level of current which charger supplies is quantified by the voltage divergence between the charger and the battery. At first, the current runs at exceedingly high value and later abates proportionately (**Figure 3**). Few disadvantages for constant-voltage charging are that the starting current can turn out to be remarkably high and prolonged charging times will occur. Constant-voltage chargers can be used for example as fast chargers to gain maximum charge at a lowest possible time. /2/

2.5.3 Taper-current Charging

A taper charger can be a beneficial alternative for economical applications. In taper-current charging, the current commences high and declines progressively in line with the increase of the cell voltage (**Figure 3**). Many inexpensive household chargers utilize this method with the maximum available current restricted to a couple of amperes. /2/

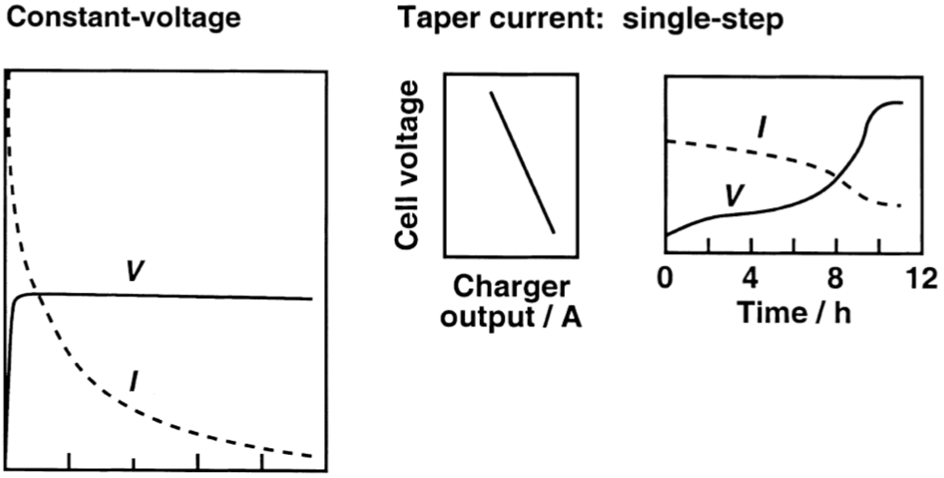


Figure 3. Constant-voltage and taper-current charging /2/.

2.5.4 Constant-current-constant-voltage Charging

With constant-current-constant-voltage charging structure, the current remains stationary until the battery voltage obtains a pre-designated value where gassing will most probably start to occur (**Figure 4**). When this point has been achieved, the voltage is kept stable, and the current can decrease exponentially as in constant-voltage charging. /2/

When a battery pack has series-connected cells, different troubles may transpire during the charge-discharge process. Subtle fluctuations in construction and assembly in different cells will cause differences in the interior resistance and the entire capacity of each cell. In addition to alterations in the new batteries, the aging process of each will differ greatly from each other resulting in major unevennesses. /2/

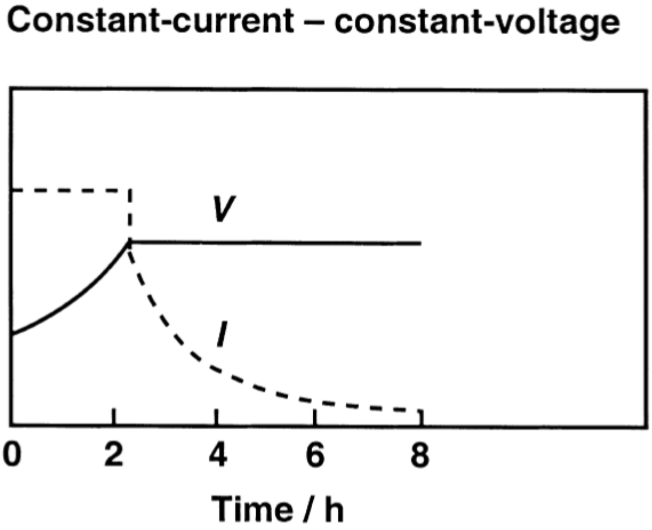


Figure 4. Constant-current-constant-voltage charging /2/.

2.6 Series and Parallel Connection

To obtain a congenial operating voltage, the cells can be connected in series when voltage potential in each cell is combined or with a parallel connection which enables higher capacity by summing the total ampere-hours. /11/

2.6.1 Single-Cell Configuration

A single-cell application is the simplest battery pack. A protection circuit can be kept elementary, and the cell does not need any adjustments. Some examples of single-cell batteries are wristwatches, wall clocks, tablets and mobile phones which utilize a low power consumption. /11/ The following table illustrates nominal cell voltages for different batteries.

Table 2. Different Nominal Cell Voltages /11/.

Battery Type	Nominal Cell Voltage (V)
Nickel-based	1.2 V
Alkaline	1.5 V
Silver-oxide	1.6 V
Lead-acid	2.0 V
Primary lithium	3.0 V – 3.9 V
Li-ion	3.6 V
Li-phosphate	3.2 V
Li-titanate	2.4 V
Li-manganese	3.7 V

2.6.2 Cell Balance

The exact capacity of a cell is extremely hard to predict during the manufacturing process. Lead-acid and other batteries that involve manual assembly are especially vulnerable for inconsistencies. Even if the cells are manufactured in clean, unpolluted, and fully automated conditions, performance alterations will occur. Thus, each cell is measured, isolated, and classified according to their capacity levels as part of a quality control. The differences in capacity and performance will translate straight into a life expectancy. /12/

Compared to lower-quality colleagues, high-class cells can perform further, and the evanescence of charge is more stable and controlled. The incompatibility of cells is a usual reason for malfunction in industrial batteries. A weak cell is discharged sooner, and its counterparts will wear it out even to the point where an excessive load can push the weak cell into a reverse polarity. When charging, the weakest cell turns into heat-generating overcharge and the other normally functioning cells will continue to charge as expected. /12/

2.6.3 Series Connection

When a single cell does not provide a sufficient voltage, two or more cells are connected in series. Adding cells increases the voltage but the capacity stays the same. Since most devices operating with a battery can endure a slight over-voltage, the end battery voltage does not need to be the same, provided it is higher than the used device requires. Batteries operating with a high voltage demand a diligent cell matching especially when running at cold temperatures or drawing substantial loads. The possibility of one cell decomposing is always present; therefore, some large battery packs include a switch enabling to bypass the malfunctioning cell. With this option, operation can be continued with a lower string voltage (**Figure 5**). /11/

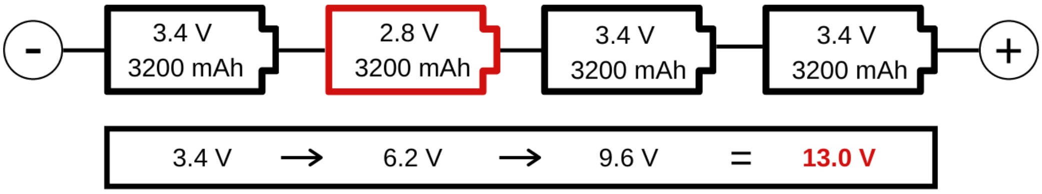


Figure 5. A series connection with a defective cell.

2.6.4 Parallel Connection

When the desired voltage is achieved but the current is on an inadequate level, a parallel connection will be a functional solution. Depending on application, one or more cells can be connected in parallel. Most battery chemistries enable parallel structures with minimal adverse effects. Unlike with a series connection, parallel configuration is less vulnerable for a defective cell. However, the faulty cell will decrease the total capacity of the battery but in theory, the utilization can be continued normally (**Figure 6**). The battery can face a short circuit through an inverse polarization or dendrite growth. In addition to a shortened lifetime, the shorted cell can cause excessive heat or even a danger of fire. To maintain functionality, large battery packs often contain a fuse that intercepts the faulty cell from the parallel circuit. /11/

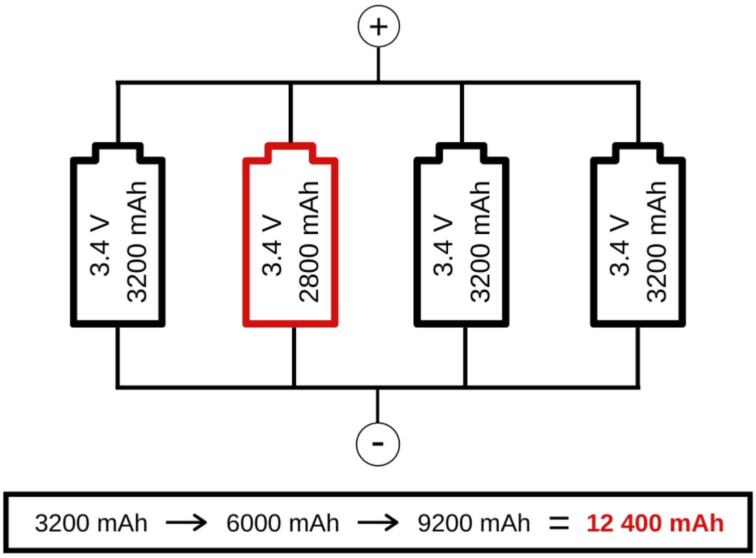


Figure 6. A parallel connection with one faulty cell.

2.6.5 Series-parallel connection

The series-parallel configuration allows supreme design resilience, and the necessary voltage and current values can be achieved with reasonable cell pack sizes /11/. As an example, shown in **Figure 7**, the total power is the sum of the voltage times the current.

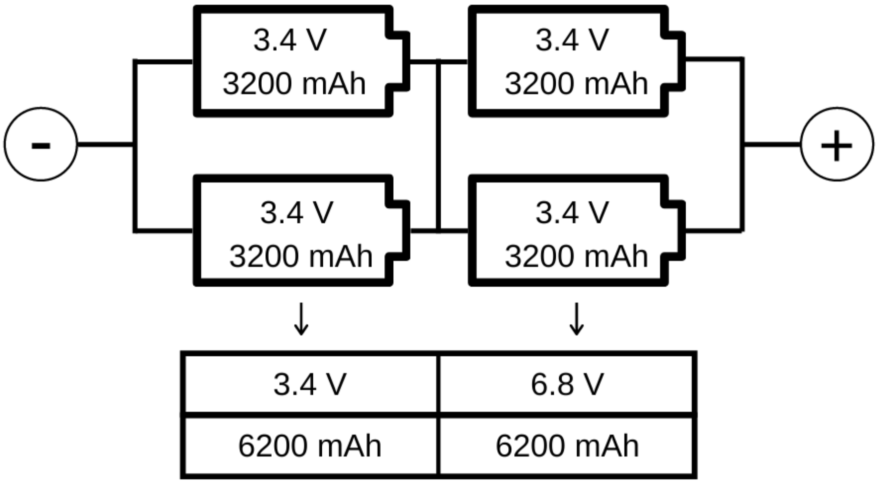


Figure 7. A series-parallel connection with four cells.

$$(3.4\,V + 3.4\,V) * (3200\,mAh + 3200\,mAh) = 43{,}52\,Wh \tag{4}$$

However, as with a basic series connection, a weaker cell will cause an imbalance. Therefore, batteries with equal voltages and capacities should be utilized to avoid unwanted consequences.

2.7 Different Types of Batteries

Batteries can transform the chemical energy included in their active material into electric energy utilizing an electrochemical oxidation-reduction reverse reaction. Nowadays, modern batteries are manufactured for various applications with different sizes and supplied powers may vary from one watt to hundreds of kilowatts. Widespread commercially available secondary batteries can be distributed to a few fundamental groups: standard batteries ($Lead - Acid$, $Ni - Cd$), modern batteries ($Ni - MH$, $Li - ion$, $Li - pol$), special batteries ($Ag - Zn$, NiH_2), flow batteries ($Br_2 - Zn$, $vanadium - redox$) and high temperature batteries ($Na - S$, $Na - metal\ chloride$). /13/

2.7.1 Lead-Acid Battery

When compared to other electrochemical energy sources, lead-acid batteries have multiple benefits. A relatively high cell voltage (2 V), a good availability of lead and a long cycle life will guarantee the affordance and accessibility of lead-acid batteries. Due to a low price and prominent power parameters, lead-acid batteries are the most appropriate for medium or large energy storage operations. /13/

Essential construction elements of lead-acid batteries are electrolyte, electrodes, separators, ventilation, and a vessel with a lid. The electrode composes of a grid and an active mass. The grid must be mechanically solid as a bearing structure as well as corrosion-proof because corrosion transforms lead alloy to lead oxides with a lower mechanical solidity and an electrical conductivity. The grids are manufactured of lead alloys, such as lead-calcium or lead-antimony with a mixture of tin, cadmium, or selenium to ameliorate corrosion resistance. The active material consists of lead oxide which is electrochemically transformed into lead dioxide on the positive electrode and to cellular lead on the negative electrode. /13/

As addressed in Chapter 2.3, separators are utilized to divide the positive electrode from its negative counterpart. In addition to preventing short circuits, separators are beneficial for retaining the active material in nearby contiguity with the grid and holding the plates in their designated locations. Separators can be made of different materials including cellulose, wood veneer, polyvinyl chloride (PVC), rubber, polyethylene (PE) and glass-microfiber. /13/

The vessel inside a battery must tolerate the burden caused by the weight of the inner components and the internal pressure caused by gassing. The most common material for the vessel is polypropylene but also rubber and PVC are used. /13/

Overall chemical reaction for the lead-acid battery during discharge can be shown as:

$$PbO_2 + Pb + 2\ H_2SO_4 \leftrightarrow 2\ PbSO_4 + 2\ H_2O,\ E° = +2.048\ V \qquad (5)$$

The reaction advances in a reversed direction when charging. /13/

An iterative charging and discharging of the lead-acid battery causes several problems. $PbSO_4$, the output of the discharge reaction reserves a larger capacity than the positive active material PbO_2. However, the charging of the cell will not rehabilitate all the lead dioxide. When the positive electrode expands, the battery will have an excess amount of the positive active material. The leftover material is not able to attend to the current collection process; thus the overall capacity will decrease. /13/

2.7.2 Nickel-Cadmium Battery

The positive electrode of a nickel-cadmium cell consists of nickel hydroxide while the negative electrode is made of cadmium. Potassium hydroxide acts as an electrolyte. The nickel-cadmium battery has several significant benefits compared to its counterparts. The battery has a long-standing cycle life, stable discharge rate, overcharge capability and it can also be used at low temperatures. However, the manufacturing and construction of nickel-cadmium cells is significantly more expensive compared to lead-acid cells. When low maintenance and reliability are the most important factors of a battery, the nickel-cadmium is a remarkably good alternative. /13/

The reaction in the nickel-cadmium cell during the discharge:

$$2\,NiOOH + Cd + 2\,H_2O \leftrightarrow 2\,Ni(OH)_2 + Cd(OH)_2,\ E^{\circ} = 1.30\,V \qquad (6)$$

One disadvantage of the Ni-Cd battery is a high rate of self-discharge at high temperatures. Ni-Cd batteries also experience the memory effect. It is an inverse process which results in a momentary degradation of the capacity. /13/ The memory effect may occur when the battery is frequently charged before all its stored energy is utilized completely. This will lead the battery to act like it would memorize the diminished life cycle and accordingly, the capacity will be reduced. /14/

2.7.3 Nickel-Metal Hydride Battery

Nickel-metal hydride (Ni-MH) technology dominates a remarkable market for situations where price and volume energy are essential factors. For long, Ni-MH batteries were utilized in various applications for wireless devices, but the technology has been mainly superseded by lithium-ion cells. However, most rechargeable battery packs still consist of Ni-MH due to their nominal voltage which is close to alkaline batteries. /15/

Nickel-metal hydride batteries were needed to supplant the toxic technology of the nickel-cadmium battery. A metal hydride was able to replace the negative cadmium electrode. The main features of the metal hydride are, for example a tense electrochemical reactivity, notable oxidation resistance, low-pressure hydrogen balance and the aptitude to store hydrogen to obtain a high energy density. /15/

The overall reaction for nickel-metal hydride can be illustrated as:

$$NiOOH + MH \leftrightarrow Ni(OH)_2 + M,\ E^\circ = 1.35\,V \tag{7}$$

The anodes used in the cells are miscellaneous alloys comprehending several different metals, such as lanthanum, vanadium, zirconium, and chromium. /15/

Other nickel-based batteries include for example nickel-iron (Ni-Fe) and nickel-zinc (Ni-Zn) technologies. Nickel-iron batteries were introduced in 1901 and later utilized mainly for powering submarines and lightning and traction in mines. /15/ Nickel-zinc batteries were developed to override nickel-cadmium technology due to non-toxic and inexpensive qualities of zinc. Despite many advantages, the weak long-lasting performance of nickel-zinc batteries in cycling has slowed down its industrial development. /15/

2.7.4 Lithium-Ion Batteries

The lithium-ion chemistry was firstly introduced in 1990. After its introduction to the early 21st century, lithium-ion became the most manufactured cell in the world. The reason for the fast increase in reputation and use of lithium-ion was its higher energy density compared to other competitors. For example, lithium-ion enables the creation of the same amount of energy as nickel-metal hydride with almost half of the weight and size. /16/

The operating principle for lithium-ion batteries does not differ remarkably from other battery cells. When charging, the lithium-ions located in the cathode are dislocated through an electrolyte into the anode. Compared to lead- and nickel-based batteries, lithium-ion chemistry allows a higher cell voltage operation. The increased cell voltage signifies that fewer cells are needed to fulfill the desired voltage in a series connection. In addition to the higher operation voltage, lithium-ion batteries have a lower self-discharge rate. Many lithium-ion technologies will lose only 1-5 % of the total capacity per month which is significantly less than many other battery types. /16/

During a discharging process, lithium is oxidized in the anode made of lithium-graphite according to following reaction:

$$C_6Li \rightarrow 6\,C + Li^+ + e^- \tag{8}$$

Produced lithium-ions travel to the cathode through the electrolyte where they are compounded into lithium-cobalt oxide.

$$Li_{1-x}CoO_2 + x\,Li^+ + x\,e^- \rightarrow LiCoO_2 \tag{9}$$

The chemistries of lithium-ion batteries also enable a significant cycle life. Typically, lithium-ion cells may obtain 1000 cycles with 100 % Depth of Discharge (DOD), but several thousand cycles may be achieved with a lower DOD-value of 80 %. /16/ Lithium-ion technology has also its drawbacks, the largest disadvantage being a high price. Additionally, the charging process must be regulated carefully, particularly when approaching the high top of charge voltage. Detrimental oxygen gas might get released if the positive electrode decomposes due to overcharging. /13/

2.7.5 Vanadium Redox Flow Batteries

In conjunction with the development of renewable energy sources, cost-efficient and high-performance energy storage systems are continuously needed. Developed in the 1980s, vanadium redox flow batteries are considered as one the most auspicious stationary energy systems. Compared to lithium-ion technology which has a risk for overheating and fire, the acidic aqueous vanadium electrolytes used in vanadium redox flow batteries seem significantly more secure in practical applications. /1/

In a vanadium redox battery, two electrolytes in two different loops are divided by a proton exchange membrane (PEM). The electrolyte is produced by dissolving vanadium pentoxide (V_2O_5) into sulfuric acid (H_2SO_4). /13/

The overall chemical reaction can be simplified as:

$$VO^{2+} + V^{3+} + H_2O \leftrightarrow VO_2^+ + V^{2+} + 2\,H^- \qquad (10)$$

The operation succeeds when the reacting anolyte is kept in oxygen-free conditions due to $vanadium^{2+}$-ions' oxidation in air. /1/

The large capacity of vanadium redox batteries makes them a functional solution especially for solar and wind power production. These erratic and periodic energy sources benefit from storage applications that can even out the fluctuations. However, vanadium redox batteries have several disadvantages including a high price, a low energy density and relatively low charge efficiency. /13/

2.7.6 Zinc-Bromine Flow Battery

Zinc-bromine redox flow batteries (ZBBs) have a high cell voltage, energy density and they are made of low-cost materials compared to many other battery technologies. As with vanadium-redox, the zinc-bromine redox flow batteries are mainly used in large-scale energy storage systems. The ZZBs are exceedingly safer compared to lithium-ion and sodium sulfur batteries due to unlikelihood of flammability. /1/

The zinc-bromine cell technology consists of bipolar electrodes which are made of gauzy carbon-plastic composite. The reacting ions can pass through the separator due to a porous plastic material. The battery has a negative and a positive loop and the electrolyte circulates in each supply tank. /13/

The comprehensive chemical reaction during discharge is:

$$Zn + Br_2 \leftrightarrow ZnBr_2,\ E^\circ = +1.85\ V \tag{11}$$

In charging, bromine is emancipated on the positive electrode while on the negative electrode, zinc is deposited. A liquid polybromide complex is achieved when the bromine is blended with an organic substance. These produced drops are then separated from the electrolyte in the loop of the positive electrode. /13/

The main weakness of the zinc-bromine flow battery originates from the prolonged kinetics of the positive electrode. This intricate chemical process significantly restrains the performance capabilities. A higher efficiency and capacity can be achieved with a more coherent and concentrated zinc dissociation. /1/

2.7.7 Sodium-Nickel Chloride Battery

Many different alternatives for storing the energy of the renewable energy sources are continuously needed. One notable applicant is the sodium-nickel chloride secondary battery ($Na - NiCl_2$). When compared to more traditional batteries, the use of elemental sodium has multiple advantages in different situations. The sodium-nickel chloride batteries have been used in various applications for over 25 years and especially safety has been one of the most important features of the battery technology. First introduced in 1978 in South Africa, the sodium-nickel chloride is also known as ZEBRA battery due to an abbreviation of Zeolite Battery Research Africa Project. /1/

The ZEBRA has a high energy density and a high operating temperature. A solid electrolyte, a ceramic known as β''-alumina, separates a fluid sodium anode from a positive electrode. Transition metal chlorides ($NiCl_2/FeCl_2$) and surplus metals

(Ni/Fe) constitute the positive electrode in conjunction with liquid $NaAlCl_4$ electrolyte. A remarkable power density enables the sodium-nickel chloride battery to be a great solution for powering electric vehicles. Additionally, a long lifetime and a deep discharge cycling competence allows thousands of charge and discharge cycles to the battery. /1/

By combining the reactions occurring at the anode and the cathode, a following formula can be achieved:

$$NiCl_2 + 2\,Na \leftrightarrow Ni + 2\,NaCl,\ E° = 2.58\,V \tag{12}$$

Even though the sodium-nickel chloride batteries have a high reliability rate, the transportation of the cells and batteries are considered as a hazardous operation due to the existence of elemental sodium. /1/

2.7.8 Sodium-Sulfur Batteries

Lithium-ion technology has dominated the battery business for a long time, but several challenges complicate its implementation from the current, mainly portable usage to stationary systems. The manufacturing of lithium-ion batteries is expensive and the raw material resources lie either in distant or politically delicate locations. Thus, sodium-based rechargeable electrochemical cells may become a reasonable option for medium- and large-scale stationary systems. The advantages of sodium are its low cost and relatively substantial redox potential. /1/

As sodium, also sulfur is highly obtainable in nature and cheap to exploit. However, the main problem with sodium-sulfur batteries is to discover a usable electrolyte. Aqueous electrolytes cannot be utilized, hence a ceramic material beta-alumina ($\beta - Al_2O_3$) is used to serve the purpose. Beta-alumina is an electronic insulator but with temperatures over 300 °C a high conductivity for sodium ions is present. /13/

The operating principle consists of sodium ions passing from the negative electrode through the electrolyte to the positive electrode made of sulfur. The reaction results in formation of sodium polysulfides. /13/ The discharge process occurs in two phases:

$$5\,S + 2\,Na \rightarrow Na_2S_5,\ E° = 2.076\,V \tag{13}$$

$$3\,Na_2S_5 + 4\,Na \rightarrow 5\,Na_2S_3,\ E° = 1.78\,V \tag{14}$$

Despite the many advantages, sodium-sulfur technology has many weaknesses, mainly related to the safety of the reaction. Due to the high operating temperature, an uncontrolled chemical reaction can cause a fire and emphasize the corrosion tendency of the battery's electrodes. /13/

2.8 Candidates for the Future Energy Storage

2.8.1 Solid-State Batteries

In recent decades, notable progression has been made to develop solid-state batteries. Instead of liquid or polymer gel electrolytes, a solid-state battery utilizes solid electrodes and a solid electrolyte. During the following years, a market niche for small capacity all-solid-state batteries (ASSBs) will increase when large companies will introduce their products utilizing all-solid-state technology. For example, a Japanese multinational automotive manufacturer Toyota has announced the ASSB production to take place in 2025 or earlier. /1/

All-solid-state batteries have gained a lot of interest due to their high energy density and chemical and physical stability. Conventionally, the used lithium metal anode has issues regarding dendrite formation but ASSBs can physically block the incident to occur. Other benefits include the lack of liquid leakage and an endurance of the cell in high temperatures compared to conventional lithium-ion batteries. However, many obstacles need to be exceeded before the ASSB technology can be implemented in large-scale mass production. /1/

2.8.2 Lithium-Sulfur Batteries

The energy storage industry continuously needs alternatives for the dominant lithium-ion battery. Nowadays approximately 90 % of portable electronic devices use lithium-ion technology. Optional cathode materials are needed to obtain a higher storing capacity and simultaneously costs should be reduced. Sulfur is an abundant element which provides a lower environmental impact and as an electrochemical cathode, provides three times larger energy density compared to current lithium-ion batteries. Additionally, the price of sulfur per ton is as low as 150 dollars while the most universal lithium-ion cathode, $LiCoO_2$, costs approximately 10 000 dollars per ton. /1/

Nevertheless, as with almost all new inventions, lithium-sulfur batteries also have its drawbacks. According to Passerini, the chemistry of the battery experiences diverse structural changes involving reiterated phase conversions between solid-state sulfur, solid-state lithium sulfides and liquid-state lithium polysulfides. These intricate reactions cause challenges to achieve a high efficiency, minimalistic self-discharge, and a constant cycle-life. /1/

2.8.3 Lithium-Oxygen Batteries

For almost 30 years, lithium-ion batteries have dominated the battery industry, but the technology is now facing its theoretical limits. For example, lighter and more beneficial redox-active elements are needed. The global need for sustainability also obliges better recyclability instead of the generally used transition metals. New chemistries can store charge utilizing different reactions compared to intercalation. One of the new metal-air chemistries is $Li - air$ $(Li - O_2)$ which enables remarkably high specific energy. /1/

Generally, lithium-air batteries substitute intercalation substances by using lithium metal to replace the graphite anode and the O_2 molecule as a cathode in lieu of transition metal combinations. However, one of the biggest challenges of the technology are the adverse effects caused by the reacting intercessors. These effects cause a weak cycle life and a high charging voltage by decomposing both the electrode and the electrolyte. /1/

2.8.4 Sodium-Ion Batteries

Wind and solar power generation systems are crucial factors concerning our use and production of electricity. Energy storage systems are mandatory to attach generators to a grid for leveling an electric load and to alleviate vicissitudes in an output power. Sodium-ion batteries are observed as feasible candidates for working as a stationary energy system allowing a secure, cheap, long-lasting, and extensive way of storing the renewable energy. Unlike lithium, sodium can be classified as an abundant resource everywhere around the Earth. /1/

Compared to high-temperature sodium-based batteries on the market, Na-ion technology enables the battery to operate at its surrounding temperature without sodium metal. The operation principle of the sodium-ion battery is primarily identical apart from the Li^+-ions which are replaced with the Na^+-ions. The battery has two distinct sodium enhancement materials as negative and positive electrodes. The electrodes are ionically combined by an electrolyte which is usually manufactured from an organic solvent and a sodium salt. Like many other new inventions, Na-ion batteries also have issues that stand in the way of mass production. For example, compared to Li-metal, Na-metal is exceedingly reactive, and the development of a passivation film causes difficulties. /1/

2.8.5 Aqueous Zinc Batteries

One of the cheapest and most used batteries, aqueous alkaline batteries, have an acknowledged history of over 100 years of inexpensive energy. In addition to the affordability of zinc, it serves a prominent energy density and therefore is regarded as one of the most promising alternatives for storing the energy of the renewables. As with sodium, aqueous zinc batteries are based on abundant substances which enable an economical and scattered availability. The advantage of zinc batteries is the ability to use aqueous electrolytes with the zinc metal electrode. On the other hand, alkali metals are known for reacting severely with water and a steady combination of an organic electrolyte and a lithium-metal has not been found. /1/

As a contrary for the desirable energy and power densities, aqueous zinc batteries have been facing setbacks slowing down the evolution of the technology. During the charge and discharge process zinc dissolves and results in limited lifetime due to incessant alterations in the structure of the electrode. Additionally, passivating layers are formed when discharging. The formed film layers slow the transportation of the particles down and in the worst case, the whole electrode becomes inoperative. Despite the current downsides, the aqueous zinc batteries remain as a significant candidate for post-lithium-ion technology. /1/

2.8.6 Full-Organic Batteries

A demand for different energy storage alternatives is constantly increasing and new technologies are needed to specialize in distinct applications. For example, some technologies and chemistries are suitable for a high specific power and capacity while others shine on tasks regarding a long lifetime and recyclability. Most of the used materials for both the negative and the positive electrodes are made of inorganic substances and the mining of these materials causes several economic, environmental, and social issues. By substituting the inorganic compositions with organic alternatives, sustainable and practical solutions can be obtained. /1/

The vast organic chemistry allows multiple materials to be utilized in storing energy. Some of the organic material groups are radial polymers (RP), sulfur-based materials, conjugated polymers (CP) and carbonyl-based materials. Each of the families have their own specific features and more practical and efficient results can be achieved by combining the materials. Thus, the diversity of the organic chemistry enables a wide range of operational potential and specialized capacities. /1/

However, most of the organic active materials are not able to produce sufficient electronic conductivity. Therefore, an exorbitant amount of carbon is needed to accomplish the desired capacity. In addition to the weak conductivity, a low mass density and a solubility of the organics are in the way of mass producing full-organic batteries. The low mass density originates from the use of nonmetallic elements and due to the vulnerability to dissolution, a loss of active material results in a bad cycle stability. /1/

3 PROJECT IMPLEMENTATION

3.1 The Objective

The aim of the thesis was to produce a practical system for charging, discharging, and measuring lithium-ion batteries in collaboration with Technobothnia. Technobothnia is a laboratory department co-owned by three universities, the University of Vaasa, VAMK, University of Applied Sciences and Novia University of Applied Sciences /17/. The completed project will be utilized for educational purposes as a laboratory exercise for corresponding courses and as a source of information on how battery cells operate during the charge and discharge process.

The main target was to illustrate practically how the capacity of each battery will affect other batteries in series and parallel connection. As discussed in Chapter 2.6.2, the exact capacity of a cell is particularly hard to predict during the manufacturing process. Even if the cells are completed in clean, fully automated, and unpolluted conditions, performance alterations will occur. During charging, the cells containing the exact same capacity will continue to charge linearly while the weakest cell might turn into a heat-generating overcharge. Whereas, during the discharge process, the weakest cell will be discharged the quickest and its counterparts will wear it out, which, in the worst case, can turn the cell into reverse polarity.

At the start of the project, a research was made concerning the need of mandatory equipment. After various inquiries, all the required hardware was ordered, and the practical implementation of the project could start. The order form is attached to the Appendix 8.

3.2 LabVIEW

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a software designed for the elaboration of any engineering application that requires test, measurement, or control. LabVIEW uses visual programming language from NI (National Instruments). Initially released in 1986, LabVIEW's graphic language is named as "G" whose graphical approach to programming enables the user to build the code logically and practically. One major benefit of LabVIEW is the ability to seamlessly integrate hardware measurement devices, such as data acquisition boards and laboratory benchtop instruments. NI, the manufacturer of the program, offers several editions of LabVIEW, each having different functions depending on the intended use. /18/

The studying of the program and the design of the project is implemented with the LabVIEW Community Edition, which is available free of charge for non-commercial use. Five different LabVIEW programs were developed to showcase different behaviors in different charging scenarios. The operation principle with the generated codes and user interfaces will be illustrated more profoundly in Chapter 3.6.

3.3 Equipment

3.3.1 Data Acquisition Device

In addition to LabVIEW and a computer, one core element for the project is NI USB-6008 Multifunction DAQ I/O device which makes the data acquisition possible (**Figure 8**). The USB-6008 provides eight single-ended analog input (AI) channels, two analog output (AO) channels and 12 digital I/O ports. Differential analog inputs have a resolution of 12 bits and single-ended measuring provides precision of 11 bits. The device has a lightweight enclosure and is bus powered from the computer's USB-port. The desired signals and sensors can be connected to the device with a screw-terminal connectivity. The size and the portability enable the USB-6008 to be effectively and easily used in various instances. /19/

Figure 8. NI USB-6008 DAQ USB Device.

The DAQ has four differential analog inputs but in order to measure eight different channels at the same time, a single-ended mode needs to be used. The full range of the analog-to-digital converter (ADC) can be utilized in differential mode providing 12 bits of resolution. However, instead of measuring the positive and the negative differences between the analog inputs, the ADC expects a positive input with respect to the common ground in the single-ended mode. This leads to a lower resolution of 11 bits. /19/ Since the USB-6008 can measure a voltage range of 20 V (±10 V), the smallest change the device can detect can be calculated with a following formula:

$$\frac{20\,V}{2^{11}} = 0{,}009765625\,V \approx 9{,}77\,mV \tag{15}$$

Due to a low resolution of the device, the margin of error is relatively notable.

The NI USB-6008 is only capable of measuring voltage values but the amount of current is also crucial to charge lithium-ion batteries properly due to constant-current-constant-voltage (CCCV) charging. As described in Chapter 2.5.4, in the CCCV-charging, the current remains stationary until the voltage of the battery obtains a pre-designed value. When this point has been achieved, the voltage value is kept steady, and the current will decrease exponentially.

Current measurements can be obtained by measuring voltage difference over an external resistor and calculating the current value in the LabVIEW software according to Ohm’s law. For example, when using an external resistor with a resistance of

1 Ω, a voltage value of 3 V results in a current of 3 A. However, the use of resistors with a high resistance value results in a significant voltage drop in the circuit.

3.3.2 Rechargeable Lithium-Ion Batteries

The selected battery type for the project is KeepPower 14500 lithium-ion battery with a voltage value of 3.7 V and a capacity of 800 mAh (**Figure 9**). In addition to a protection from a short-circuit, the battery has a protection circuit against over-current, -charge and -discharge. /20/

Figure 9. KeepPower 14500 800 mAh Lithium-ion Battery.

Essential specifications according to the manufacturer are:

Table 3. KP-14500A Lithium-ion Battery /20/.

KP-14500A Protected Battery	
Minimum Capacity	700 mAh
Charge Voltage	4.20 V ± 0.05 V
Standard Charge Current	400 mA
Standard Charge Time	2 hours
Standard Discharge Cut-off Voltage	2.75 V

Standard Discharge Current	400 mA
Standard Discharge Cut-off Current	30 mA
Protection Trip Current	3.0 A

3.3.3 Laboratory Power Supply

LabVIEW has a broad support for numerous I/O devices. For example, Aim-TTi QL564P power supply can be operated remotely via USB and LabVIEW I/O Assistant /23/. In an ideal scenario, the used batteries can be charged by giving the command from the computer with the programmable laboratory power supply. The required constant-current-constant-voltage charging regime for lithium-ion batteries is effortless to program within the created LabVIEW software.

However, a non-programmable laboratory power supply was used in the charge and measurement project (**Figure 10**). The operating principle is the same as when utilizing a programmable power supply without the added flexibility of remote controlling everything from the computer screen.

Figure 10. Laboratory power supply.

3.3.4 Enclosure, Sockets, and Resistors

When deciding how to build an enclosure for the used batteries and resistors, a polycarbonate plastic case with a transparent lid turned out to be the most practical solution (**Figure 12**). Sufficient dimensions enabled a practical and portable solution, and the transparent cover helps the user to see the wiring without sacrificing safety. Holes were drilled to both sides of the enclosure to be able to install 4 mm isolated banana sockets (**Figure 11**).

Figure 11. Isolated banana sockets.

Figure 12. Enclosure with the sockets installed.

In order to use the lithium-ion batteries effectively, corresponding battery holders were installed to a separate metal plate along with the 1 Ω resistors which are necessary for the current measurements via voltage (**Figure 13**). The resistors were chosen with such a high resistance value due to the low accuracy of the used DAQ device. For example, 0.01 Ω resistors would have a lower impact on the voltage measurements and the resistors would not diminish the voltage of the whole circuit so remarkably.

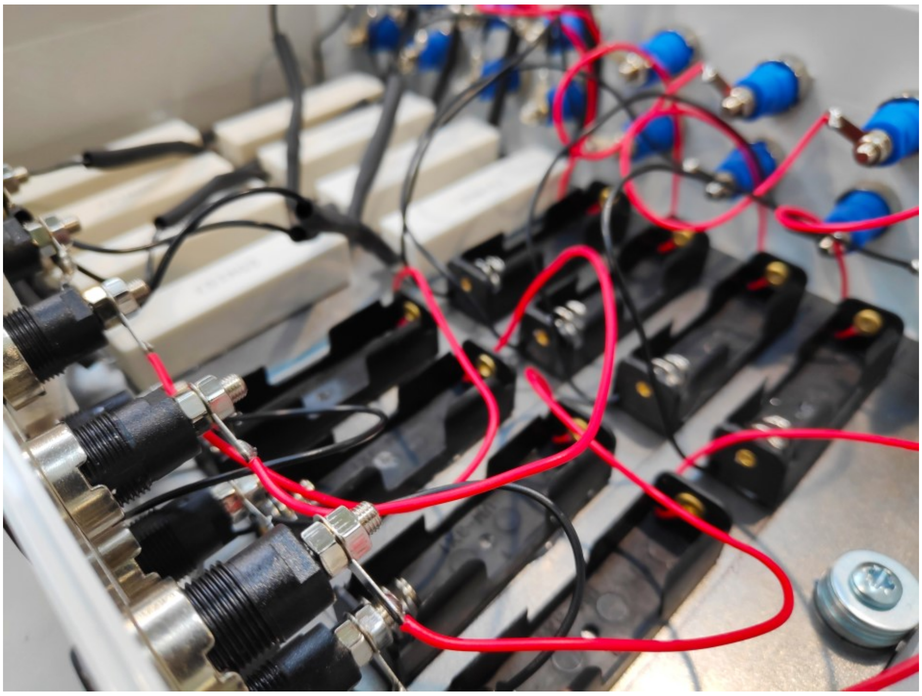


Figure 13. The installation after wiring and soldering.

3.3.5 Solid-State Relay

Although the used KeepPower lithium-ion batteries have built-in protection circuits, the safest way to organize the charging process would be to use an external solid-state relay. With LabVIEW, an output command can be sent to a physical device if the measured input signal exceeds the preset value. The used NI USB-6008 DAQ device can only deliver an output of 0-5 volts and a 5mA current /19/. The output resource was not enough for the available solid-state relays without amplifying the signal with a transistor. Thus, the LabVIEW program will only give a visual sign if the used voltage or current will not stay in the permitted range.

3.4 Temperature Measurement

When charging and testing batteries, the temperature of the cell and its surroundings will usually have a prominent impact on how the battery will operate /1/. However, since the charging system of the project was designed to function in clean laboratory conditions and in room temperatures, the different temperatures inside or outside of the enclosure do not have a vital role in the measurements. Additionally, the used NI USB-6008 DAQ device has only a limited amount of input channels, therefore the temperature measurements could not be obtained with the available resources.

However, measuring temperature is practical and effortless while utilizing the LabVIEW program. A common way to measure a temperature with a data acquisition device is to use thermocouples which are advantageously priced and easily obtainable. The operating principle consists of a generated voltage that varies based on temperature. With a thermocouple, the voltage can be measured and then converted to a temperature value within the software. Example devices for the task are NI's E-, J-, K- and T-Type Thermocouples as well as NI USB-TC01 which works straight from a computer's USB-port without an external DAQ device. /21/

3.5 Resistance and Resistivity

As with all installations and electrical calculations, electrical conductivity and resistivity are important factors to consider. According to Shahat, the resistivity of copper is $1{,}67994 * 10^{-8} \Omega m$. /22/ The resistances of the used electric copper cables can be calculated with a following formula:

$$R = \rho \frac{L}{A} \tag{16}$$

$R = resistance\ (\Omega)$

$\rho = resistivity\ (\Omega m)$

$L = length\ of\ the\ cables\ (m)$

$A = cross - sectional\ area\ (m^2)$

Thus, the resistance of the used cables inside the enclosure can be calculated as:

$$R = 1{,}67994 * 10^{-8}\Omega m * \frac{0{,}3\ m}{0{,}00022\ m^2} = 2{,}290827273 * 10^{-5}\ \Omega \qquad (17)$$

Due to the relatively low precision of the used NI USB-6008 data acquisition device, the additional resistance caused by the wires will not have a notable significance for the project.

3.6 LabVIEW Program Demonstration

The programs that are created using LabVIEW are called virtual instruments (VIs). The name originates from the similarities with physical instruments such as multimeters and oscilloscopes. When creating a new VI, the Front Panel window and the Block Diagram window are both introduced to the user without any information in them. The user can begin to craft a new program with the Controls Palette in the Front Panel or with the Functions Palette within the Block Diagram window. /24/

In this chapter, the first and the simplest developed LabVIEW program (1. Single Battery, **Figure 14** and **Figure 15**) is introduced providing information of the operation principle of all five different virtual instruments. The most essential building blocks of the code are introduced enabling a new operator to understand how the generated programs function (**Table 4**).

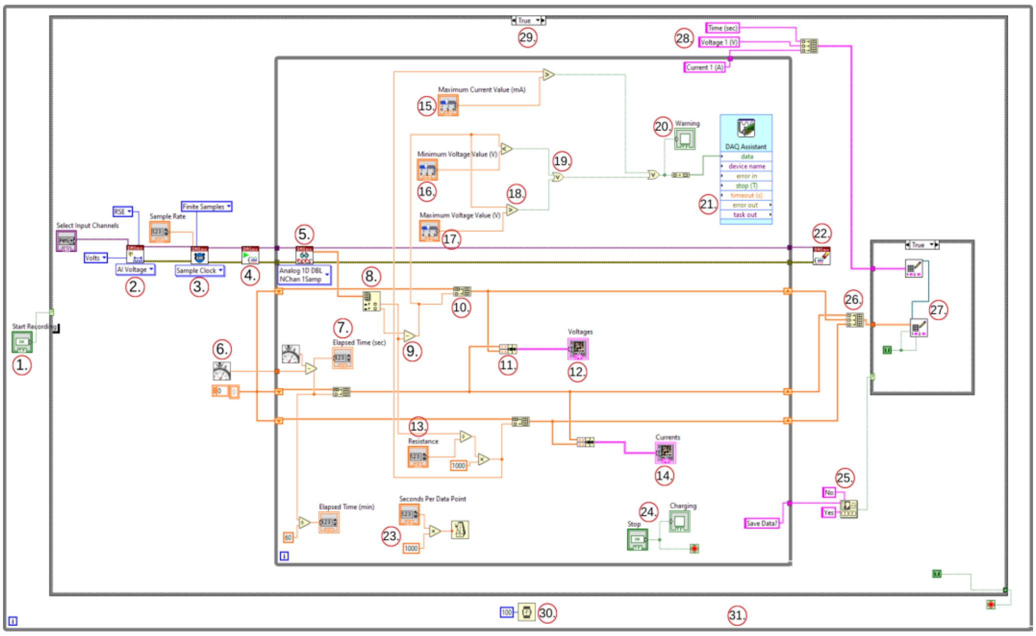
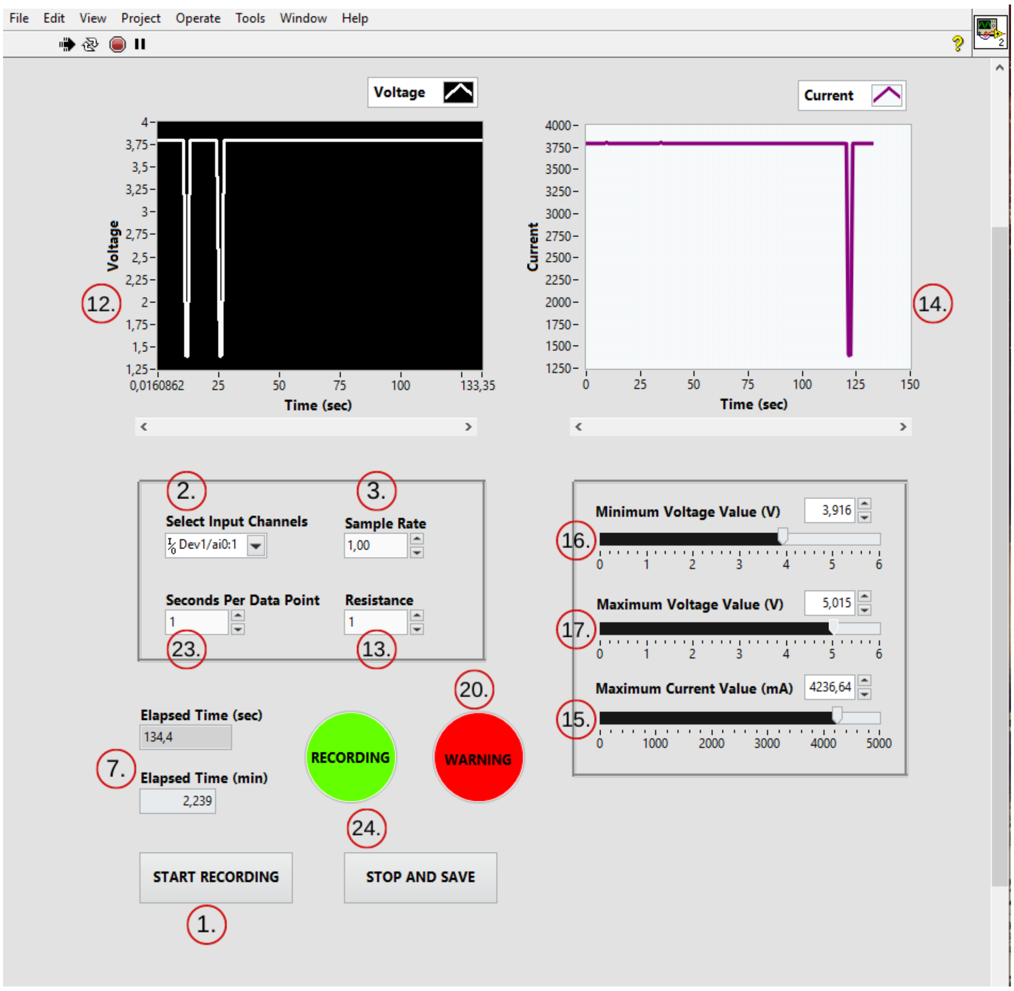


Figure 14. LabVIEW Block Diagram. Program 1. Single Battery.



Select Input Channels: Dev1/ai0:1

Sample Rate: 1,00

Seconds Per Data Point: 1

Resistance: 1

Minimum Voltage Value (V): 3,916

Maximum Voltage Value (V): 5,015

Maximum Current Value (mA): 4236,64

Elapsed Time (sec): 134,4

Elapsed Time (min): 2,239

Figure 15. LabVIEW Front Panel. Program 1. Single Battery.

Table 4. LabVIEW Code Analysis /25/.

Number	Name of the block	Function in the program
1.	Boolean (True or False) controller	Starts the program.
2.	DAQmx Create Channel	Creates channels to measure voltages.

3.	DAQmx Timing Sample Clock	Sets the sample rate and the number of samples to acquire.
4.	DAQmx Start Task	Transitions the task to a running state and begins the measurements.
5.	DAQmx Read (Analog 1D DBL)	Reads a single floating-point sample from each channel in a task that contains one or several analog input channels.
6.	High Resolution Relative Seconds	Returns the relative current time in seconds. The counter starts from zero every time the program gets started.
7.	Elapsed Time	An elapsed time is measured by computing the difference between the inside and the outside values of the while-loop.
8.	Index Array	Returns the subarray or element of n-dimension array at index.
9.	Subtract	Computes the difference of the inputs. Similar Multiply and Divide functions are also widely used.
10.	Build Array	Chains multiple elements or arrays to an n-dimensional array.
11.	Bundle	Accumulates a cluster from individual elements.
12.	XY Graph (Voltage)	Displays voltage as a function of time
13.	Resistance	User will determine the resistance value according to the physical resistors used. After dividing the voltage with the resistance, current can be calculated.
14.	XY Graph (Current)	Displays current as a function of time

15.	Maximum Current Value	The user can determine a maximum permissible current value in the front panel. If the measured value surpasses the limit, a warning sign will light up in the front panel.
16.	Minimum Voltage Value	The user can determine a minimum permissible voltage value.
17.	Maximum Voltage Value	The user can determine a maximum permissible voltage value.
18.	Greater-than	Returns True if x is greater than y. Otherwise the function returns false. Less-than sign is also used.
19.	Or	Counts the logical or of the inputs. If both inputs are False, the function returns False.
20.	Boolean (True or False) controller	The user gets a warning sign in the front panel with a Boolean true value.
21.	DAQ Assistant	In this instance, sends a digital output command at the same time when the warning sign turns on in the front panel. Can be utilized to control an external solid-state relay to disconnect the charging circuit.
22.	DAQmx Clear Task	Clears the task. Releases any resources the task has reserved.
23.	Seconds Per Data Point	Controls the while loop's execution rate. The user can determine a suitable interval in the front panel.
24.	Stop Sign	A button in the front panel to stop the while loop and the whole program.
25.	Two Button Dialog	Presents a dialog box which includes a message and two buttons. After stop sign is pressed, a dialog box asks user whether to save the collected data or not.

26.	Build Array	Combines the collected time, voltage, and current values.
27.	Write Delimited Spreadsheet	Used to save the measured values to a text or Microsoft Excel file.
28.	String Components	Used to give corresponding headers to the text or Excel files.
29.	Case Structure	The start recording (1.) button is wired to the case structure's selector input to determine when the structure and the code in it executes.
30.	Wait (ms)	Waits the specific number of milliseconds and returns the value of the millisecond timer. Used to recognize when the Start Recording button (1.) has been pressed.
31.	While Loop	Repeats the code within its subdiagram until a specific condition occurs.

The Block Diagrams and the Front Panel views of all the five produced LabVIEW programs are attached to appendices 1-5. The names of the programs and their intended use is represented below.

Table 5. Generated LabVIEW programs

Program name	Type of connection	Appendix
1. Single Battery	One battery, one resistor in series	1
2. Dual Series	Two batteries, one resistor in series	2
3. Dual Parallel	Two batteries in parallel, two resistors in parallel	3
4. Dual Series and Dual Parallel	Two batteries in series, two batteries in parallel, two resistors in parallel	4

5. Dual Series and Dual Parallel (connected)	Two batteries in series, two batteries in parallel, two resistors in parallel with an alternative wiring	5

4 CONCLUSIONS

The objective of the study was to build an educational measurement system for lithium-ion batteries using LabVIEW software. The finished applications and the constructed measurement system are meant to be used in the Technobothnia laboratory unit in Vaasa.

The theoretical segment of the thesis extensively addresses the issues and details which are essential for various battery technologies. After a brief introduction of the primitive battery evolution, the operating principle of charging and the different connections are introduced. Additionally, various battery technologies and potential future solutions demonstrate what the main challenges of the development of the battery industry are. The most important theoretic concept is to understand how the battery cells have alterations in their capacity and how it will directly translate to performance and life expectancy.

The main component of the thesis was to build LabVIEW programs for five different charging and discharging situations. The original idea of developing a fully automatic charging and discharging system was not fulfilled due to a lack of a programmable laboratory power supply. However, the produced programs can be effortlessly modified to work with multiple I/O (Input/Output) devices due to the same operating principle.

The objective of the study was achieved in relation to the available resources. One major benefit of the generated LabVIEW programs is the ability to use them on any computer with any data acquisition device allowing more accurate measurements. In addition to the different programs, illustrative pictures, wiring diagrams and an instruction manual were made to help perceiving the entire outcome for a new user (Appendices 1-7).

As represented, to gain a preferable benefit from the research, more compatible equipment should be utilized. In addition to a programmable laboratory power supply and a more precise data acquisition device, the ability to measure the temperature and the use of a relay for an automatic safety controller would make the entire study more suitable for various purposes. One of the most remarkable degenerative factors is the high resistance values of the resistors. More precise resistors would be beneficial for further development allowing better voltage controllability in the whole circuit.

Overall, the project will have an extensive educational value as a source of practical information. As a laboratory exercise, students can get a more profound understanding on how batteries are charged and what it signifies when each battery of the system will not have the same capacity. A comprehension of the subject allows solutions for various complexities around battery technologies.

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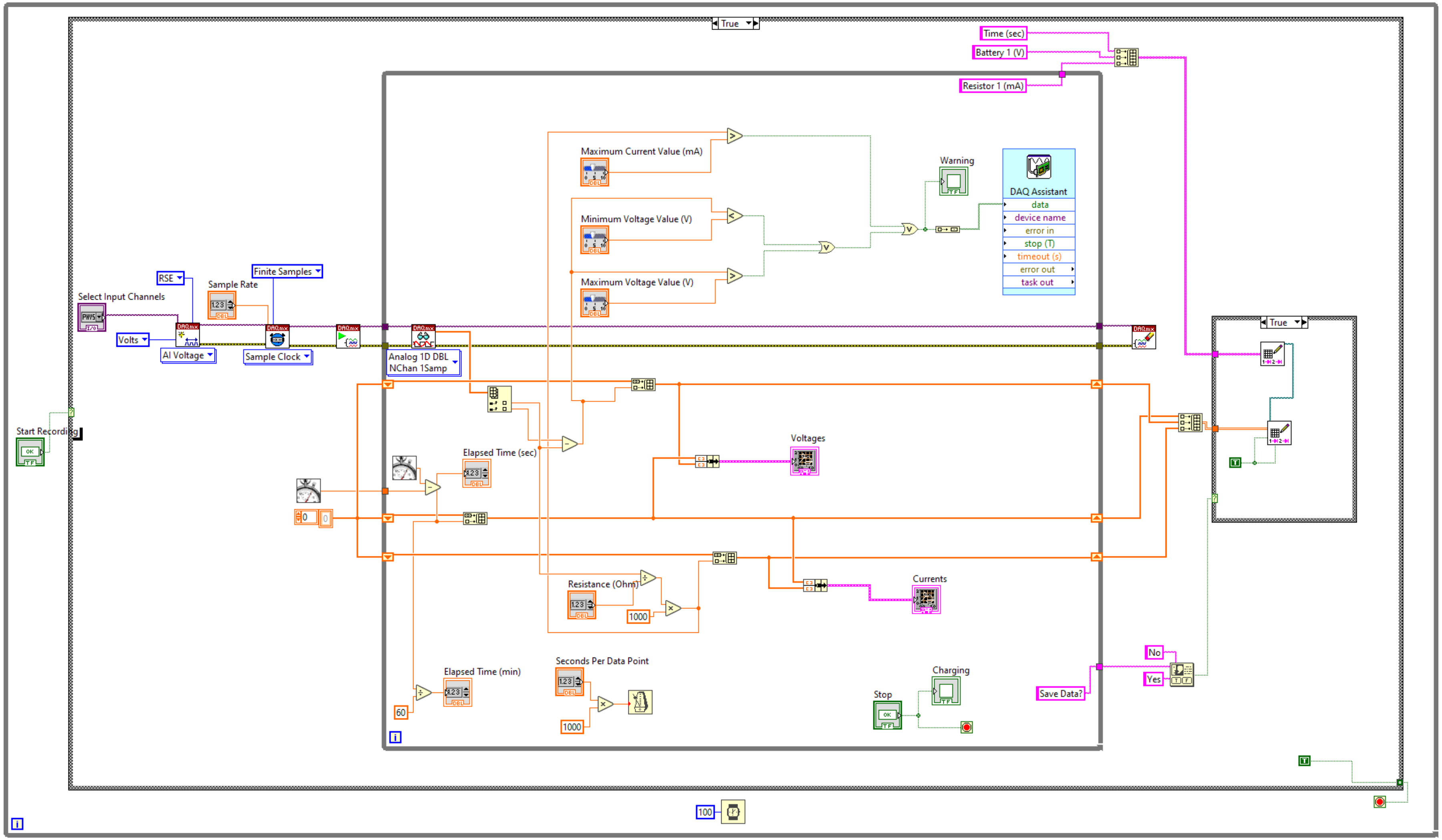
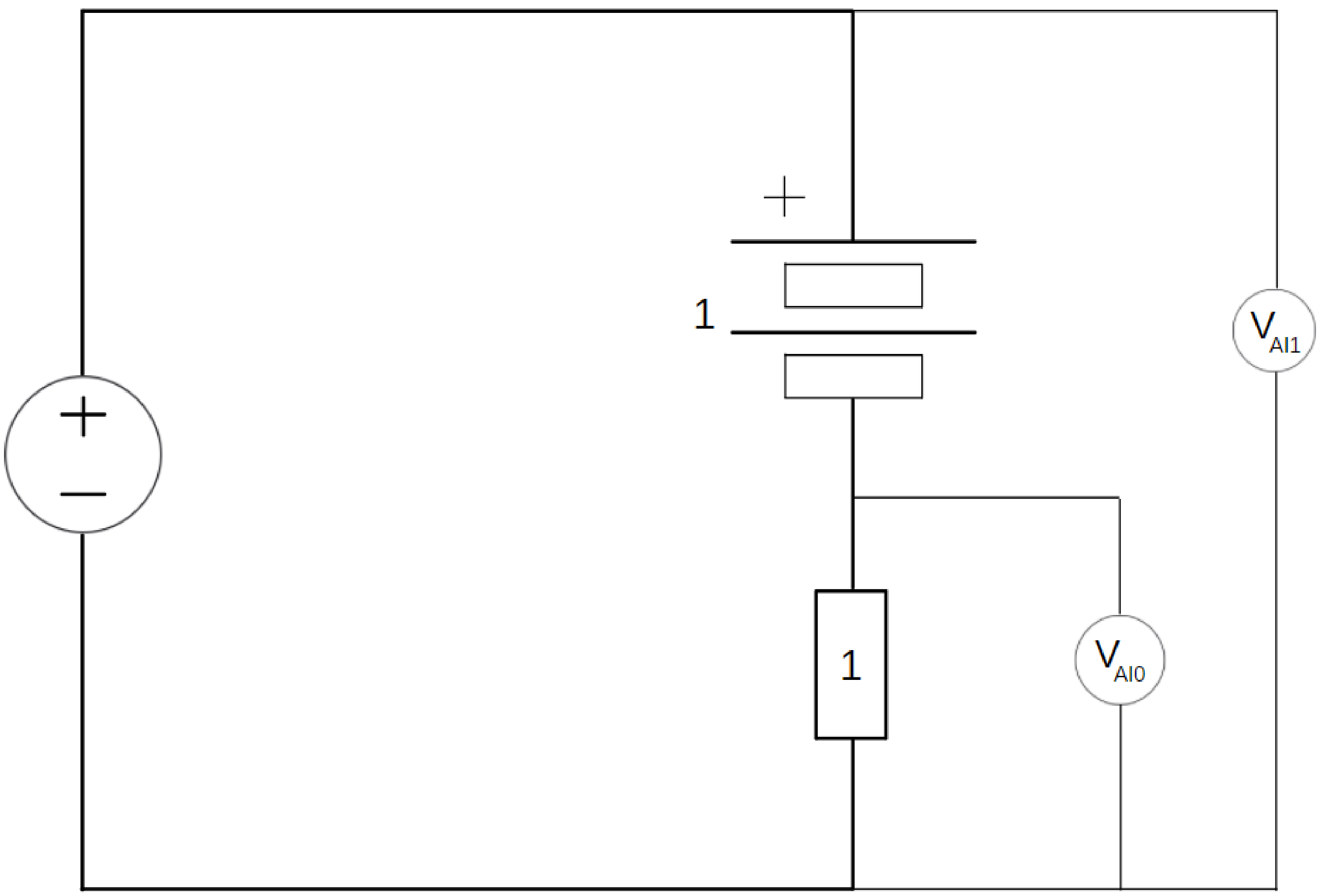
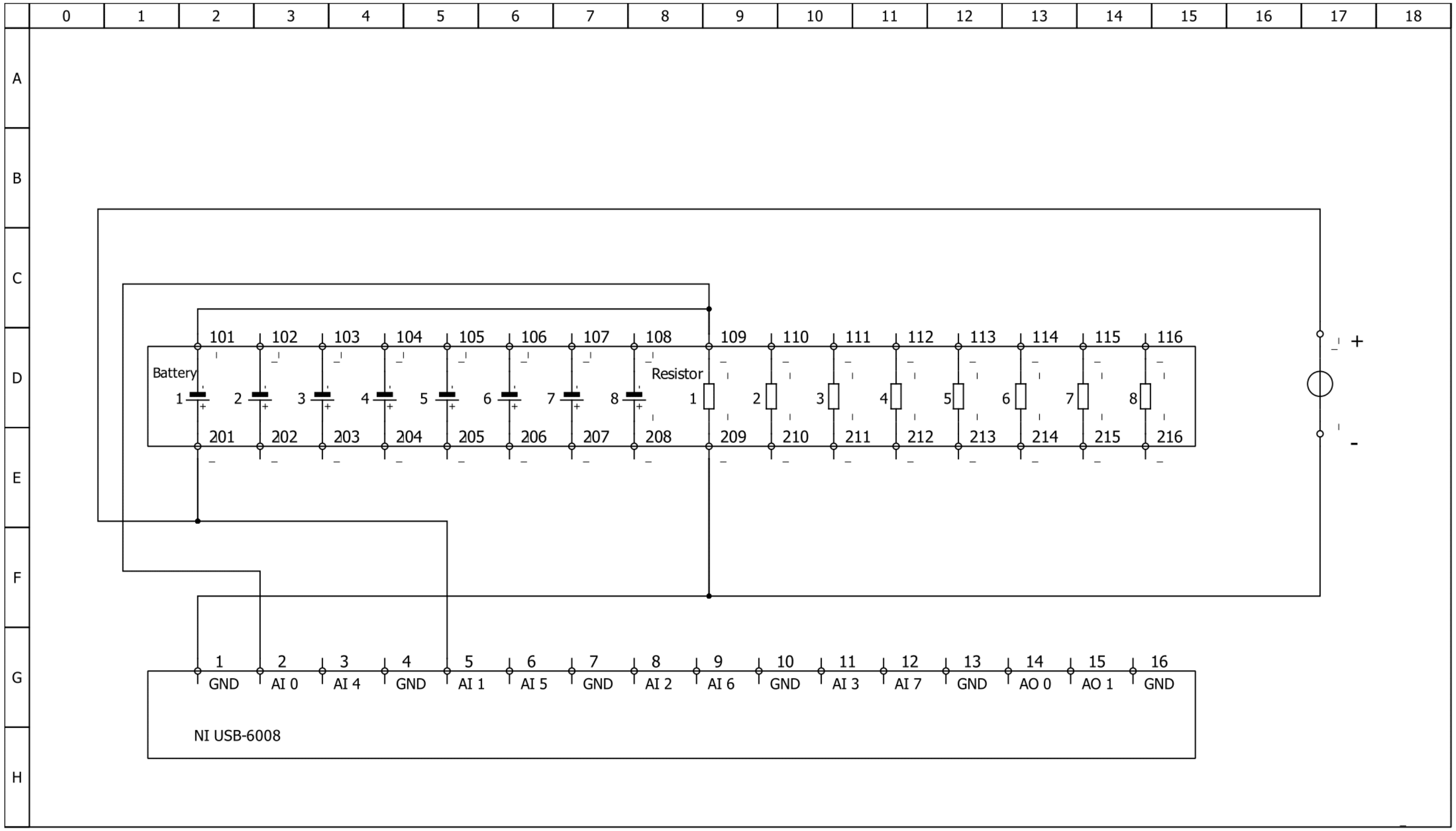
APPENDIX 1


True
Time (sec)
Battery 1 (V)
Resistor 1 (mA)
Maximum Current Value (mA)
Minimum Voltage Value (V)
Maximum Voltage Value (V)
Warning
DAQ Assistant
data
device name
error in
stop (T)
timeout (s)
error out
task out
RSE
Finite Samples
Sample Rate
Select Input Channels
Volts
AI Voltage
Sample Clock
Analog 1D DBL
NChan 1Samp
True
Start Recording
Elapsed Time (sec)
Voltages
0
Resistance (Ohm)
1000
Currents
Elapsed Time (min)
Seconds Per Data Point
60
1000
Stop
Charging
Save Data?
No
Yes
100

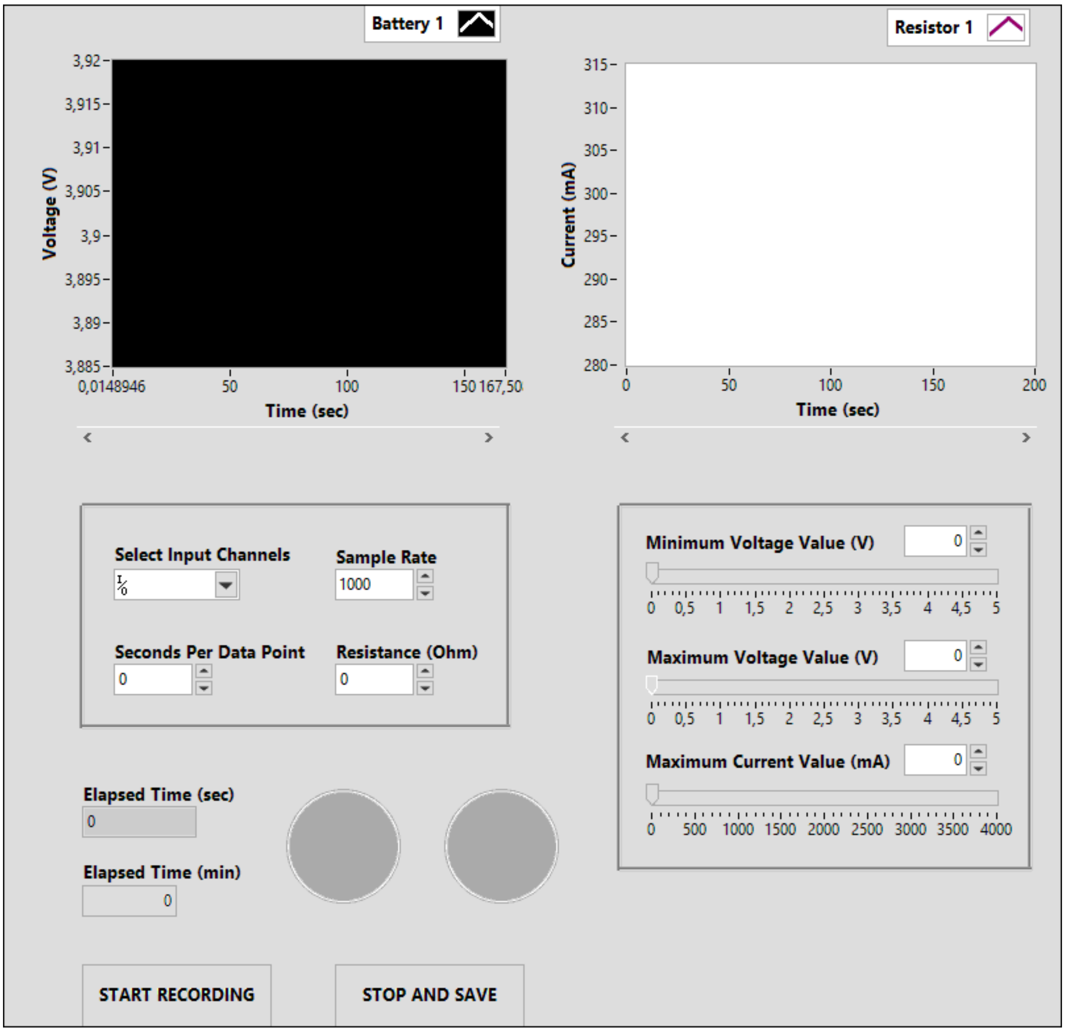
APPENDIX 1



APPENDIX 1


0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
A B C D E F G H
101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116
Battery
1 2 3 4 5 6 7 8
Resistor
1 2 3 4 5 6 7 8
201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216
+
-
1 GND
2 AI 0
3 AI 4
4 GND
5 AI 1
6 AI 5
7 GND
8 AI 2
9 AI 6
10 GND
11 AI 3
12 AI 7
13 GND
14 AO 0
15 AO 1
16 GND
NI USB-6008

APPENDIX 1



Sample Rate: 1000

Seconds Per Data Point: 0

Resistance (Ohm): 0

Elapsed Time (sec): 0

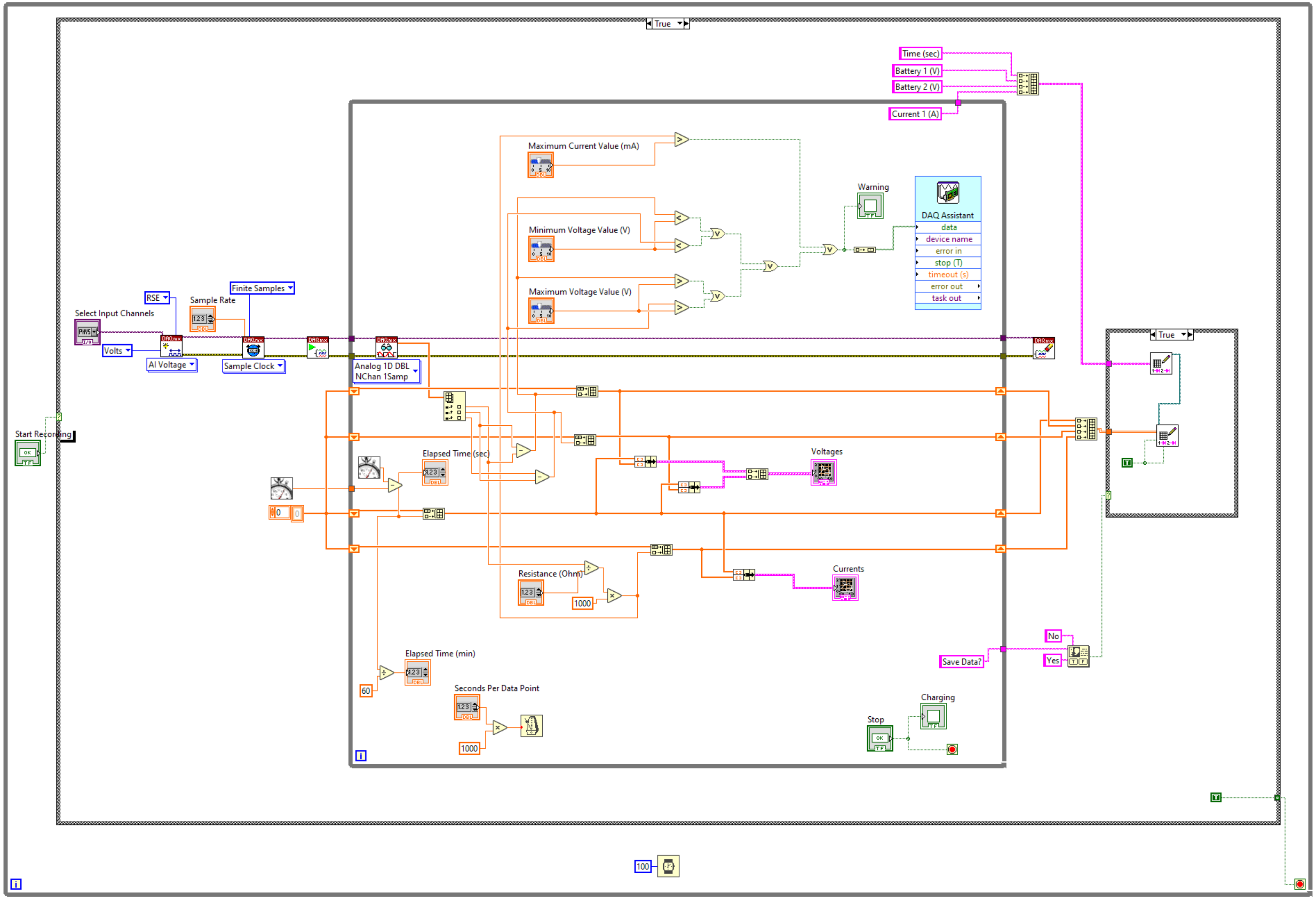
Elapsed Time (min): 0

Minimum Voltage Value (V): 0

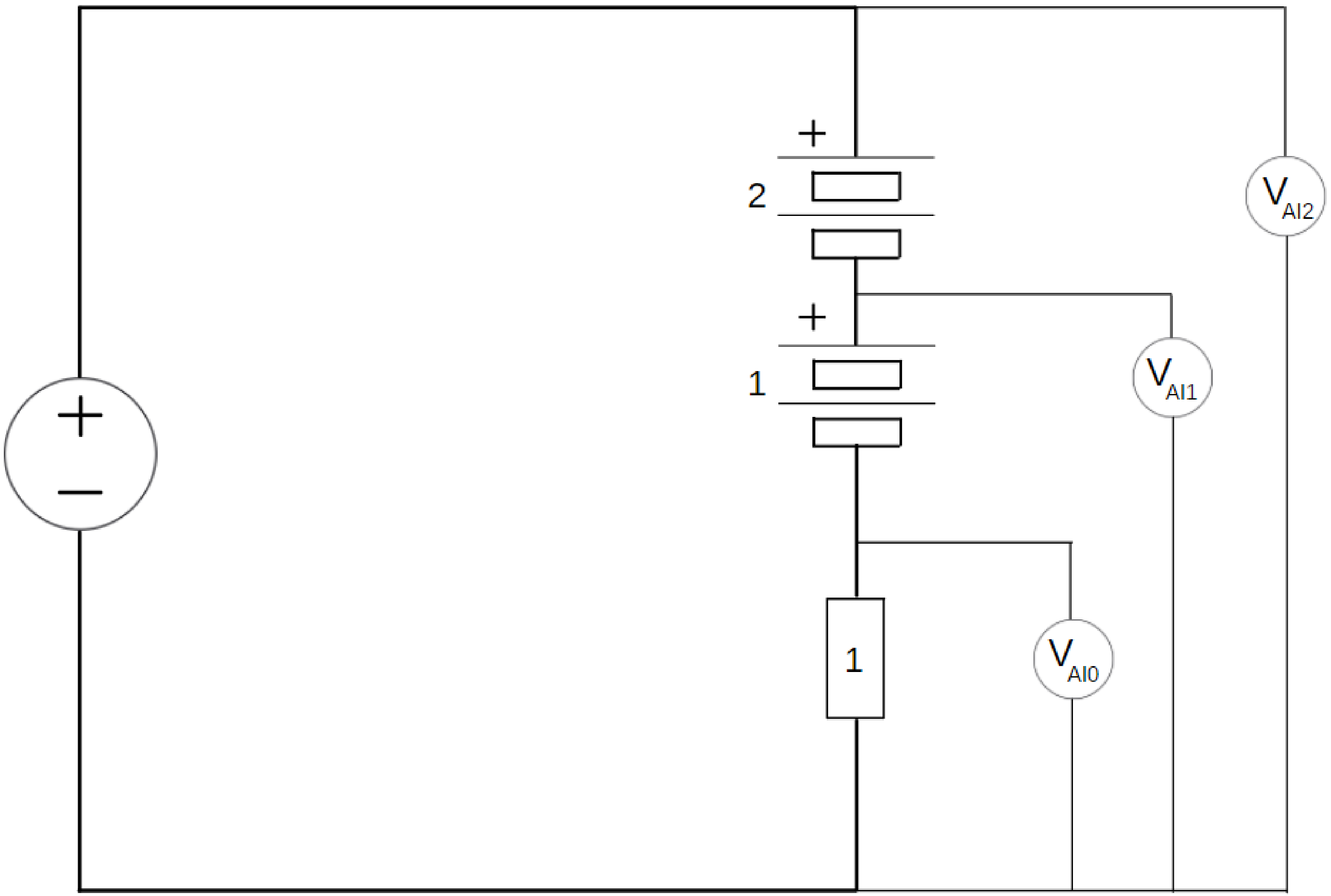
Maximum Voltage Value (V): 0

Maximum Current Value (mA): 0

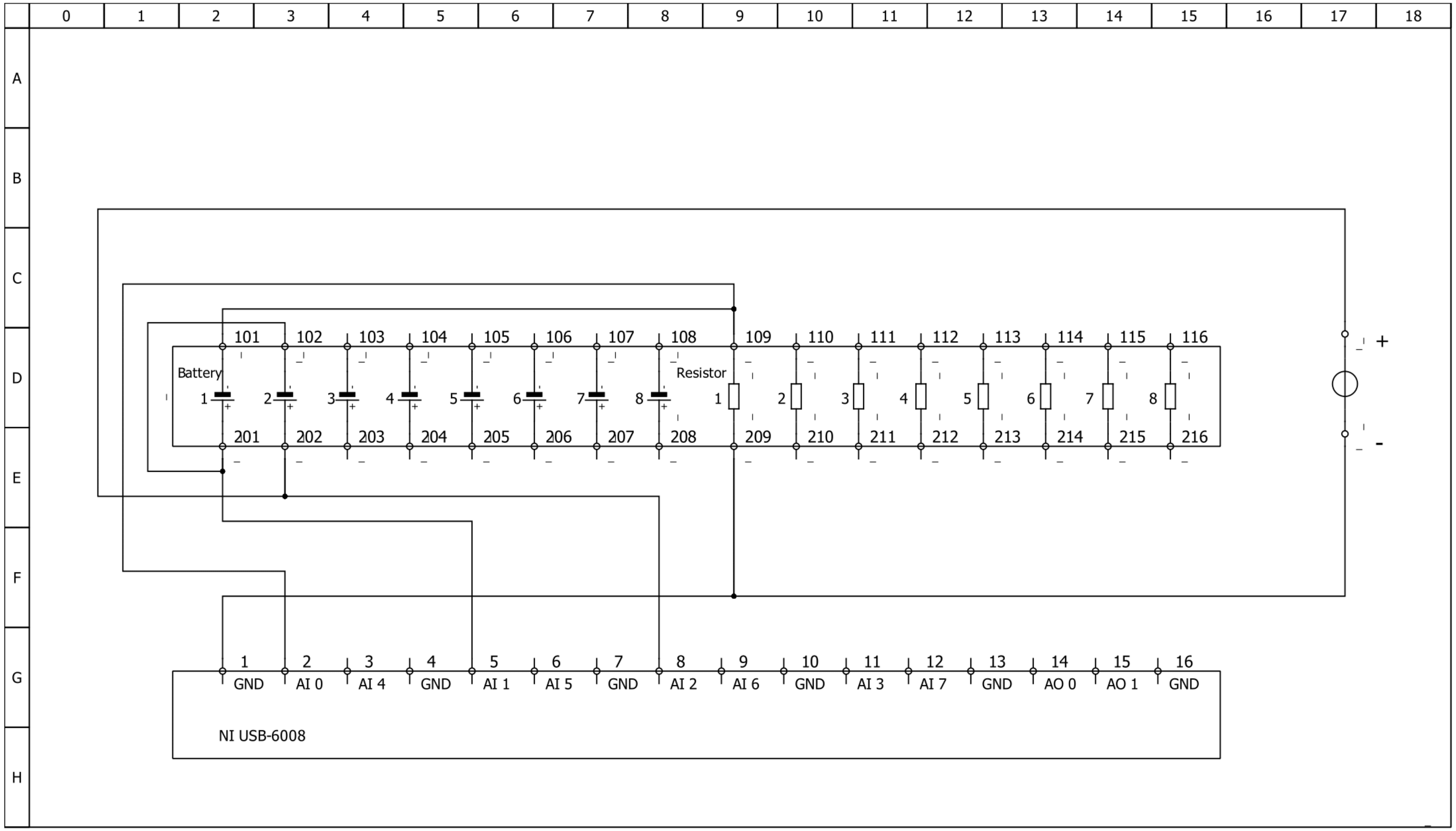
APPENDIX 2


True
Time (sec)
Battery 1 (V)
Battery 2 (V)
Current 1 (A)
Maximum Current Value (mA)
Warning
DAQ Assistant
data
device name
error in
stop (T)
timeout (s)
error out
task out
Minimum Voltage Value (V)
Maximum Voltage Value (V)
RSE
Finite Samples
Sample Rate
Select Input Channels
Volts
AI Voltage
Sample Clock
Analog 1D DBL
NChan 1Samp
True
Start Recording
Elapsed Time (sec)
Voltages
0
Resistance (Ohm)
1000
Currents
No
Yes
Save Data?
Elapsed Time (min)
60
Seconds Per Data Point
1000
Charging
Stop
100

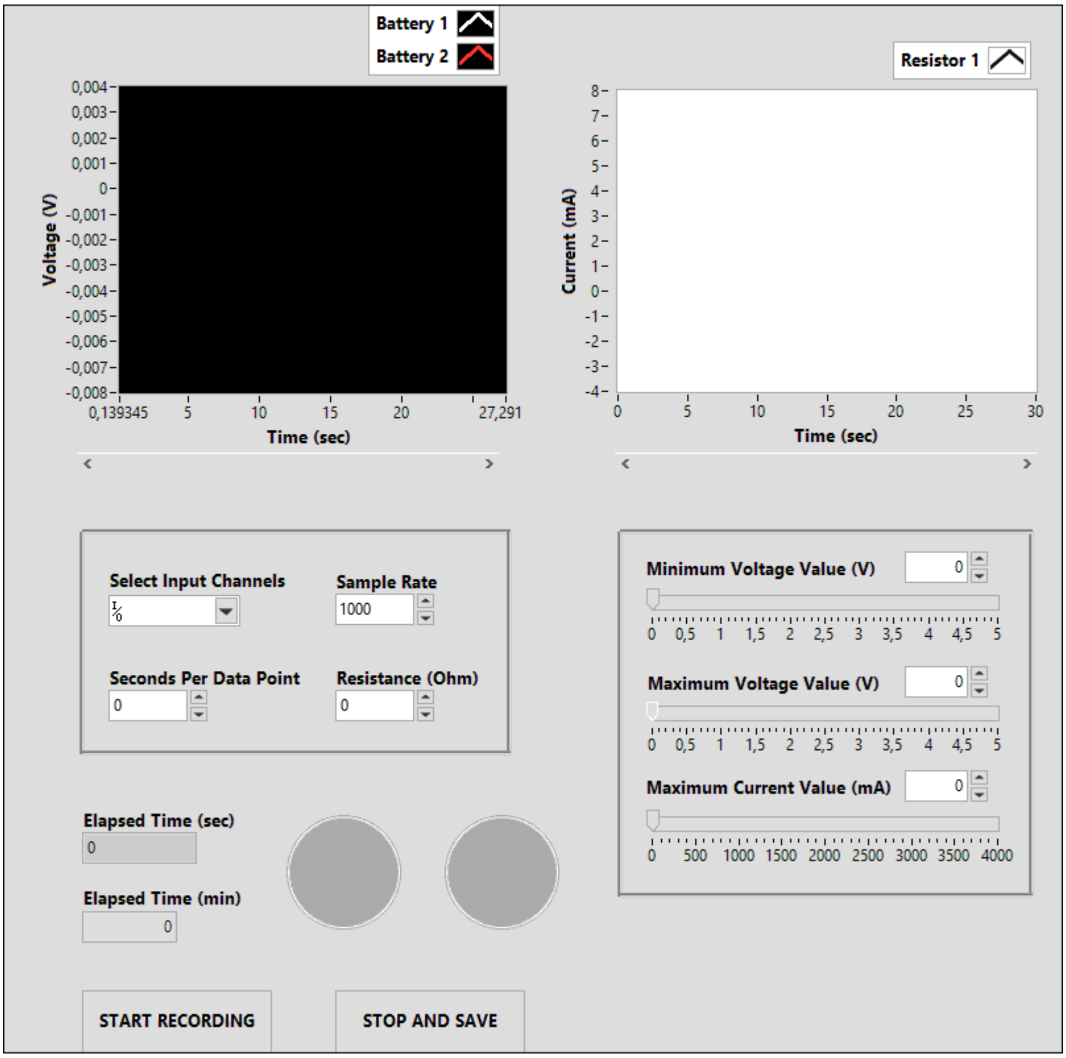
APPENDIX 2



APPENDIX 2


0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
A
B
C
D
E
F
G
H
Battery
Resistor
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
1
2
3
4
5
6
7
8
1
2
3
4
5
6
7
8
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
+
-
1 GND
2 AI 0
3 AI 4
4 GND
5 AI 1
6 AI 5
7 GND
8 AI 2
9 AI 6
10 GND
11 AI 3
12 AI 7
13 GND
14 AO 0
15 AO 1
16 GND
NI USB-6008

APPENDIX 2



Select Input Channels: I/O

Sample Rate: 1000

Seconds Per Data Point: 0

Resistance (Ohm): 0

Minimum Voltage Value (V): 0

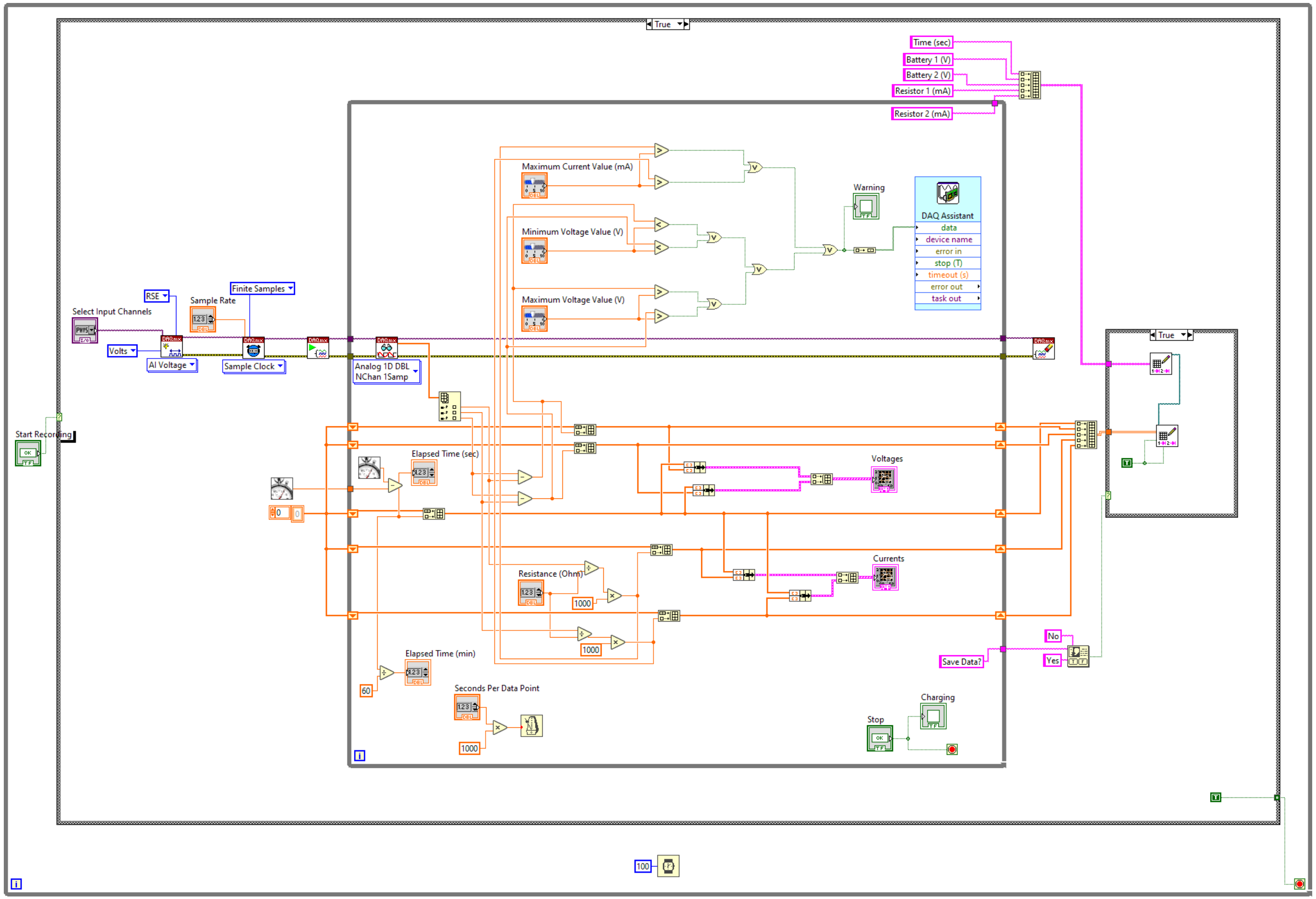
Maximum Voltage Value (V): 0

Maximum Current Value (mA): 0

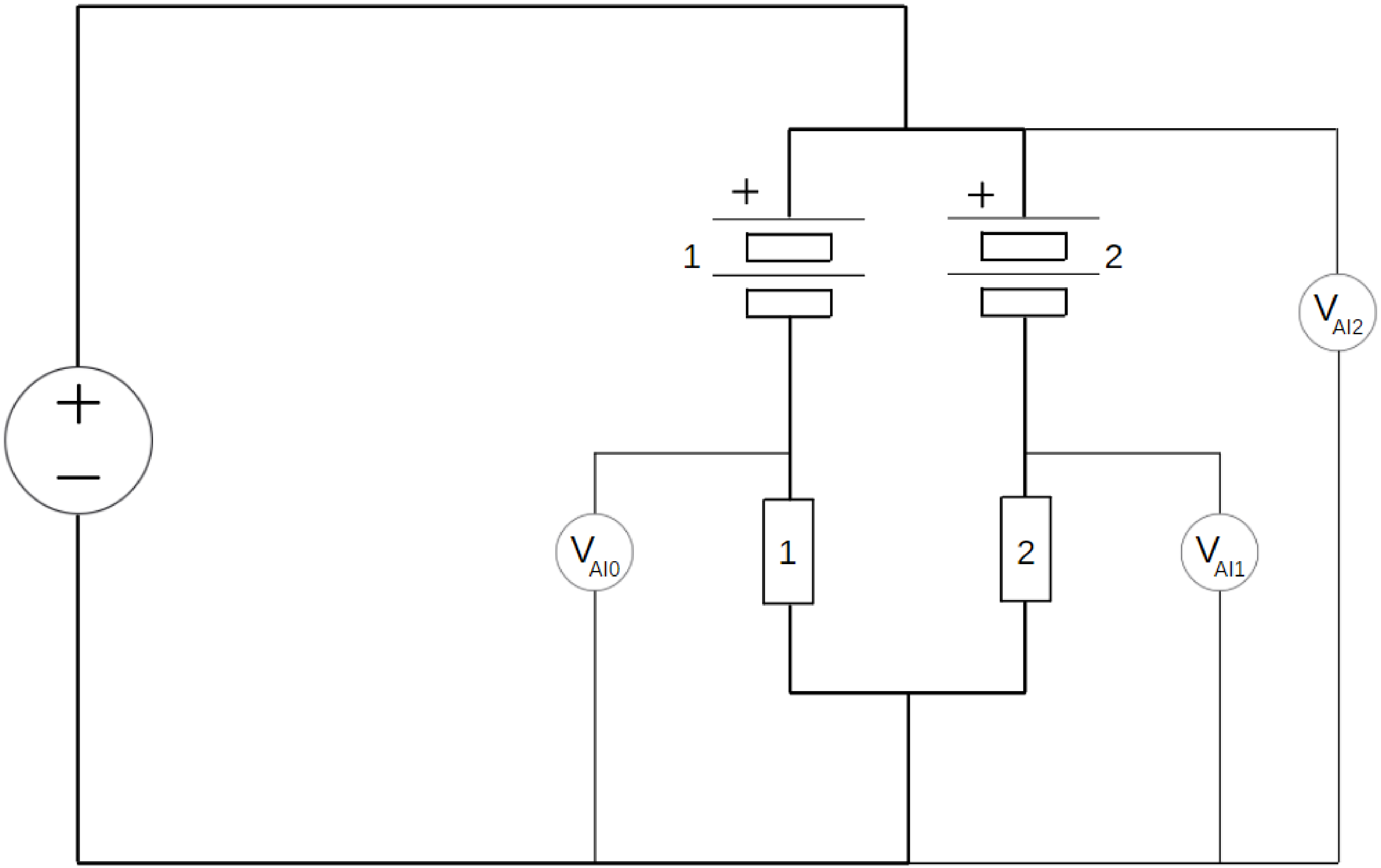
Elapsed Time (sec): 0

Elapsed Time (min): 0

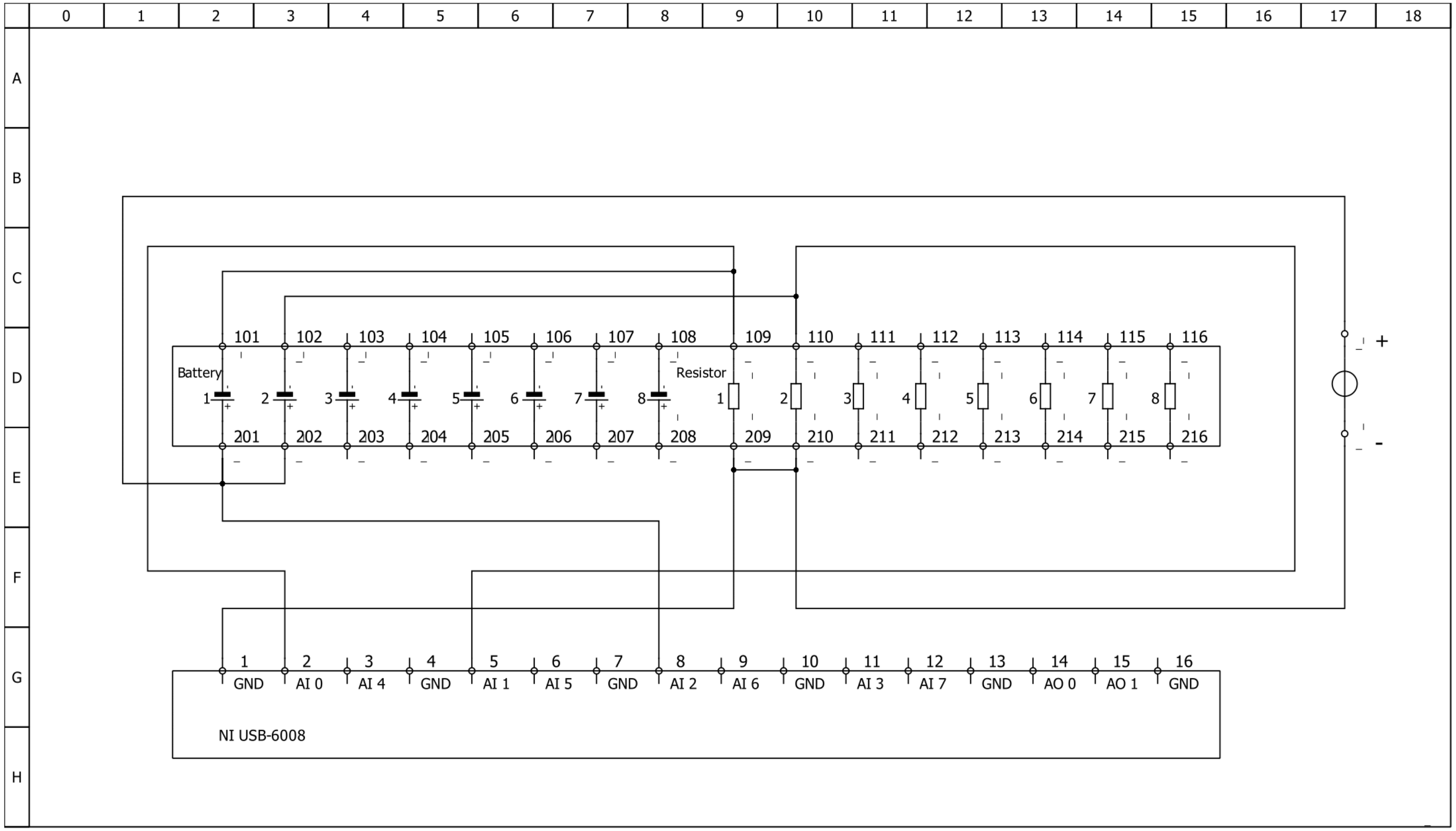
APPENDIX 3


True
Time (sec)
Battery 1 (V)
Battery 2 (V)
Resistor 1 (mA)
Resistor 2 (mA)
Maximum Current Value (mA)
Minimum Voltage Value (V)
Maximum Voltage Value (V)
Warning
DAQ Assistant
data
device name
error in
stop (T)
timeout (s)
error out
task out
Select Input Channels
RSE
Sample Rate
Finite Samples
Volts
AI Voltage
Sample Clock
Analog 1D DBL
NChan 1Samp
Start Recording
Elapsed Time (sec)
0
Voltages
Currents
Resistance (Ohm)
1000
1000
Elapsed Time (min)
60
Seconds Per Data Point
1000
No
Yes
Save Data?
Charging
Stop
True
100

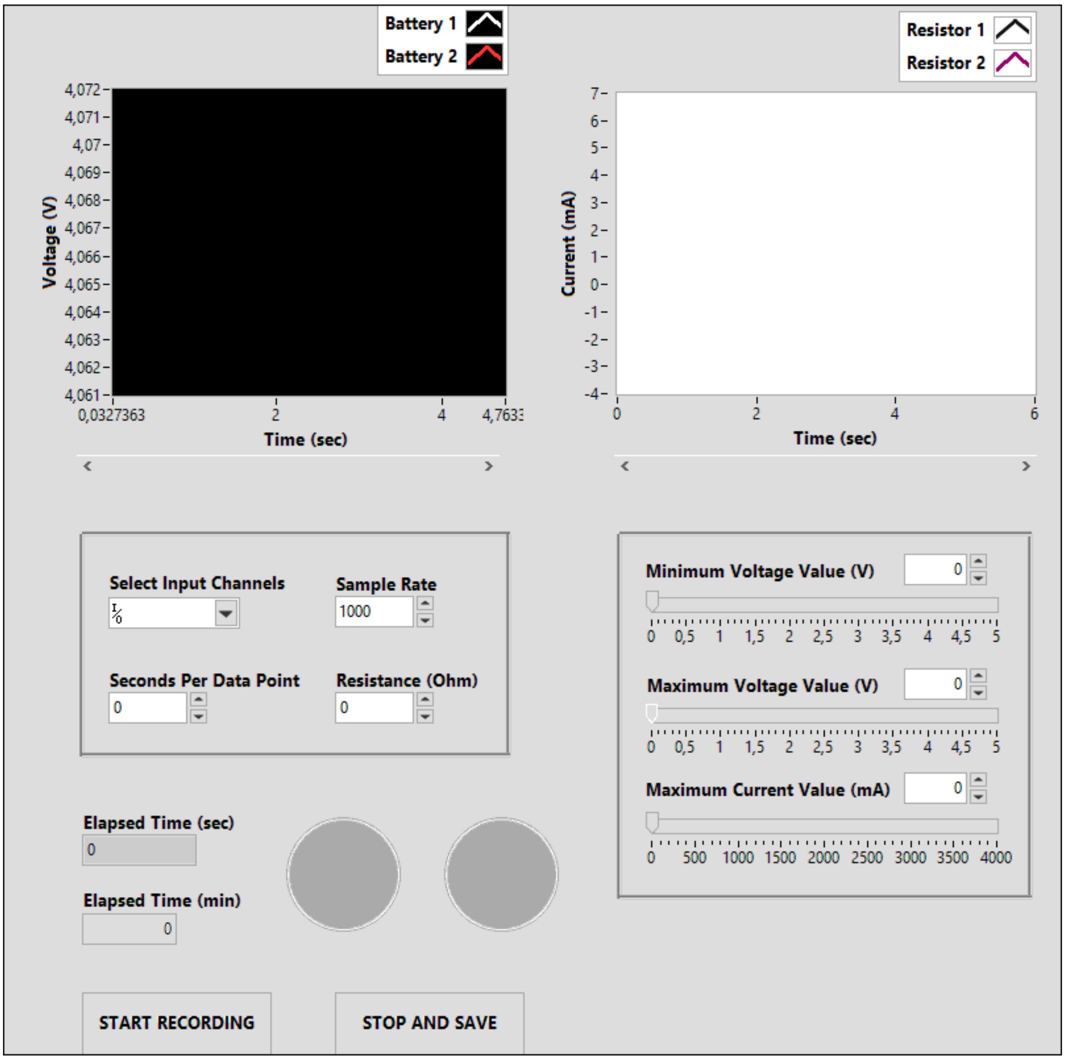
APPENDIX 3



APPENDIX 3


0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
A
B
C
D
E
F
G
H
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
Battery
Resistor
1
2
3
4
5
6
7
8
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
+
-
1 GND
2 AI 0
3 AI 4
4 GND
5 AI 1
6 AI 5
7 GND
8 AI 2
9 AI 6
10 GND
11 AI 3
12 AI 7
13 GND
14 AO 0
15 AO 1
16 GND
NI USB-6008

APPENDIX 3



Select Input Channels

Sample Rate: 1000

Seconds Per Data Point: 0

Resistance (Ohm): 0

Minimum Voltage Value (V): 0

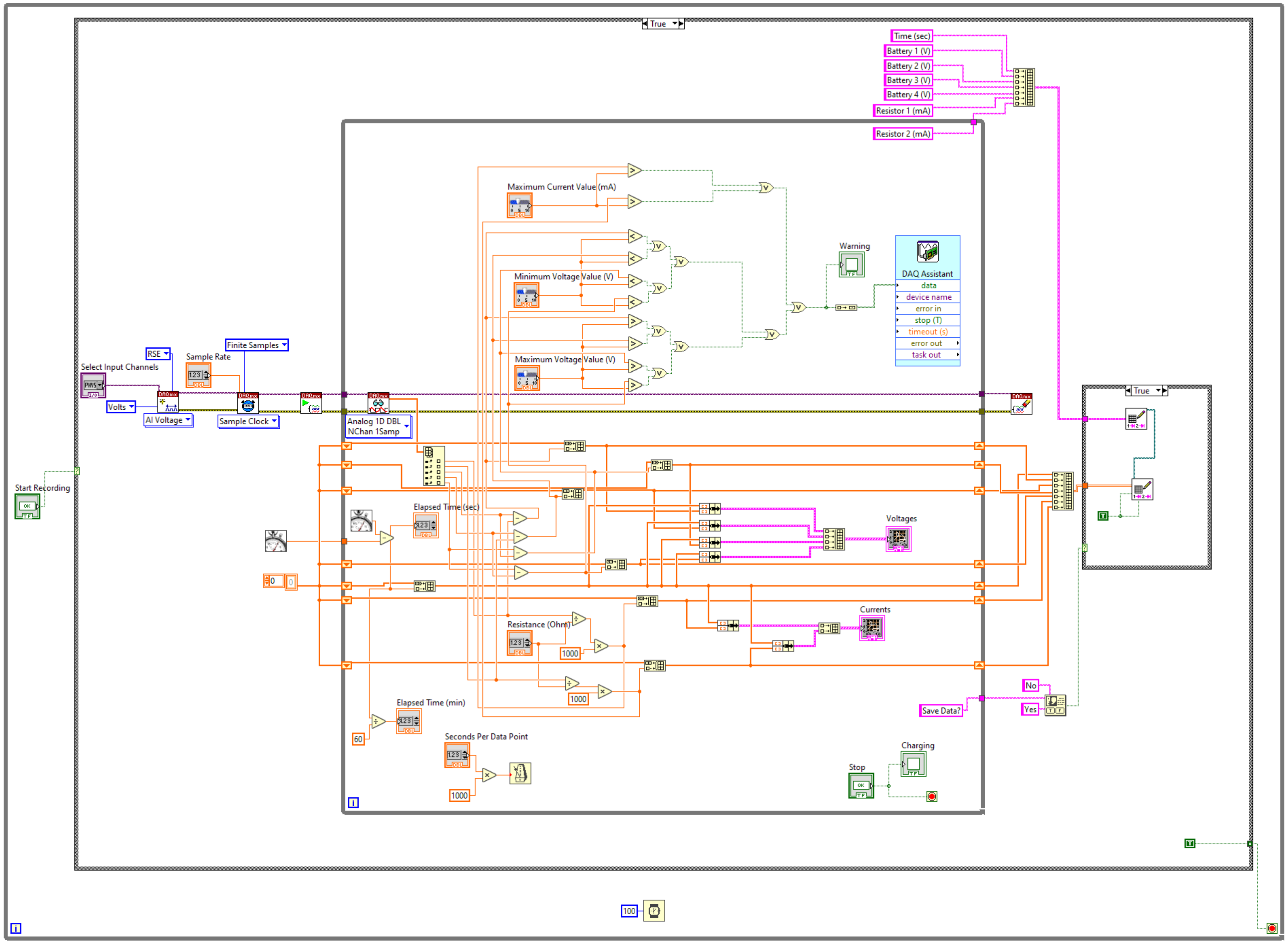
Maximum Voltage Value (V): 0

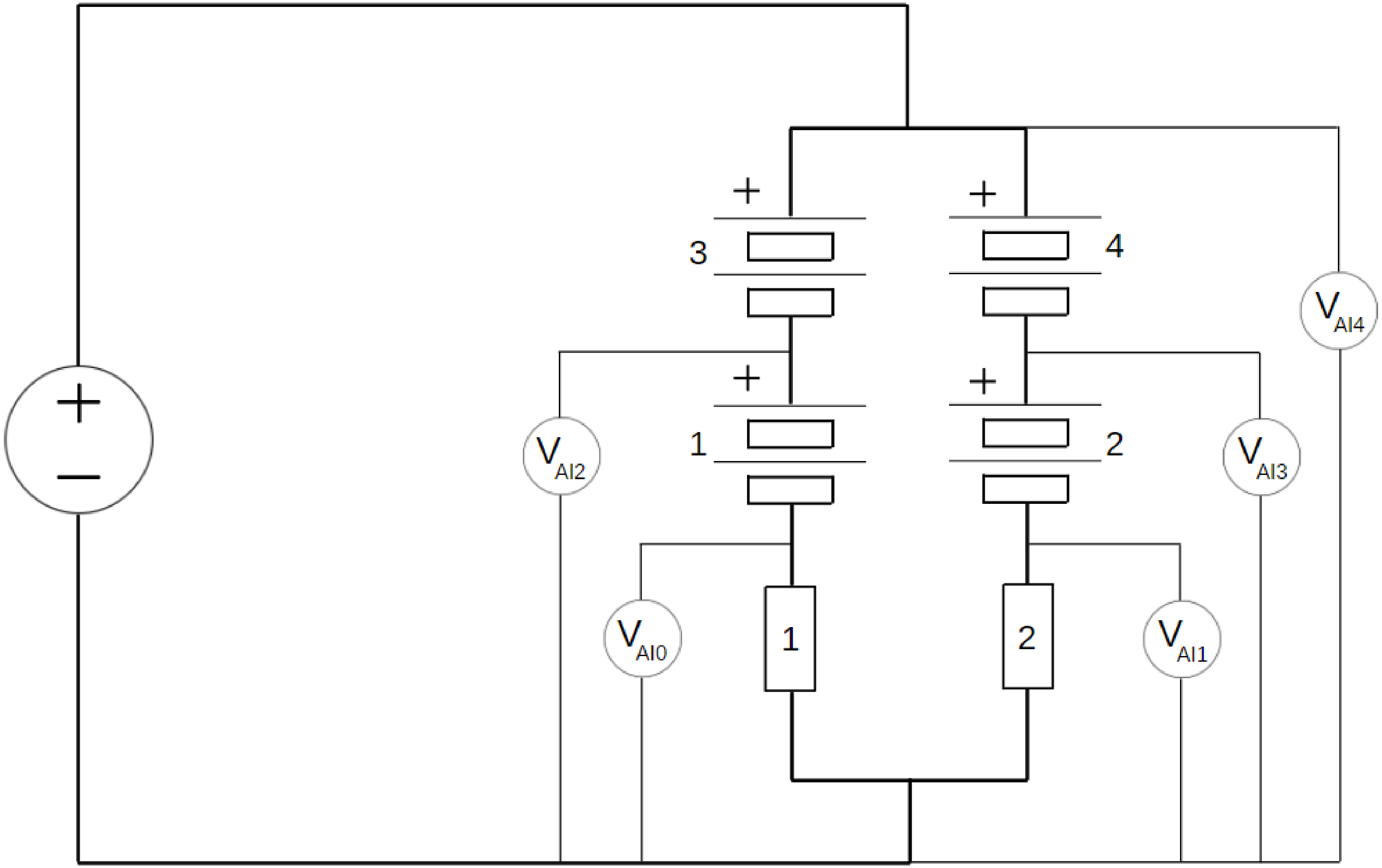
Maximum Current Value (mA): 0

Elapsed Time (sec): 0

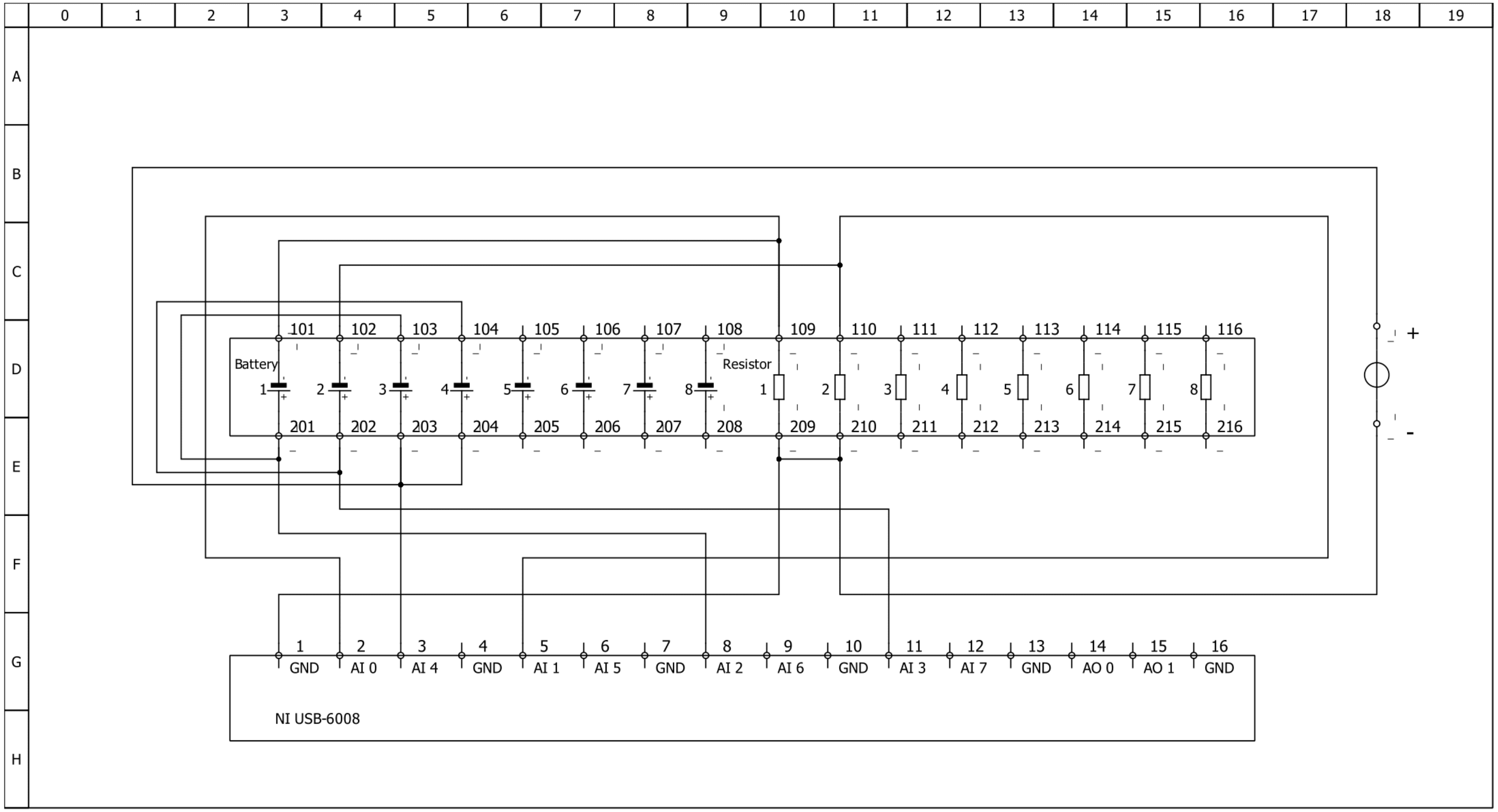
Elapsed Time (min): 0

APPENDIX 4

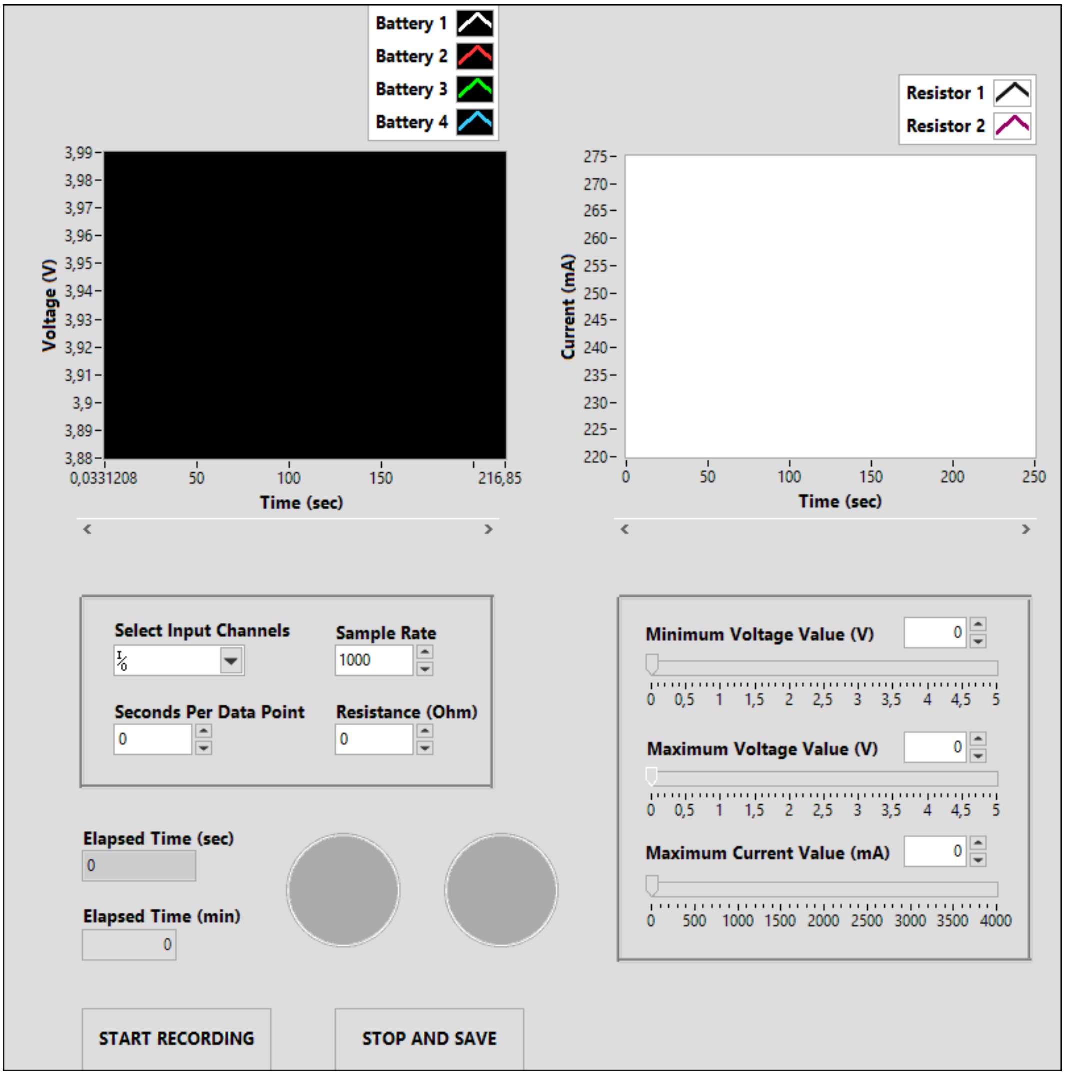

True
Time (sec)
Battery 1 (V)
Battery 2 (V)
Battery 3 (V)
Battery 4 (V)
Resistor 1 (mA)
Resistor 2 (mA)
Maximum Current Value (mA)
Minimum Voltage Value (V)
Maximum Voltage Value (V)
Warning
DAQ Assistant
data
device name
error in
stop (T)
timeout (s)
error out
task out
Select Input Channels
RSE
Sample Rate
Finite Samples
Volts
AI Voltage
Sample Clock
Analog 1D DBL
NChan 1Samp
True
Start Recording
Elapsed Time (sec)
Voltages
0
Currents
Resistance (Ohm)
1000
1000
Elapsed Time (min)
60
Seconds Per Data Point
1000
No
Yes
Save Data?
Stop
Charging
100


+
−
+
3
+
4
V_AI4
+
+
V_AI2
1
2
V_AI3
V_AI0
1
2
V_AI1

APPENDIX 4


0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
A
B
C
D
E
F
G
H
101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116
Battery
1 2 3 4 5 6 7 8
Resistor
1 2 3 4 5 6 7 8
201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216
+
-
1 GND
2 AI 0
3 AI 4
4 GND
5 AI 1
6 AI 5
7 GND
8 AI 2
9 AI 6
10 GND
11 AI 3
12 AI 7
13 GND
14 AO 0
15 AO 1
16 GND
NI USB-6008

APPENDIX 4



Sample Rate: 1000

Seconds Per Data Point: 0

Resistance (Ohm): 0

Elapsed Time (sec): 0

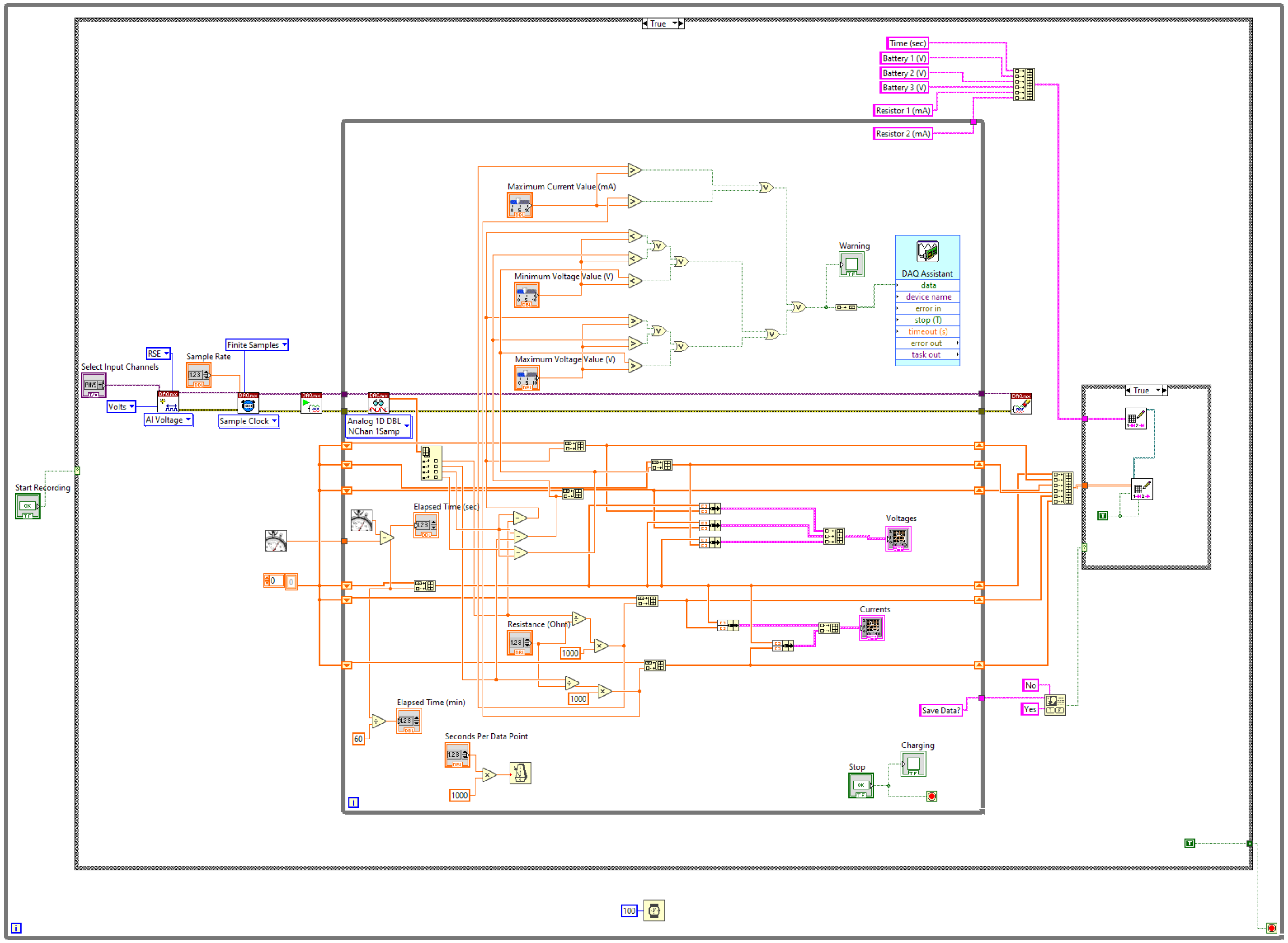
Elapsed Time (min): 0

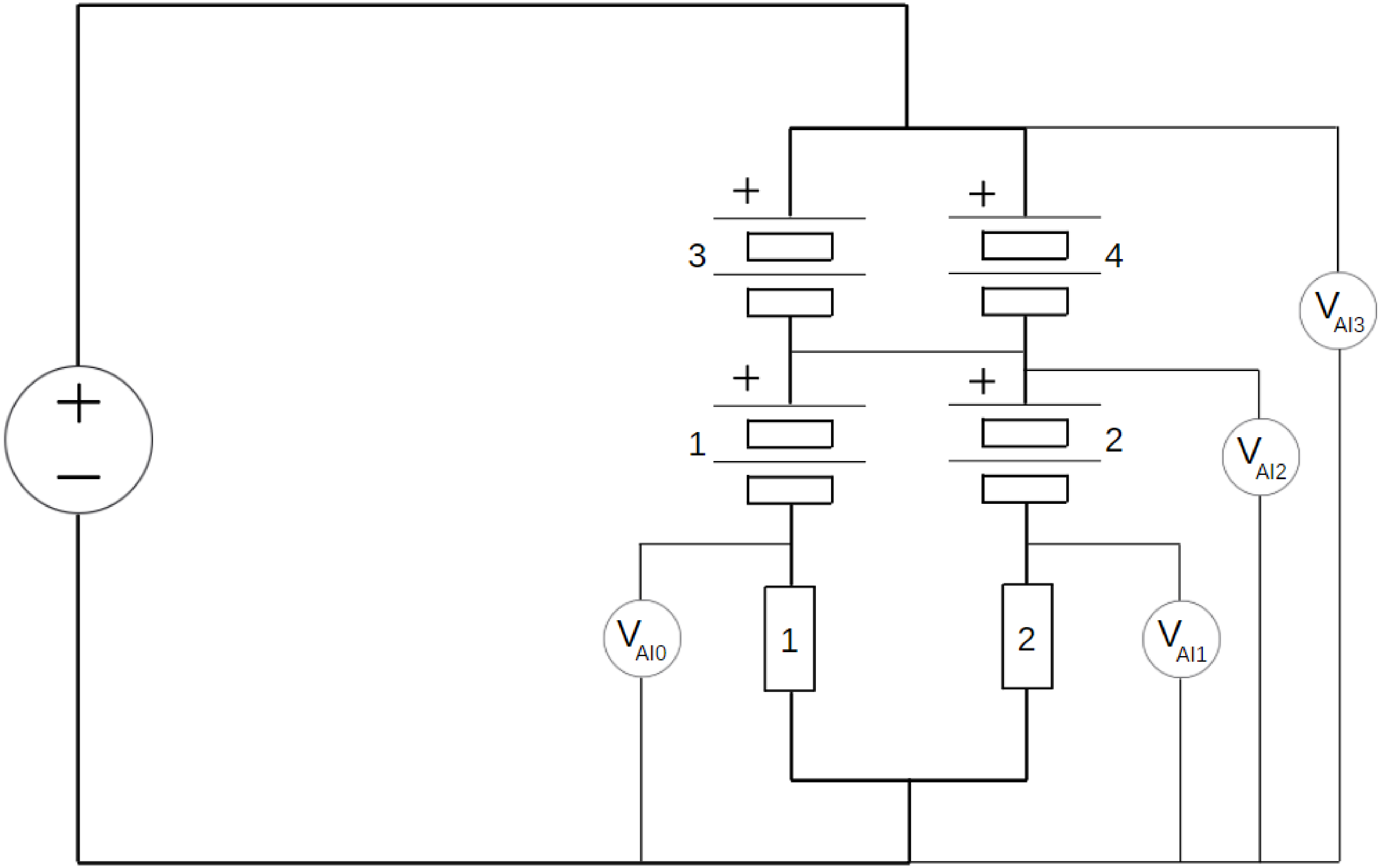
Minimum Voltage Value (V): 0

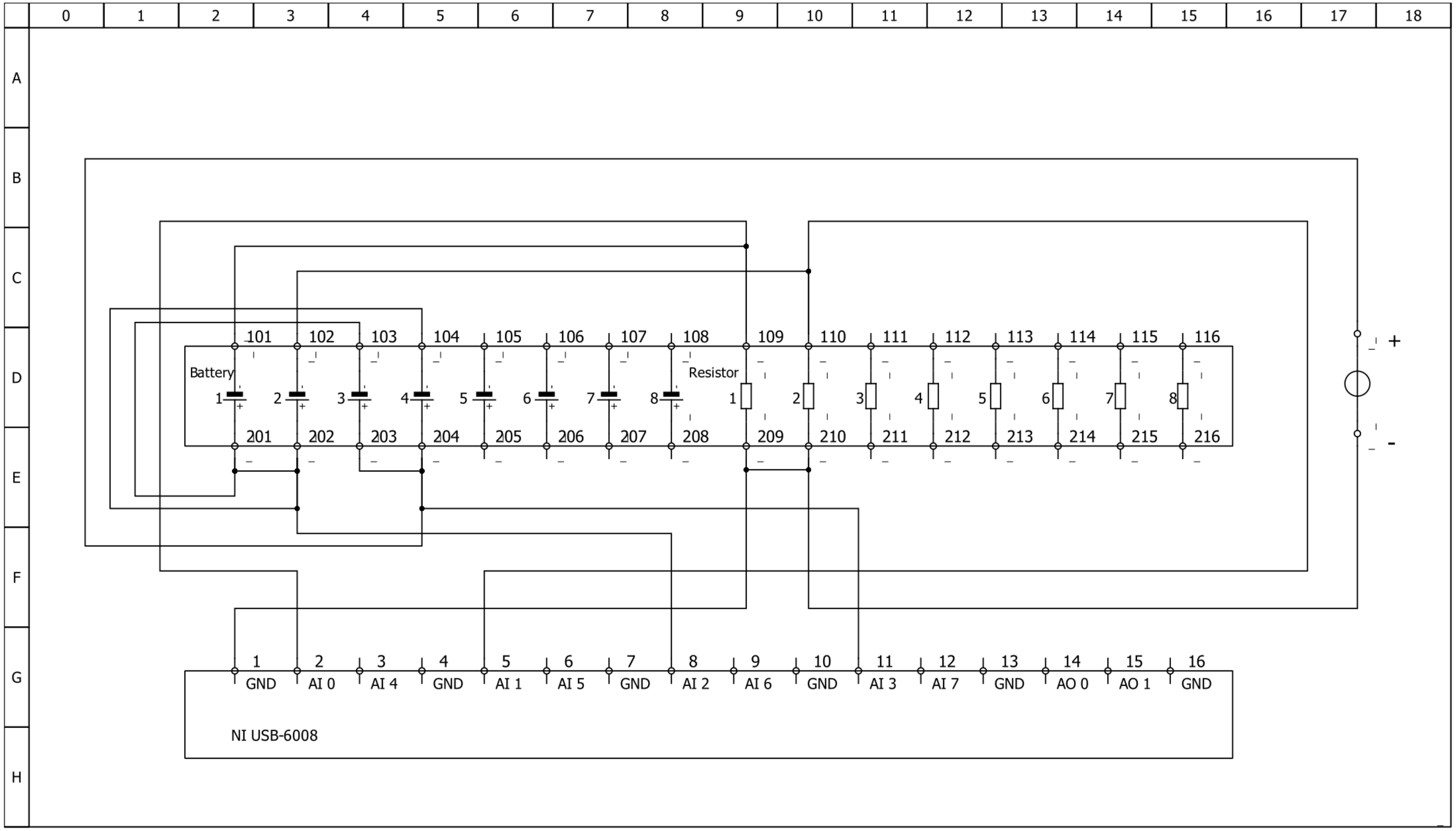
Maximum Voltage Value (V): 0

Maximum Current Value (mA): 0

APPENDIX 5


True
Time (sec)
Battery 1 (V)
Battery 2 (V)
Battery 3 (V)
Resistor 1 (mA)
Resistor 2 (mA)
Maximum Current Value (mA)
Minimum Voltage Value (V)
Maximum Voltage Value (V)
Warning
DAQ Assistant
data
device name
error in
stop (T)
timeout (s)
error out
task out
Finite Samples
RSE
Select Input Channels
Sample Rate
Volts
AI Voltage
Sample Clock
Analog 1D DBL
NChan 1Samp
True
Start Recording
Elapsed Time (sec)
Voltages
0
Resistance (Ohm)
1000
Currents
1000
No
Save Data?
Yes
Elapsed Time (min)
60
Seconds Per Data Point
1000
Stop
Charging
100


+
−
+
3
+
4
+
1
+
2
V_{AI3}
V_{AI2}
V_{AI0}
1
2
V_{AI1}


0
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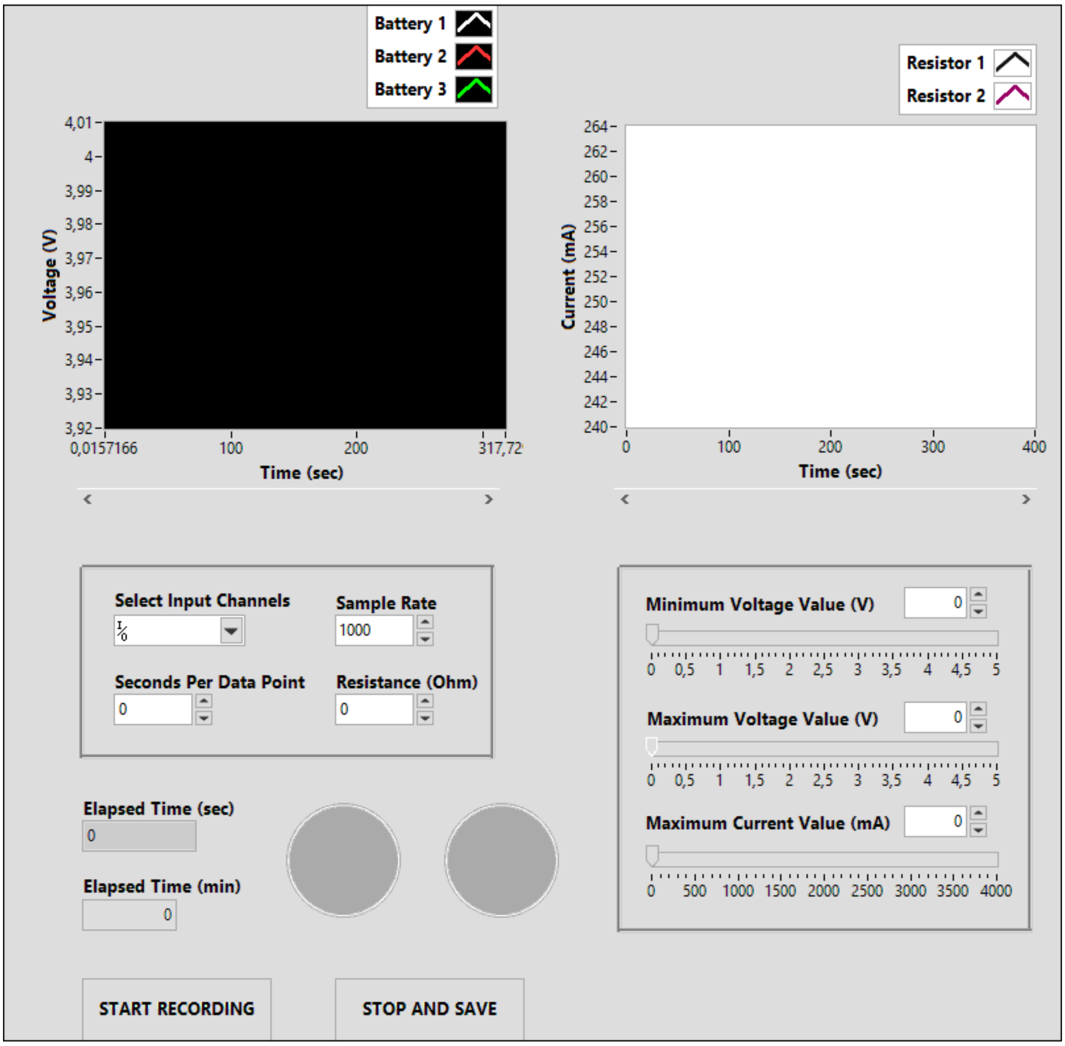
A
B
C
D
E
F
G
H
Battery
Resistor
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
+
-
1 GND
2 AI 0
3 AI 4
4 GND
5 AI 1
6 AI 5
7 GND
8 AI 2
9 AI 6
10 GND
11 AI 3
12 AI 7
13 GND
14 AO 0
15 AO 1
16 GND
NI USB-6008

APPENDIX 5



Select Input Channels:

Sample Rate: 1000

Seconds Per Data Point: 0

Resistance (Ohm): 0

Elapsed Time (sec): 0

Elapsed Time (min): 0

Minimum Voltage Value (V): 0

Maximum Voltage Value (V): 0

Maximum Current Value (mA): 0

APPENDIX 6

Instruction Manual:

LabVIEW Battery Programs

---

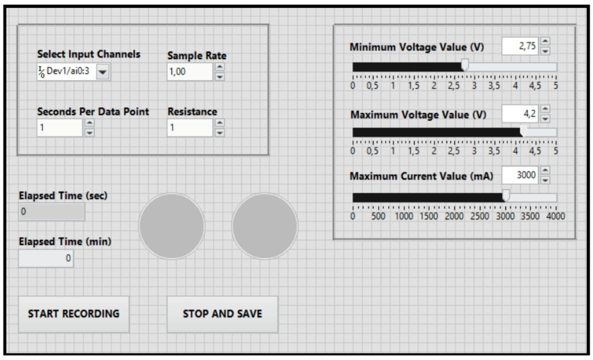
1. Open the program from desktop/start menu
2. **Select Input Channels** according to the wiring diagram:

Browse → **Select the corresponding AI-channels*** → **OK**

*Select multiple channels by holding Ctrl

3. Determine the following values:

	Example values
Sample Rate	**1,00**
Seconds Per Data Point	**1**
Resistance (Ω)	**1**
Minimum Voltage Value (V)	**2,75**
Maximum Voltage Value (V)	**4,2**
Maximum Current Value (mA)	**3000**



Select Input Channels: Dev1/ai0:3
Sample Rate: 1,00
Seconds Per Data Point: 1
Resistance: 1
Elapsed Time (sec): 0
Elapsed Time (min): 0
Minimum Voltage Value (V): 2,75
Maximum Voltage Value (V): 4,2
Maximum Current Value (mA): 3000

4. Press **START RECORDING** button
5. When the charging process is completed press **STOP AND SAVE**
6. Save the data as **XLS** file format (e.g. testfile.xls)
7. Open the file in Excel

04/2021

APPENDIX 7

1. Single Battery				
Wire Number	From	Terminal	To	Terminal
1	USB-6008	1	Battery Case	209
2	USB-6008	2	Battery Case	109
3	USB-6008	5	Battery Case	201
4	Battery Case	109	Battery Case	101
5	Power Supply	+	Battery Case	201
6	Power Supply	-	Battery Case	209

2. Dual Series				
Wire Number	From	Terminal	To	Terminal
1	USB-6008	1	Battery Case	209
2	USB-6008	2	Battery Case	109
3	USB-6008	5	Battery Case	201
4	USB-6008	8	Battery Case	202
5	Battery Case	109	Battery Case	101
6	Battery Case	201	Battery Case	102
7	Power Supply	+	Battery Case	202
8	Power Supply	-	Battery Case	209

3. Dual Parallel				
Wire Number	From	Terminal	To	Terminal
1	USB-6008	1	Battery Case	209
2	USB-6008	2	Battery Case	109
3	USB-6008	5	Battery Case	110
4	USB-6008	8	Battery Case	201
5	Battery Case	109	Battery Case	101
6	Battery Case	110	Battery Case	102
7	Battery Case	201	Battery Case	202
8	Power Supply	+	Battery Case	201
9	Power Supply	-	Battery Case	210

4. Dual Series and Dual Parallel				
Wire Number	From	Terminal	To	Terminal
1	USB-6008	1	Battery Case	209
2	USB-6008	2	Battery Case	109
3	USB-6008	5	Battery Case	110
4	USB-6008	8	Battery Case	201
5	USB-6008	11	Battery Case	202
6	USB-6008	3	Battery Case	203
7	Battery Case	109	Battery Case	101
8	Battery Case	110	Battery Case	102
9	Battery Case	201	Battery Case	103
10	Battery Case	202	Battery Case	104
11	Battery Case	203	Battery Case	204
12	Power Supply	+	Battery Case	203
13	Power Supply	-	Battery Case	210

APPENDIX 7

5. Dual Series and Dual Parallel (connected)				
Wire Number	From	Terminal	To	Terminal
1	USB-6008	1	Battery Case	209
2	USB-6008	2	Battery Case	109
3	USB-6008	5	Battery Case	110
4	USB-6008	8	Battery Case	202
5	USB-6008	11	Battery Case	204
6	Battery Case	109	Battery Case	101
7	Battery Case	110	Battery Case	102
8	Battery Case	201	Battery Case	103
9	Battery Case	201	Battery Case	202
10	Battery Case	202	Battery Case	104
11	Battery Case	203	Battery Case	204
12	Power Supply	+	Battery Case	204
13	Power Supply	-	Battery Case	210

APPENDIX 8

Order Form 16.2.2021

Thesis - Jaakko Yli-Sorvari

Product	Address	Price	Quantity	Total
KeepPower 14500 Li-ion Battery 800 mAh	Akkula.fi	6,50 €	8	52,00 €
A301W Battery holder 1xAA/R6	Starelec.fi	0,35 €	8	2,80 €
G238C Plastic case 265x185x95 mm	Starelec.fi	28,71 €	1	28,71 €
20W-0R1 Wire wound resistor	Starelec.fi	0,81 €	8	6,48 €
BS324S-PU Banana socket red	Starelec.fi	1,35 €	10	13,50 €
BS324S-SI Banana socket blue	Starelec.fi	1,35 €	10	13,50 €
4181-24VDC Solid-state relay	Starelec.fi	26,00 €	1	26,00 €
PI-50BE Relay socket	Starelec.fi	3,30 €	1	3,30 €

Total	146,29 €