Analysis of the properties of supercapacitors and possible applications for the technology

By

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Abstract

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Supercapacitors have a lot of excellent qualities that would make them a great substitute for batteries when it comes to electrical energy storage systems. Supercapacitors can discharge and charge very rapidly, they have a lifespan in the realm of millions of cycles, and they are much more efficient than batteries. Unfortunately, they cannot hold nearly as much charge as batteries. This paper seeks to further investigate the properties of supercapacitor technology and the best way to exploit these properties with the purpose of integrating them into renewable energy systems. There is currently a lot of research occurring around the world with supercapacitors. This research mostly revolves around improving advanced carbon materials that will allow supercapacitors to have an even higher capacitance so that may begin to truly compete with batteries. Other research is looking to incorporate supercapacitors into renewable systems. This ranges from wind generation systems to solar energy systems to even hybrid battery/supercapacitor storage systems. Undertaking my own experiments, I sought to better understand the properties of supercapacitors by comparing them to standard batteries and by constructing a hybrid energy system that utilizes supercapacitors in tandem with batteries. Over the course of this research, it was determined that, while supercapacitors certainly have very unique and advantageous properties, with their current limits they would best be used in tandem with a battery. However, a hybrid system is possible and supercapacitors can charge a battery, which greatly increases the voltage range that a battery can be charged with. The system constructed contained six 10 F supercapacitors wired in series to a 12 V 20 A battery. The supercapacitor bank was able to charge the battery up to 0.009% of its full charge with one cycle. While this seems to be an insignificant percentage, it demonstrates that a hybrid system would be effective, and scaling up the supercapacitor bank would yield better results. In the future, it would be worthwhile to create a more sophisticated circuit to test this system outside with a real wind turbine. Through future testing, it will be determined how much more efficient it is to capture wind energy with a hybrid system compared to a wind turbine with only batteries for storage.

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Introduction

Supercapacitors are an emerging technology. They have several unique properties that could allow them effectively replace batteries or boost the efficiency of systems by working in tandem with a battery. The most important of these properties is their ability to accumulate and release large amounts of charge in a very small amount of time. This project is the investigation of these properties of supercapacitor technology in an effort to find a realistic application for this technology within the realm of renewability and sustainability.

The research areas of renewable energy and sustainability are constantly looking to improve on existing designs in order to make power systems more efficient and cost effective. If the system is a power generation system that converts clean energy, such as a PV solar array or wind turbines, then an increase in the efficiency allows for a greater rate of generation of the clean energy for the same cost. If the system is an operable system, such as the HVAC system for a commercial building or the breaking system of a car, then an increase in efficiency will cause a reduction in the carbon footprint of the system. In both scenarios, these help achieve key goals for those who work in the field of sustainability. By investigating and better understanding the abilities of a supercapacitor, it will be possible to find an application for the technology with the goal of improving the capacity factor of the system. The capacity factor is defined as the actual electrical output over a given time period, over the maximum possible electrical output over the same amount of time.

At the beginning of the project, a lot of time was spent reading electrical engineering textbooks and other sources of information in order to gain the necessary background knowledge to work with supercapacitors and other electrical components safely. As a mechanical engineer, I came into this project with a very limited understanding of how to create working circuits or how many electrical components worked. After several weeks of studying electrical concepts, an understanding formed and experiments could safely be performed. The importance of knowing what one is doing while wiring a circuit cannot be stressed enough. It is much more difficult to see where things are going wrong inside of an electrical wire or component that it is in an engine, in my opinion. So, I had to first fully understand what would happen in each of the circuits I created before I put any sort of power through them.

The goal for the first term of this project was gain a knowledge in electrical components, to research applications and past research involving supercapacitors, and begin initial testing of supercapacitors in order to have my own data set on their charging and discharging curves to work with. The goal for the second term of the project was to define an application for this technology (a hybrid energy storage system), design a prototype and beginning experimentally testing the concept.

As previously mentioned, many sources and books were read for a better understanding of electrical engineering theories. As will be discussed in the next section, there were many sources of literature to read to learn about research that is happening with supercapacitors, within the realm of sustainability and otherwise. After this, the methods I took to undergo my experiments with batteries and supercapacitors are discussed at length, followed by the results I obtained from these experiments. After this there is a section discussing the meaning of my results and how that information will help shape and guide future work and real-life applications for the research that was conducted.

Background and Literature Review

Background

Supercapacitors and batteries are both capable of storing energy, but they do so through fundamentally different means. Batteries store and release charge through the use of chemical reactions. There are several ways to do this. Two of the most common types of batteries are the lead acid battery and the lithium ion battery. The names of these batteries are in reference to the metals and materials that make-up the battery itself and allow it to work as intended. One end of a battery is called the anode and it has a negative charge. The other end is called the cathode, and it has a positive charge. A voltage difference is built up by the chemicals separating the two ends, called an electrolyte. Energy is released when the chemicals react and release electrons that then travel through the circuit to power whatever load is wired to the battery [1].

Supercapacitors do not rely on a chemical reaction to store or release energy. Supercapacitors are able to store energy through the build-up of static charge between two opposing plates. This is shown in the figure below.

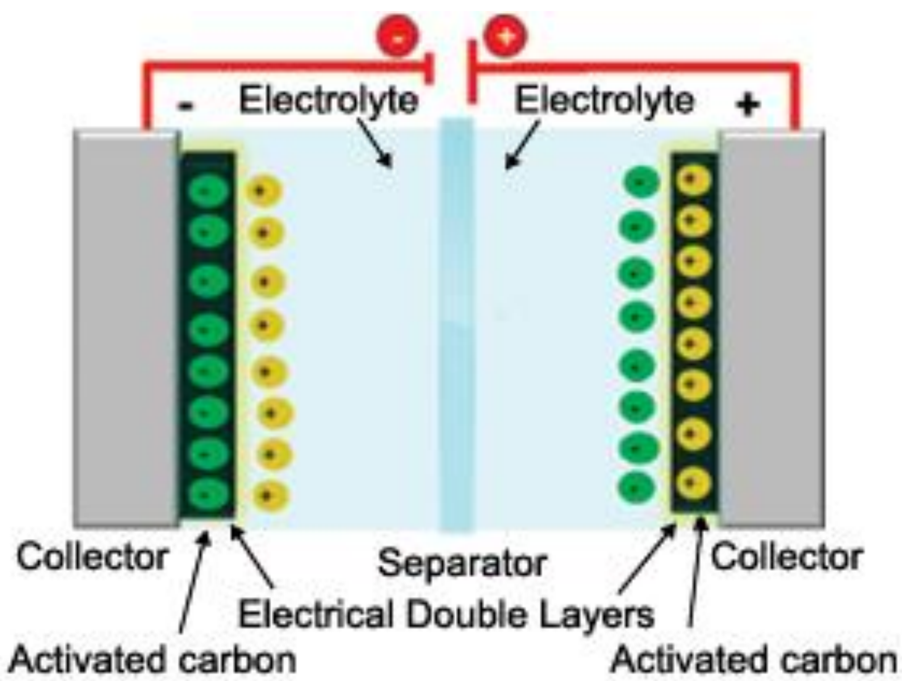

Figure 1. An example of the interior of a supercapacitor with a labeling of the parts.

The two plates, labeled collectors in the figure above, often have a layer of activated carbon on the surface where electrons accrue. The carbon, which is often highly porous, greatly increases the surface area of the collector. Greater surface area allows for a greater build-up of electrons which directly leads to a larger build-up of static-potential. The separator between the two plates, often made of paper or even air, prevents the collectors from coming into contact to allow for the static energy to build up during charging. When the supercapacitor is charging, there is a buildup of electrons on one of the plates, causing it to have a highly negative charge. As it collects all these electrons, this causes the other plate to lose electrons, creating a highly positive charge. This total charge is called capacitance and is related in units of Farads (F), which is simply coulombs per volt. When the supercapacitor is allowed to discharge, the plate seeks to reach an equilibrium of charge, so all the electrons that were built up on one plate rapidly go through the circuit to the other plate [2]. The main difference between supercapacitors and regular capacitors is their storage capabilities. Material science has allowed for a much larger capacitance to be created by increasing the surface area, which greatly boosts the total capacitance. The other major difference between supercapacitors and capacitors is the addition of the "double electric" layer, which can be found in Figure 1, above. This layer is only present in supercapacitors and creates a double layer of positive and negative charge, forming a sort of double boundary layer which allows for more total electrons to be captured.

These fundamental differences give supercapacitors several advantages and disadvantages over batteries. Supercapacitors are known for, first and foremost, their incredibly high specific power. Specific power is a power-to-mass ratio. This means that supercapacitors can take a lot of charge very quickly. While batteries can often take several hours to fully charge, supercapacitors have the ability to charge within seconds. Likewise, they can also release all of their stored energy very rapidly and discharge fully in a similar timespan. This gives them a unique property that batteries do not possess. As a tradeoff to this, supercapacitors have a very low specific energy. Specific energy is an energy-to-volume ratio. This means that their overall energy storage capabilities aren't very high. While batteries have the ability to store a lot of energy in a relatively small container, a supercapacitor's storage limits is directly proportional to its size. So, in order for a supercapacitor to store the same amount of charge as a battery, it would need to be many times larger than a battery. However, with the advancements of advanced carbon materials such as carbon nanotubes, supercapacitors are being developed with a very high surface area, with respect to their size, which allows for ever-increasing values of total energy storage. Another important advantage that supercapacitors have over batteries is that supercapacitors have a significantly longer lifespan. While batteries typically have a lifespan of several hundred to the low thousands of usable cycles, supercapacitors have a lifespan upwards of a million cycles (a virtually unlimited lifespan). This means that supercapacitors rarely need to be replaced due to fatigue. For systems that require the use of many cycles per day, supercapacitors would be a much preferred alternative to a battery. Additionally, supercapacitors are more efficient at using all of their stored charge. Supercapacitors can safely and regularly discharge 100% of their stored energy, while batteries can only discharge 50-80% of their stored energy. If batteries discharge more than that, they run the risk of greatly reducing their lifetime. The main hang-up of supercapacitors, besides their low total storage, is that they normally only operate at a voltage range between 2.5-2.7V. Applications with a higher voltage demand would require several supercapacitors wired in series to reach the desired voltage output [2].

Possible Applications and Literature Review

Supercapacitors are especially useful in bridging power gaps that require a specific amount of energy for a short duration. Supercapacitors are starting to find use in transportation. For example, the Long Island Railroad has begun testing the effectiveness of using a supercapacitor to aid in the acceleration of trains [3]. In this case, supercapacitors are used for a large discharge of energy in a short period of time to rapidly get the train up to speed, then the supercapacitor needs to rapidly charge again for immediate use to decelerate the train, if necessary. This rapid charge and discharge cycle, through many train trips every day is the exact situation that a supercapacitor is ideal for. Although this is an ideal application, this scope of this project is to key on the properties of a supercapacitor and how to apply these properties to a renewable application, specifically.

A lot of research has gone into improving the capacitance of supercapacitors, their ability to store charge. As previously mentioned, it seems that the key to increasing the capacitance, without making the supercapacitor unrealistically large, is to find materials that greatly increase the overall surface area. The research in this area seems to mostly in the field of experimenting with various new carbon materials. This research varies from the actual chemical composition of the material to the molecular layout of the material. In 2013, Duay et al. published a paper detailing their research into how various oxides of manganese have a very high theoretical capacitance [4]. It had been theorized that the capacitance of manganese oxides could be greatly increased if the material was broken down to the nano-scale and was layered in a particular pattern. By using a hierarchal structure, they were able to create a nanostructure that greatly (~42%) increased the capacitance of the material. They found that this was quick charging material would be useful for application in supercapacitors.

Other research that's been done is the investigation of the capacitance of "onion-like carbon materials" by Bushueva et al [5]. Onion-like carbon materials are a substance created by vacuum annealing nanodiamonds and within a certain temperature range. This research wanted to test their ability to mass produce this material and compare its ability to hold charge in relation to the ability of carbon nanotubes, which is another hot topic of research. In the end, they found when the onion-like carbon material was applied to a double electric layer, such as those found in supercapacitors, they had a similar capacitance to carbon nanotubes.

Further materials research that's been done is research into the field of "super-short carbon nanotubes" by Zeng et al [6]. This research was looking to increase the utilization of closed-pore volumes of carbon nanotubes by synthesizing super-short carbon nanotubes in conjunction with reduced graphene oxides as supports. By successfully synthesizing these nanotubes, they were able to test the capacitance and find that this material has a useful possible application for a high rate supercapacitor.

All of these papers deal with aspects of material science researchers employ in order to boost the properties of materials to increase their overall capacitance. Advances in the capacitance of materials is what allow *super*capacitors to be developed in the first place. Continued advances in the technology will allow supercapacitors to continue to bridge the gap between them and batteries, making them a much more useful alternative. While this project doesn't delve much into changing the properties of supercapacitors, it is important to understand the research that has been to done to see where advancements are being made and where other people are trying to take this technology.

Beyond material improvements, there is also a lot of people working on finding applications for supercapacitors as they already exist. One area where supercapacitors can be implemented, in the domain of renewable energy, is to be integrated into solar installations for storage. This mostly involves creating a circuit with supercapacitors in tandem with batteries. An example of this is seen in the project created by Burnett and Borle in Australia [7]. These engineers sought to create a hybrid solar/hydrogen fuel cell vehicle to traverse across the continent of Australia. Supercapacitors became an invaluable addition to their design because the supercapacitors were able to release a large burst of sustained power for a short duration of time. This large burst of sustained power, with 90% efficiency from the supercapacitors, supplied most of the power needed to accelerate the vehicle from standing to 60 kph. This is an application more suited for a supercapacitor than a battery because it requires a large flux rather than a long duration of sustained power. By taking on this demand, the engineers were able to reduce the size of the fuel cell because it no longer needed to provide energy for acceleration, this was supplied by the supercapacitor which draws energy from the solar panels mounted on the vehicle. Reducing the size of the battery, in exchange for solar powered supercapacitors actually reduced the cost of the overall vehicle and made it more environmentally friendly.

Thounthong from Thailand has also looked to couple solar installations with supercapacitor arrays [8]. His research focuses on what he calls “intermittency problems”. This refers to issues, mostly found in renewable power systems, with inconsistent power generation. With regards to solar, this means periods of the day, week, or months with limited amount of sunlight. In order to counteract this, he created a system of supercapacitors wired to the solar installation to act as an auxiliary power storage system. This is ideal for supercapacitors because they can easily take large fluxes of solar energy when the sun is strong, and release them at a constant power output when the sun wanes. He found that this system worked very effectively at reducing the likelihood of power drops or load drops and makes the solar installation a much more reliable source of energy.

Significant research is also going into the benefits of integrating supercapacitors into wind energy operations. Abbey and Joos in Canada investigated the use of supercapacitors as a means to reduce inconsistency in wind energy generation [9]. Supercapacitors were used as a short-term storage of energy for a variety of reasons. First, supercapacitors were able to collect energy from low energy winds that wouldn't normally trip a battery. Furthermore, with supercapacitor's ability to release energy quickly, they can act as backup generation when wind dies, to continue charging the main battery in an effort to reduce intermittency. Finally, by first making the voltage go through a supercapacitor bank, the researchers were able to more confidently regulate the voltage going into the battery so that it was less random or based on the variance in the wind.

Li, Joos, and Jean were able to model the previously mentioned approach of a battery-supercapacitor hybrid energy storage systems [10]. The researchers made a computer simulation to test the abilities of a hybrid energy storage system. After considering all the possible variables and successfully creating a real-time simulation of such a device, they were able to determine that using a combination of a battery and a supercapacitor bank for energy storage, the overall system had a lower battery cost, a longer battery life, and a more efficient system. This is compared to a system that only used a battery for energy storage.

Sun and Zhou took a different approach to look at the usefulness of supercapacitors in renewable systems [11]. They took an economic approach and used costs and energy balancing equations to create an algorithm that would find the cheapest system possible. As a result from this, the algorithm was able to determine that in order to make the cheapest hybrid wind/solar generation system, there would definitely need to be a supercapacitor bank involved. Part of the considerations that went into the algorithm was how capacitance and total voltage was changed based on the configuration of supercapacitors (in series or parallel), and what those costs would be in comparison to batteries. In the end, to make a useful system for the lowest price, supercapacitors would be needed.

There is a lot of research involving supercapacitors and applying them to renewable energy systems. Once tests are completed to understand how these electrical components work, first hand, it will be simple to find and test an application for supercapacitors in this field.

Experiment and Methodology

This section details the methods taken to undergo data collection. The results from these experiments are given in the next section. The first part of the project was spent trying to create voltage discharge curves for batteries, to gain a better understanding of how they discharged. This was done by wiring two Pro-Elec 1.5 V batteries into a standard battery pack to then be discharged into two 0.5Ω resistors that were wired in series. The setup of this circuit is shown in the diagram below.

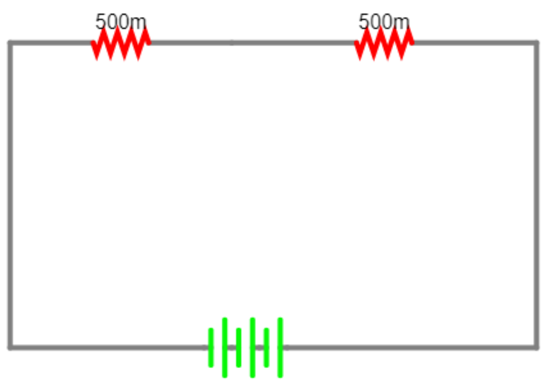

Figure 2. Shows the circuit schematic of the first test with two 0.5 Ω resistors and a 3V power source.

The voltage difference across both resistors was monitored using a USB-2048 data acquisition module from Measurement Computing. The test was run for one hour and collected points at a rate of 2 Hz. Another test was conducted, with the same setup as Figure 2, however new batteries were used and the test was run for three hours instead of one hour to allow for a complete discharge of the batteries.

In order to get an understanding of how the amount of resistance in the circuit affected the discharge of the batteries, another circuit was constructed. This circuit, again, used two Pro-Elec AA batteries wired into a battery pack. In this circuit, only one 0.5 Ω resistor was used (half the total resistance of the previous circuit). This is shown in the Figure 3 below.

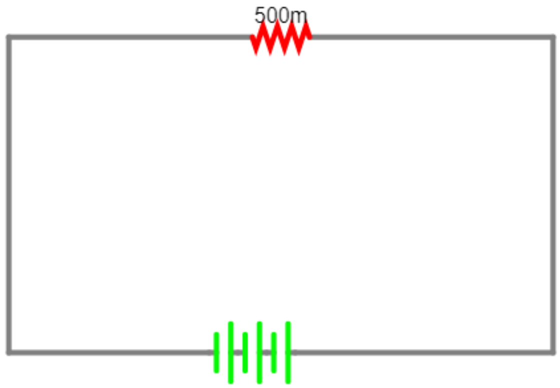

Figure 3. This shows the circuit schematic of the third test run that used one 0.5 Ω resistor and had a power supply that provided a total of 3V.

This circuit also recorded the total voltage drop across the resistor and this was recorded using the same data acquisition software. This test was recorded over the time period of two hours with data acquired at a frequency of 2Hz.

Two new variables were introduced into the fourth test. The circuit was of a similar design, however the two AA batteries are rechargeable batteries rather than single use and only supplied 1.5 V each. Additionally, to test the effect of total resistance on the discharge rate of batteries, a single 2 Ω resistor was used (twice the resistance used in Tests 1 and 2). The two rechargeable batteries were placed in the battery pack, which were then wired in series with the resistor. The schematic for this circuit is shown below.

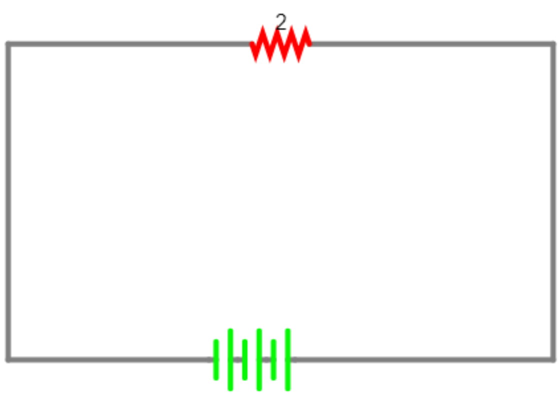

Figure 4. This shows the circuit schematic of the fourth test run that used a single 2Ω resistor and had a power supply that provided a total of 2.4 V.

This circuit recorded the voltage difference across the resistor using the same data acquisition software and was run at a frequency of 2 Hz for a total of 7 hours. With these tests completed, there was enough data to compile an understanding of the discharge curves of batteries. Next, tests were completed to understand the charge and discharge rate of several capacitors.

The first test conducted with the capacitors was done by wiring a 10 Farad Maxwell supercapacitor in parallel with a 470 Ω resistor. This set up was then wired to DC power supply which provided 2.5 V. Since the supercapacitor was rated for a voltage of 2.5-2.7, it was only charged to 2.5V in order to avoid possibly overcharging or damaging the supercapacitor. The circuit schematic for this test is shown below.

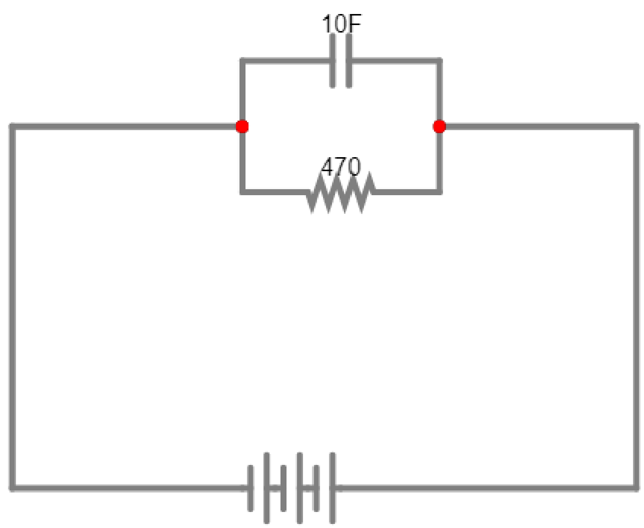

Figure 5. This shows the circuit schematic for the first supercapacitor test with the 10 farad supercapacitor wired in parallel with a 470Ω resistor, which in turn are both wired to a DC power supply that proved a total of 2.5 volts.

This test was run using the same software to record the voltage difference across the supercapacitor. The data was collected at a frequency of 1 Hz for 10 minutes. The power supply was turned on until the current from the supply dropped to 0.5 A. It was turned off before the current hit zero to avoid overcharging of the supercapacitor. Once the power supply was turned off, the supercapacitor immediately started discharging through the resistor, and voltage difference across the supercapacitor was continuously recorded.

The next test conducted with supercapacitors was designed similarly to the above schematic. However, there are two supercapacitor/resistor loops wired in parallel. The schematic for this is shown below.

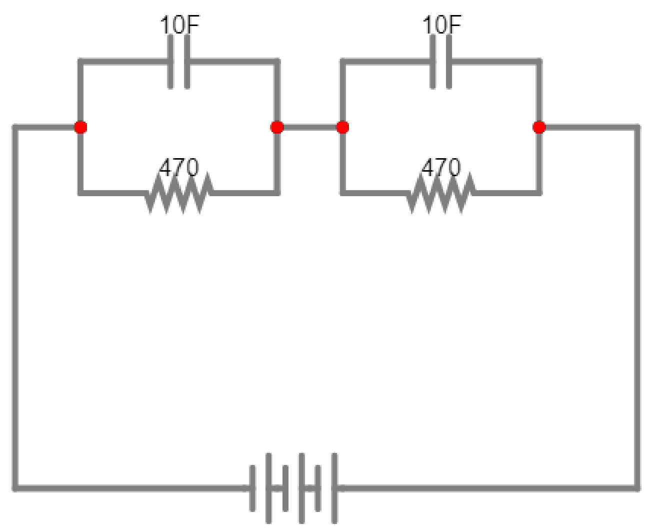

Figure 6. This shows the circuit schematic for the second supercapacitor run. Two 10F and two 470Ω resistors are each wired in parallel loops and connected in series with each other and a DC power supply providing 2.5V.

The test collected data using the same data acquisition software. Two channels were used this time to collect voltage difference data across each of the two supercapacitors. The DC power supply only provided 2.5 V of power, to determine how the two supercapacitors would divide the available voltage. The test was run for 10 minutes, with the power supply being turned off when the current reached 0.5 A, and the data continued to monitor the discharge of each supercapacitor after that moment.

The next test was conducted with the exact same set up as Figure 3, except that the two 470 Ω resistors were replaced with two 5 Ω resistors, respectively. The resistors remained in the circuit to continue to prevent an overcharge of the supercapacitors, but the lower resistance value was implemented to monitor a faster discharge rate of the supercapacitors. The DC power supply was also increased to provide a voltage of 5V (to provide approximately 2.5 volts to each supercapacitor). Data was collected by monitoring the voltage difference across both of the supercapacitors at a rate of 3 Hz. The power supply was turned off when the supplied current reached 0.5A, and the test ended when the voltage difference across each of the supercapacitors reached zero (this took approximately 2.5 minutes). This test was run with the exact same conditions 3 times, to ensure reproducibility of curves.

The final test was, again, run with all the same conditions, except that the two 10 Farad supercapacitors were replaced with two 25 Farad supercapacitors, respectively. All other parameters and methods from the previous test were kept the same. This test was also run three times to ensure reproducibility of curves.

The second term of this project revolved around the creation and testing of a hybrid energy system. To begin, the lead acid battery that was purchased was discharged. The battery is a 12V 20Ah lead acid battery that was discharged through two 5 Ω resistors, and two 1 Ω resistors all wired in series for a total resistive load of 12 Ω. The battery was discharged at approximately 12V, 1A for 16 hours, leaving about 25% of the total energy capacity still within the battery. Using the same aforementioned data acquisition software, the voltage across 6 Ω was monitored (the full 12Ω could not be monitored because of a 10V limit on the hardware) at a rate of 0.18 Hz. The data was collected at 0.18 Hz for 16 hours.

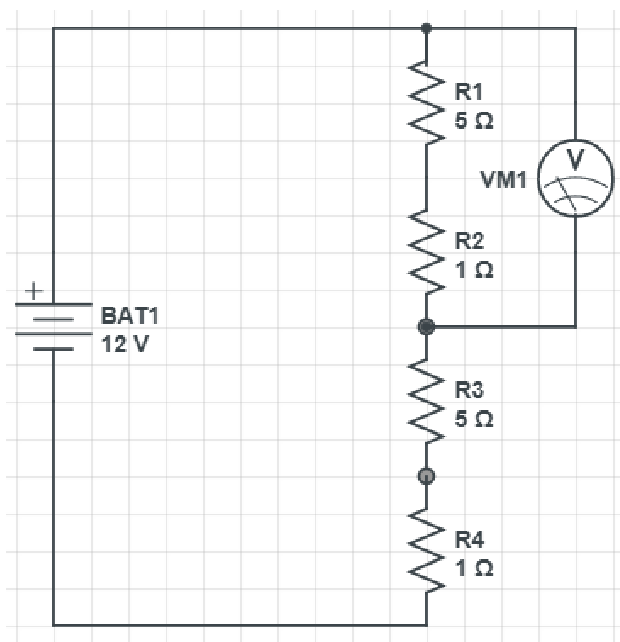

Figure 7. This shows the schematic for the 12V battery discharge over 16 hours. There is a voltmeter placed across 6Ω of the resistance load to show where data was collected.

Next, many tests were designed in order to record and understand the charge and discharge of supercapacitors in various circuit arrangements. One of the first tests conducted was an arrangement to test a circuit that charged the supercapacitors with a battery, then discharged them through resistors. An electric power generator, the same one used in prior tests, was set to 12.5 V. The generator then charged two rows of five 10F supercapacitors to a charge of 2.5V each. The circuit was then rearranged (shown by switches in the diagram), to then discharge the supercapacitors through two rows 10Ω of resistance composed of two 5Ω resistors. In order to switch from charging the supercapacitors to discharging the capacitors, all four switches were charged from one setting to the other. Voltage was monitored across the first capacitor in each row during charging and voltage was monitored across the first resistor in each row during discharge. Voltage was monitored at a rate of 3 Hz. This was repeated two more times for repeatability. This is shown in the schematic below.

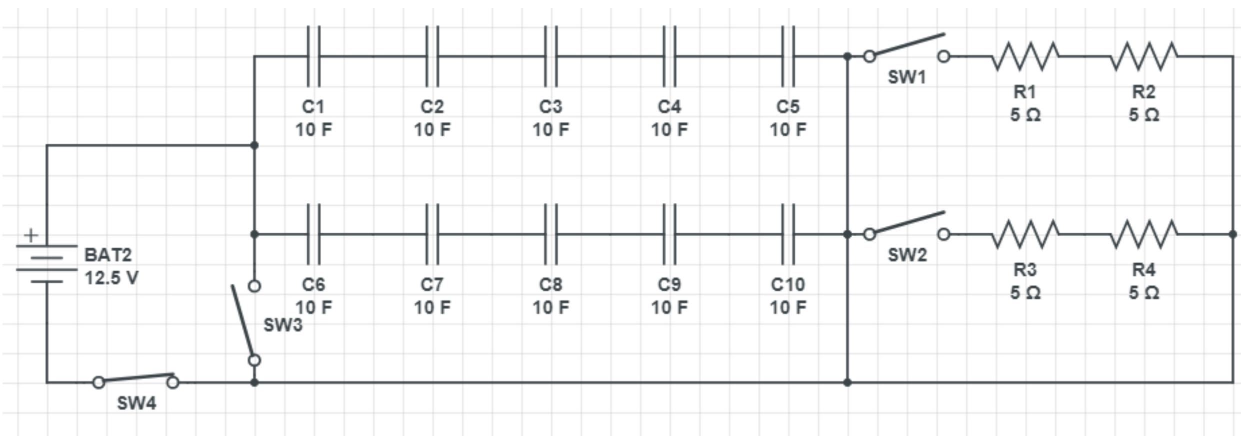

Figure 8. This shows the charging and discharging of several supercapacitors for the initial testing that was completed.

The next series of tests that were conducted was to test charging the supercapacitors with a hand-cranked generator in order to simulate voltage variability. The generator used is a “Deluxe Hand Crank Generator” by Arbor Scientific. This was done by slowly increasing the speed that the hand crank was rotated until the supercapacitors had been charged to approximately 2.5 V each. This test was conducted using the same data acquisition and voltage was monitored at a rate of 3 Hz. This circuit was arranged with only a single row of five 10 F supercapacitors and the discharge was not monitored. This test was completed three times for repeatability. Voltage was monitored across the first and last supercapacitors in the circuit during charging and the voltage was monitored for the first resistor in each row for the discharge. The schematic for this is shown below.

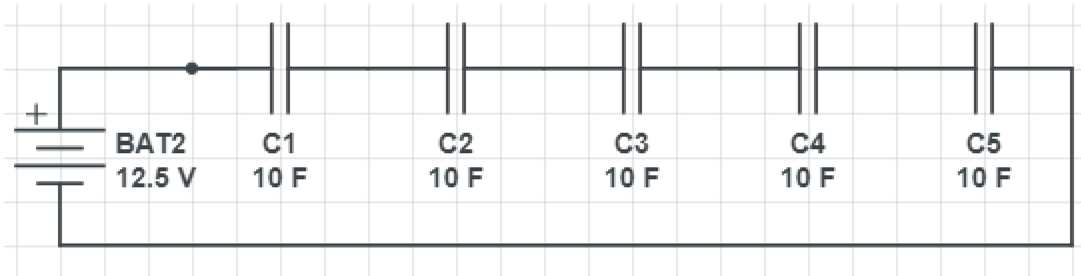

Figure 9. This shows the circuit as designed to charge the supercapacitors in series through the aid of a hand-cranked generator.

Using the same circuit setup, an 18 V Ryobi Electric Drill was attached to the hand-cranked generator so that manual power didn't need to be used to charge the supercapacitors. The same capacitors in the series were monitored with the Daq system, and the drill was slowly sped up to mimic manual increase in speed. This test was completed three times to ensure repeatability and in order to accurately compare results from charging the supercapacitors with manual labor versus with an electric drill.

Now that there was data to understand the charge and discharge on supercapacitors in various circuit designs, calculations were completed to determine the best way to wire a circuit to provide the most amount of charge possible to charge a battery. It was known that the full energy storage of the battery used in testing was 240 Wh. Based on the electricity laws governing how capacitance is added in series/parallel and how these values affect the total voltage that is able to be stored, it was determined that the best setup to charge the battery was one row of six 10 F supercapacitors wired in series. A circuit and experiment was designed in order to test the amount of Watt-hours that left the supercapacitors to charge the battery. Since it was known that the supercapacitors can take variable charging to any voltage supplied, a power generator was used to charge the supercapacitors to ensure a more accurate charge level. The power generator supplied 15 V to the six supercapacitors to charge them to 2.5 V each. This enabled their discharge to be high enough to trip the charging of a 12 V battery. Once they were charged, the Daq system was used to monitor the voltage across each of the six supercapacitors as they discharged. They were connected to a "Precision Watt Meter and Power Analyzer" by Powerwerx to determine the amount of energy that was flowing into the battery. The discharge was recorded at 4 Hz. The schematic shows the discharge of this test.

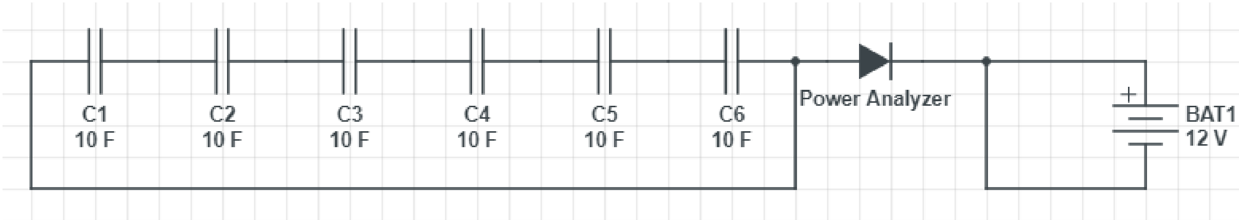

Figure 10. This figure shows the schematic of the circuit that was used to discharge the supercapacitors into a 12V20A battery.

Unfortunately, the power supplied from the supercapacitor bank was too small to register on the power analyzer. But, the amount of energy discharged from the supercapacitors could be calculated since the voltages were recorded throughout the discharge. Knowing the starting voltage and the end voltage, it is possible to calculate the total energy dissipated from the supercapacitors using the equation below:

$$W = \int_{V2}^{V1} CV \; dv \tag{1}$$

Where W is the work (energy), C is that total equivalent capacitance, V is the voltage, V1 is the starting voltage, and V2 is the final voltage.

After this, the efficiency of the charging circuit was calculated. This was done through several tests. To find the losses in the circuit, the internal resistance of the supercapacitors and the internal resistance of the battery needed to be known. In order to find the internal resistance of the supercapacitors, the series of six 10 F supercapacitors were charged and then discharged through a single 1Ω resistor. By taking the resistance and the instantaneous voltage at the beginning of the discharge, it was possible to use Ohm’s Law to calculate the current. Since it is a circuit in series, then the current is the same throughout. By then using the same current and the max voltage of the supercapacitors at the moment of discharge, it was possible to use Ohm’s Law again to calculate the internal resistance of the supercapacitor bank.

Next, to calculate the internal resistance of the battery, the no load voltage of the battery was found. Then the voltage across a 471Ω resistor was found. The internal resistance of the battery was then found using the following equation:

$$V_{load} = V_{no-load}(\frac{R}{R+r}) \quad (2)$$

Where $V_{no\text{-}load}$ is the voltage across the battery with no load, V_{load} is the voltage across the resistor, R is the resistance of the resistor, and r is the internal resistance of the battery. With this information, one last test was conducted to find the efficiency of the circuit. The efficiency is found by calculating the voltage output over the voltage input. Or, the total voltage leaving the supercapacitors over the voltage actually entering the battery to charge it. Once again, the six 10 F supercapacitors were charged to 15 V, and then discharged in an identical configuration to Figure 10, above. When discharging, the power analyzer was able to give a max current, which occurs when the voltage is highest (which is the instant the supercapacitors start discharging). By using this max voltage, the max current, and the known internal resistances, it was possible to calculate the voltage actually entering the battery for energy storage. The equation used is shown below:

$$V_{total} = I(R_1 + R_2) + V_{charging} \quad (3)$$

Where V_{total} is the maximum voltage supplied by the supercapacitors, I is the max current, R_1 is the internal resistance of the battery, R_2 is the total internal resistance of the supercapacitor bank, and $V_{charging}$ is the voltage supplied to actually charge the battery. Solving for $V_{charging}$, it is possible to use this value to calculate the efficiency of the charging circuit.

Last, a theoretical model of a supercapacitor discharge was created to compare an ideal discharge to the one discussed in the last test of the previous section. The equation to create this model is shown below:

$$V(t) = V_0 e^{(\frac{-t}{RC})} \quad (4)$$

Where V(t) is the voltage of the supercapacitor at time, t, V_0 is the initial voltage of the charged supercapacitor, R is the resistance of the circuit, and C is the total capacitance. This equation displays exponential decay.

Results and Discussion

Results

After running several tests, it was determined that the small batteries that were tested followed the theorized discharge for a battery. The batteries discharged at a relatively constant voltage, with a small linear decrease, until the battery reached the end of its storage and then there was a steep drop in the provided voltage. This can be seen in the graph below.

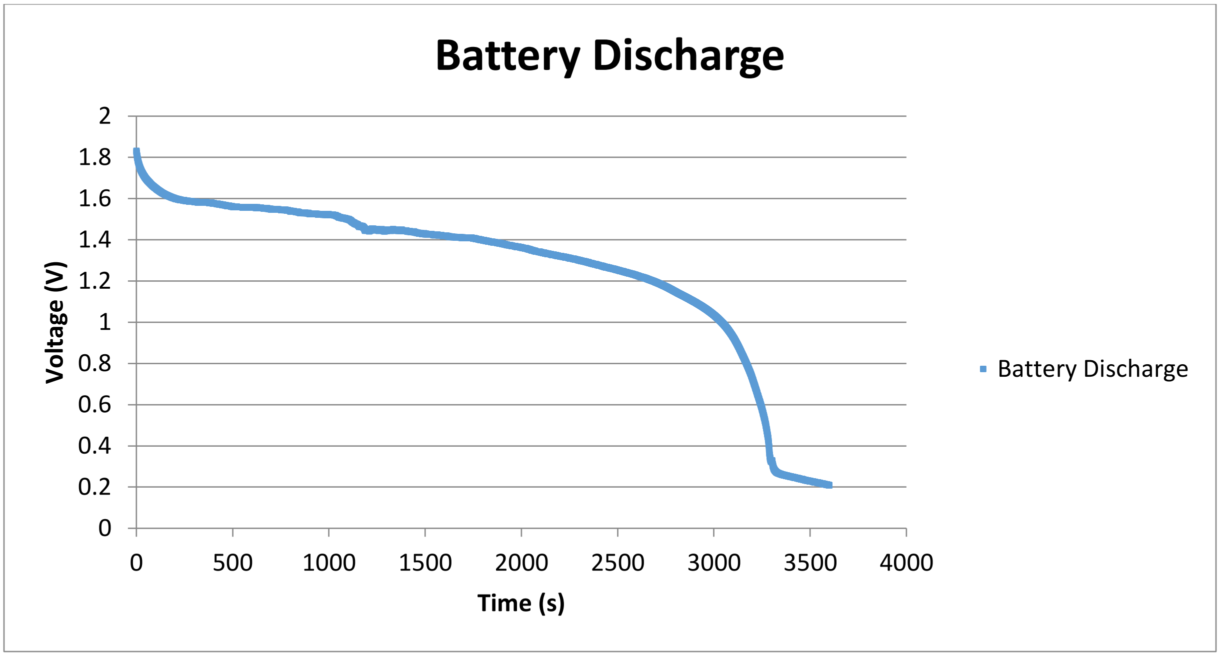

Figure 11. This shows the voltage difference across a resistor that is wired in series with two AA batteries. This is the setup from test 1 described above. The y-axis is the time in seconds, and the x-axis is the provided voltage in volts.

As can be seen in the graph, the voltage is a relatively consistent, linearly decreasing output until the voltage reaches 1.2 V. At this point there is a dramatic drop to nearly zero of the supplied voltage of the battery. This is consistent for the other battery tests. Tests 2 and 3, which are nearly identical to the above graph, can be found in APPENDIX A. Test 4 offered the most distinguished difference from the other three. The graph for this is shown below.

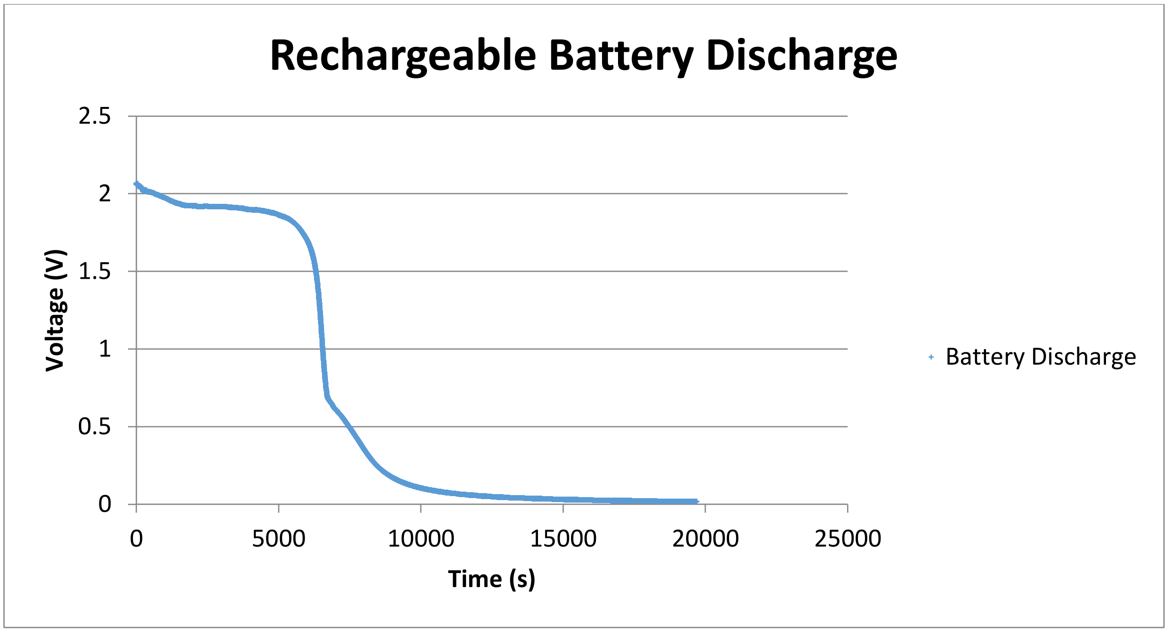

Figure 12. This shows the battery discharge voltage over time for Test 4, which was conducted with two rechargeable batteries. The full explanation of this circuit is described in the Methodology section.

In this test, the discharge voltage was much more constant before the incredibly steep discharge around 7000 seconds. Although this could only appear to be so because it's over twice the time frame as the other tests. Discussion of this appears later in the paper.

The first two supercapacitor tests were conducted to look at the curves that are generated specifically when the supercapacitor is charge, what happens when it reaches its maximum storage capacity, and what the initial discharge looks like. In the first supercapacitor test, it was charged to capacity, then allowed to discharge through a large resistor for several minutes.

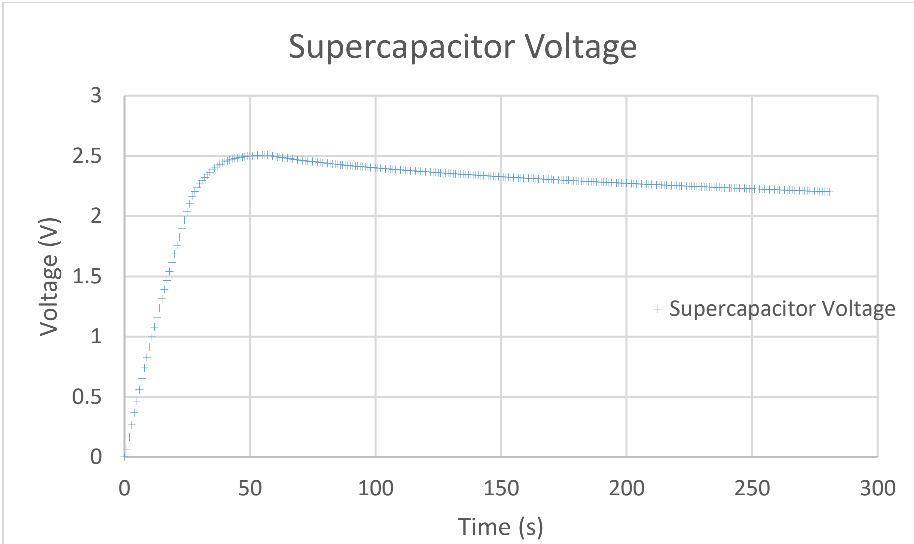

Figure 13. This shows the voltage charge/discharge of the 10F capacitor from the test described earlier.

As can be seen, it took the supercapacitor less than a minute to fully charge. Once charged, the voltage leveled, briefly, at 2.5 V as the supercapacitor stopped accepting charge. At this point, the power supply was turned off so the supercapacitor began discharging through the resistor. The supercapacitor discharged linearly. While this looks similar to the discharge of the battery, this curve is much more linearly constant, and it is doing so at a faster rate through a resistor that is 470 times larger. The next test, as described above, was to test the charging patterns when two identical supercapacitors were wired in series with one another. This is shown below.

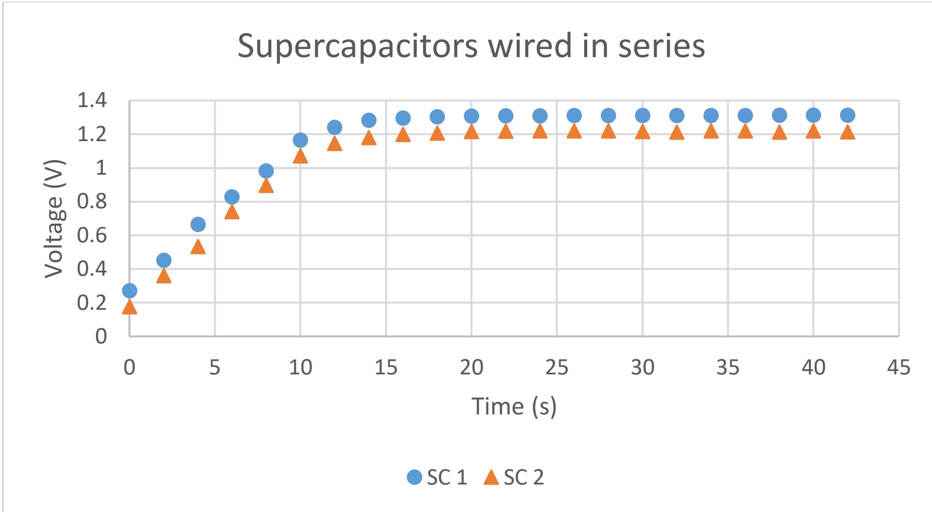

Figure 14. This shows the voltage difference across two supercapacitors wired in series as they were charged to 2.5V total.

Since the power supply was only set to 2.5 V the two supercapacitors appeared to split the supplied voltage nearly evenly. Once the supercapacitors reached their maximum charge for the supplied voltage, they stopped accepting current and their total charge leveled out. In this case, it took the two supercapacitors around 15 seconds to reach their maximum charge for a supplied 2.5V, they then each stopped receiving charge and the current of the power supply dropped to nearly zero (some current remained as current went through the resistors that were wired in parallel with each of the supercapacitors, respectively).

The last two tests were conducted to better observe the discharge patterns of supercapacitors. For ease of testing, the total time of testing was kept the same for both the 10F supercapacitors and the 25 F ones. As a result of this setup, the 25F supercapacitors were not allowed to discharge fully within the allotted timeframe, but enough time was given so that the curve could be observed and studied. The results from the 10 F supercapacitor test are below.

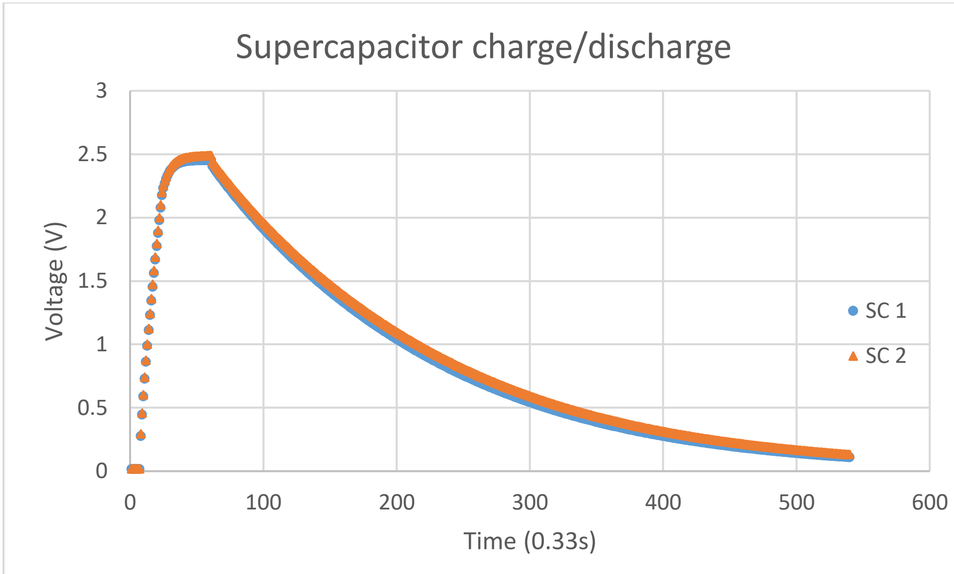

Figure 15. This graph shows the results from the charging and discharging test of two 10F supercapacitors, as described in methodology.

By setting the power supply to 5V, both supercapacitors were able to charge to 2.5V. They were able to quickly discharge through the resistors at a constant rate, as their voltage declined. This test confirmed the theory behind supercapacitors that their discharge is incredible consistent and linear. The other, identical, iterations of this test can be found in APPENDIX A. A similar experiment was conducted with larger supercapacitors. The results are below.

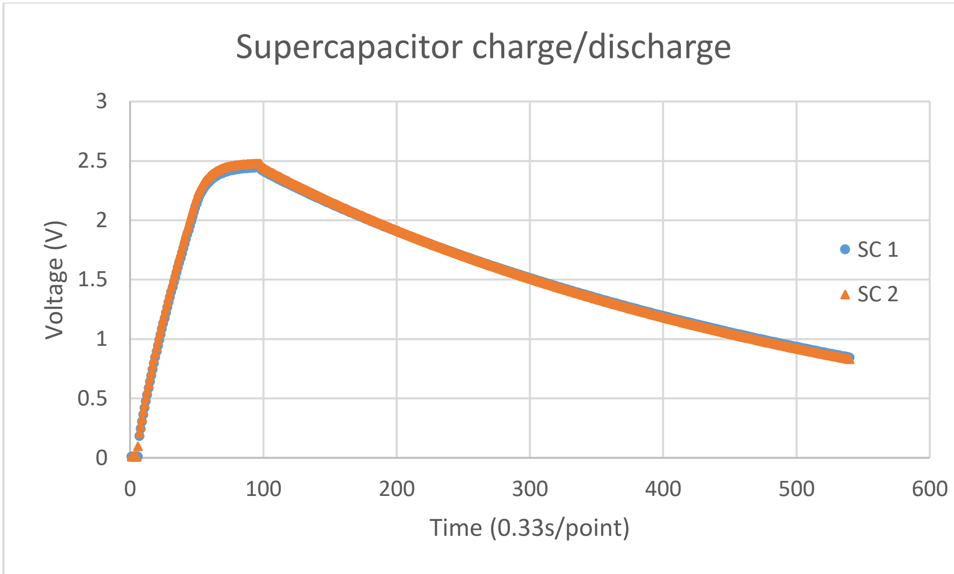

Figure 16. This graph shows the results from the charging and discharging of two 25F supercapacitors.

As expected, even though the two supercapacitors were charged to the same voltage (2.5 V) as the previous experiment, it took the larger supercapacitors longer to charge. This is due to their larger capacitance which allows them to physically hold more charge at the same voltage as smaller capacitors. The other iterations of this test can be found in APPENDIX A.

The discharge of the 12V battery over 16 hours matched a similar discharge as the small batteries. It maintained a constant discharge voltage for the duration of the test. Since the battery was not discharged completely, there was no significant drop in the voltage level toward the end of the test. However, the voltage did slowly drop over the course of the discharge and about halfway through the test, the voltage became increasingly unstable. The results of this can be seen in the graph below:

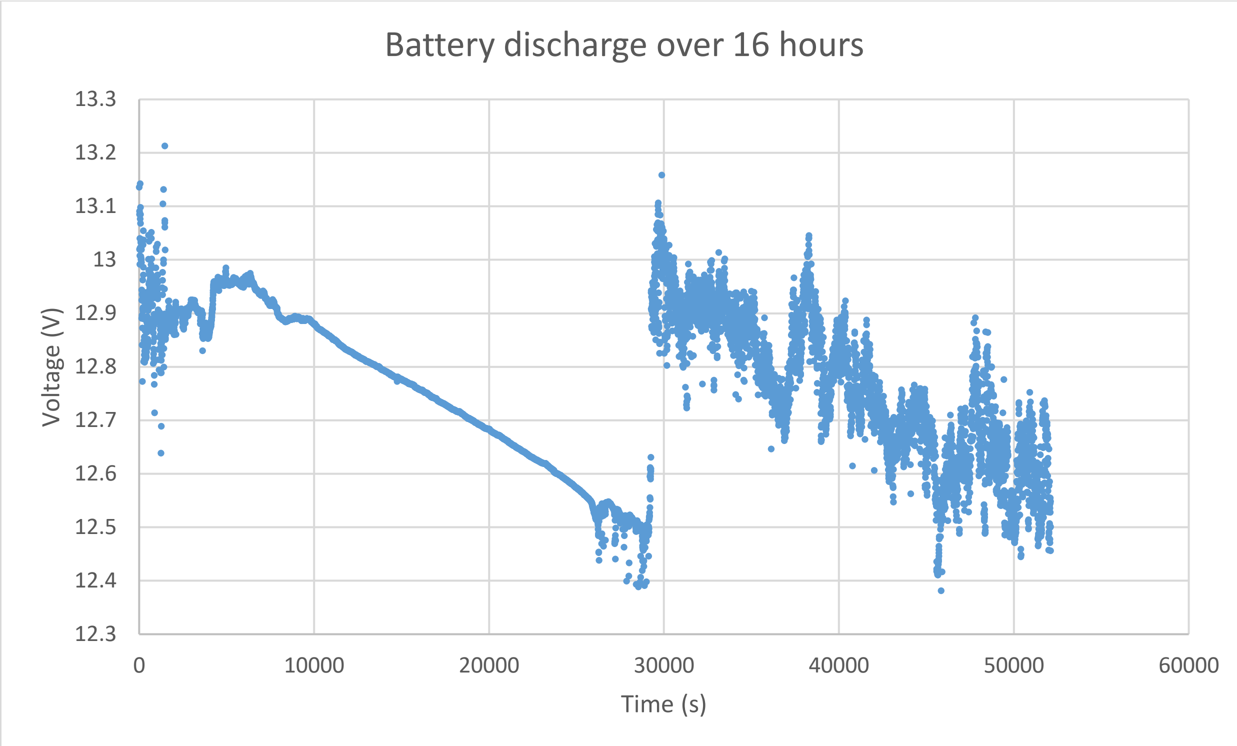

Figure 17. This shows the 12V battery as it discharging through 12Ω of resistance for 16 hours.

The tests run with the circuit shown in Figure 8 provided data that showed all the supercapacitors charged and discharged at the same rate. The graphs show that the supercapacitors charge and discharge at the same rate by having overlapping data points for charging the supercapacitors and overlapping voltages when discharging through different resistors. The repeated tests can be found in Appendix A.

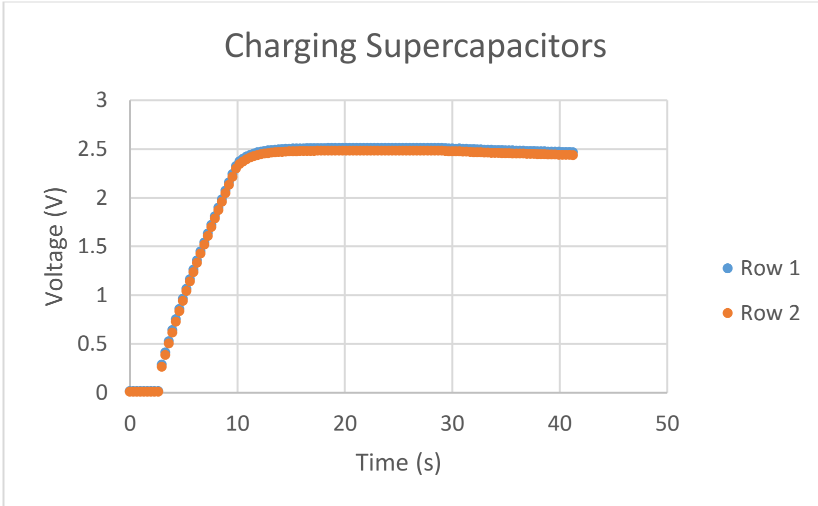

Figure 18. This graph monitors the first supercapacitor in each row from the circuit described in Figure 8.

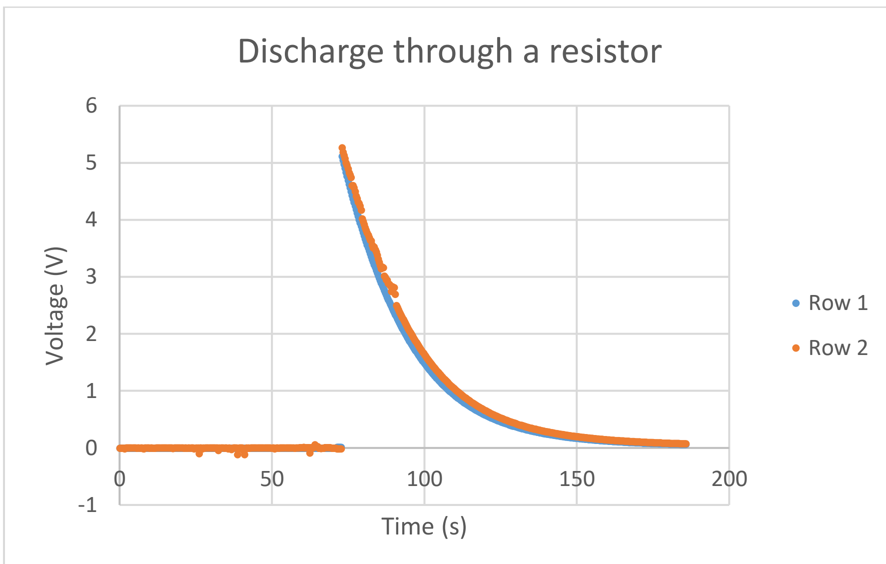

Figure 19. This graph shows the voltage of the first resistor in each row (from Figure 8) as the supercapacitors discharge.

Charging the supercapacitors with the hand-crank generator showed slightly more unsteady lines (which is expected as it was supposed to simulate variable winds/voltage source), but still showed the same type of charging curve that past tests have shown for supercapacitors. This is shown in the graph below. Two other repeated experiments can be found in Appendix A.

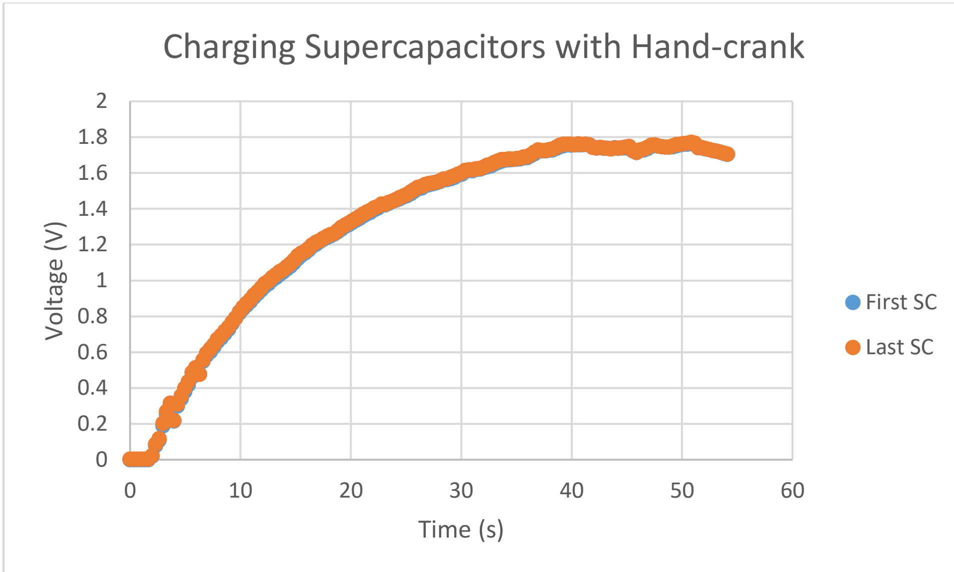

Figure 20. This graph shows the charging of the first and last supercapacitors of a series of six as it gains charge from a hand-cranked generator.

The results from charging the supercapacitors with the drill showed that the voltage was equally unstable but still produced a comparable curve with repeatability. The resulting graph can be seen below and the repeat can be found in Appendix A.

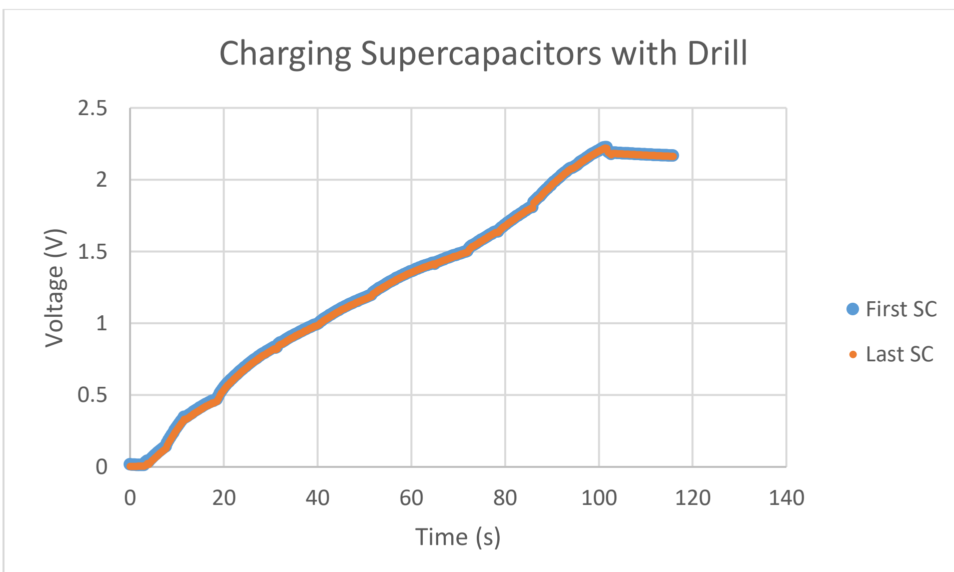

Figure 21. This graph shows the charging of the first and last supercapacitors of a series of six as it gains charge from a drill turning the generator.

By doing the calculations described in the previous section, the total energy supplied by the supercapacitors in the final circuit were found. Using Equation 1, it was determined that the supercapacitor bank was able to ideally supply 81.88 J of energy. Using conversions, this comes out to 0.0227 Wh, or 0.009% of the total energy storage of the battery. Using the other equations and methods discussed, the internal resistance of the supercapacitor bank was found to be approximately 0.973 Ω and the internal resistance of the 12V battery was found to be approximately 0.391 Ω. By using these values, the efficiency of the charging circuit was calculated to be 90.76%. The data from these tests, and the hand calculations are available by request.

Finally, the graph of the theoretical model is shown below. It matches the experimental test that is shown in Figure 15 nearly identically.

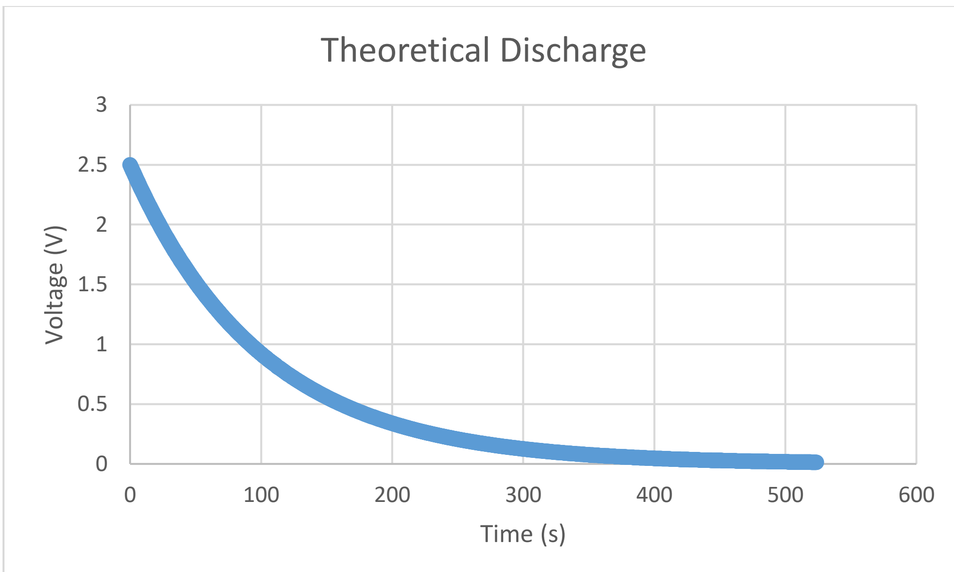

Figure 22. This graph shows the theoretical discharge to match the test and setup of the experiment described in Figure 15.

Discussion

The batteries were able to somewhat maintain a consistent voltage during their discharge, until a certain point. Once they had expended a certain amount of their charge, the voltage they could supply dropped dramatically. Conversely, supercapacitors could not maintain a voltage, however their reduction in supply was predictable and linear overtime. Supercapacitors were also able to fully charge and discharge very rapidly, where it took batteries a very long time, comparatively. This is due to the superior specific energy properties of batteries. Overall, both the batteries and the supercapacitors behaved nearly ideally as they should have.

Charging the supercapacitors with the hand-cranked generator showed that the technology is adept at charging under variable power supply conditions. This is important because in real-life use, wind turbines are often subject to large wind changes causing different fluxes in the voltage generated by turbine. Supercapacitors can handle these voltage fluxes, as shown by the data above. Running several tests also shows that supercapacitors can charge a battery with minimal loses to the circuit and internal resistances. Although the supercapacitor bank constructed had minimal impact on the total charge of the battery, it proves the concept that a hybrid energy storage system can be effectively used. Using the work equation listed above, it can be calculated that in order to charge the battery 25% with one charge, the circuit would need a supercapacitor bank with a capacitance of 5333 F. Prices vary by seller, but a 3400 F capacitor can be bought between $50-75. Which means a supercapacitor bank that is nearly 10 times larger than the one constructed for this research can be purchased for around twice the price. Overall, the expense of such a bank is not that expensive, and a large one could be constructed for a larger system, such as one for a real world application.

Conclusions/Future Work

After reading other research and personally looking at the behavior of supercapacitors, it seems that the best use for supercapacitors, at their current limitations, is to be used in tandem with batteries. Supercapacitors are able to take in and withstand random surges in energy that are likely to happen from solar and wind generators. They can also receive energy from low levels of solar radiation or slow wind speeds that may not trip a battery. Supercapacitors also have the ability to take in these random surges of energy and can put out a relatively constant power level. As seen in the research done by those who created the hybrid solar vehicle, supercapacitors can put out a constant power level by manipulating the current as voltage linearly drops. Despite all these advantages, supercapacitors still do not yet have the large storage capabilities that batteries do, which is a crucial feature if these systems are needed to power large scale things such as buildings.

Based on my research and experimental results, it can be confirmed that it is possible to create a hybrid energy storage system that utilizes both supercapacitors and batteries. This tandem system allows for energy to be captured over a larger voltage range, making the entire system more efficient than an energy storage system composed solely of batteries. While supercapacitors seem better for capturing and storing energy in these types of situations, they will not be able to overtake batteries until their ability to hold larger charges for the long-term is greatly enhanced. Until then more research should be done about the viability of hybrid energy storage systems.

In the future, to enhance the steps taken by this research, the system constructed should be tested with a real wind turbine. Testing the system outside will determine how effective it truly is at capturing and storing energy. For this, an electrical engineer should be brought in to make the circuit design more sophisticated. Some recommendations for the new circuit would be to include a voltage amplifier, so that when the voltage of the supercapacitor bank drops too low, the voltage amplifier would turn on to further increase the usefulness of the supercapacitor. Additionally, a switch should be placed in the circuit so that if the wind is producing a high enough voltage to charge the battery, then the electricity bypasses the supercapacitor bank and goes directly into battery storage. These additions are beyond my expertise but would be useful to create a better design. Future testing should include monitoring the amount of energy captured and stored of a hybrid energy storage system from a wind turbine opposed to a wind turbine with only a battery. By comparing these two values, it would be easy to calculate how much more or less efficient the hybrid system is than the battery. Overall, this seems like a promising method to make small scale renewable energy collection more efficient and thus a more viable alternative to fossil fuel energy generation.

References

[1] "BU-204: How do Lithium Batteries Work?," Battery University , 31 July 2017. [Online]. Available: http://batteryuniversity.com/learn/article/lithium_based_batteries. [Accessed 2 November 2017].

[2] "BU-209: How does a Supercapacitor Work?," Battery University, 21 April 2017. [Online]. Available: http://batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor. [Accessed 2 November 2017].

[3] "IOXUS TECHNOLOGY SELECTED TO HELP LONG ISLAND RAIL ROAD TRAINS REDUCE ENERGY CONSUMPTION," Ioxus Technology, 15 April 2014. [Online]. Available: http://www.ioxus.com/english/media/press-releases/ioxus-technology-selected-help-long-island-rail-road-trains-reduce-energy-consumption/. [Accessed 4 November 2017].

[4] J. Duay, S. A. Sherrill, Z. Gui, E. Gillette and S. Bok Lee, "Self-Limiting Electrodeposition of Hierarchical MnO2 and M(OH)2/MnO2 Nanofibril/Nanowires: Mechanism and Supercapacitor Properties," *ACS Nano*, vol. 7, no. 2, pp. 1200-1214, 2013.

[5] E. Bushueva, P. Galkin, A. Okotrub, L. Bulusheva, N. Gavrilov, V. Kuznetesov and S. Moiseekov, "Double layer supercapacitor properties of onion-like carbon materials," *Physica Status Solidi*, vol. 245, no. 10, pp. 2296-2299, 2008.

[6] F. Zeng, Y. Kuang, N. Zhang, Z. Huang, Y. Pan, Z. Hou, H. Zhou, C. Yan and O. G. Schmidt, "Multilayer super-short carbon nanotube/reduced graphene oxide architecture for enhanced supercapacitor properties," *Journal of Power Sources*, vol. 247, no. 1, pp. 396-401, 2014.

[7] M. Burnett and L. Borle, "A power system combining batteries and supercapacitors in a solar/hydrogen hybrid electric vehicle," *Vehicle Power and Propulsion* , 2005.

[8] P. Thounthong, "Model Based-Energy Control of a Solar Power Plant With a Supercapacitor for Grid-Independent Applications," *IEEE Transactions on Energy Conversion*, vol. 26, no. 4, pp. 1210-1218, 2011.

[9] C. Abbey and G. Joos, "Supercapacitor Energy Storage for Wind Energy Applications," *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*, vol. 43, no. 3, pp. 769-776, 2001.

[10] W. Li, G. Joos and B. Jean, "Real-Time Simulation of a Wind Turbine Generator Coupled With a Battery Supercapacitor Energy Storage System," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1137-1145, 2010.

[11] W. Sun and T. Zhou, "Optimization of Battery–Supercapacitor Hybrid Energy Storage Station in Wind/Solar Generation System," *IEEE Transactions on Sustainable Energy*, pp. 408-415, 2014.

Appendix

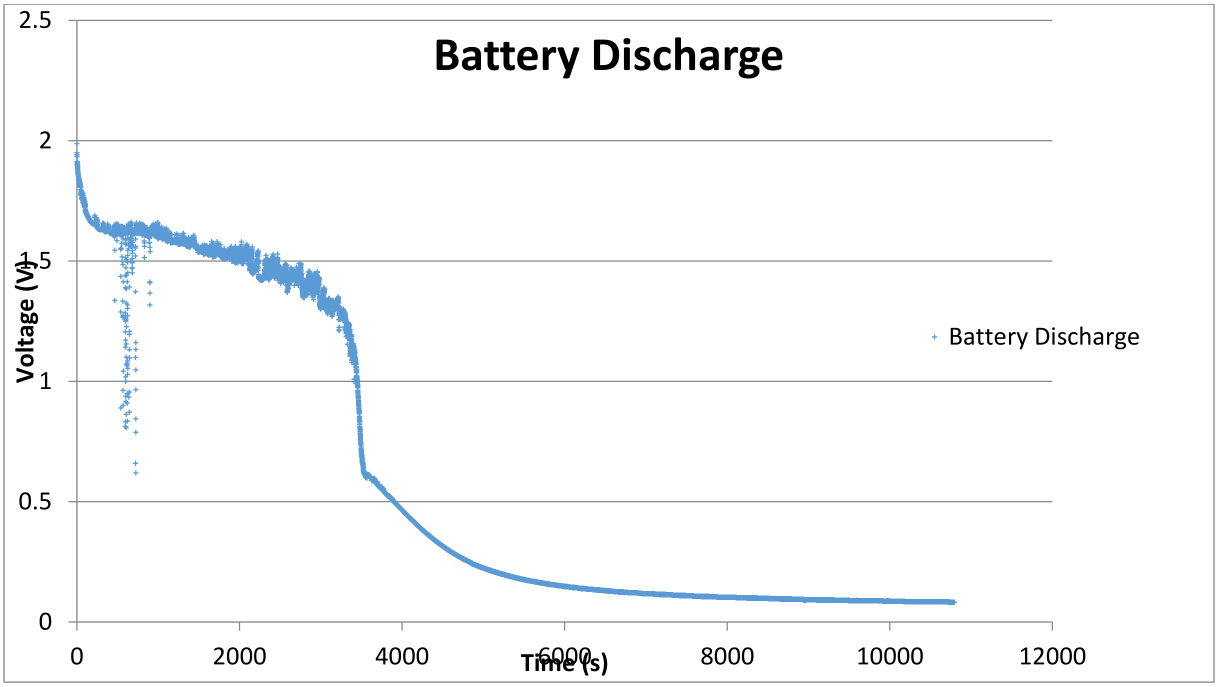

Figure 23. This graph shows the battery discharge over a longer period (compared to test 1), with a nearly identical curve.

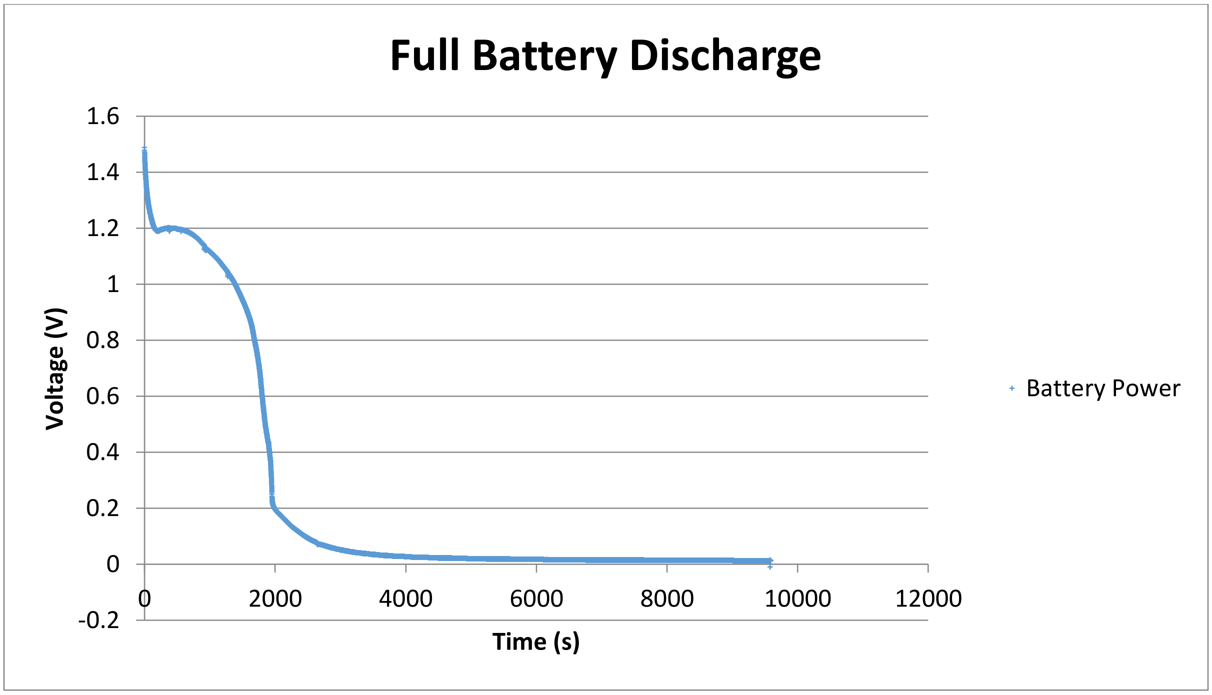

Figure 24. This graph shows the battery discharge with a smaller resistance. The relationship is between resistance and discharge time is direct so with half the resistance the same batteries discharged with the same curve but in half the time.

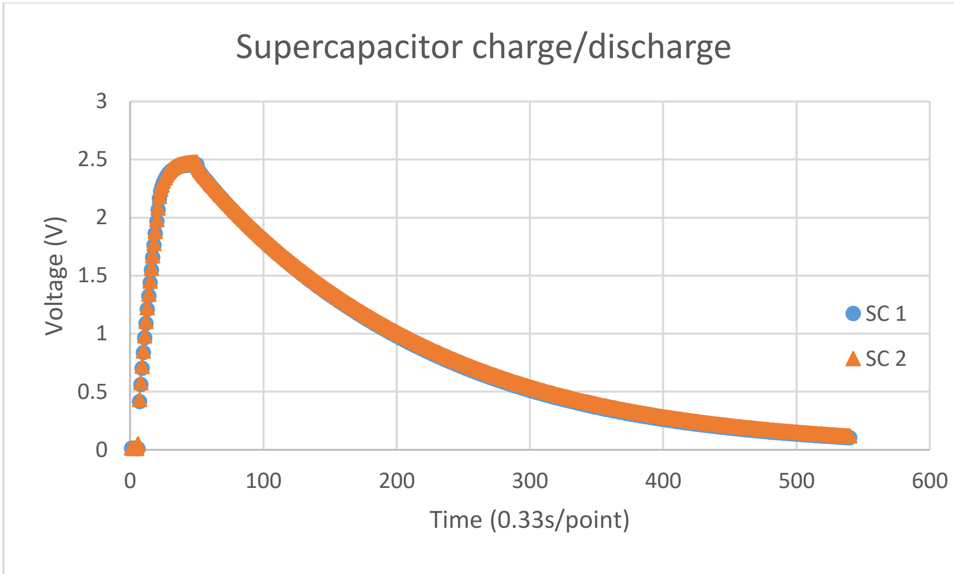

Figure 25. This shows the second iteration of the two 10F supercapacitor test.

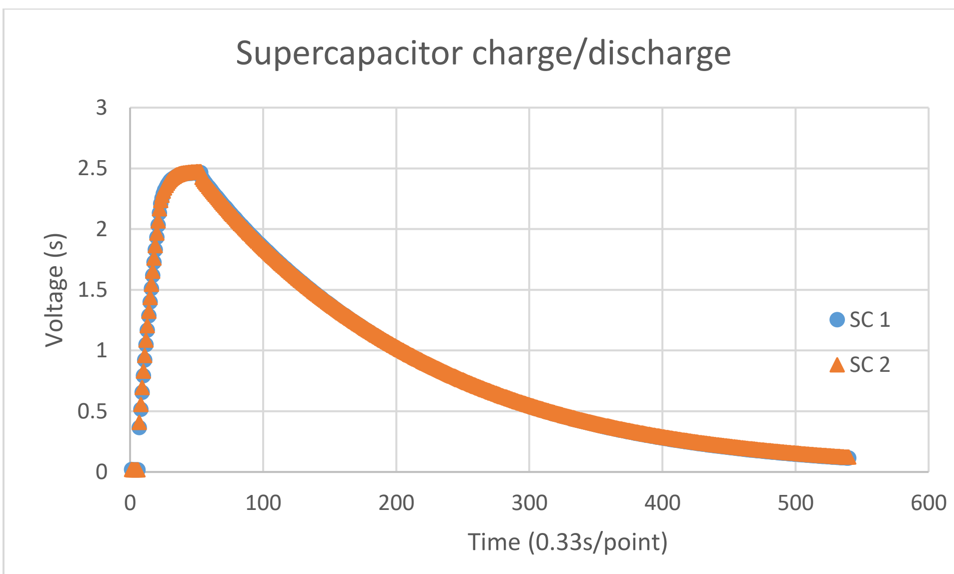

Figure 26. This shows the third iteration of the two 10F supercapacitor test.

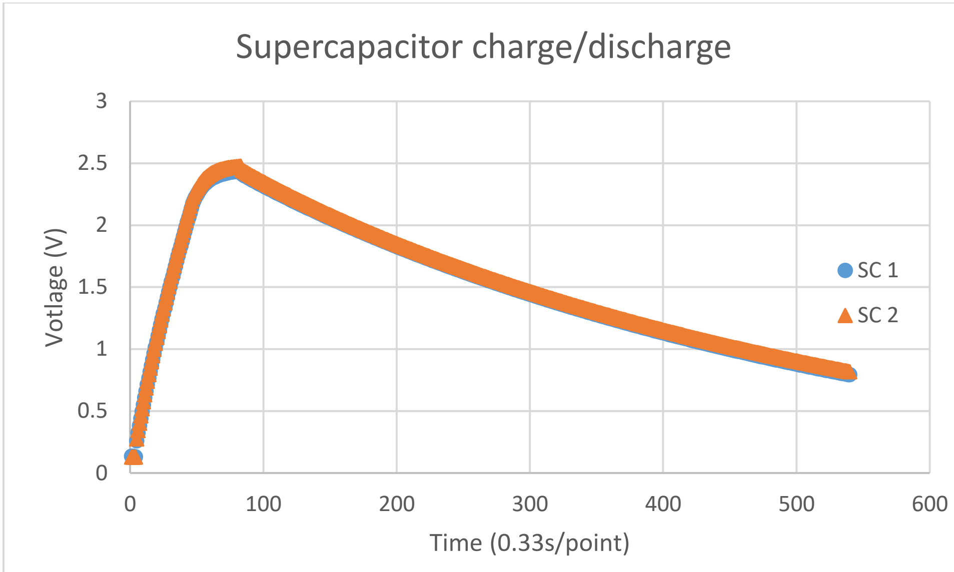

Figure 27. This shows the second iteration of the two 25F supercapacitor tests.

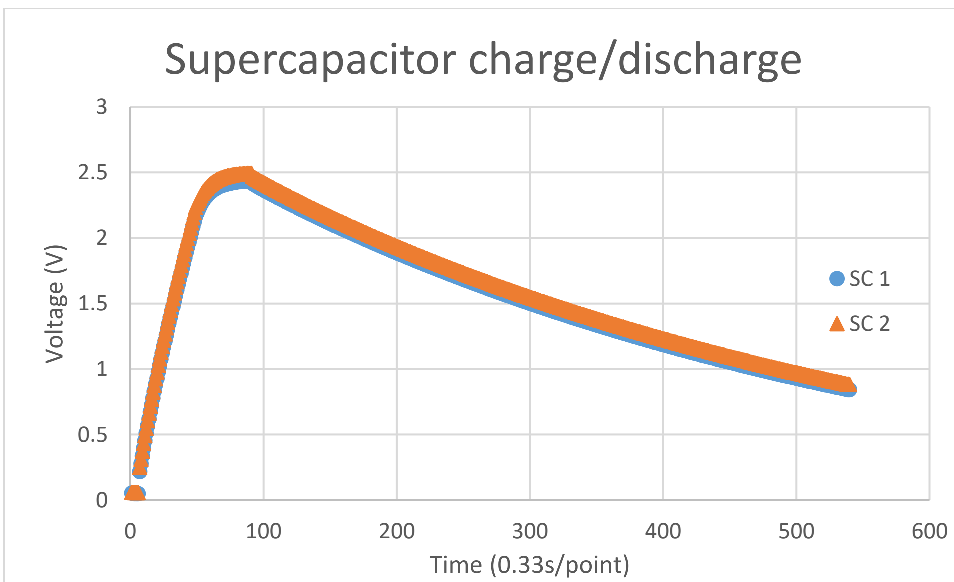

Figure 28. This shows the third iteration of the two 25F supercapacitor tests.

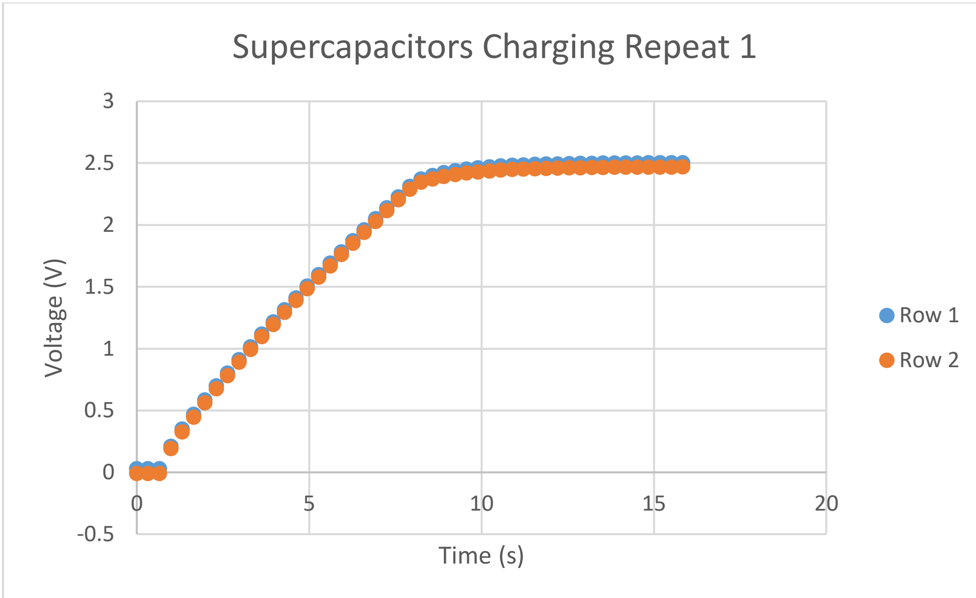

Figure 29. This shows the repeat experiment of charging the supercapacitors as arranged by Figure 8.

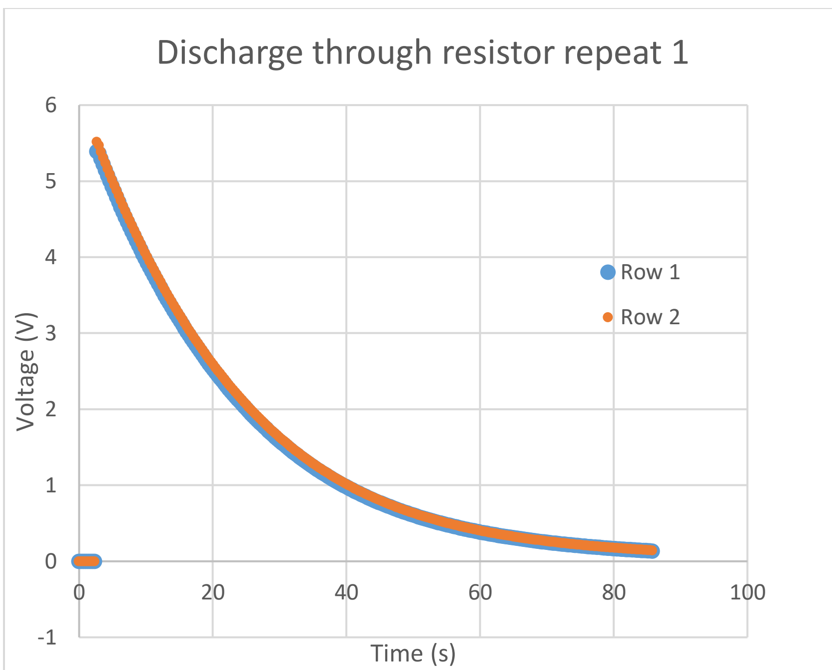

Figure 30. This shows the first repeat experiment of discharging the supercapacitors through a resistor as shown in Figure 8.

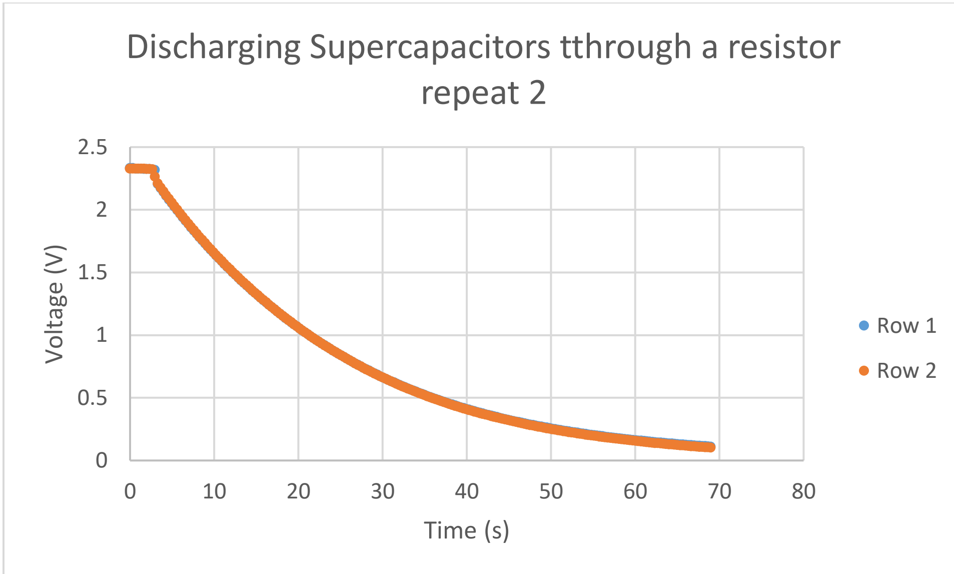

Figure 31. This shows the second repeat experiment of discharging the supercapacitors through a resistor as shown in Figure 8.

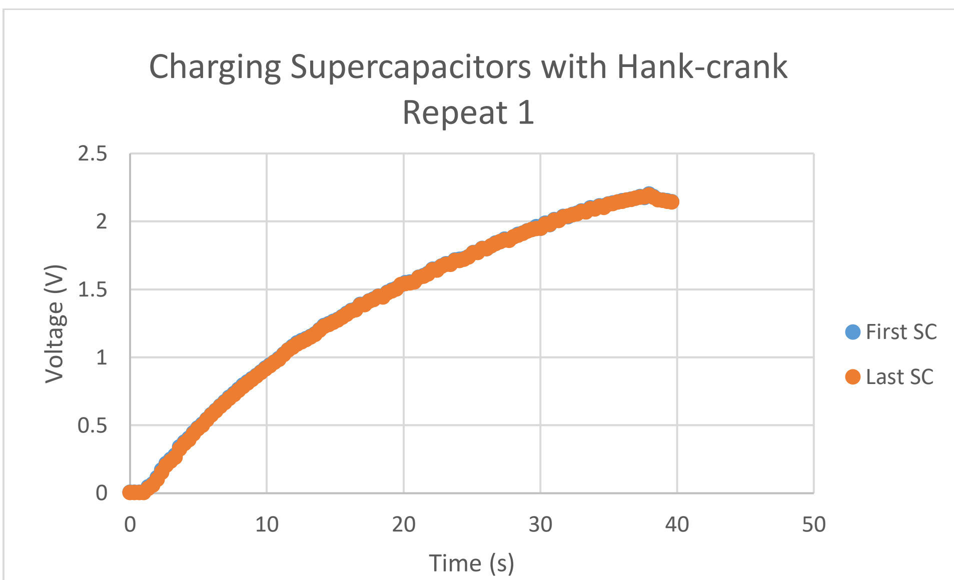

Figure 32. This graph shows the first repeat of charging the first and last supercapacitors of a series of six as it gains charge from a hand-cranked generator.

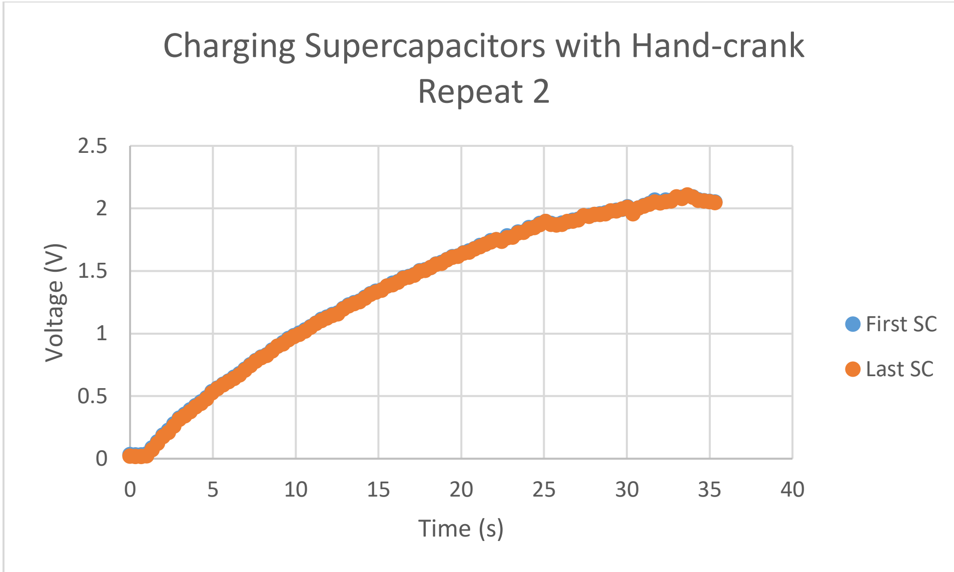

Figure 33. This graph shows the second repeat of charging the first and last supercapacitors of a series of six as it gains charge from a hand-cranked generator.

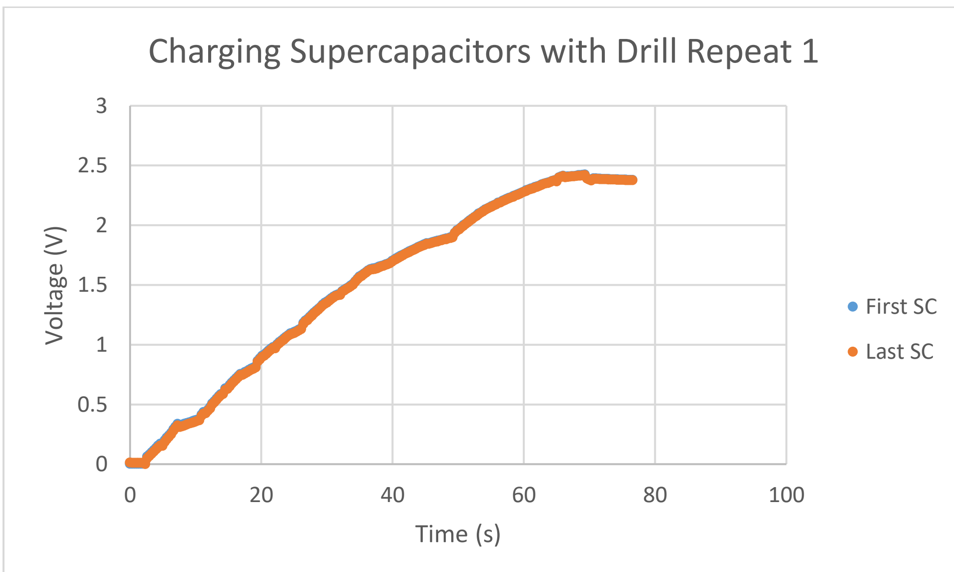

Figure 34. This graph shows the repeat of charging the first and last supercapacitors of a series of six as it gains charge from a drill turning the generator.