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MaRC S-Park

Magnetic Resonance Coupling with Sophisticated Parking

Group F

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1. Executive Statements

1.1 Executive Summary

The project presented in this design documentation is for a project based on technology first conceived by the great Nikola Tesla in his pursuit of designing a method of energy distribution which would revolutionize the distribution of electrical power. The technology spoken of is none other than the technology of wireless power, a concept so cutting edge at the time of Nikola Tesla's creative spark, with the Wardenclyffe tower, that it was summarily suppressed as an idea until the time of William C. Brown in 1964 when research on the topic began to return to the possibilities of engineers. Concepts of this have been thrown around for the application of this technology, but with low efficiency as attempts to create electromagnetic fields to carry the power is the primary methodology used in these systems. This is a project to prove the concept so long ago sought, as a viable method of transporting electricity at higher power outputs.

The design took an input power (outlet power), translated it to a carry-able signal (AC-DC-AC) through a set of inductors in coupling, and charged an ultra-capacitor array (AC-DC) which was used as a containment system for the load. The load itself was a remote control car. This was chosen for the fact that there has been a recent advent of electric vehicles, meaning there is a higher demand to have effective charging systems for these vehicles. This design aims to eliminate the need for the driver to plug in their vehicle after use, and permits them to simply drive over a pad/platform that will begin to recharge their vehicle after detecting its presence.

The main reason why this project intrigued us is that it would provide a practical use for both wireless power and a low cost ultra-capacitor array since wireless power is typically tough to achieve with the need for high efficiency hinging on the need for a strong coupling between the inductors. Another reason for having pursued this project is that it remains a fascinating concept, since the majority of technology that is electrically based requires a power cord or power source of its own. The power signal strength depends heavily on the precise distance between the inductors to achieve effective coupling. The Supercapacitor array maximum storage potential decided the amount of energy that could be stored, requiring a circuit to be responsible for maintaining output levels, giving a high capacity with regulated voltage and current output.

Imagine getting power without the need for a bulky transformer attached to a phone which is powered by a paper thin inductor connected to a small full wave rectifier that feeds the phone the power it needs. This project proved the feasibility of electronic technologies that cannot utilize a power cord, or where charge time is not a limiting factor of the uses of ultracapacitor technologies attached to a simple AC-DC conversion circuit, and even showed that wireless power can be an effective means of charging/recharging systems connected to an inductor coil in magnetic resonance coupling. It is an endeavor that should be researched by power companies as an alternative power distribution method as it is both a way to greatly increase the viability of electric vehicles, but also acts as a model for future designs, such as a non-invasive way to recharge a pacemaker or other internal medical apparatuses.

1.2 Motivation

The reason why we pursued such an unproven technology to base our design around is because the technology holds a great potential for innovation by its very nature of being a new concept. This technology could reduce tremendously the material costs accrued by the manufacture of wired transmission. Those resources can then be repurposed for more pertinent uses. On the other hand, the system could also provide a highly practical use for wireless power as a quick and easy car charging method, even if it solely is for recreational car use (toy cars). The main argument against electric vehicles has always been a poor effective range; electric vehicles, like gas-powered vehicles, must be recharged when their fuel is depleted, an instantaneous process for gas-powered vehicles yet a lengthy one for electric vehicles. We live now in a time where instant gratification is prevalent and time is a major factor in the considerations of the individual who wants to make the most of every second. This could satisfy the needs of those people with a more environmentally friendly electrical system that harnesses the power of a singular source rather than have multiple sources creating the same volume of energy at a tremendously higher impact upon the environment.

There also is an explanation for the use of ultracapacitors, primarily based around the physical principles of a capacitor versus a battery. A battery is good for applications where voltage regulation is important, as they tend to regulate energy output by chemistry rather than electrical properties of metals. Though batteries hold the advantage of being very simple to use, they lack the ability to handle high current, which rapid recharging requires. The lifespan on batteries as well is an important factor of why capacitors will some day overcome batteries. The chemistry of a battery tends to break down over time in the form of lost charge capacity (internal impedance) or physical corrosion of the cell itself. A capacitor on the other hand can theoretically have a running lifetime of nearly 100 times more cycles. A battery may be able to run over 100 or 1000 times, but ultracapacitors could theoretically cycle hundreds of thousands of times. This could be a highly advantageous medium for energy storage.

As a group, the purpose of the project was so we can better understand how these recent technologies work and apply an impressive method of their usage. Wireless power and Ultra-capacitors are relatively new to the technology fields with few applications as of yet. The purpose was to understand their use and possible places which these technologies can be used in other fields. But, as a proof of concept, this project coupled the two parts together. The project required the use of data collection, experimental technology, and tried and true concepts within the field of electrical engineering. The application of the skills in the programming of microcontrollers, power systems, and hardware design were tested and, at times, stressed. Data and hardware linking was utilized with the hope to better understand the duties of an engineer.

1.3 Goals

The aim of this project was simple to design, prototype, and test a working and practical wireless charger utilizing Supercapacitors and inductive resonance coupling technology. To do this, there were three goals to accomplish, the effective signal boosting from wall power 120V 60Hz to at least 8V 3.2 MHz, resonance coupling, and charge and discharge management of capacitors and its accompanying circuitry. The overall goal was to have as high efficiency as possible with this project and that requires the goals above.

With regards to the signal boosting, it required more than just the simple oscillator crystal or voltage controlled oscillator. This was a step which was paramount in maintaining a higher efficiency for later portions of this design. The 120V to at least 8V brought down the voltage to a useable level while the frequency increase brought up the stability of the signal and allowed for coupling. This way, the signal was strong enough for an efficiency level of roughly 50% from the input of the system to the supercapacitor array accompanied by the RC car.

Resonance coupling was the second factor that was important to the application of wireless power. It determines the transmission efficiency from one side to the other side of the inductor within the inductor resonance. The aim for this portion was for around 75% -65%. To achieve this, the inductors were fabricated with a specific diameter, keeping in mind that the “sweet spot” would be at roughly 1/4th the diameter of these inductors. The specific dimensions will be outlined later in the Magnetic Resonant Coupling sections where the entire MRC networks are discussed.

The capacitor array was the last major goal of this project. This was where the efficiency paid off, where the energy collected could be calculated with regard to charge time. The priority of this part was to be able to have a regulated discharge and a quick charging speed. Because they are capacitors, by their very nature they were able to smooth and regulate the output of the 3.2 MHz signal, which was rectified by a schottky diode bridge, thus eliminating the need for a lot of regulatory components. This was due to the fact that the capacitors were so large in value, voltage ripple was almost non-existent for the car.

By the end, the goal was to prove that these technologies have an important use in the technology of the future. Scalability was an overall goal for this project as well since the technology at hand is important and has applications at all levels of scale from micro-electronics to automotive; from home appliances to industrial power distribution applications. Scalability will also be able to serve as the longevity of this project model, as its many practical uses are innovated through future generations of engineers. Though the project does not reach the scope of encompassing many different types of applications, the use of both together is a milestone on its own by proving the worth of their abilities. The better we could implement and understand these technologies, the better and cleaner the future will hopefully be and the better we will understand the state of current technologies.

Our biggest hope in creating this design has always been that this will help pave the way for future engineers who are interested in this topic, allowing them to see that even concepts which are deemed outlandish or impossible could prove to be the standard some day. It is this creative thinking that allows us to adopt these new ideas more readily and to utilize them more efficiently.

1.4 Objectives (In list organization)

There were a few key points that needed to be achieved through this project:

AC voltage drop – This step is to bring the voltage down to a useable level that the inductor coils can use for the purpose of creating a magnetic field to allow for coupling. This was important for the protection of the circuits in the system and to lower the physical constraints that limit cost effective designing of the system.

AC frequency boosting – The second iteration of alternating current was to allow for a strong magnetic coupling. In the 1-10 MHz frequency, we were able to achieve strong coupling over a distance of a few inches. When the frequency is lower, the strength of the signal is stronger at distance, but coupling may not be as strong overall, save for a few harmonic frequencies in the 100 kHz range. Designing a high frequency system would improve the gain and inductor gap allowed in the resonance coupling system.

Inductive Resonance Coupling tracking – Since the magnetic field fluctuates ever so slightly as the system is active, the optimal efficiency air gap can be theoretically tracked to find the right distance on to get the optimal efficiency. This will then allow for the maximal efficiency of the inductor system. This was actually accomplished through manual testing, since our distance is very limited, and the coils themselves have inherent resonant frequencies (found to be 3.2 MHz here)

Electrical data collection – The collection of data is important for the tracking of the system efficiency and current state of the car and charging mechanism. A microcontroller was implemented to both detect when the car is there (through push button acting as pressure sensor) and to disable the charging mechanism when the car isn't there. This disable feature was implemented by manipulating the voltage controlled oscillator used to generate the 3.2 MHz signal before our amplifier. Another microcontroller was used on the car to determine how much voltage is left on the supercapacitors and to display this information through an array of LEDs.

2. Specifications and Requirements

2.1 Power Supply

In order to determine the specifications and requirements of the power supply, we first needed to determine the requirements for the rest of the project in order to understand how much power the power supply was going to need to generate, and at what voltages.

With the other parts of the project designed, we determined the specifications and requirements of the power supply to be as follows.

- 2 rails
    - 1 at 8V for the class E amplifier, and it must be able to handle up to 5 amps.
    - 1 at 5V for the integrated circuits on the station, such as the MCU and the programmable oscillator. The current draw for this rail is quite small.
- Receives 120V at 60Hz from a standard wall outlet.
- Voltage ripple is not a major concern for our project, but it should be no greater than 5%.

2.2 RF Power Signal Generator

For our project, the design of the RF power signal generator was critical, as it's performance will have a massive impact on the performance of the resonators, the efficiency of the entire design, and the power transferred ultimately to the RC car.

Our best estimates to our designs originally required that our signal be about 10 Megahertz, so our RF power signal generator needed to be able to generate a frequency of at least this value. Another key consideration was to consider the method of transferring the power; in our project, we used magnetically coupled resonators, and current is a critical factor in magnetic coupling. When there is a greater current passing from the transmitting resonator to the receiving resonator, the coupling will be greater, and therefore the better the efficiency. For this reason the RF power signal needed to be able to generate a signal of at least one half of an ampere of current. These specifications are summarized below.

- Generate a range of frequencies from 1MHz to 20MHz on the fly for tuning
- Generate at least 1W of power
- The higher the efficiency the better

The RF power signal generator required simply a dc source from the power supply to power the amplifier, the gate driver, and to power the oscillator. The requirements are summarized below.

- 8 volts DC at an absolute max of 3 amps for the amplifier
- 5 volts DC for the oscillator

2.3 Magnetic Coupled Resonators

The Magnetic Coupled Resonators are used to deliver power to the capacitor array once it's over the wireless charging pad. The point of this component is to allow us to transfer power to the car without any direct contact, hence wireless charging, but it had to be sufficient enough to deliver power reliably, efficiently, and quickly to the capacitor array. As such, the MCRs (Magnetic Coupled Resonators, used interchangeably with MRC, Magnetic Resonance Coupling) had several requirements to meet the following standards.

- Small form factor. The MCR network could not interfere with the normal operation of the car through physically obstructing the car's path, rendering the car unable to travel where it would other be able to travel, or any other means of physical interference.
- Electronically stable. The MCR network could not interfere with the normal operation of the car through electromagnetic interference, such as blocking signals to be received from the control mechanism, disrupting power to be transmitted from capacitor array or the car, or by otherwise causing the car's electrical systems to malfunction.
- Reliable. The MCR network on the car must have been able to receive a reasonable amount of physical trauma and withstand the elements without ceasing to function. It must also remain in place so as not to misalign itself when placed over the charging mechanism, which is highly sensitive to displacement.

The MCR network was supplied with a +15V AC, 3.2 MHz signal after the amplifier circuit, with a spike in signal exceeding 45V. It needed to transmit at least 15V AC, 3.2MHz successfully to its receiving end so as to successfully power the capacitor array with little to no issues. It definitely met this requirement and surpassed it, allowing the supercapacitors on the other of the circuit to charge at a relatively consistent rate.

To gain the maximum amount of efficiency, the MCR network was created with the size of the car and distance between the two coils in mind. Originally, we intended to have inductors etched on RO4003 board (copper microstrip on a dielectric), but opted instead for coils made from winding 18AWG wire since it was considerably cheaper and allowed for easy manipulation.

2.4 RF to DC Power Supply

Since the power going into the RC car from the receiver coil is at RF frequencies, special considerations needed to be taken into account for such high frequencies when converting it to DC. The determined specifications and requirements are as follows.

- Be able to convert to 15V DC from 3.2 MHz AC
- Be able to handle currents up to 3 Amps
- Voltage ripple is not a huge concern, but it should be no greater than 5%

2.5 Capacitor Array

The Capacitor Array was used to power our RC car. We decided to go with a capacitor array as opposed to a standard battery pack to ensure quick charging, so as to easily demonstrate our wireless charging of the RC car. Leaving a battery pack in would take far too long to be able to demonstrate the device to a commitee. Supercapacitors allow us to charge quickly and to store large amounts of energy. The Capacitor array must adhere to the following conditions:

- Able to hold at the absolute minimum 6V worth of charge. The more, the better. Ours was able to hold 8.1V.
- Able to dispense at least 1.5A of current, as per the requirement of the RC car, and the ability to hold this 1.5A current for an extended period of time, which it exceeded.
- Low ESR (Equivalent Series Resistance) to allow for quick charging without overheating or damaging the capacitors.
- Small form factor. If they are too large, the capacitors will disrupt regular functions of the RC car. The ones chosen are roughly the size of D Cell batteries
- Lightweight. Large amounts of weight will require more power from the motor. More power means less run time. Ours were roughly 30g each.
- Reliability. The capacitors are worth very little to us if they cannot be used to repeat our tests a significant number of times, and replacing them is just another source of frustration for any potential clients. The ones chosen can be recharged 500,000 times, roughly 1000 times more than the standard battery pack.
- High peak current output. Higher peak current output means the capacitors will be able to supply the car with enough power to allow the car to keep operating, even when there is a large, sudden load from the car. Such loads occur when the car is attempting to perform a sharp turn and accelerate at the same time.

The capacitors were powered by the 3.2MHz signal being full-wave rectified. To avoid being charged to over voltage, the capacitors needed to be monitored by a protector circuit. This circuit monitored the analog voltage of the capacitors through a microcontroller and displayed a warning light when 8V was reached. For our purposes, the capacitor array has an 8.1V rating with an 8.25V absolute maximum. Therefore, to ensure the safety of the observing committee, and our group, as well as the continued success of this project, our protector circuit warns us to stop charging at 8V.

2.6 Data Acquisition Parameters

The parameters required for the data acquisition portion of the project are at minimum for the microcontroller needs, wireless requirements and high voltage management for discharge and charging.

2.6.1 Microcontroller

The microcontroller required the following parameters:

1. A minimum number of 10 I/O
2. Compatibility with the use of I2C connectivity
3. Clock rate to allow for effective and real-time use of a display
4. LCD usability
5. ADC resolution minimum of 10-bits
6. Power consumption of microcontroller of less than 5V
7. 2 comparators.
8. Connectivity to extensive peripherals
9. Minimum of 128k Memory
10. Less than $100 microprocessor and hardware
11. Low cost software
12. Respectably sized user community
13. Experienced user language (MIPS, C-code, etc.)
14. Wireless peripheral compatibility
15. Control of digital peripherals

2.6.2 Wireless

The wireless communicators, should we put them in future designs, require the following parameters:

1. Low cost (under $20 per unit)
2. Zigbee or IEEE 802.15.4 standard
3. Unused frequency to communicate (ex. 2.4GHz or 886MHz)
4. Low powered (3.3V Max)

5. Minimum range of 100 Feet
6. Does not interfere with inductor resonance frequency (10MHz)
7. 10-bit resolution minimum

2.6.3 High Voltage Management

To manage high voltage, we required the following parameters:

1. ADC components with as high definition as possible
2. Methods to reduce voltage and current to manageable levels.
3. Secondary circuit's in-case of overload (fuse circuit, rerouting, or shunts)

3. Research

3.1 Similar Projects and Products

With the emergence of wireless charging pads that charge your mobile devices, a plethora of consumer products have been developed to fill the market. In this section, we will be taking a look at these products as well as Witricity. Witricity is a new and emerging technology which is essentially the same thing that we are doing, the wireless transfer of power via magnetically coupled resonators on planar coils. Therefore it would be quite wise to take a look into this technology to help with our own project.

3.1.1 Inductive Wireless Power

Inductive charging is a very near field, within the range of 1cm to 2cm, wireless power transfer technology. It's also very inefficient even at very close ranges. Regardless of these disadvantages, it's quite widespread in use due to its small footprint and ease of production. It's found in a variety of applications such as RFID chips, implanted devices, and the wireless charging stations introduced to the market a few years ago that wirelessly charge your mobile devices.

It's interesting to compare induced wireless power transfer technology to the magnetically coupled wireless power transfer technology that we are working on in this project. Magnetically coupled wireless power transfer technology is a much farther field power transfer technology when compared to inductive charging. The difference is in circuit design: inductive charging is similar to a transformer, where two coils share magnetic flux, while magnetic resonant coupling ensures both the transmitting and receiving end will resonate at a specific frequency and can transmit power much more efficiently and over greater distances at the cost of bandwidth. The magnetically coupled resonators can transfer power quite efficiently at ranges up to a meter, and even beyond if done in a 4-coil array with a resonator/transmitter coil between the base and load coils. This puts it into a whole other realm of applications compared to inductive wireless transfer technology. You can use magnetically coupled resonators to wirelessly charge a car as it’s parked, something that inductive wireless power transfer could never do, nor do at efficiencies in the ranges of magnetic coupling.

The main advantage inductive wireless power transfer technology has over magnetically coupled resonance wireless power transfer technology is that right now magnetically coupled resonators are quite bulky; the systems generally developed and studied today utilized a drive loop, a resonator coil, a receiver coil, and a load loop. What Witricity has developed and we are essentially replicating is to consolidate all of those coils into just one planar transmission coil, and one planar receiver coil. Inductive wireless power transfer technology also operates at much lower frequencies than magnetic coupling resonance, which makes it easier to design power systems to drive the inductance. 2-Coil networks can also be used to facilitate the size constraint, but are comparatively much more limited in efficiency and distance.

3.1.2 Witricity

Witricity is a company which manufactures products for wireless power transfer using strongly coupled magnetic resonators. This technology is extremely similar to our project, and I would even go as far as to say that they are exactly the same, except that our main purpose is demonstrate the ability to wirelessly charge electric vehicles. Witricity has demonstrated the ability to power a 60 watt light bulb from 2 meters away, even when the light of sight was blocked with a wooden panel. They have also demonstrated the ability to power a television wirelessly. All of this is a good demonstration as to the validity to our project, as we are only looking to transfer about 30 watts to wirelessly charge a capacitor array on an RC car.

3.2 AC/DC Power Supply

This project design called for a steady, strong and reliable Direct Current (DC) signal that would introduce very minimal if any oscillations. This, in turn, requires a source of mains and its conversion from Alternating Current to DC. In our design, we have implemented this technique via a power supply designed around the necessary specifications required. In recent years, similar projects have considered many topologies such as Full Wave Rectifier Diode Bridge in low frequency applications. Using the positive half cycle of an oscillating input signal to charge a smoothing capacitor and dissipate only some of its energy during the negative half cycle of the input signal to a parallel load streaming the output voltage. In even more recent years, these diodes have been substituted for more efficient components such as MOSFETs, more particularly, Power MOSFETs.

The whole idea of using Power MOSFETS, and will be considered in the design portion, is related to:

1. Power MOSFETs in forward active mode will have very little forward voltage drop as compared to the 2N2222.
2. The Linear Active mode Resistance from Drain to Source is close to nothing and can be advantages when high current output is needed.
3. Power MOSFETS have a considerably fast switching time (for the time it takes to reverse the bias in the FET and no longer allow the flow of current through the component.

As we get closer to today's day in age, the demand for the right power supply has shifted. More economical solutions to power supplies are taken into consideration with lower wattage requirements and intuitive techniques. Our means of power for this project in turn must remain economical in a way such that our power consumption is on average with commercial power supplies available today.

Moreover, the power supply has been and always will be a component in which the engineer and consumer must be aware of the dangers that come along with manufacturing and use of this product, protection has been implemented such that if the supply is quickly removed from its source there will be a means of power dissipation and "cutoff" of feedback current negatively affecting the integrated circuit components. This is one of the major considerations in on both our design and power supplies in general, due to the destruction not only the integrated circuits but a possible threat to user/consumers health.

Our design fortunately did not call for considerable protection which would involve different techniques such as diodes that cut off feedback current, Zener diodes to regulate the voltage across transistor components such as a MOSFET to insure that the Drain to source voltage does not exceed the maximum threshold requirements, heat sinks if the power dissipation amongst components becomes too high, and fuses to protect against current becoming relatively too high.

3.2.1 Voltage Regulation

Voltage regulation is one of the most important aspects of this project simply because this is where it all begins. The foundation of our power supply that will enable our overall goal will be to obtain a reliable and economical source of DC power. This pure DC signal will provide more than just power and so it must be done in careful consideration of the proceeding components, their requirements and specifications.

3.2.1.1 Linear Regulator

One of the ways in which we have considered initially regulating the voltage is to use a linear regulator. This will simply regulate an incoming voltage signal down to the specified voltage (specification done by the manufacture) and the difference in voltage will be burned off into a heat sink attached to the regulator itself. One condition must remain constant when using the Voltage Regulator is that the difference in input voltage and output voltage must be more than the drop off voltage (referenced in each Voltage Regulator's Datasheet).

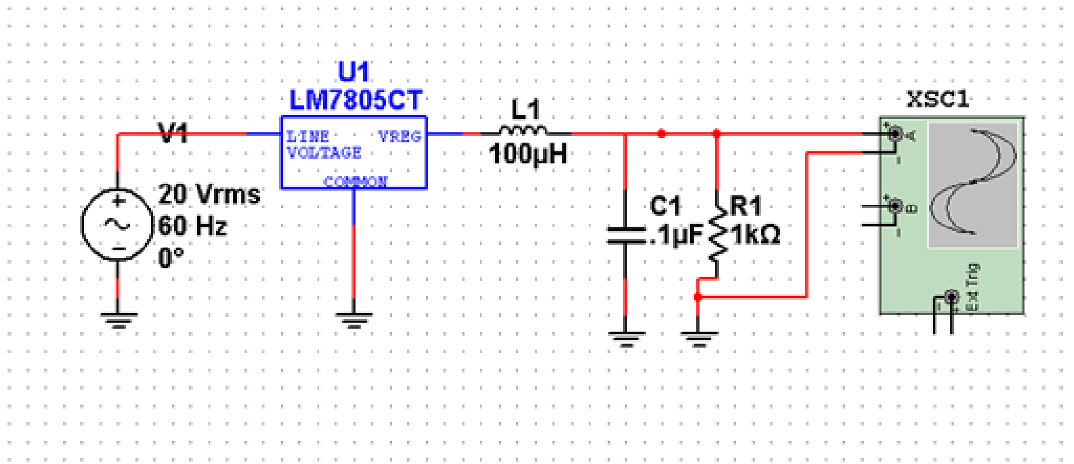
$$Efficiency = \frac{Output\ Voltage}{Input\ Voltage} * 100\%$$

Linear regulators also have attribute that are disadvantageous. To start with the most obvious this method isn't the most efficient nor is it the economical. To show this, take consideration maybe you have a 5V regulator available and you wanted to test this out with an input voltage of 15V. As efficiency, or gain as in electronics, is defined

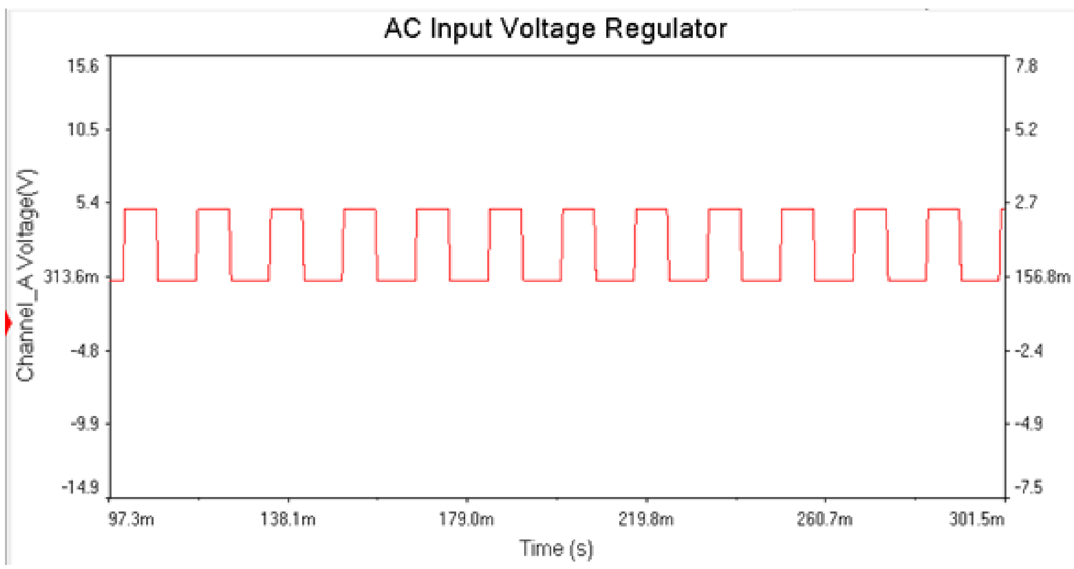
If you apply this equation, you will see that the voltage regulator only achieves a transfer efficiency of 33.33%. Our project and applications frowns upon this method because if we must apply the same principle we will obtain 25% efficiency.

One thing that we must also consider is the fact is that our project input signal is *AC* not DC. The polarity on a Voltage Regulator is not meant to be switched. In doing so the user may damage the integrated circuit permanently especially if the Voltage Regulator was not properly protected with reverse protection diodes.

Given below is an example of a Linear Voltage Regulator with an AC input and the resultant output in 3.2.2.1 Figure 1 and 2 respectively. This implementation shows that with an AC current, once the voltage is above the drop off voltage the, input is regulated to 5 volts. Once the output drops below the drop off the output almost immediately drops to zero and the negative half cycle is rectified. Standing wave will exist without the presence of the inductor and its impedance suppressing them. Moreover, the capacitance cannot be charged fully and fast enough to store energy and dissipate it over the load constantly if we chose to use this design as then rectifier.



3.2.2.1 Figure 1: Multisim Schematic of Linear Voltage Regulator With Alternating Current Input

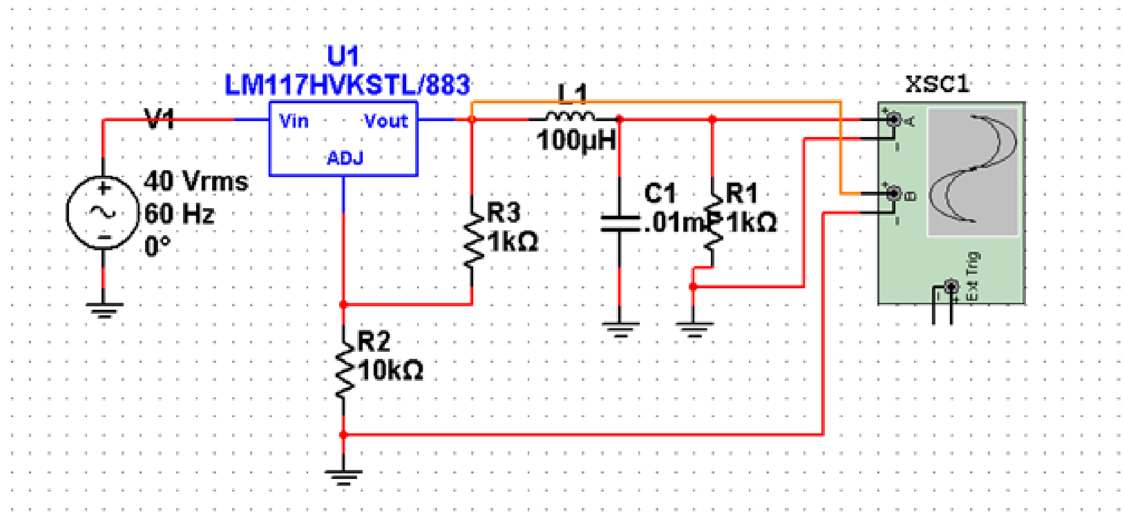


3.2.2.1 Figure 2: Multisim Output Voltage of Linear Voltage Regulator with Alternating Current versus Time

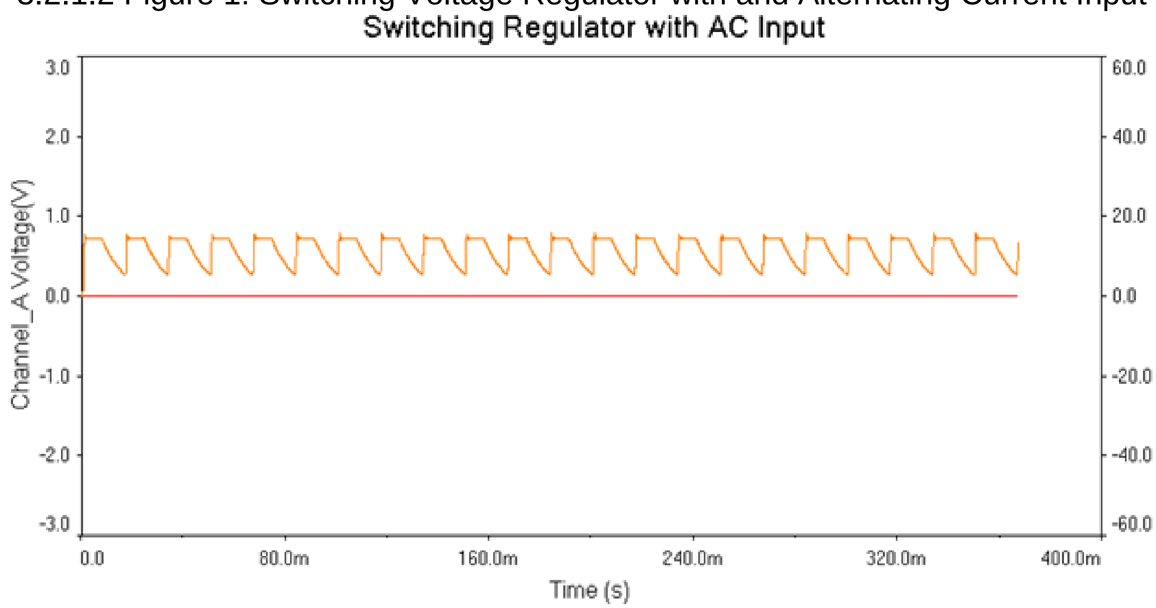
3.2.1.2 Switching Regulator

The switching regulator, a lot like the Linear Voltage Regulator but is more efficient when efficiency is critical like power management as in our project's power supplies. The output voltage can be adjusted such that the regulator doesn't have to burn so much energy off. This economical advantage is rather useful and has absorbed a lot of our consideration. Furthermore, the Switching Regulator will, a majority of the time, use bypass capacitors from input to ground and output to ground to really diminish the amount of noise on both sides but this comes with a cost. If the Switching Regulator is suddenly cut off from its input voltage spikes can occur resulting in reversing the bias on the regulator, again, resulting in permanent damage of the integrated circuit chip. One last consideration is that we are still using an *AC* input signal so this method may not be beneficial to our project in terms of regulation in voltage.

3.2.1.2 Figures 1 and 2 show an example of a switching regulator with an AC input and its output respectively. The switching regulator can obtain the gain needed but cannot maintain the charge long enough across the capacitor to quickly keep the load discharging for rectification use. Furthermore, this does not produce a stable stepped down AC signal and is no longer a possibility for converter design.



3.2.1.2 Figure 1: Switching Voltage Regulator with and Alternating Current Input



3.2.1.2 Figure 2: Output of Switching Voltage Regulator with Alternating Current Input. Output shows unstable AC signal with no rectification.

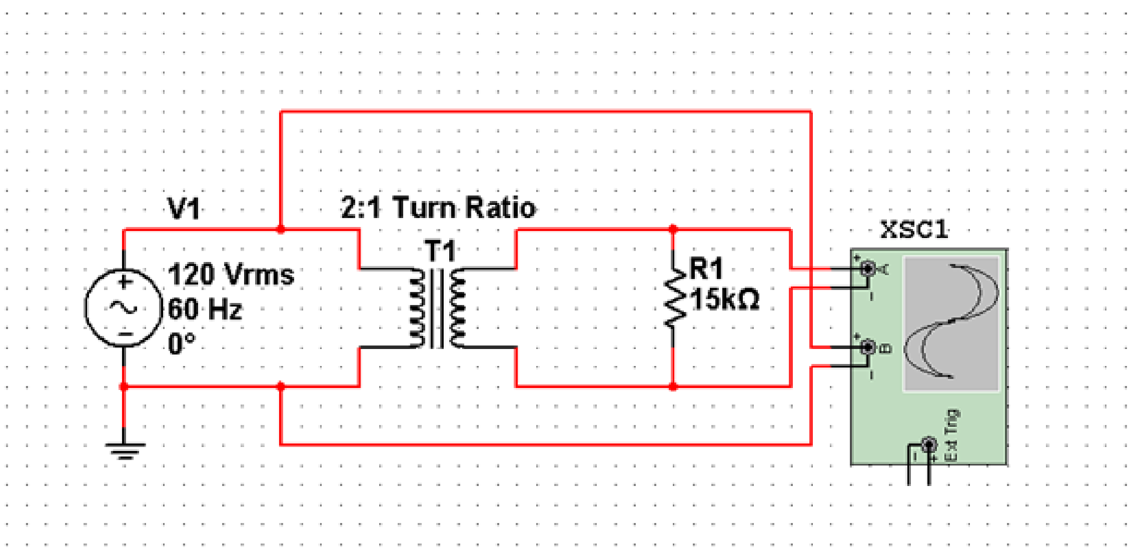
3.2.1.3 Step Transformers

Step up and step down transformers are a completely different spin on voltage regulation. The transformer's output in AC is a ratio of the number of turns on the primary voltage side to the number of turns on the secondary voltage side. The equation below shows this relation,

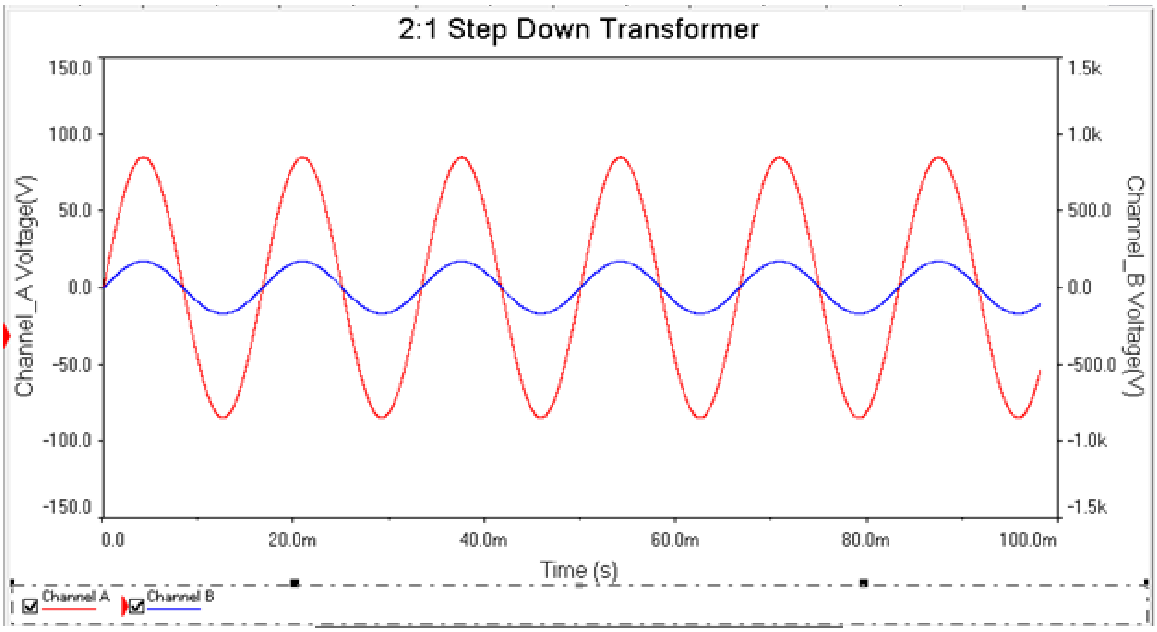
$$\frac{Voltage_{Secondary}}{Voltage_{Primary}} = \frac{Number\ of\ Turns_{Secondary}}{Number\ of\ Turns_{Primary}}$$

which is derived from Faraday's Law. The ideal transformer doesn't allow any energy to be wasted. One important note to keep in mind when dealing with a transformer is that since there is no significant change in resistance, then by Ohm's Law, the current much change to keep the law consistent. This is not only true but also very applicable to our project application. Not only will we be able to regulate the voltage down to our feasible work means, but we are also boosting the current when the voltage drop occurs. In this type of design, it can play a big role in how our capacitive array will function in terms of charging time and efficiency.

3.2.1.3 Figures 1 and 2 below show a perfect example of the step down required with stability.



3.2.1.3 Figure 1: Step down Transformer with a Two to One Turn Ratio. Expected Output Voltage to be Half the Input.



Time	Channel_A	Channel_B
12.419 ms	-84.808 V	-169.626 V
4.104 ms	84.825 V	169.658 V
-8.315 ms	169.633 V	339.284 V

3.2.1.3 Figure 2: The 2:1 Step Down Transformer Output Displaying Proper Step Down with Stability (Channel A: Input Voltage =120Vrms Channel B: 59.98 Vrms)

3.2.2 Rectifiers

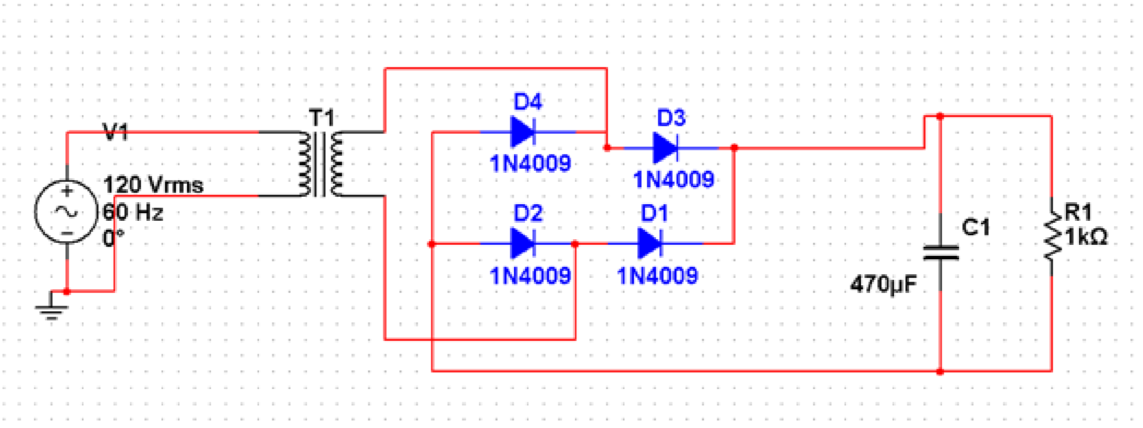
In any AC to DC converter there is in some way, shape, or form the rectification of an alternating current signal into a direct current power source by means of rectification. By rectification we can establish the DC power signal necessary to power our whole design. The process of rectification is a simple task but can become more complex depending on the following factors:

· How much power dissipation the designer does and does not want amongst different components
· Which components the designer would like to use in addition to or in replace of others
· If the designer wishes to eliminate some noise or reduce the noise to an absolute minimum
· And how much Voltage and current is needed for further component specification and requirements.

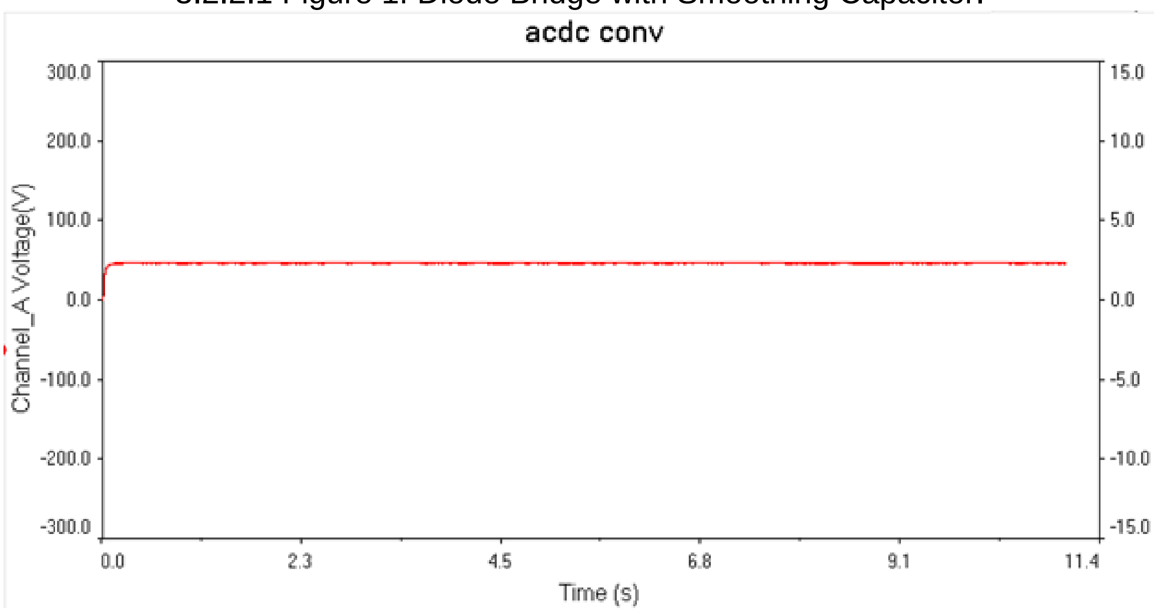
3.2.2.1 Diodes

Diodes are the most common way for rectifying any alternating current signal. The 1N4000 series, very commonly used P-N junction diodes, work excellent for half wave and full wave rectification, and AC to DC conversions. The forward voltage drop on these diodes range from 0.65V to 1 V and have a DC blocking potential of up to 1000V. Needless to say the AC to DC converter design will not need such extreme blocking, but its principle use is its contribution.

3.2.2.1 Figures 1 and 2 show an example using 1N4000 series diodes at high current of 3 Amps and output respectively.



3.2.2.1 Figure 1: Diode Bridge with Smoothing Capacitor.



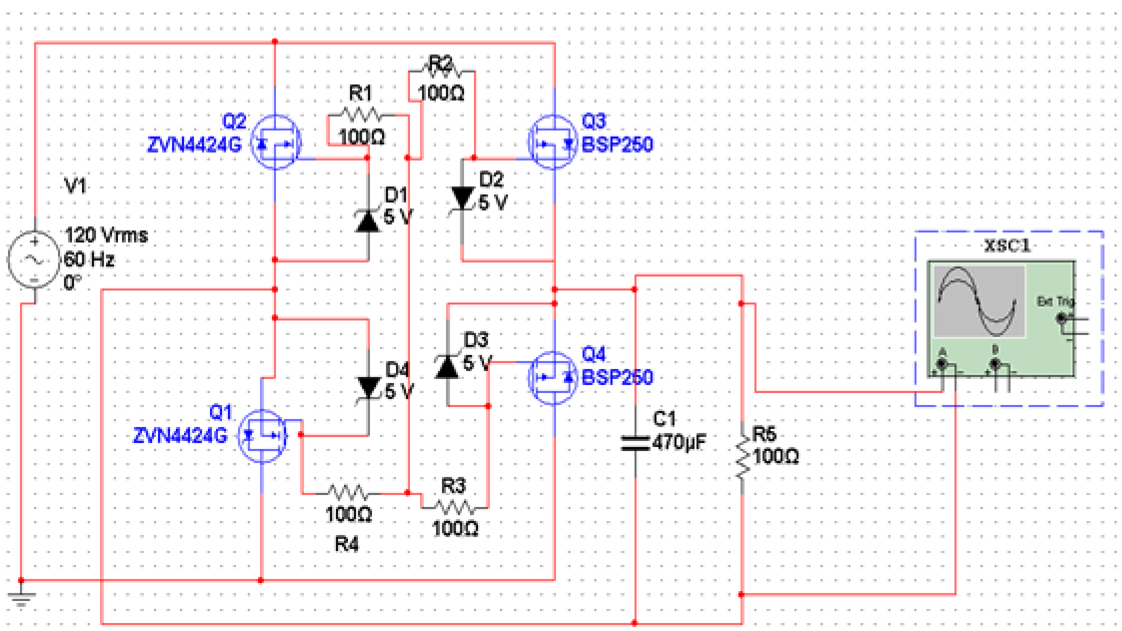
3.2.2.1 Figure 2 Output of The AC/DC diode Bridge with a clean DC signal.

3.2.2.2 Power Diodes

Power diodes were another consideration when we made our rectification choice. These diodes are capable of withstanding very high currents with an ultra-small reverse recovery time. In comparison with the regular diodes, the power diodes were not as cost effective but in case power dissipation became an issue in the design we were prepared to implement them. Another tradeoff was to consider the loss of current when in deciding to use resistors to dissipate excess heat and/or a heat sink. Power diodes are known for their ability to withstand currents ranging from 1A to more than 40-50A. All of the components after the AC/DC power supply are estimated to pull anywhere from 2.5 to 3 amps of current. These Power diodes are definitely components that we considered in our design.

3.2.2.3 MOSFETS

MOSFETs are another interesting option to use for rectification. This will involve a little more complexity but the results are worth working for. In addition to a MOSFET being a simple switch, the also have extremely low Active Forward Mode resistances down to the tenths of Ohms. The rectification process can be done using an H-Bridge using two P-Channel and two N-Channel MOSFETS of the designers choice.



3.2.2.2 Figure 1 Power MOSFET Bridge Consisting of Two N Channel and Two P Channel Power MOSFETS

3.2.2.3

3.2.2.4 Power MOSFET

The Power MOSFET is widely used in converters, supplies and even different types of controllers due to their high voltage rating switching capabilities. The have a very low forward threshold voltage making switching between forward active and cut off a very simple thing to do. The switching frequency of the Power MOSFET can be approximated by its input impedance, which it generally low in the milliohms to the tens of Ohms, and the input capacitance which can be found in the specific datasheet of the component. This RC relation can also approximate if not give the upper operating frequency limit in which gives insight into to the Power MOSFET's frequency response. The frequency response would play an important role in our power supply design if we decide that using MOSFETs in the rectification process is the best implementation due to the capacitive properties of the MOSFETs relative to the following:

- Overall size of the Power MOSFET
- The material used in the MOSFET gate separation. Depending on whether the material is a poly-silicon gate or more of a pure metal oxide will affect the overall input impedance slightly adjusting the switching time and upper limit on operating frequency range.
- The distance between the Drain and the Source and how this distance relates to the capacitive value
- The orientation of the MOSFET, e.g. using a Vertical DMOS Power FET versus using standard P or N Channel MOSFET of a certain size. (This also is a contribution to the previous point above about the capacitance relative to the distance between the Drain and the Source.)

3.2.3 Resistors

In many of the considered designs, resistors play a significant role in many ways, and even though simulations may not take what material the resistors are into account our project will. The ideology behind using different types of resistors are:

- The material used in the resistor may not be able to withstand the power demands of the supplies in terms of voltage, current and power requirements.
- The actual impedance of the resistor must be high enough to eliminate noise enough for a clear signal but not to overkill the design by dissipating too much heat or taking too much voltage that is required for the remaining circuitry.
- Beyond the specifications of the power supplies, many voltage division must be made such as comparator designs will function according to the project requirements

3.2.3.1 Power Resistors

The power resistor will be a very important contribution in meeting the specifications and requirements of the power supplies involved in our project. Power resistors will enable the power supply to safely dissipate heat and withstand the current requirements. Most of the metal oxide films and ceramic resistors commonly used today are rated at only a 0.25-0.5 Watts of power. This means that, for example if we wanted to have a resistive element with impedance of 2000 Ohms, then this means we can only pass a current of 0.25 milliamps. This is wattage doesn’t even scratch the cusp of the necessary wattage needed to power the rest if this happen to be the load impedance of the supply voltage. At a current of 3 Amps, this 2000 Ohms ceramic or metal oxide resistor will inevitable catch on fire, damaging other integrated circuits and possibly harming an individual.

This problem is solved by using low impedance, high power resistors that will by far be able to stand up to the requirements of our project.

3.2.3.2 Capacitors

Capacitors have many uses in the power supply design of our project. The major role that they played in our project was the following:

· Filtering out any noise from the final DC power signal output
· The “smoothing’ technique referenced in the diode bridge. The capacitor will charge and discharge in the positive and negative half cycles, respectively, of the sinusoidal input to remain a constant voltage across the load at the output.
· The size of the capacitance relative to the frequency to maintain constant voltage drop across the output load.

3.3 RF Power Signal

In order to wirelessly transmit power from the transmission coil to the receiver coil via magnetically coupled resonators, we must drive the coils with a very high frequency. According to papers detailing previous work on magnetically coupled wireless power transfer, this range is generally within 1MHz to 10MHz. The efficiency of the wireless power transfer is dependent upon the resonance of the transmission and resonator coils, the distance between them, and the frequency of the signal powering the system. Although we could derive the optimum frequency to drive the coils and then base the signal generating stage to generate a signal of that frequency, it would be much more flexible and easier to “tune” if we develop a signal generating stage that could generate a wide range of signals as efficiently as possible.

Upon researching the generation of high frequency power signals, which is a popular topic in RF transmission, it has been determined that the best course of action is to generate a low power, high frequency signal, and then amplify that signal to the required current levels in order to generate enough flux between the transmission and receive resonators.

General Objectives:

- Develop a stand-alone oscillator, that is easy to adjust and that can generate a wide range of frequencies from at least 1MHz to 10MHz
- Develop an efficient amplifier that can drive the oscillator signal up to sufficient current levels in order to produce enough flux in the transmission coil to induce the magnetic resonance in the receiver coil to efficiently transmit power to the RC car.

The following sections detail the various methods to generate high frequency signals and their corresponding advantages and disadvantages and then how to efficiently amplify those signals to our desired power ranges.

3.3.1 Oscillators

In the following sections, we will be discussing the various methods of generating a high frequency signal at least in the range of 1 MHz to 10 MHz; further consideration will be taken to generate signals up to 2 0MHz just for the flexibility and to help alleviate the inadvertent troubles that develop from taking designs from paper to prototype, that is, have some wiggle room for the inevitable losses that will be incurred when we developed the physical prototype. We will be focusing on stability, efficiency, complexity of design, requirements, feasibility of implementation and tuning, and the strength of the output signal.

3.3.1.1 Crystal Oscillators

A Crystal Oscillator Circuit utilizes the mechanical resonance effects of certain piezoelectric materials to create an electrical signal with a very precise frequency. A crystal oscillator can be modeled as an electric RLC circuit, such as in figure 3.3.1.1-1:

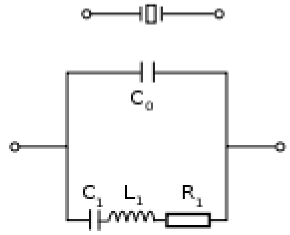


Figure 3.3.1.1-1 Equivalent Crystal Oscillator Circuit (Permission: Wikipedia)

Crystal Oscillators can be used to within circuits as a high Q RLD tank to generate a signal in various circuits such as the Pierce Oscillator in figure 3.3.1.1-2:

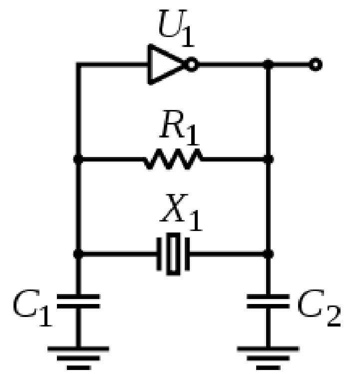


Figure 3.3.1.1-2 Pierce Oscillator (Permission: Wikipedia)

We can also use a crystal oscillator in the positive feedback of an op-amp to drive it to oscillation in resonance with the crystal device.

The advantages of using crystal oscillators is that they have a very high Q-factor, in the order of 4 to 6 orders of magnitude, compared to generally 2 orders of magnitude for LC oscillators. This is desirable for a very precise, stable signal, but greatly hinders the range in which crystal oscillators can operate over. Crystals are also very resilient to changes in temperature.

For our project, we wanted to be able to design the signal generator to operate over a wide range of frequencies because it is much easier to adjust such a signal generator than to remanufacture the transmitter and receiver plates. Since we cannot completely pre-determine the resonant frequency of the plates, a wide band signal generator would allow us to tune to the actual physical resonant frequency of the plates. For this reason, crystal oscillators wasn't a very good option because they have such a limited range of frequencies of which can be adjusted without completely redesigning the circuit with a different crystal.

3.3.1.2 Oscillator Circuits

LC oscillator circuits are similar to the crystal oscillators in that they use a tuned circuit to resonate at a particular frequency, but as opposed to a piezoelectric material fulfilling the tuned circuit duties, an LC "tank circuit" is used to drive the circuit into resonance. These are very well studied and quite easy to design. Some common LC oscillator circuits are the Hartley oscillator shown in figure 3.3.1.2-1.

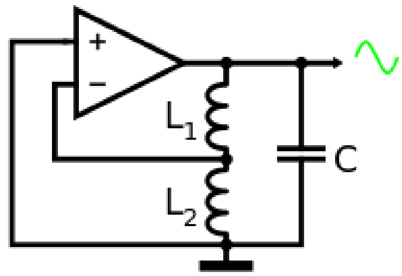


Figure 3.3.1.2-1 Hartley Oscillator (Permission: Wikipedia)

Another popular possible oscillator circuit that would fulfill our oscillator needs is the Colpitts oscillator depicted in figure 3.3.1.2-2.

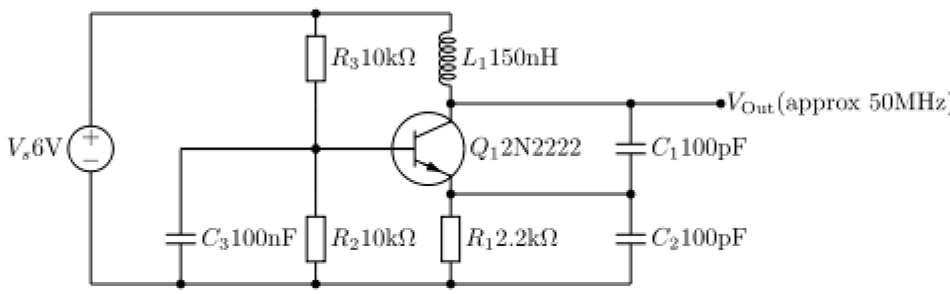


Figure 3.3.1.2-2 Colpitts Oscillator (Permission: Wikipedia)

One last oscillator researched was the Clapp oscillator, which is a rather simple and robust design and is depicted in figure 3.3.1.2-3.

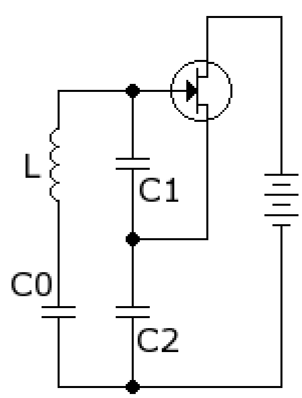


Figure 3.3.1.2-3 Clapp Oscillator (Permission: Wikipedia)

Although LC oscillators have a much lower Q-factor and are more subjective to fluctuations in temperature when compared to crystal oscillators, they make up for this in their simplicity, easibility in tuning, and their wide range of possible frequencies with just the use of a variable capacitor. This makes this option especially attractive to our project because a change in the oscillation frequency would just require changing a capacitor.

One thing to be careful of with these circuits is to make sure that the active devices in them are capable of handling our high frequency needs. Many op-amps, BJTs, and MOSFETs cannot handle being driven at such high speeds, and therefore special care and consideration needs to be taken into choosing such a device if we choose to use an LC oscillator for our initial signal generation before the power stage.

3.3.1.3 Voltage-Controlled Oscillators

Voltage-Controlled Oscillators, or VCOs, are common off the shelf oscillator devices that do a great job of generating a wide range of frequencies based upon a voltage applied to the circuit. They are generally used for generating signals for various communication transmission schemes such as frequency, and phase modulation, but can be easily adopted to generate the frequencies required for our project. There are both VCOs which utilize op-amps, as well as crystal oscillators, which both have their strengths and weaknesses similar to the oscillators discussed in 3.3.1.1, and 3.3.1.2.

Crystal VCOs have very high Q-factors, and such are very stable and accurate, but lack a wide range of producible frequencies, although it is possible to generate more signals from the division of such frequencies, this over complicates our design for our project and still lacks and fine tuning ability between the divided frequencies.

Op-amp based VCOs are inherently less stable and precise, but the range of producible signals is much greater. This made this a more attractive option for our project compared to the crystal-based voltage controlled oscillator because it's more important for us to generate a greater range of frequencies than having an extremely stable signal; the stability of these op-amp based VCOs is plenty for our project.

One thing to consider when determining to use a voltage controlled oscillator is how we would control it. We could use a rotary potentiometer, an analog output from a microcontroller, or a digital signal from a microcontroller to a digital to analog converter to the VCO.

3.3.1.4 Programmable Oscillators

Programmable Oscillators are great little integrated circuits similar to VCOs in that they are able to produce a wide range of frequencies without changing components, but they are programmable in the sense that a serial input can control the output frequency. They are generally used to generate clock signals for processors and other digital circuits.

The frequency they produce can be adjusted via a serial input from a microcontroller, which greatly simplifies the process of controlling a voltage controlled oscillator from a microcontroller. Since we will be having a microcontroller in our designs to measure various currents, powers, and efficiencies throughout our design, it wouldn't be difficult to have it adjust a programmable oscillator to drive the wireless power transmission via some onboard interface.

Something to consider with programmable oscillators is that they generally produce square waves at their output. That means if we are to use certain amplifier designs which are best driven via a sinusoidal input, we must have a low pass filter after the programmable oscillator in order to convert the square wave to a sinusoidal wave. Certain amplifier designs however, are actually driven quite well from a square wave, and therefore makes the programmable oscillator even more attractive if one of those designs is determined best suited for our project.

3.3.2 RF Amplifier

Driving high frequency signals to the range of 20 to 30 watts requires a unique set of solutions compared to lower frequency signals such as audio. From section 3.3.1, we have a selection of signal generation methods which all provide small power outputs in the range of microwatts to a milliwatt. These signals are not strong enough to drive RF power MOSFETS into saturation, or even into linear mode; therefore, we had to consider designing and implementing a driver amplifier or pre-amplifier to drive the small signal into levels usable to drive the large RF power MOSFETS used in the power amplifier stages. We will be discussing Class A, C, D, and E amplifier designs because these designs are the most common when dealing with RF frequencies. Then we will discuss what we determined the best course of action for the amplification of the signal to our desired power levels.

3.3.2.1 Class A Amplifier

Class A amplifiers are designed to be driven entirely in the linear mode of the transistor. This is achieved by applying a biasing voltage to the base-emitter for BJT or gate-source junction for a MOSFET. This provides a very clean, highly linear, and undistorted amplified signal at the collector. The general topology of the class A amplifier can be found in figure 3.3.2.1-1

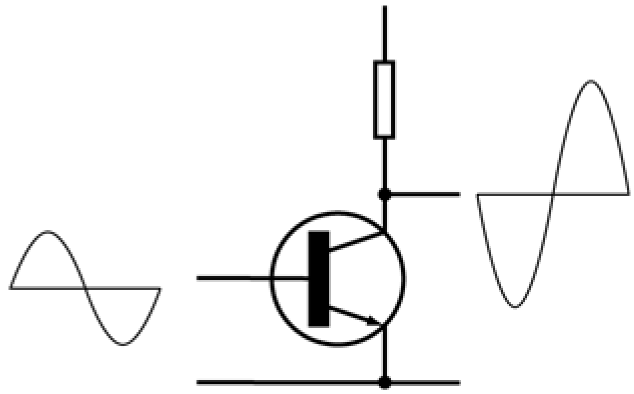


Figure 3.3.2.1-1 Class A Amplifier (Permission: Wikipedia)

The problem concerning this type of amplifier is that it's extremely inefficient, to the extent of well below 50% efficiency. Aside from the large power loss due to this design, it would also dissipate huge amounts of heat and need a method of cooling the active device. All things considered, a class A amplifier would be a poor choice for the main power amplification stage of our RF power amplifier, but it could be a great choice for an earlier driver stage due to its linear operation, the fact that you don't want to cause too much distortion early in the amplification of the RF signal, and the power and heat dissipation would be negligible due to the very small signal being amplified in the early stage.

3.3.2.2 Class C Amplifier

Class C amplifier design is a tuned amplifier in which conducts during a small portion of the signal. In a class C design, the active element only conducts during a small portion of the input signal, and therefore the period of time that current is flowing and there is a voltage drop across the base-emitter or source-drain is minimized; this minimizes the power dissipated by the transistor. Theoretical efficiencies can be up to 100%, but real devices cannot pass infinite current over an infinitesimally small time, so realistic efficiencies are around 75%.

In order to keep the signal going during the off-portion of the device, class C amplifiers generally have a tuned output circuit to resonate with the desired frequency. Due to the tuned nature of the design, it is not applicable to wideband applications, and has to be tuned to the particular frequency desired to be transmitted. This is not an issue if we have a chosen operating frequency for the magnetic resonance, but can be an issue if we want to vary the frequency significantly. The tuned nature of the design also allows the transistor to only have to conduct for a small portion of the signal, and therefore increases the efficiency dramatically. The general topology for the class C amplifier, excluding the output LC tank circuit is shown in figure 3.3.2.2-1.

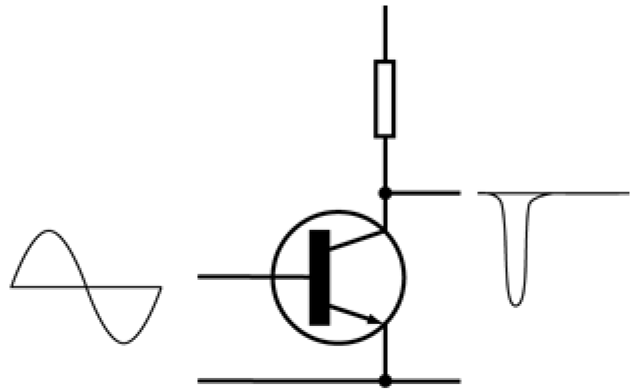


Figure 3.3.2.2-1 Class C Amplifier (Permission: Wikipedia)

3.3.2.3 Class D Amplifier

Class D amplifiers are a high efficiency design which utilizes MOSFETs as switches to output pulses of power in relation to the input signal of the amplifier. Class D designs are generally more complicated than the previously discussed amplifier designs; minimally, they must have 2 MOSFETs and a method to invert the input signal for one of the MOSFETs. This is needed because the design of the class D amplifier is such that the MOSFETs are driven one at a time to allow current to flow from the power supply or to the ground. The unadulterated input signal drives the MOSFET connected to the power supply, this will give the top half of a square wave of the frequency of the input signal, and the inverted signal is used to drive MOSFET connected to the ground, which will give the bottom half of the square wave output. The general topology of a class D amplifier is shown in figure 3.8.

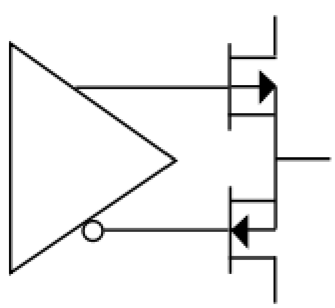


Figure 3.3.2.3-1 Class D Amplifier (Permission: Wikipedia)

Class D amplifier designs have a few key considerations to take when determining their viability for our design, the highly non-linear design and the switching frequency. Class D amplifiers highly distort the input signal by generating a square wave regardless of the input signal, as ideally the MOSFETs will be completely on or off in a class D design. This is not so much a concern for us because we didn't need a highly accurate signal to get the transmitter and receiver coil to resonate. The switching frequency of the class D amplifier might of been a concern though. Non-ideal MOSFETs aren’t able to switch from ‘on’ to ‘off’ instantaneously, and therefore have a switching time, and to operate at frequencies as high as 20 Mhz, that switching time would have to be very small. There are high power RF MOSFETs out there that can handle switching at these speeds, but then you have to consider power consumption to switch the MOSFETs. Non-ideal MOSFETs consume very little power to switch from ‘on’ to ‘off’ and vice versa, but when you have to switch them millions of times a second, that power begins to add up and eat into your efficiency. These are all things that we took into account when deciding to use a class D amplifier or not.

3.3.2.4 Class E Amplifier

Class E amplifier designs are essentially a beautiful mix of both the class C amplifier topology and the class D amplifier topology. Much like the class C amplifier design, it utilizes a tuned output LC tank to allow the transistor to be driven during less of the input signal and still generate a full signal. It is similar to the class D amplifier design in that it uses a MOSFET as a switch to turn fully ‘on’ and ‘off’. Like the class D, the theoretical maximum efficiency is 100%, but alas, MOSFETS do not turn instantly ‘on’ and ‘off’, and also take a small gate current to drive the MOSFET ‘on’ or ‘off’. Like the class D amplifier design, this is where the majority of the inefficiency of the class E amplifier comes from. The general form of this design is shown in figure 3.3.2.4-1.

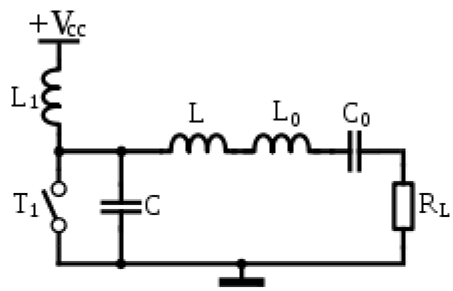


Figure 3.3.2.4-1 Class E Amplifier Topology (Permission: Wikipedia)

The key merger of the class C and class D amplifiers into the class E is how the class E requires only one MOSFET as opposed to the two from the class D, and uses the LC output tank circuit from the class C amplifier to maintain the output signal as that single transistor is not conducting.

It is surprisingly easy to operate the class E amplifier among a wide range of frequencies, which is important for our design considerations. The output LC tank circuit can be designed to have a wide bandwidth with its resonant frequency centered at a frequency relevant to our designs, such as 10 MHz.

The two key considerations to the class E amplifier topology to our project is the selection of the MOSFET and the design of the output LC tank circuit. The MOSFET must be able to run in high frequencies up to 20 MHz as well as supply a large amount of current, up to 5 amps. The output LC tank circuit must be designed to have a very wide bandwidth, and therefore a low Q value, as well has have a high resonant frequency of around 10 MHz.

3.3.3 Gate Driver

Amidst researching how to generate a sufficient high frequency, high power signal for our wireless power transmission project, I continued to have trouble determining how to develop sufficient currents from the oscillator circuits and devices in order to drive the large power MOSFETs required in the amplifier designs to generate the power necessary for our demonstrations fast enough. I was thinking of all kinds of ways to step up the current from the oscillator via smaller class A amplifiers and such, but this all added so much to the complexity of the design, the number of components required, and areas for a failure or fault to find its way into our design. I've always believed in the simpler is better mentality, for the most part, and this was beginning to feel far too complicated; that is, until I stumbled upon this magical little device called a gate driver, and it pains me that I stretched my brain so much trying to come up with what this simple little $1 integrated circuit can do so efficiently.

A gate driver does simply what its name describes. It's an integrated circuit which is specifically designed to take a small current, high frequency signal, generally from some sort of clock source, like the programmable oscillator discussed in section 3.3.1.4, and step up its current and voltage to sufficient levels to drive large power MOSFETs into saturation and into cut-off rapidly.

3.3.4 Conclusion

From starting off with the basic goal to generate a 10 MHz signal to power our transmission coil enough to transmit sufficient power to our receiver coil, I have come a long way in understanding how such a signal can be produced. This section will outline what I determined to be the best solutions for generating the high frequency signal, how to amplify that signal, and how to drive the power transistors from the oscillator.

After researching various high frequency oscillator schemes with the goals of simplicity, easiness of adjustability, range of producible frequencies, and with our project in mind, I determined that the voltage controlled oscillator best suits the needs of our project.

Much research, thought, and consideration went into choosing which amplifier topology best suited our project, and with the goals of simplicity, wide-band, high frequency, and high efficiency in mind, I determined that the class E amplifier design was the best option for our project. Amongst researching other teams and researchers that have successfully implemented magnetic resonance wireless power transfer technology, I noticed that the majority of them utilized the class E amplifier in their designs. I determined that this was because of the high efficiencies class E amplifiers can achieve as well as their simplicity in design and widespread use in RF communications. Class E amplifiers can be designed in such to effectively amplify a wide range of high frequencies such as 1 MHz to 20 MHz, which is perfect for our project. It is also easy to achieve efficiencies over 70%, which is beneficial to our environmental focus as well as to the overall design of the power signal generation stage because with lower efficiencies, more power is wasted as heat, which brings another set of considerations such as heat dissipation.

After much headache and frustration, I was immensely relieved to have found the gate driver IC and I used this in our designs to drive the power MOSFET in the class E amplifier. Using a gate driver is immensely simpler and more efficient than designing a multi stage pre-amp to gradually step up the current, and is therefore the easy choice for our project.

3.4 Magnetic Resonance Coupling

This project all plays into near-field technology, which is the grouping of any form of WPT within a relatively short distance, considered to be under 10 meters. Other ranges include midfield and farfield, but neither one of those two have any noticeable practical implementations yet, at least not in a direct sense.

Some modern implementations of farfield technology allow for the “theft” of radio signals and other electromagnetic waves to power a device by scavenging their energy, but that is not part of this design and therefore not something we will discuss in this report. Two practical designs of wireless power transfer are Magnetic Resonance Coupling and Wireless Capacitive Coupling.

Wireless Capacitive Coupling is basically making a really big capacitor, where a transmitter holds the positive plate and the receiver holds the negative plate, and air acts as the separation between the two plates. Effectively the air gap in the capacitor is the distance over which you want to transfer power. However, this system is grossly inefficient for anything with any noticeable separation. Even though our design will experience only minor separation (about 1.5 to 2 inches), even this is too much for how large we could make the capacitor plates.

We would need large plates and a large amount of power for this design to even work, let alone work well. Furthermore, even if we did get the coupling to occur as a capacitor, the large separation would mean an astronomically small capacitance, which would mean enormous impedance would be seen by the circuit. Instead, we used Magnetic Resonance Coupling to implement wireless power transfer.

Magnetic Resonance Coupling is an electrical system of two or more large (size-wise) inductors connected to their own RLC networks that share the same resonant frequency. One of the two acts as the transmitter, and one acts as the receiver. When a high-power RF signal is passed through the transmitter, the circuit behaves like a transformer which carries the electrical signal to the receiving end. The key difference obviously being that there is no ferrite core linking the two coils.

This design type is not without its problems. One of the biggest problems with this system is the loss over distance. This was counteracted through a few measures. First, the inductors we made have diameters of roughly 3-4 times the distance of separation. The RC car only clears the ground by roughly 1.5 inches, and the thickness of the inductors makes this even shorter, so we made inductors roughly 4 inches in diameter. By making them the same diameter and total number of turns, we achieved a resonant frequency of 3.2 MHz.

We had the option of making these inductors from either wirewound design (using 18 AWG wire) or from etched teflon substrates made from RO4003 board. We opted for the former due mainly to the ease of construction and variability, but also found the affordability and disposability of these inductors to be useful as well. RO4003 board isn't cheap, and it would cost roughly 10 times as much to implement these inductors, not factoring in equipment necessary to produce these inductors or the time spent calculating their dimensions.

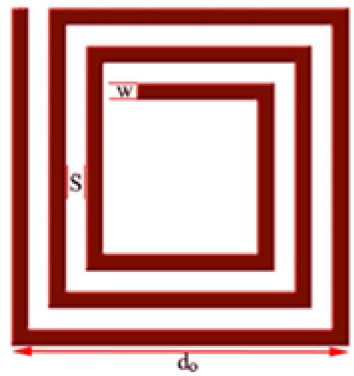
Even dimensions such as spacing and thickness play a major role in the performance of these etched inductors. The thickness and spacing of each of the lengths of wiring that will make up the inductors should be relatively large compared to its radius. If this spacing is too small, the inductors do not link together properly, and thus lose a large degree of their efficiency.

Below is a table demonstrating matched coils with certain wire diameters and spaces, and their strength through lossy mediums such as tissue. This was originally used in a study to show the application of Resonant Magnetic Coupling for biomedical purposes, thus the testing through tissue. As clearly demonstrated with all other things being equal, inductors that have a proportionally larger spacing and thickness in our project will help to overcome loss.

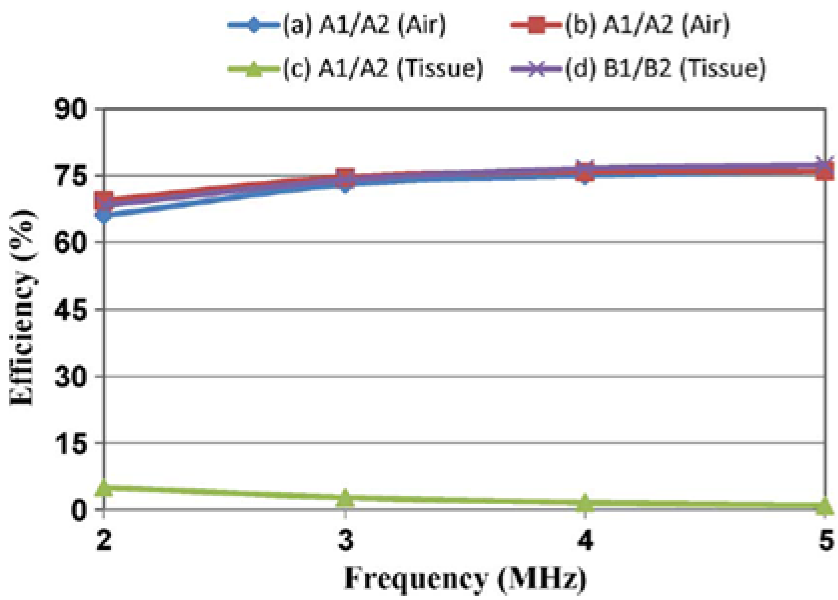
TABLE I
COIL GEOMETRY FOR [11] AND OPTIMIZED COILS

	Coil A1	Coil A2	Coil B1	Coil B2
Number of turns (N)	17	20	1.4	1.5
Outer diameter [d_o](mm)	40	20	40	20
Trace width [w] (μm)	750	150	4700	3200
Trace spacing [s] (μm)	250	150	3600	1500
Media 1	10mm Air			
Media 2	Skin (1mm), Fat (2mm), Muscle (7mm)			
Substrate	1-oz FR4 (ϵ_r = 4.4, thickness 1.5mm)			
Skin	ϵ_r = 580, σ = 0.111 S/m			
Fat	ϵ_r = 38.72, σ = 0.0475 S/m			
Muscle	ϵ_r = 308, σ = 0.586 S/m			
Frequency	5 MHz			
Re{Load}	500Ω			

(1)



(2)



(3)

Figure 3.4.1 – (1) Table demonstrating the effect of space/thickness in the inductor segments (2) Variables as shown in a square planar inductor and (3) Efficiency of various inductor pairs in various mediums. Information provided by Dr. Meysam Zargham and Dr. P. Glenn Gulak in “Maximum Achievable Efficiency in Near-Field Coupled WPT System”, presented by IEEE in *IEEE Transactions on Biomedical Circuits and Systems Vol. 6 No. 3* (Permission Pending)

Another major problem with this system, regardless of inductor type is its directionality and alignment. This design is extremely sensitive to any change in angle between the two planes and any misalignment between the two coils, though the system is much more sensitive to the latter. Because of this, we don’t have any current practical way of indefinite charging through constant connection, but we were able to implement a charging period that is quick and easily accessible. The car can simply be placed or driven over the top of the charging panel, and it will begin a stable charging process. We were able to firmly demonstrate this in our design.

In scaling this up to the concept with an electric car, there is also the possibility of putting a large number of these inductors in parallel underneath a road, so an electric car could be wirelessly charging while it's driving. A model of this concept is shown on the next page. This could, in essence, be the solution to the limited range of electric cars, who must charge for relatively long periods of time before they are ready to drive again. In terms of an RC car, especially one for our purposes and with our limited budget, this is neither practical nor feasible unless the RC car had a pre-determined path. Such a system is in development by interested parties, but has a while to go before it can successfully be implemented.

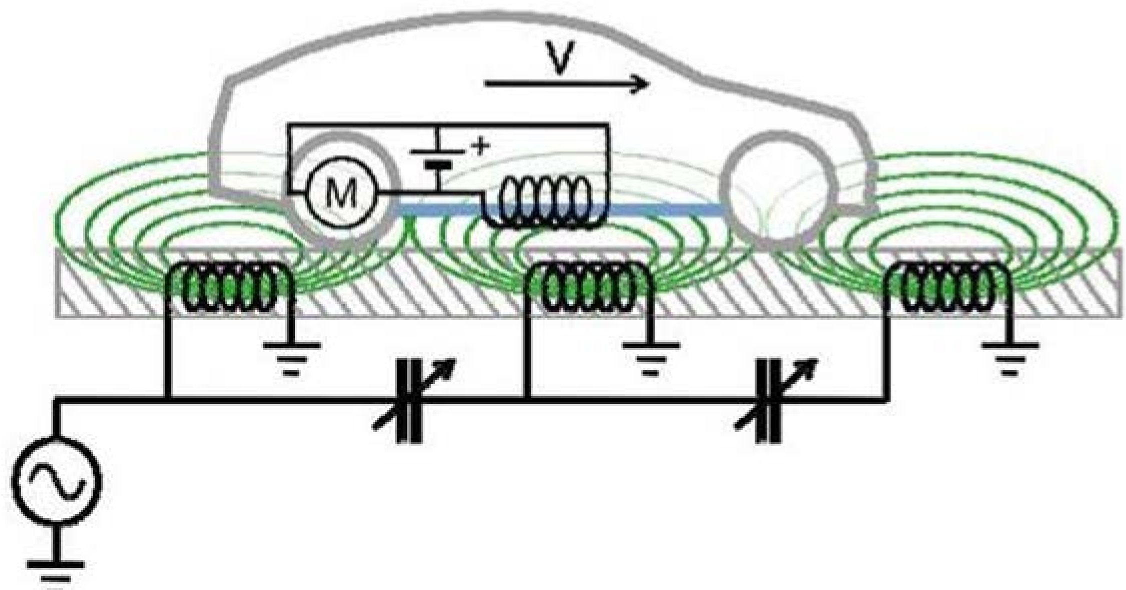


Figure 3.2.2 - Model of car driving over inductive road. Model provided by Charles Murray in "Wireless Power Pitched as Replacement for EV Batteries" on DesignNews.com. Copyright UBM LLC 2013. All rights reserved.

One of the great things about using wirewound inductors as opposed to etched inductors is that exact matching is no longer an issue, since we can easily test and retest performance on inductors that can be remade with ease and low cost. For example, if we had felt a specific frequency was necessary, it would be easy to rewind the coils to achieve a specific value of inductance, or we could change its diameter if we felt the size was a problem. It can also be useful when fine-tuning the MRC network because manufactured capacitors are not precise either, and have predefined values instead of exact ones.

Wirewound inductors also allowed us to easily add more loops as necessary. Etched inductors can only have 4-5 turns before the inductance added from each successive loop experiences large diminishing returns. This is because the loops cannot be etched on top of each other since they are fabricated on a single layer of RO4003 board. However, wirewound inductors can theoretically (obviously not practically) be looped an infinite number of times within a single coil without sacrificing diameter with each successive loop.

We chose circular inductors because it was easiest to wind them around cylindrical objects. Other shapes were also an option, and don't necessarily offer and benefits or disadvantages: they are just different. For example, had we picked a square or even rectangular shape, we would have most likely seen a drop in the inductance value. Again, this is neither advantageous nor disadvantageous; it's just a different value and these coils would have a different self-resonant frequency.

Had we gone with etched inductors, they would have been square in shape. First, lithography machines will find it easier to properly construct a square/rectangular shape than anything else, since the shape can be perfectly recreated, regardless of the machine's resolution. Secondly, our simulations showed that square planar inductors had some of the highest inductances for their given surface area, next only to circular. However, for such machines, there would have been pixelated edges that would have taken away from the circularity of the inductors.

We wanted our inductors to be roughly 50-100 uH in value. This would allow us to pick a very small capacitance (~0.1nF) when making a resonator tank network, which would increase the overall Q value of our circuit. With a higher Q value, we saw more overshoot in the receiver, and thus an increase in transmission efficiency. This larger Q value, however, would also mean an increase in coupling coefficient. By increasing this coupling coefficient, we also increase the effect that mutual inductance has on our inherent resonant frequency. This meant that at point blank, the MRC network had a much lower transmission efficiency than when we separated the coils to roughly 1 inch. This is because the mutual inductance changes the resonant frequency. Since our MRC network acts as a passband filter, the 3.2 MHz signal was not being allowed to transmit power to the car. Thus, the highest efficiency actually occurred at roughly the distance of the car's clearance from the ground, which is what we wanted to achieve.

You may already be familiar with technologies which use Magnetic Resonance Coupling. One such example is the Powermat, a wireless charging device. However, this device works at roughly the same power level (less than 10W versus our 5W) and at almost point blank, give or take a few millimeters from the plastic enclosure. This is an example of tuning the network to meet this shifted resonant frequency. While we could very well have shifted our resonant network's resonant frequency, doing so would present no advantages for our design.

3.4.1 2-Coil Network

The methodology used to accomplish this design was the 2-Coil Network configuration. 2-Coil network configuration is a solution to an MRC network configuration which uses only two inductors two transmit power between the transmitting branch and receiving branch. Effectively, this is simply a transformer circuit the the receiver load being the load of the transformer. The key to this type of model, though, is that the transformer will be using a 1:1 turn ratio and has a coupling coefficient equal to the transmission efficiency. Mutual inductance is a very important factor in this design, seeing as the two inductors are within direct proximity of one another.

The advantage of the 2-Coil network was that it is very small in profile and simple in calculation and theory. Because there are only two inductors, there is very little space required, with the largest consumer of space being the distance between the two inductors rather than their actual size. These inductors can also be made planar with an inward winding manner, so they can be made extremely low-profile, although we opted for wirewound inductors.

The disadvantage to this network is that mutual inductance becomes a much larger factor since the inductors are so close to one another. This means we took a lot of caution when selecting components because, for example, even the standard 20% tolerance of manufactured capacitors became an issue. Also, the planar format of inductors has a much higher parasitic capacitance, so this was taken into consideration as well.

3.4.2 4-Coil Network

Another possible solution was the 4-Coil network. The 4-coil network uses two single-loop inductors close to their own resonant inductors, which are not directly connected to anything. This helps to increase the range and stability of the MRC network. However, there were issues with this that proved to be too costly and impractical for our use.

The main advantage with this network is its stability and range. However, we don’t need much range, and the 2-Coil network will be plenty stable for our purposes. This means that any advantage we would gain from using this configuration is null and void and would be a waste for this project. The only useful advantage is that this configuration will eliminate most of the issue with mutual inductance interfering with our resonant frequency, and even this is something we could correct manually.

There are also several large disadvantages to this design that make it extremely problematic for our purposes. First, we would need 4 inductors as opposed to two. Not only would this be more costly for us, it will also mean more calculations, more design time, more fabrication time, and a much larger profile on the bottom of the car. This would go against our design specification, which requires a low profile which is flush with the chassis of the car to avoid interfering with normal operation. Furthermore, the extremely short separation distance would make it nearly impossible to practically implement this design. As a result, we chose a 2-Coil network.

3.5 RF to DC Power

For our RF to DC section, we will need to translate a 3.2 MHz signal into a rectified DC signal. A standard bridge will not work because this is a high frequency signal. Standard high-frequency diodes will not work either, because this is a 30+W signal, most 4148 diodes and the like would not be able to handle the amount of current flowing through them given that they will have roughly 2-3A through them and have a forward voltage of about 0.65. This would translate to over a watt of power burned in the diodes. Since standard 4148 high-speed diodes and similar models can only stand half a watt of power before burning, we searched for a new diode type to perform these functions.

We have found through our research that a bridge model is still the best way to approach rectification of these signals, even though it is such a high frequency signal. A diode bridge would be best in accomplishing this end. However, we cannot use a Wein Bridge model or some other way of eliminating the forward voltage of the diodes from being consumed before the output signal. This is because these kinds of models use an op-amp, and most op-amps can't even operate at 1 MHz, let alone 10 MHz. While this is fine for the original AC-to-DC conversion, it may be a problem at this stage. To counteract this, we'll have to design this stage to have ample power going to ensure that enough power will be transmitted to the car in the capacitor array.

3.6 Capacitor Array

For our design, we've implemented a supercapacitor array in place of the battery pack that comes with the RC car. The main purpose of this is to display in a quick fashion that our wireless power transfer circuit is actually charging the device without a long wait period. Standard battery packs can take hours to charge and our model is no exception. Capacitors, by their very nature, have an extremely low internal resistance, which means they can easily and quickly disperse large amounts of power. However, our final design consumes less power than we had originally intended, thus this advantage means little. I will first explain why supercapacitors were chosen, what advantages they have over the standard battery pack, what considerations needed to be made, and what model we're finally going with, as well as how to maximize its use potential.

In recent years, a new evolution of capacitors, called supercapacitors, have eked their way into the market, boasting a thousand to a billion times the capacitance of standard consumer capacitors. Standard capacitors used in AC to DC conversion, which are still considered large, are usually in the range of between 400 to 1000 microfarads. Supercapacitors can be manufactured with ratings of up to 1000 farads (no, that is not a typo), and ultracapacitors have produced results of over 3000 farads. They are close to gaining the best of both batteries and capacitors: large amounts of energy storage with very quick energy absorption/dispersal. Below is a graph demonstrating energy density vs. power density for common power storage components.

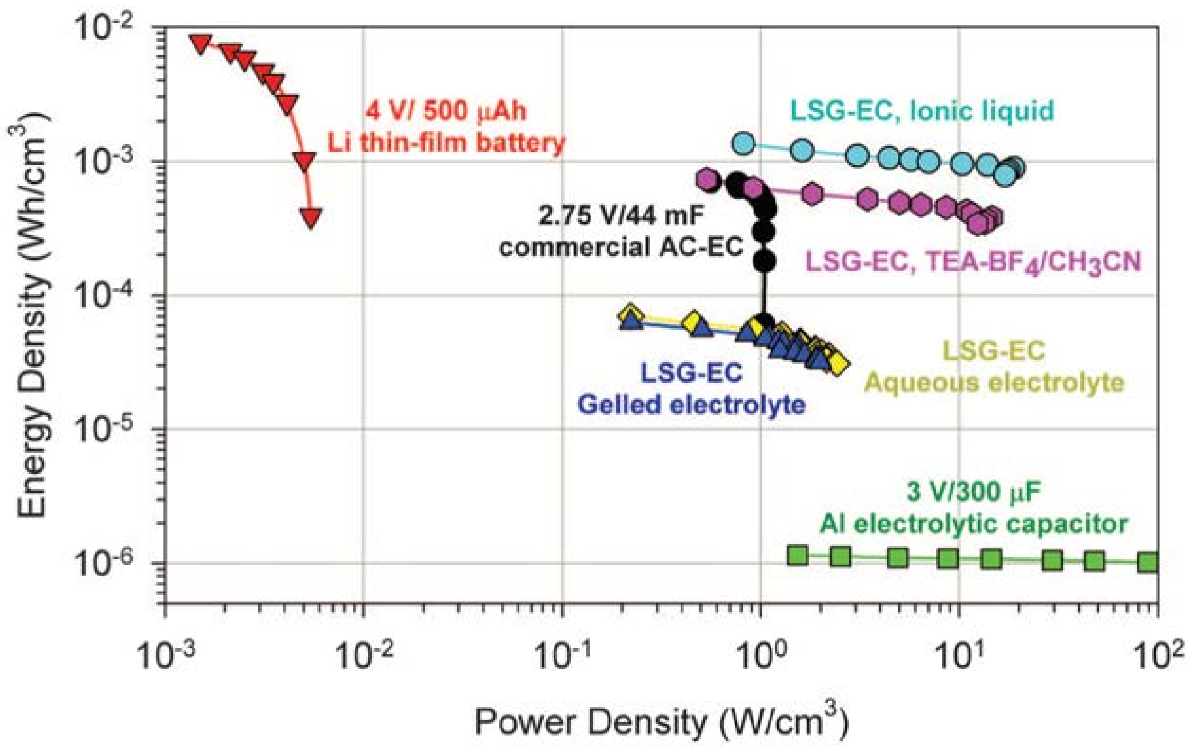


Figure 3.6.1- Energy Density vs. Power Density, Used with permission from Ziff Davis Publishing Holdings Inc. Copyright 2013 All Rights Reserved.

Testing both the charge and run times several times for our default battery yielded an average charge time of 3-5 hours for roughly 30-40 minutes of standard operation time. Standard operation time assumes that there is an average load on the battery, which is to say not too much weight, the terrain is not particularly challenging to the device, and it is not constantly running. Considering the battery is rated at 6V, 700mAh, assuming the battery is able to completely exhaust its charge, our battery contains 4.2 Wh of energy, or roughly 15 kJ of energy. Using a conservative estimate of 30 minutes (1800 seconds) run time, and 15 kJ of energy, the has an average power consumption of 8.4W.

With these specs in mind, we chose a capacitor array that could keep the car functioning for at least 3-4 minutes, if not 5. While not a great amount of time, it's about all that's needed for most users of RC cars, and larger designs can be implemented as needs arise. Upon researching our options, we found a relatively inexpensive yet practical model. We need to design the capacitor array around 2 features: The capacitors must be able to provide enough energy, and they must provide enough voltage. If there isn't enough energy, the car doesn't run for a long period of time. If there isn't enough voltage, the components/motors within the car will not work. We found 350F capacitors rated at 2.7V each made by Maxwell Technologies. Considering the car runs at 6V, we need to have at least that much voltage. Further testing revealed that the car can run at as low as 4.2V, though generally shuts off shortly after 4.4V is reached.

Because of the way capacitors behave, it's better to beat this required run voltage by a fair margin, as the capacitors will lose voltage as their give off current. We decided to go with 3 of these capacitors in series, which will make an equivalent capacitor with a rating of roughly 117F and rated at 8.1V. Specifically, we went with the 350F model because it has a large amount of capacitance, but the 350F model is significantly cheaper than most other supercaps, even those with less capacitance than itself. The 350F model is also going to give us a lot of energy to use without taking up too much space like the ultracap models do. Some of the ultracaps are roughly as large as a 23 ounce aluminum beverage can, and some larger than that still. Putting something so large and weighty on the RC car will greatly increase the load and thus increase the current draw, so the larger size would negate any gains we had in energy storage. The Supercaps are only the size of a D-Cell battery each, so putting a few of them on an RC car isn't an issue. Below is what these supercaps will look like and how large they are.

Figure 3.6.2 - A couple of 350F Supercaps from Maxwell Technologies

Given that the energy stored within a capacitor is calculated as 0.5*C*V^2, this array will contain roughly 4 kJ. Applying a linear extrapolation of the energy value for our 15 kJ battery would make us assume that our car will run for between 7.5 and 10 minutes on just this array. However, because the car requires at least 4.4V to power its components, it will stop working shortly after the capacitor drops below this value, which means that the capacitor array will still have roughly 1 kJ of energy left within it when the car shuts off, and that only 3 kJ of energy will be dispersed to the car.

Applying the same extrapolation, we estimated that the car will only run for 3-4 minutes of constant use, assuming ideal conditions. In actuality, the ran for almost 10 minutes of normal operation, due mainly to the fact that a normal user does not constantly run the car. While we entertained the idea of using two such arrays in parallel to effectively double the operation time, we didn't feel this addition was necessary; the car ran well in testing and demonstrated our wireless charging well. There were no significant behavioral changes, short of a reduced operation time.

In the case that this array doesn’t provide sufficient run time, and to further maximize the potential of the capacitor array, we considered implementing a boost circuit that will allow the capacitors to draw energy at even lower voltages. However, due to the nature of capacitors, we felt this would be too difficult to implement for a feature that isn't even necessary. The goal of our design was wireless power transfer, so increasing the operating time of the car was extraneous. Not to mention we would be increasing the voltage at all times, not just low voltages, meaning the car would burn energy quicker due to the increase in voltage at the high end, thus negating the benefit such a circuit would provide.

We originally chose supercapacitors because they would be able to charge quicker. However, our final design only consumes 5W, and even then our efficiency is 50-60%, thus this benefit of the supercapacitors is negated. To take advantage of this, we would need a much more powerful system to deliver more power to the capacitors. This power would be characterized by the same voltage that the capacitors see in our current design (roughly 15V) with a larger amperage.

Overall, though, they are a much more efficient mechanism with which to power our device. They are able to supply higher amperage, which ensures the car will never experience a drop in performance due to an increase in load, such as when the car turns and accelerates simultaneously. The supercaps are also rated to tolerate 500,000 recharge cycles, which means they have an effective lifespan 1,000 times greater than an average RC battery. All other things being equal, this means the supercapacitors pay for themselves 200 times over seeing as they cost 5 times as much.

One of the other major advantages to supercapacitors or any capacitor for that matter over standard batteries is their charge retention rate. Batteries are notorious for dissipating or entirely losing their charge value if left alone long enough. As a result, it can be problematic for people who have equipment requiring electrical current to operate that is left to sit for a long time. Many times leaving an emergency flashlight in storage for years will render them unusable until the batteries within them are changed out. High-storage capacitors on the other hand, especially super- and ultra capacitors, dissipate their charge extremely slowly when compared to batteries.

They can be manufactured to have high parasitic, sometimes called leakage, resistance which is effectively a resistor in the 100M- to 1G-ohm range. This equivalent resistance is a series resistance the capacitor experiences when it is actually in open circuit, and the higher the value, the better the retention rate. There is also the Equivalent Series Resistance, which we want to be as low as possible to avoid any severe buildup of heat within the capacitor. The ESL we want to have as low as possible as well. Higher inductance will mean that the component is more resistance to step response, something we'll encounter when turning the car on/off and when it begins charging. Ultimately, unless the ESL is some absurdly high value, it shouldn't have a dramatic impact on our capacitor, since the capacitor is going to be used in a DC configuration.

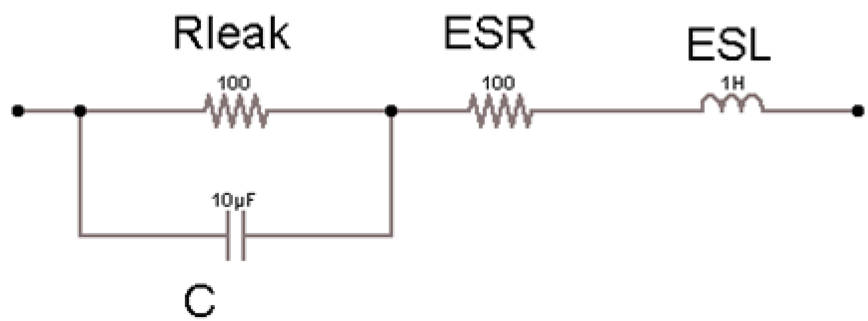


Figure 3.6.3 - Equivalent Model for Standard Capacitors

Our main interest behind this type of project was the hopes of scaling this up to electric vehicles. There, weight and size won't be nearly as much of an issue, and standard automotive capacitors show that the engineering community is on its way to getting capacitors with significantly higher energy density levels. The biggest problem facing electric cars today is their charge times. Standard home outlets require 5+ hours to charge a car enough to let it drive 200+ miles. Reaching this level of performance is still quite a while off, and would require roughly 2.5 mega-farads to match that energy capacity, a difference of almost 1000 times what modern ultracapacitors can store. This number is made even larger when you consider that you would need 5 or more ultracaps in series to match the voltage of a standard car battery, which is 12V, effectively quintupling the required capacitance. Basically, it will be a long time before cars can be run on an ultracap array, but we can see from recent advances in capacitor technology that such a concept may be realized one day.

While not as ideal as never having to charge the car, the supercap array still forgoes the horrendous charge to run time ratio seen by most modern RC cars. As seen by our car, the charge time to run time of most batteries may be higher than 10:1 for more inefficient designs. By implementing our system, we were able to achieve a charge to run ratio of about 5:1. If our system was capable of transmitting more power, we could achieve a better ratio seeing as our only limit to how quickly we charge the capacitors is how much power we can supply them with.

In our design, we were also able to implement a microcontroller to display information to the user regarding the capacitor array's total current charge. Using an Atmega 328p, we were able to display a sequence of 8 LEDs that would indicate 10% power increments, up to 80%. Once the array is charged to 95%, a final warning LED comes on to warn the user to remove the car. Below 10%, the final LED More information on this is discussed in the Data Acquisition and Microcontroller sections.

3.7 Data Acquisition

Information is vital to this project; not only preliminary research information, but information regarding periodic samples taken as the project runs. The data needed will be paramount for testing and operational effectiveness of this project as we determine the component level inputs and outputs, to system level efficiencies. In the following sections, the tools utilized to and reasons for data acquisition are explained.

The different layers of information that will be collected at specific points as testing for each level of the project is conducted serve to aid in determining the important values of this project, namely the efficiency of the inductor coils in the use of the wireless transference of power. To do so, voltage, and inductance values need to be monitored. This data must be gathered in parallel at the junctions that connect each of the vital systems which allow for the system to work as a whole. The vital junctions were those between the 60 Hz AC to DC; DC to 10 MHz AC; inductor resonance coupling efficiency; 10 MHz AC to DC; DC to capacitor bank; and finally to load use.

This portion of the project required a system of organizing and digitizing the information. At the beginning and end of the inductor coils and load of the project major subsystems, there were voltage potential efficiency being taken periodically so to understand the gap required maintaining the right resonance coupling. Information was gathered using a set of sensors at different key positions. (See figure 1. Data collection and power flow)

3.7.1 Programmable Systems Other than a Microcontroller

In order to do this, a system of data collection is necessary. There were two primary methods of which to do this, the use of and FPGA or the use of a specialized microcontroller. The FPGA will be discussed first.

The FPGA holds the benefit of being very flexible in usage, encompassing any potential uses that can be thought of. The FPGA can be purposed to the customized needs of the user through the use of highly complex gate arrays which serve as programmable logic systems. Because of this very principle, an FPGA can be purposed as any multitude of microcontroller architectures or even microprocessor set up as well. It would have been ideal if in an application of industry where a multiuse chip is a viable option for future repurposing to improve hardware efficiency.

A technology that has become available in recent times for cost effective testing purposes is the possibility of using a Digital Signal Processor (DSP). This became an option when Texas Instruments took lead of the industry and made mass producible DSP development boards and chips. Primarily, DSP boards are used for complex mathematical calculations (i.e. fast Fourier transformations, fast Fourier filters, or Laplace transformations) and image processing purposes. This is because the rate at which the DSP processes data at such a pace that information needs to enter and leave quickly. The DSP controller comes with the added benefit of being C-code compatible, making them remarkably easier to program then an FPGA which requires a hardware description language to design a code to form complex functionality. Despite this, digital signal processors are also compatible with the use of hardware description languages with data processing (again primarily for image or high volume information applications).

Like an FPGA, they can be purposed to many different functions and ramp up processing speeds dramatically. This means that sensor data would be accessed quickly and in large volumes. Of the data being able to be observed and processed, a very quick response to system changes as well as extremely accurate observations can be taken from the system with the use of the DSP chip. The necessity for such an up to date sampling is not exactly required for the scope of this project as well as for simple measurements being sampled are our primary input from this project, so it is not considered a primary choice for what the project requires.

The following flowcharts were our initial plan for the microcontroller and data collection.

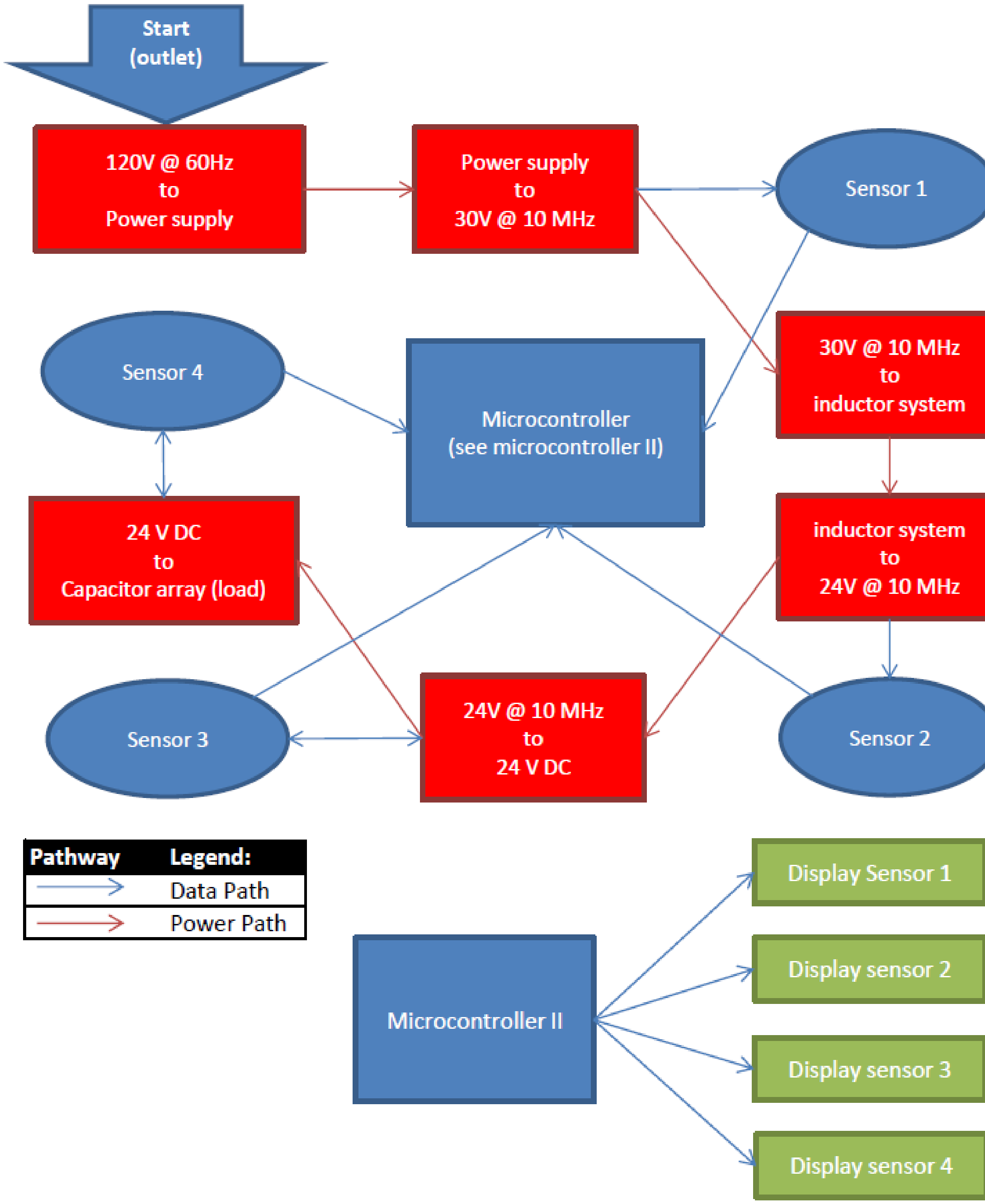


Figure 3.7.1-1 Data collection and power flow

For the scope of this project though, the interchangeability (of both FPGA and DSP chips) were unnecessary and potential bottlenecks of the project. The one potential downside to the use of an FPGA though is that they are highly complex to code due to the use of these complicated gate systems. The practicality of using an FPGA is possible if given enough time, but to better use time, it may serve better to consider this a secondary option with too much coding expertise necessary to use it as a method of data collection when more practical options exist in the use of microprocessors. For the DSP chip, the programs required to program a digital signal processor are extremely expensive, typically ranging from hundreds to thousands of dollars which places it far from the reach of ordinary hobbyists or independent projects not connected to a large corporation with large coffered to dip into. However, a DSP addition to a microcontroller is a viable option to be able to calculate a frequency value to verify working of the oscillator circuit.

The second issue with the use of a field programmable gate arrays are that they are very costly to purchase due to their primary benefit, being field programmable. The functionality of the FPGA is also different than that of a microprocessor in that there a better programming basis for microprocessors versus FPGA Microprocessors of comparable use age have significantly lower price overhead since they have a set programmable, it translates into simplicity of the manufacturing process. In addition, there are many different types of microcontrollers to choose from. The downside is there are over thousands to choose from, so how do we know which to use?

There are numerous companies to choose from for usage of the microcontroller part. Texas Instrument makes numerous models of processors from the MSP430 to the Stellaris ARM Cortex. Microchip is another processor designer with their many different PIC and dsPIC lines. Another company which notably designs microcontrollers for this purpose is those of Atmel and their AVR series. The last possibility is the microprocessor of Parallax with their Basic Stamp line of products. To choose one of these would be best, the selection process will be discussed more in the Research section for Data Acquisition.

After this, the decision of how to transmit the data between the microcontroller (or data collector) to the computer where the data will be compiled must be decided, it can be hardwired or wireless. For ease of use, it was hardwired, but if possible (for convenience sake) it can be wireless.

This lead to the final decision of how this data was to be translated into visual data by choosing the proper software to display the information collected by the microcontroller.

In the following section, the topic of microcontroller choice and justification shall be discussed. The three primary equipment requirements of this project are a microcontroller, sensors, and the analysis software. After, the ideas of how this was configured, and designed and coded will be discussed.

3.7.2 Microcontrollers

Aside from being responsible for the purpose of collection of real time data, the microcontroller (unlike the FPGS (easily) and the DSP) is capable of controlling an analog output and input. In the instance of the project at hand, this means the microcontroller is also responsible for halting charge when the capacitor array is full, indicating low capacitor array voltage, monitor charge level of capacitor system, and coordinate with a smaller, wirelessly enabled smaller microcontroller to be able to speak and collect data to monitor the voltage levels of the capacitor array for safe application. To better understand what specific architecture to use with this project, a quick observation of the different primary architectures from which all architectures derive from.

3.7.2.1 The Basic Architectures

Before tackling the topic of which microcontroller to use, it is imperative to understand the architecture used by the microprocessors in question. It becomes important when understanding the microcontroller offerings in the next portions of the microcontroller decision.

The main reason for making this portion of the paper is to understand the different architectures and their benefits and downsides towards the project. The three main types of architectures that will be examined will be that of Von Neumann/Princeton Architecture, Harvard Architecture, and Modified Harvard Architecture.

3.7.2.1.1 Von Neumann Architecture

Von Neumann (also sometimes referred to as the Princeton Architecture) is one of the most hardware efficient style architectures used today on the market. Dating back to the 1940’s, it is also one of the oldest architectures still in regular use today. Von Neumann architectures have evolved from large rooms with large parts, to being as small as fitting an entire architecture that can be compiled onto a single chip. The primary outcome of this architecture is that it will remain simple with one dedicated set of stored-programming. Because of this, it is possible to reduce it to efficient hardware design to memory, processor, and an input and output device which can act like memory to function external input and output functions. This translates into lower power requirements for any architecture configured in this architecture. All data within this style are stored in read-write, random access memory. It was the first architecture to incorporate the concept of a universal coding concept that is applicable to all computing possibilities imaginable. It is the basis for what is to become low cost modular architecture which focuses on minimal hardware needs with complexity based in the software. This is a highly adaptable architecture for a microcontroller since it has such basic hardware needs. Cortex-M0 lines and MSP430 microcontrollers architectures are notably Von Neumann. The one setback for this though is that it will not sample as quickly as the next architecture consideration.

3.7.2.1.2 Harvard Architecture

The Harvard Architecture is a more recent development than its simpler Princeton Architectural brother. An architecture which is marked by a clear distinction between storage and signal pathways, all of the data flow at one point rushes through a central processing unit or control unit acting as a midway between instruction memory, data memory, an arithmetic unit, and the input/output device. It is a more complex architecture compared to that of the Von Neumann architecture and because of so, it can act multiple operations at once. Hardware requirements for this though increase as the data paths are more intricate by two full separated systems as compared to the single data path for all functionalities of the Von Neumann architecture. For an example of this, it means that the Harvard architecture can read an instruction and access memory simultaneously. Complexity can also vary within the Harvard Architecture by being able to utilize different sized memory and instruction values for the purpose of making more efficient the coding with set known set sized values. COP8 is a microcontroller architecture primarily used by the products of national instruments which is influenced by the Harvard Architecture. The DSP chip model TM320 from Texas Instruments uses this hardware architecture as well to utilize in full the time efficiency of the architecture since bottlenecks are a non-issue thanks to the fully separated addresser and memory model. In microcontroller offerings, AVR from Atmel, PIC family of microcontrollers from Microchip, and Cortex-M3 from ARM utilize a Harvard Architecture.

3.7.2.1.3 Modified Harvard Architecture

This next architecture is an interesting architecture since it is not strictly a Harvard Architecture or a Princeton Architecture. In fact, it is viewed typically as a hybrid of both systems. By utilizing the same architecture as that of the Harvard Architecture, it can read and write to both instruction and memory similarly to that of the Princeton Architecture by using combinational Modified Harvard Architecture. By this idea, the architecture can benefit from both of their advantages with little addition to downside. It will be allowed similar speeds to that of the Harvard Architecture, but with the accessibility and memory/input-output addressing concept as that of the Von Neumann/Princeton Architecture which simplifies the data flow of the microcontroller or microprocessor. The data and instruction are still stored separately, but mapped differently with program-stored instructions typically taking precedence over data memory. The distinction between a Harvard Architecture and a Modified Harvard Architecture, and by use of some examples of purely Harvard Architecture, one can see what separates the original from the modified format of the Harvard Architecture of computer architectures.

3.7.2.1.4 Wrap up of relevance

By observation of the finer aspects of their respective build, it can be seen that some examples as to why the PIC family of microcontrollers from Microchip, as well as the AVR family of microcontrollers by Atmel are regarded as, clearly and distinctly, Harvard modeled machines because they do maintain a distinct and finite separation between instruction code addressing memory and data addressing spaces, and address 'zero' of each does, in fact, refer to a physically different piece of memory. However, the convention of considering them identifiably distinct is made opaque by the colloquial use of the term "modified Harvard architecture" to refer to such that work upon the idea of including special instructions to read and/or write the contents of code space as though it were data. It is this distinction that makes Modified Harvard different from the architectures spiritual parents of Princeton Architecture and Harvard Architecture. It is important to understand this distinction since (as stated earlier) that the AVR family and PIC family of microcontrollers are based upon this model of data processing.

What is important as well with specific architecture style is the size of the architecture. They are typically broken down to 3 primary sizes. 8-bit architectures are the simplest can easily store large instruction sets. A 16-bit architecture is useful in being of moderate size and not too burdensome to be too heavy for use with a small project. A 16-bit architecture in this consideration is probably one of the most useful aspects of this project as it is not too long to take up too much of the memory/input program space.

A 32-bit is likely the largest microcontroller on the market today. This would only needed if the requirements for the project are to reach into high amounts of calculation or numerous sets of complex and varying actions depending on memory or peripheral manipulations. Many of these microcontrollers which are of the 32-bit size use an ARM-based high-speed microprocessor. Beyond the standardized format by ARM, other companies like Atmel, Infineon and a host of other microcontroller providers provide other types of large instruction microcontrollers. One benefit of such a style of microcontroller is that it can allow for microcontrollers which could have integrated Digital Signal Processors. But this again, is the testament to the high data throughput required to make such large microcontroller use reasonable.

3.7.2.2 Microcontrollers

Microcontrollers maintain being a focal point with respect to the area of data collection and overall digital computation of a project, it functions as the processor of the project, and directing data and action flow at near instantaneous to human speeds. What made them integral to this project is that the microcontroller is an inclusive package for which data, sensor input, and visual outputs can be processed

They are a viable option now as opposed to years previous as of currently due primarily to economy of their use. They have reduced down to such simple hardware that many microcontrollers can now be packed onto a single embedded chip. What once took the machination of a room with complex and power needy equipment can now be found on the tip of one's finger. The recent advances in flash memory has been a large player in this, as data can now be compiled onto a microchip rather than on bulky hard disc which require housing and moving parts. The advent of better technology on the nanoscale and architecture has led to them being available for use on this project. With build-up of their being economical, microcontrollers are now cheap and simple enough for hobbyist project use.

In addition to strides in cost effectiveness, steps have been made into making strides in accessibility of these products. The improvements in the design of development systems for have aided in support of the microcontroller of various designs and makers. TI with code composer and Microchip with MPLAB have allowed, for example, uniform systems in which entire families of microcontrollers can be programmed. This will be discussed more in the software design specifications.

Beyond this though, the architectures used by all microcontrollers have turned from proprietary systems to mostly open source programming which is a large benefit for the development community who strive to make their niche within their programming and project needs. To stream line this as well, an added benefit to some of the newer software to program these microcontrollers, they come ready to be programmed in higher level code like C-code. With this, it is the result of easy access to help from fellow programming enthusiast on digitally heavy projects can be tackled more easily than in previous generations. With respect to this project, applications can be found for any of the microcontrollers that are on the market, only to find the right one will be the question.

The next section is one of the most important considerations with regards to the collection of data upon this project. It will limit the equipment types we can use and what language will be programed since each has their distinct assembly level language and syntax. Some peripheral uses with this project using the microcontroller are displaying data, frequency calculation, and managing manual adjustments.

The reason a microcontroller instead of a regular computer is the fact that the microcontroller itself is relatively very low power needs, meaning that use of these will have minimal impact on the working of this project.

It is best to discuss all possibilities of microcontroller possibilities. As will be stated in the Design phase of this report, to see a few of the primary competitors for the process of selecting a microcontroller for data acquisition are those of Texas Instruments, Microchip, Atmel, Infineon, NXP, and Parallax and their respective chip and processor architectures. In this section, we discussed the process, the positives and negatives of each with respect for this project broken down into models.

3.7.2.2.1 Texas instruments

On Texas Instruments, they are the most prospective company to work with regards to the semiconductor technology to use, as their technology is what is taught in embedded systems. On top of that as well, the work of coding the microprocessor can also be done in C++ with their MSP430 series of embedded microcontroller. The company's two main offerings on this project would be their MSP430 and Stellaris lines.

It is best to focus on MSP430, though, since it is their primary contender for the position of low powered microcontroller. The MSP430 family of microcontrollers utilizes the Von Neumann Architecture with a 16-bit instruction size to keep the power requirements and hardware requirements of the microcontroller low. This though is at the sacrifice of slower data flow from shared data and program memory buses. There are many variations on the MSP430 family as each suit more specifically the needs of the customer. To single out one specific type, one needs to understand the design first. This will also be the similar concept that will pertain to all other pursuits with searching for the proper microcontroller from each company.

A second offering from Texas Instruments is their line of digital signal processors (DSP). As recent years, Texas Instruments has pioneered the commercialization of this technology. One potential product that Texas Instruments provides to fit our needs is their TMS320 line of DSP boards. The benefit of this technology is that they can process information quickly due to the data being analyzed in digital format from analogue and then summarily retranslated into an analog signal. They can as well sample at extremely fast rates than typical microcontrollers. This is due to their need for the processing style requiring large amounts of data in order to operate to the technologies fullest potential. An older, but similar technology that TI offers which could be used as a DSP is their aging OMAP chip set for multimedia. Since this project does not encompass that, it is not a good fit for this project right off the bat.

Both of Texas Instruments DSP and MSP430 are compatible with the C-programming language, which is an added benefit of the use of their products.
An added benefit to the DSP chip though is the potential use of hardware languages as well as C languages to improve the functionality of the processor. But, a monetary issue arises though when the microcontroller exceeds 16Kb of

programming and the use of DSP programming. They would require software costs ranging from a few hundred to a few thousand dollars in order to program and compile using these chip sets. Their baseline program Code Composer is complimentary up to the 16Kb size code.

TI overall though, did not sport as large overall community support as compared to their two rivals. Also, unlike their primary rivals, TI offers a large incentive to use and market their products by using them in one's project by offering a contest and a possible grant in parts for an arranged price ceiling. Their technology as well sports the lowest energy requirements of their field.

3.7.2.2.2 Microchip

On Microchip, it had accrued a strong user base with large community support for projects and development. Their primary offering as a company is that of the 8-bit and 16-bit PIC microcontroller or their dsPIC microcontrollers. Because of the strong offerings of the PIC community, they can provide a good template to streamline the design and prototyping process of the project as well as host many current enthusiasts whom are highly knowledgeable in the application of their chipsets.

To program Microchips, they host the MPLAB line of compiler software. This software is the universal basis for coding on any of their chips from PIC to their dsPIC lines as well as their PIC32 MCU (which is not a microcontroller). The program offering are its free, standard and pro editions which primarily very by the optimization levels as well as the complexity of which the user can pack more operations onto the chip as any given time. For the use of this project, such compactness is not necessary, as baseline specifications will only require the most basic functionalities of the microcontroller.

Their products boast that the possibility of using graphical displays for ease of use as well as access the majority of interfacing methods. Sensor equipment is compatible with the use of this family of chips as well.

The primary point that sold this line of product is the fact that they offer a long line of experience in the field of college project style programming and microcontroller experience. With respect to Microchip's history, their PIC or dsPIC lines of microcontrollers prove to be a strong contender for data collection and manipulation.

The PIC family of chips primarily hosted cost effectiveness, energy efficiency, and reliable performance with which it all comes packaged in a system which is at the most important level, a highly flexible system which will allow easy integration into many different projects.

DsPIC controllers are a derivative of Microchip's PIC controllers. They combined the use of a microcontroller and digital signal processor for the combined use of fast pace processing power of a DSP with the architecture of a microcontroller. These, though, are ideal for the processing of advanced data heavy applications like image or audio processing algorithms.

3.7.2.2.3 Atmel

On Atmel, again like Microchip, they hosted a strong user base and can fill many roles of providing a good template to streamline the design and prototyping process of building this project up from the ground up. Their primary draw though is that they claim high flexibility in scalability as well as an exceptionally strong community which to troubleshoot a problem when need be.

Atmel offers four different types of microcontrollers; the AVR line, ARM derivatives, MCU wireless, and 8051 architectures.

Of these, AVR is probably the most likely candidate for use of microcontroller since it boasts 8-bit and 32-bit variations as they are designed with economy and ergonomics in mind. The family of chips can be coded in either C or assembly languages and boasts performance levels at very cost effective levels including being highly energy efficient. This family of chips will be discussed more later on in the design portion of the data acquisition. Though this family does carry many variations of a similar architecture, what is important is that there is a large support base for this line of product.

Another line of Atmel chip are their ARM derived controllers. These are ARM style chips, native to the 32-bit processing memory size, are the primary choice for applications requiring high rates of cycling, for example, in instances of image and audio processing. The chip family itself can handle enormous amounts of data for being a microcontroller possibility, but it is not a microcontroller by its nature. It is primarily a microprocessor which can perform as a very low power computer chip. The chip can be configured to work like a microcontroller if given the proper hardware to do so. But, like the DSP and FPGA chips, the complexity of this architecture of chip is not necessary (if not overkill) for the scope of this project.

Next is the wireless microcontroller unit. In this package, the primary size for the consideration of the consumer is the 8-bit single-chip microcontroller. All packages of the wireless communications concept would be aided by the fact of their performance are intertwined. If larger microcontroller architectures were to be pursued, a 32-bit AVR or ARM architecture would be compatible with an external transceiver unit attached as a wireless communications peripheral. In this class of microcontroller, this holds an advantage in the field of microcontrollers by being a set which is guaranteed viable as an option for the applications of wireless connectivity with the car (load) in the later portion of this project where wireless communications is a necessity to be able to sense in real-time the power usage of the system.

Atmel prides itself with the experience it has in the field of the utilization of Intel's 8051 architecture. Being consistently an 8-bit microcontroller architecture that utilizes the Harvard Architecture, it has the guarantee of being able to be space efficient with its program code since it uses a tried and true instruction set. Included is the fact that Atmel also hosts a very strong support for project development with this microcontroller since it has been under use for an exhaustive history of project usage.

As a side note, Atmel products are the controllers used Arduino prototyping platforms which have been popular within the last years with hobbyists which can be hand built or pre-assembled.

The next two companies' products are typically aimed towards industrial applications and use in many different fields of which small efficient computers are needed to digitally control and direct logic systems to automated functions. Infineon and NXP are well known in their respective fields of application from the medical industry to the automotive industry.

3.7.2.2.4 Infineon

Infineon is a company which focuses primarily on industrial applications by use of the automotive industries microcontroller needs in the ever digitizing car equipment. Their highest offering thus far is microcontrollers built around a 32-bit ARM or Infineon's TriCore architecture. With smaller architectures, Infineon designed the 16-bit C166 architecture which improved upon their previous chip offering based on the 8051 Intel Architecture.

The 32-bit ARM architectures break down into two specific types, the XMC1000 and XMC4000, with the 1000 series intended for motor control, display interfacing, power conversion, as well as being a general workhorse. The 4000 series though is an upgrade from its predecessor as an industrial controller for the same uses as the XMC1000 including heavier duty responsibilities like Input/outputting, power inversion, and generally heavier processing purposes. Due to their product being for industrial purposes though, their ARM series of products may be too over-powered as well as being costly for its industrial certification.

The 32-bit TriCore is an original design by Infineon as a 32-bit RISC microcontroller with DSP capabilities integrated into a single chip. It would come with special software which improved the safe operation of the hardware. It was originally designed with a safe, reliable and efficient controller which is specific to the automotive applications. For this, it is not a primary consideration of microcontroller architecture choice. It is worth noting though it is possible to use and understand better as the architecture holds promise for large scale use in its target industry.

C166 architecture came from when the company was owned by its parent company, Siemens Semiconductor Division. For their size, it is quicker than the 32-bit architectures in some models due to its low-latency design. But, they are intended for industrial, automotive, and communications applications, not exactly the target for this project. It is worth looking into so one can better understand the flexibility and intended use of all architectures for the best fit.

Like other 8051 Architectures, Infineon's 8051 chip are designed into the XC800 Family of Microcontrollers. This is further broken into two different applications, automotive and industrial. Automotive models can be used in motorcycle sensors, automotive throttle controls, window motors, and simple applications within car systems. Industrial models can be found in air conditioners, digitally controlled power supplies, and basic motor controls. Again this family of chips is not exactly intended for our use. Infineon can be determined as most likely not a good fit for use on this project with collecting sensor data.

3.7.2.2.5 NXP

NXP provides microcontrollers from the standard 8-bit to 32-bit instruction sizes, as well as a series of wireless microcontrollers. The 32-bit architectures range from the ARM7 to ARM9, and a various set Cortex series architectures. Both ARM (number) and Cortex are derived from arm architectures, but are not distinctly the same except for their instruction sizes and their use of RISC architectures.

Like previous competitors with similar hardware, their 32-bit hardware range specifications can be similar, varying only in essence on built in functions, the Cortex series being a prime example of this. Each type model available have different points depending on consumer cost and built in functionality. Like other higher levels of the 32-bit processors, they can boast built in DSP and low-power A to D or D to A devices. NXP prides its technology on their legacy of being a workhorse of the semiconductor industry. To hobbyist, they are not the most new user friendly but still a worthwhile company to work with as many other possibilities lay for the career digital-tinkering junkie. Their main draw for their technology comes from consumer dependence of those who are already accustomed to their technology. But other than so, they are very similar to other competitors in the field with regards to the 32-bit microcontroller market and their ability to place integrated features into their technology. What is noteworthy though is that NXP's wireless microcontroller designs are only capable within the confines of 32-bit architectures and nothing smaller. This may be too large for the needs of this project, but it can be utilized if necessary but with an increased hardware waste. What is needed is the fact that it be a wireless microcontroller.

So that places the JN5164 as a possibility for use. (To be better discussed in this design requirements)

As for NXP's offering for 8-bit architectures are based upon the 80c51 family of microcontrollers, proprietary to Philips technology. This architecture at its holds 4k of 8-bit ROM with 128b 8b RAM with a limit of 4 8-bit Input and output ports. Like other architectures, it does have capabilities of utilizing UART and additional clocks or power down interrupts which can halt the clock without disturbing the RAM. It is a tried and tested architecture based on the Harvard Architecture which makes it terrific for multitasking purposes.

At the 16-bit level, NXP offers the XA core microcontrollers which are touted for being good for industrial applications. There are three variations on the XA's with the XA-H3, XA-H4, and XA-C3 with each touting specific variations. For example, the XA-H4 is an enhanced version of XA-H3 with added DRAM, Von Neumann Architecture, Harvard Architecture, and USART supports. XA-C3 are for more communications uses with the feature of easy 8-bit architecture compatibility for ease of upgrading from an

3.7.2.2.6 Parallax

The primary offering of the Parallax Company are their line of Propeller and BASIC Stamp boards. These products are usually tools designed for beginning hobbyists and college freshmen new to robotics.

The Propeller chip is fairly basic, providing only one style of chip that utilizes a 32-bit command. It is an all-inclusive chip which can operate both high-level and low-level commands via and on-board interpreter. On top of this, there are many standardized codes which are allowed with this product. Like the other providers, they sport a multitude of peripheral applications. What is not included though is with their BASIC Microcontroller line, is compatibility with the C-programming language translator and must therefore be programmed strictly in BASIC. Their propeller line of microcontroller though requires a bit more application of higher level digital skill; although, like the BASIC, their products still maintain a high level of simplicity.

On Parallax, they provide highly elementary and simple to use equipment, but compared to those of msp430 or any of their competitors, it is exceptionally pricey. On top of these, parallax is primarily directed toward basic uses, educational purposes and a younger audience composed of beginner students. Because of this, their products are not exactly designed with building the basics in electronics understanding since the components Parallax sell are mostly pre-assembled and only require basic assembly skills of the larger components. Their equipment can fulfill the functionality required, but, their technology will not fulfill the design requirements of this project.

3.7.3 Peripherals/Sensors/Displays/Communications equipment

A microcontroller is important for a project because it is able to process many different functions. In this case, the main use is to control and manage peripherals, like an individual's brain would control their limbs and mental processes. In the case of a microcontroller, the applications are those of peripherals able to do what the microcontroller cannot inherently. The functions this microcontroller needed to do are maintain wireless connections, observe voltage inputs, control charging, observe load discharge, regulate discharge and output a visual display of what relevant values are, be they numerical or graphical, depending on the user's needs. This section will tackle what sensors and peripherals are needed to complete the necessities of this project.

3.7.3.1 Wireless communication

For the application of some sets of sensors, there needed to be wireless access, primarily within two legs of the system which consisted of between the receiving inductor plate and the DC converter; and a sensor right before and after the capacitor array. This is important for the accurate observation and tuning of the inductor coupling system as well as to monitor if the capacitor protection circuit kicked in or not. For this, wireless capability built into the microcontroller could be used for our purposes as a peripheral feature. As for the actuating of the inductor plates spacing, this will be done manually for ease of application. If time permits, digital actuation can be added in as a feature. But, alternatives do exist.

This could be done using products like Bluetooth, Zigbee, or other IEEE 802.15.4 approved designs. To explain, IEEE 802.15. a standard for wireless communications community to design around which is the basis for Zigbee, MiWi, and ISA 100.11a. It offered an available standard which allows for unique ease of use in airwaves that are usually regulated by international bodies. The Zigbee configuration of communications protocol and hardware is most likely what will be used with this project since they have proved to be field reliable for specific microcontroller architectures and peripheral devices. It is the choice for small projects for its low cost and low power features. It is ideal for the needs of a wireless communications device as simple as what the project needs.

As for hardware that Xbee's were a possibility for application of a dedicated wireless microcontroller with good data feed rates. It benefits from the use of Zigbee's standardized protocols with the ease of a simple plug and play style antenna system which is compatible as a small computer in its own right. It will require small programming, but should be able to fit the intended use for this project as a wireless device to connect a small array of sensors. It is a major contender for the spot of fulfilling the wireless needs of the project.

As stated just now, the alternative to a wireless microcontroller is a small microprocessor specifically for wireless communication with easy integration to a larger project. The alternative is an integrated wireless microcontroller which is restricted to smaller a instruction set and less hardware specifications on many wireless microcontrollers which are intended for use as a wireless microcontroller.

3.7.3.2 Voltage sensing

Voltage sensors will be needed at each transition point to be able to monitor issues as they arise and to be able to effectively tune the inductor system. An analog to digital converter can be used directly from the line in order to determine the voltage level at the node of interest. The principle of which the A/D converter is to translate an analog signal (in this case) voltage into an equivalent digital numeric value. Important aspects a converter will be its resolution and physical tolerances which will dictate the bit size of the AD Converter and cost of part depending on how costly more stress tolerant materials are. Since this is a straight conversion, it should be a simple design. This technique would only be applicable for DC .

3.7.3.2.1 High voltage issue

Because of the nature of this project, there will be observation of high voltages meaning that there must be a safe way to translate this into the ADC. To deal with this, one of the better options are to use protection circuits. This step is taken later on as when the time to observe is narrowed down. In the design portion, this issue will be tackled, but to explain here, the relevancy looking to dealing with the problem is pointed out.

3.7.3.2.2 Observing Voltage Input

Through an analog to digital converter, data collected was done at the DC to oscillator juncture in order to have a base input voltage from the inductor system. A remote value was then to be observed from the other side of the inductor system as an output inductor system to be able to calculate an efficiency value which helps in finding the maximum coupling of the system. It allowed for manual tuning by use of a potentiometer that manipulates the current into the stationary inductor plate.

3.7.3.2.3 Observing Load Discharge

Similar to the remote sensor for the end of the inductor system, another sensor was then to be connected to the output side of the capacitor array. The purpose of this is to be able to dictate logically the output of the potentiometer directly precisely and without human interaction necessary. This again required an analog to digital converter that will read into comparison logic of the microcontroller which then alternates the resistance of the potentiometer to regulate the discharge of the capacitor array.

3.7.3.3 Regulating output

Potentiometers played an important role in this project for they are important for this project to aid in regulation of the output of the capacitor array as well as potentially providing a solution for cutting off the charging process when the capacitors become full. The digitally controlled variant of the potentiometer was to be the most defining feature of the load output system which would be monitored under the microcontroller to maintain a stable 1-1.2A output with a stable voltage so the super-capacitor array is drained at a constant discharge that allows for maximum time efficiency with the charge since the capacitor array cannot control its own discharge rate like a battery array.

3.7.3.4 Output display

LCD Screen was to be most likely be integrated into the microcontroller board for simplicities sake. The type of LCD used was to be dependent upon the company used. For example, an MSP430, AVR, or PIC may use a monochromatic LCD. Depending on complexity, a Color display can be used in this application of this project, but since user interface does not need to be exactly the most aesthetically pleasing for the scope of this project, a monochromatic display for voltage observation will be enough for this project.

These screens could also be fully colored as well, but the code implementation for one is more complex and much more sensitive hardware wise and software wise in order to be able to reach the ability of implementing one. Although, the added benefit of being more aesthetically pleasing does exist because of it as well as more potential functionality is possible as the screen limitations are significantly less with a color screen. It must be maintained though that the primary focus of the project is to keep things minimalistic to cut cost and headache down.

On more advanced boards, these can be built onto the microcontroller boards a prototyping board accessory to help make prototyping easier. The LCD can also be purchased as a separate component to complement the board in use, depending on the screens compatibility with the microcontroller.

3.7.3.5 Programming the Microcontroller

Some microcontrollers utilize a separate compiling hardware to communicate from a typical computer's operating system to the microcontroller. Each model of hardware comes with a specific style of programming hardware; some are prebuilt, others can be built. What is important about this additional hardware is that they can implement debugging and make specific the read in instructions to that microcontroller. Connectivity is variable from a USB, rs-232 socket, or customized pin input. The additional hardware is quintessentially a debugger.

In the case of some of the MSP430 Launchpad or some similarly simple style of microprocessor, additional hardware is not necessary for the implementation of the microcontroller from the PC to the microcontroller.

3.7.4 Data Acquisition Software and Language

What is important to utilizing this equipment is most importantly, what program is compatible to allow the ability to program the microcontroller. Now, there are many different languages to code in; MIPS, C, C++, C#, MSP430, BASIC, etc. For this instance, it is important to realize that each company comes with their special language to code in. Many architectures are capable of being programmed in C and not require specialized languages, so being able to choose one which does work off of higher level languages is a benefit. There also are programs which exist that can code for many different microcontrollers since many of these microcontrollers are open-sourced, which then allows for libraries which are capable of housing many different basis and architecture programming parameters.

One important factor is the uniformity to operating system compatibility. Since the majority of programs which will need to be programmable in C, the programs should thusly be able to be useable from the Windows operating system. Those in the group traditionally use Windows operating system and for this project will continue to do so.

3.7.4.1 Programming the Microcontroller

Many of the architectures with the 32-bit size instructions has been applicable with the MIPS language, so it is advisable to use this language as choice for this project if the C-language is not available for compilation on the board.

There is on the other hand, a program which is free and highly integrate able with 32-bit ARM Architectures which are popular on microcontrollers. Coocox CoIDE is a type of free open software which is used for advanced software development environments. In this case, it is a general purpose program to design instruction sets for the ARM Cortex Architecture. It is possible to use on products from companies like Atmel, NXP, and Texas Instruments (to list those embedded hardware companies analyzed in this research). The only requirement is that a specific debugging adapter is necessary to aid in the use of this software.

It was most likely the best choice to use the software designed specifically for the microcontroller that will be used. Fortunately for the user, Microchip with MPLAB or MPIDE, and Atmel with AVR Studios or Arduino provide their basic programming software for free, and similarly with Texas Instruments but to a lesser extent with their Code Composer with a limit of 16 kByte programming size for its complimentary variation.

3.7.4.2 Other Software

For the intention of this project as well as many others, PCB design software was necessary to complete the senior design project criterion. One of the most important basic skills of an electrical engineer is the ability to design, map and order a Printed Circuit Board (PCB). One very popular program on the market today is EAGLE. Potential second software to potentially be used is called Fritzing.

EAGLE, itself is one of the premier programs to design out a PCB. In use for over 20-years, the company and its employ know exactly what to do when it comes down to producing affordable PCB’s and thereby pass the savings down to the customer. The company offers its Cad-software free up to specific sizes and serves as a great learning tool as to understand how design of a PCB goes as well as offer a good customer support base for the engineer in training. This program is important for all aspects of this project; from power system, oscillator circuit, inductor coil system, digital controlling, sensor stability, capacitor stability, and housing the microcontroller circuitry.

Fritzing is an open-source program that operates very similarly to that of EAGLE. Slowly they support for a program like this is growing as the need for designing more and more open-sourced software grows. Compatible with all platforms of operating system used today, it would be useful to learn. Though, it does lack in depth of use as compared to its well established rival. Fortunately, with Fritzing, there are many preset PCB designs available already, which make this a good candidate for a PCB cad-software.

4. Design

4.1 AC Outlet to DC Power

To power this project we have implemented a simple power signal rectifier for this design. After considering the many topologies, we've decided to implement a simple step down transformer followed by a rectifier bridge and smoothing capacitor to discharge to the connected load. The rectifier we have chosen to implement the full wave rectification is the 4A 400V Bridge Model 276-1173 from Radio Shack. The transformer also from Radio Shack is a 12.6 V step down transformer. These components are very simple and easy to implement, and meet and exceed our project needs.

4.2 RF Power Signal

In the following sections I will be discussing the specifications and requirements, various available and pertinent components, and final design and considerations for the voltage controlled oscillator, class E power amplifier, and the gate driver, which all make up the generation of the high frequency power signal used to drive the transmission and receiver coils in the wireless power transfer.

4.2.1 Programmable Oscillator

The design of the programmable oscillator involved determining the necessary specifications and requirements, finding which available programmable oscillators meet those specifications and requirements, and determining which one eas best for our project.

4.2.1.1 Specifications

For our project, considering what frequencies we wanted to operate at, the class E amplifier we will be using to power the signal, and the use of a gate driver to power the transistor in the class E amplifier, the specifications, requirements, and considerations, in order of importance are shown below.

- Can generate signals from 1 MHz to 20 MHz
- Good documentation to make utilizing it easier
- Availability
- Frequency step size: the smaller the better
- Price
- Low input signal current to not wear on the microcontroller too much
- Uses common rails such as 3.3V or 5V

4.2.1.2 Components

For our project, I determined that a voltage controlled oscillator would best suit our needs. The chosen VCO is shown below.

	SN74LS624N	
Price	$3.92	
Frequency Range	1Hz - 20 MHz	
Supply Voltage	5	v
Supply Current	0.2	mA
Load Capacitance	45	pF
Operating Temperature Range	0 to 70 degrees	C
Package	PDIP-14	

Figure 4.2.1.2-1 SN74LS624N Oscillator Specs

4.2.2 Class E Amplifier

In section 4.2.2 we will be discussing the desired specifications and requirements of the class E power amplifier we designed, the choice of the various components, the schematics and relevant simulations showing the proper operation of the class E power amplifier, the choice of components to satisfy the schematics and simulations, and then conclude our final designs for the class E power amplifier.

4.2.2.1 Specifications

In accordance with the projects demonstration of charging an RC car with supercapacitors instead of a standard RC car battery, we wanted to charge the car as quickly as feasibly possible. With that in mind, the class E power amplifier specifications, requirements, and considerations, in order of importance, are shown below.

- Generate at least 1 Watts of power at 10 Volts
- Be capable of effectively amplifying a range of frequencies from 1 MHz to 20 MHz
- At least 70% efficiency
- Consider heat dissipation options

4.2.2.2 Design

In order to design the class E amplifier for our project, we had to determine which transistor will best be suited for our needs, what voltage we need to supply the transistor with, and the output resonant circuit component values in order to resonate within our desired frequency range.

For our particular amplifier, after much testing, we utilized a very simple output resonator circuit with the inductors of the MRC network and a capacitor. The inductance of the MRC network was determined, and then we chose a capacitor to resonate with the found inductance value at the particular resonance that the inductors best resonate at.

For our transistor chosen in section 4.2.2.4.1, it was determined that a Vcc voltage of 10V would be optimal for our design. This would develop plenty of power and current at the output to drive our resonators.

We also have an RF choke used to block high frequency currents coming from the power supply. In order for the RF choke to operate at our frequencies, it needs to be at a value of 50uH, and be a ferrite core. The ferrite core is advantageous to an open air core because the capacitance is much less, meaning that the self resonance is much higher, and therefore better suited as an RF choke. We also need to be careful for the current saturation of the RF choke.

4.2.2.3 Schematics

For basic schematic and initial simulation testing, I used multisim to implement a class E amplifier with the component values designed in section 4.2.2.2. Sadly, I could not find a method to simulate the gate driver and programmable oscillator in multisim, so I just used a function generator. The schematic for the designed class E amplifier is shown in figure 4.2.2.3-1, the output and input waveform simulation is shown in figure 4.2.2.3-2, and the wattmeter output is shown in figure 4.2.2.3-3.

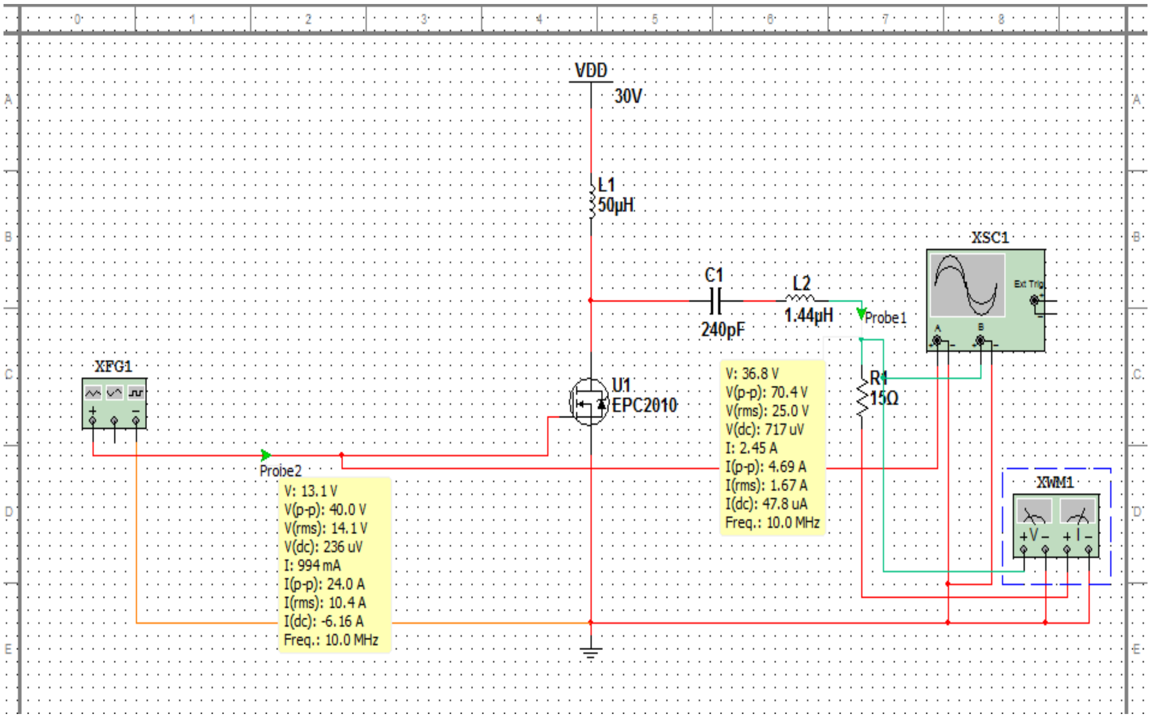


Figure 4.2.2.3-1 Designed Class E Amplifier in Multisim

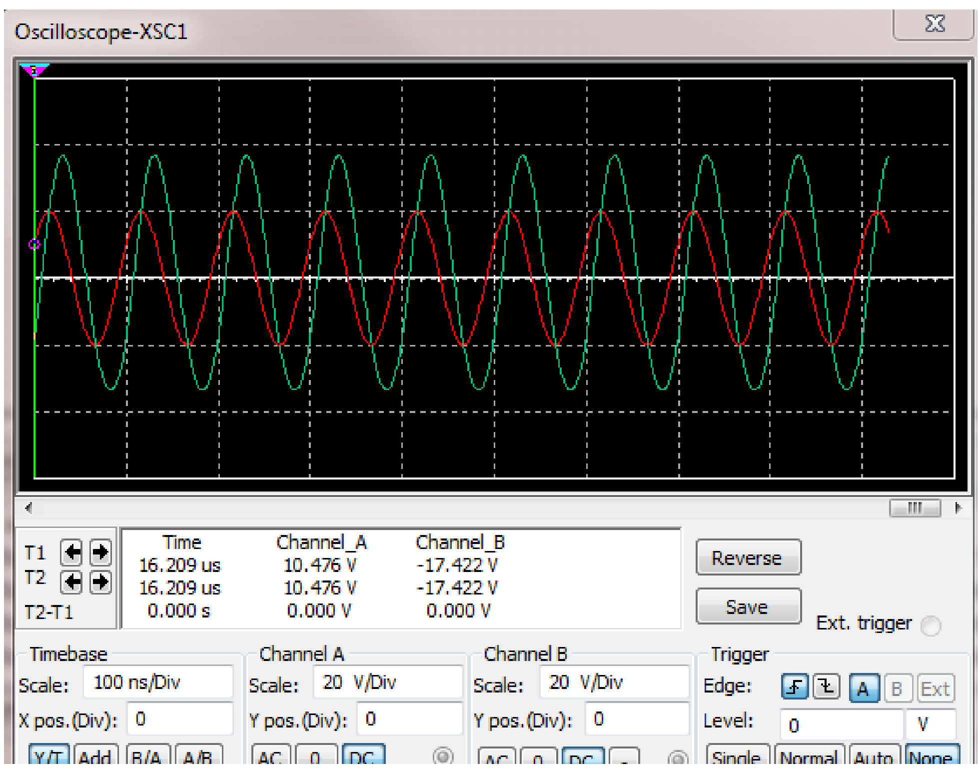


Figure 4.2.2.3-2 Oscilloscope Output from Class E Multisim Simulation

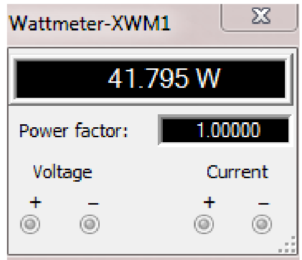


Figure 4.2.2.3-3 Wattmeter Power Output from Class E Multisim Simulation

The transistor chosen for this simulation can be found in section 4.2.2.4.1. This simulation verifies the initial designs for the class E amplifier needed to power our wireless power transfer resonators.

4.2.2.4 Components

4.2.2.4.1 Transistor

For the transistor in this design, special considerations had to be made. The transistor must be able to switch fast enough in order for the class E amplifier to effectively operate at frequencies up to 20MHz. The transistor must also be able to draw enough current at a voltage high enough to satisfy our requirement for at least 1 Watts to be generated for the resonant coils.

One transistor researched that can fill this roll is the LET20030C from STMicroelectronics. The relevant specifications for this transistor can be found in figure 4.2.2.4.1-1.

	LET20030C	
Price	$83.20	
Max Vds	80	V
Max Vgs	15	V
Max Id	9	A
Max Power Dissipation	108	W
Max Frequency	2	GHz
Igss	1	uA
Ciss	58	pF
Coss	29	pF
Crss	0.8	pF

Figure 4.2.2.4.1-1 LET20030C Specifications

Another interesting FET that I stumbled upon that looked extremely promising for our project is the high-efficiency enhanced-mode GaN FET. The eGaN FET is produced by Efficient Power Conversion, and has a really fantastic profile for our project. One interesting benefit of eGaN FETs over traditional silicon power MOSFETs is that they have a reduced Rds(on) and gate capacitance. Generally if we wanted to be able to switch a silicon power MOSFET faster, we would have to decrease the gate capacitance, but then that would lead to an increase in the Rds(on). The eGaN FETs have a significantly lower Rds(on) and gate capacitance when compared to a traditional silicon power MOSFET. You will find a comparison between 2 plausible eGaN FETs for our design in figure 4.2.2.4.1-1.

	EPC1014	EPC2012	
Price	$2.70	$2.98	
Max Vds	40	200	V
Max Vgs	6	6	V
Max Id	10	3	A
Igss	0.4	0.1	mA
Ciss	280	128	pF
Coss	115	73	pF
Crss	15	3.3	pF
On Resistance	16	100	mOhm

Figure 4.2.3 eGaN FET Specifications

Although the performance and cost of the EPC2012 is very good for our application, the size of it is only a few mm, and is therefore very hard to prototype with. Therefore we also looked into using some standard TO-220 package MOSFETS like the IRF510 described below.

	IRF510	
Price	$0.98	
Max Vds	100	V

Max Vgs	10	V
Max Id	5.6	A
Ciss	180	pF
Coss	81	pF
Crss	15	pF

Figure 4.2.2.4.1-2 IRF510 Specifications

Upon comparing the 4 transistors researched in this section, I determined that the IRF510 was the best transistor for our application. The LET20030C had a lot of very desirable specifications, but its price compared to the other two eGaN FETs made it completely undesirable, yet the extremely small size of the eGaN FETs made it very difficult to work with, so we ended up using the IRF510 with our final design, and it worked very well.

4.2.2.4.2 Inductors

For the RF choke inductor, we needed a ferrite core, 50uH, and high saturation current inductor. Again, as with the RLC tank circuit inductor, we wanted to use an inductor with the tightest tolerances as long as the price/performance is in favorable ratios. Sadly, I could not find any inductors readily available that matched our needs that was exactly 50uH, but the closest inductance that had a selection readily available to choose from was 47uH. Through DigiKey, I selected three inductors to choose from that most closely matches our design criteria. Those three can be found in figure 4.2.2.4.2-2.

Inductor	Inductance	DC Resistance	Current Rating	Tolerance	Price
Wurth WE-HCI	47uH	19.2mOhm	9A	20.00%	$6.83
IHLP-6767	47uH	108.46mOhm	5A	20.00%	$5.57
WE-HCF 2013	47uH	12.2mOhm	8.5A	15.00%	$12.96

Figure 4.2.2.4.2-2 Possible RF Choke Inductors

Although the WE-HCF 2013 inductor has the best specifications with the lowest DC resistance and the highest tolerances, it's price of nearly double the other two does not make up for its marginally better specifications. Between the WE-HCI and the IHLP-6767 inductors, I believe the Wurth WE-HCI is the best for our design because for a 16% higher cost, you get a significantly lower DC resistance, which could help with our efficiency, and offer a much better current rating, which will help for robustness of our design, and therefore I chose the Wurth WE-HCI to be our RF choke inductor for the class E amplifier.

4.2.2.4.3 Capacitors

For the capacitor in the LC output tank for the class E amplifier, we simply used a readily available through hole capacitor from David Douglas.

4.2.2.5 Conclusion

With the final components selected for the class E amplifier, we developed the final schematic with all of the corresponding specific parts. The final schematic with all part numbers can be found in figure 4.2.2.5-1, but bear in mind that the values are placeholders, and the actual tested values are different.

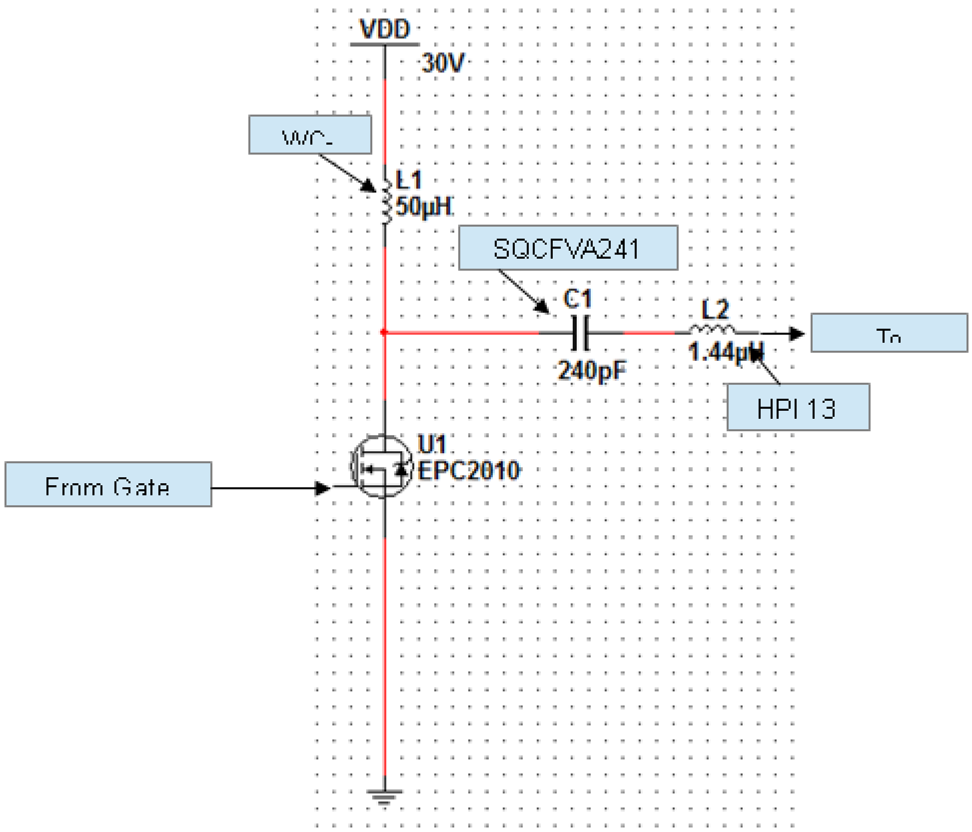


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Figure 4.2.2.5-1 Final Class E Amplifier Schematic

Component	Price
EPC2012	$2.98
EPCOS HPI 13	$3.57
Wurth WE-HCI	$6.83
SQCFVA241	$1.45
Total:	$14.83

Figure 4.2.2.5-2 Class E Amplifier Price

4.2.3 Gate Driver

In the following sections, I will be discussing the final selection and design of the gate driver used to drive the FET in our class E amplifier. We will discuss the requirements for our project and how that relates to the gate drivers necessary specifications, the specific gate driver components researched and the decision process, and the final decision as to which gate driver we used in our project.

4.2.3.1 Specifications

The requirements for a gate driver in our project is simply a gate driver which is fast enough to reproduce the amplified signal at the output up to 20MHz and outputs enough current to drive the eGaN FET fast enough to accurately amplify these signals up to 20MHz. Another specification related to our project would be the input to be either non-inverting or inverting; either of the two would have worked for our design because the specific phase of the output compared to the input of our amplifier is not critical in our design, but we did not want a gate driver which has any other type of input such as AND or OR. We also only need one output from the gate driver because we are only powering one eGaN FET in the class E amplifier. These specifications are summarized below, in order of importance.

- Delay Time below 50ns (equivalent to 20MHz)
- Current peak above 1A
- Inverting or Non-inverting input type
- Availability
- Price
- No more than 2 outputs; only one needed

4.2.3.2 Components

With the specifications listed in section 4.2.3.1 in mind, the gate driver we used in our final design can be found in figure 4.2.3.2-1.

	IXDN604PI	
Price	$1.28	
Output Current	4	A
Max Supply Voltage	35	V
Supply Current	10	uA

Rise Time	9	nS
Fall Time	8	nS

Figure 4.2.3.2-1 IXDN604PI Specifications

4.3 Magnetic Coupled Resonators

The design of our resonant magnetic coupling system is schematically similar, if not identical, to that of a transformer network. The difference is that we will not have to worry about turn-ratio and its effects on output vs. input for voltage and current, seeing as both inductors in this transformer network are identical in every way.

Efficiencies of greater than 70% have been seen by designs similar to what we've planning, so that's what we've aimed for. In some cases, efficiencies greater than 95% have been recorded, so we know it's possible, but involves a bit more technical understand than we are currently capable of. Thus, our circuit was designed to work in the 70% transmission range. We performed multiple tests to ensure this transmission efficiency, including spacing, angling, etc. We even double checked that the materials used in our project enclosure wouldn't be problematic.

To make our design work at 70% efficiency, we had to perform a lot of testing on the various dimensions of our inductors. We decided to work first with our most basic constraint, which is the diameter of the inductors. We felt that the larger we could make the inductors, the more room we had to work with in terms of acceptable separation distance, so we decided to make them 4 inches in diameter. We originally considered using Teflon substrates to produce our coils, but found that the increased permittivity of the magnetic field gave us very little benefit when it came to linking the flux between the two inductors. 18AWG wire performed well, and we were able to achieve above a 70% coupling efficiency between the two coils at the desired distance, which was found to be 3/4ths of an inch after factoring in the thickness of the coils after winding.

Safety is one of the major benefits of Magnetic Resonance Coupling. In terms of our RC car, there was originally the option of forgoing wireless power altogether and simply using contact plates, which would be two metal plates of opposite polarities placed on a mat or the floor that make contact with two matching plates on the RC car. This design, however, is susceptible to too many problems. First, the RC car needs maneuverability, something it would have to greatly sacrifice when it has two plates protruding from its underside.

Even if we made a way to shelter them mechanically, that would either require manually closing such a device, or some kind of mechanized system to close it automatically. In the case of the former, forgetting to close it could be disastrous, and in the case of the latter, that's another source of power consumption and error, not to mention something that we are not inclined to mess with as electrical engineers. Second, the conductivity of the plates would be inversely affected by exposure to the elements. Lastly, you would have to be careful in designing this system as to avoid a potential danger to a person who might come in contact with both plates.

Normally, contact with the inner circuitry wouldn't be an issue for an RC car battery. You might get a little shock, but nothing truly damaging. However, the quick charge rate of our array is accompanied with an equally high power rating, which would potentially make this, or any other form of direct contact with the inner circuitry of our wireless power supply, harmful to someone unfortunate enough to touch both leads simultaneously.

Our wireless design proved to be much safer, since there would be no need to access its internal components to charge. This design could even be safer for young children who may be tempted to try to eat or otherwise tamper with the battery pack when its removed from the car itself. Keeping everything inside the car itself is much safer and is now a possibility thanks to WPT and Magnetic Resonance Coupling. As a result, children could start playing with remote toys at a younger age without parents worrying about it harming their child. However, these are only additional benefits to the operation of an RC car. Since our intention is to have this scale to full-sized electric vehicles, these features mean little for this project.

Overall, we saw from our preliminary studies that WPT through Magnetic Resonance Coupling is definitely the way we wanted to go. The system is practical, realizable, fits into our design needs well, and it would be safer than current conditions for the consumer. The major challenge came from actually realizing this project in its entirety.

Our biggest challenge came from generating a powerful RF signal capable of efficiently transmitting energy between the two inductors while still remaining commercially and spatially practical. Something too large or too costly is not going to make a good product.

All of the parts used within our network must be able to tolerate both decent power and current, with a reasonable voltage. Individual parts should be able to tolerate as much as 10W or more, and should also be able to tolerate a large frequency. Naturally, the wires are able to handle decent amounts of current/power, so they aren't a concern. The capacitors should be of decent quality, and small variance in capacitance can play a major role in the resonant frequency of the network.

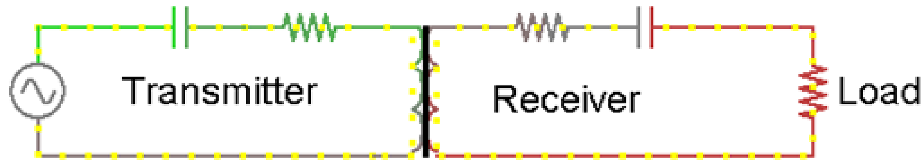


Figure 4.3.1 - Model of MRC Network

The resistors are simply models of ESR experienced by both the capacitors and inductors on either end as well as a model for the limitation in current given a certain AC voltage. The resistance here should be limited as much as possible, so we picked components with low internal resistance. Both the inductor and capacitor used naturally have low ESR, so this had little effect on our calculations.

The coils used also produce a small amount of parasitic capacitance. However, because the wires are thin and not completely uniform in their windings, this capacitance is low if not non-existent. It certainly wasn't high enough to be measured by our bench multimeter, which is capable of measuring in increments of 0.001pF.

While sensitive to the capacitance used in the tank network, the MRC complied with a standard ceramic capacitor pair quite nicely at 1.36nF. This was a cheap, cost-effective solution to the problem. As covered in the Amplifier section, we were also able to use this as the resonant network of our amplifier, saving us even more in components.

4.3.1 2-Coil Networks

The graph displayed in the Research section regarding efficiency of Magnetic Resonant Coupled Systems comes from the implementation of a 2-coil resonant coupling. As the name implies, there are only 2 coils: the resonant and transmitter coils. The block diagram of this circuit, including the general shape of the inductors, is demonstrated on the next page. For information on the Signal Generator and Power Amplifier stages, please see the section “RF Power Signal”. For information on the rectifier, please see the section “RF Power to DC Power”.

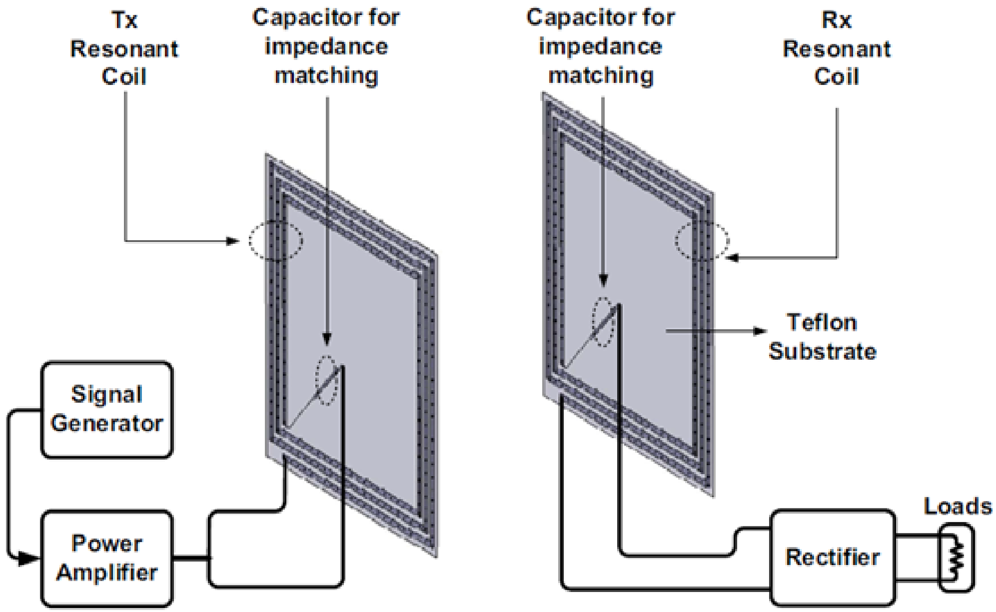


Figure 4.3.1.1 - 2-coil compact magnetic resonant coupling provided by Dr. Kim and Dr. Lee in “Design of an Integrated Wireless Power Transfer System with High Power Transfer Efficiency and Compact Structure”, hosted on IEEE Database, originally posted during the 6th European Conference on Antennas and Propagation (EUCAP) 2011, Permission Pending

Everything between the Power Amplifier and Rectifier stages can be demonstrated in Figure 4.3.1.1, but here you can get a much better idea of just how large the inductors will be compared to the rest of the components. Their large size is mostly due to the size (not necessarily value) of the magnetic field to be generated to couple the transmitter and receiver. Our research showed that strong coupling occurs anywhere between 0-1 diameters of the coils used. As a result, we chose coils with a 4-inch diameter, since this would be easy to implement on the car and would give us a good range of usable separations.

The key difference between this design and the one we’ve implemented in our design is that we couldn’t use a signal generator, the project had to be standalone. Because we planned on operating at a single frequency for the transmission of power, we could use low-profile, low-cost parts to both generate and amplify the signal, as well as to rectify it for DC loads. The main advantage to this design is that it will allowed us to maintain this low-profile design on the car since there are only two inductors, with only one of those on the vehicle followed by the UC3610N Schottky Diode Bridge discussed previously. But, this isn’t the only known way to implement this type of WPT circuit.

Furthermore, the simplicity of this design is in and of itself another advantage. This is a simple circuit that has been demonstrated to work, so why complicate it? Well, first we considered whether or not other designs might wind up being more efficient, even if they are more complex. Generally, this isn’t the case, since a simpler design will mean fewer components to consume power as well as fewer constraints or sources of error. In any case, it was worth a look.

4.3.2 4-Coil Networks

One such design is the 4-coil resonant network. In this architecture, there are 4 coils: the power coil, send coil, receive coil, and load coil. The 4-coil network expands the transmitter to power and send, while expanding the receiver to receive and load coils. The goal behind this design is, much like changing the distance, to avoid the negative effects of mutual inductance and achieve, theoretically at least, a much higher efficiency design. While this design was something to consider, one of the major problems it presents for our design was that it isn't nearly as low-profile as the 2-coil planar inductor system above. For comparison, there is a visual representation of a 4-coil resonant network on the bottom of this page.

So, when all of these factors are weighed together, we saw that while a 4-coil resonant network presents a higher efficiency, its geometry was inherently too flawed for our design purposes. There is no point in a higher efficiency if it will either cause our car to consume even more energy in its normal operation cycle from the additional weight, or to have part of it collide with the ground. Therefore, unless a more compact version of the 4-coil network presents itself, we chose the 2-coil network model.

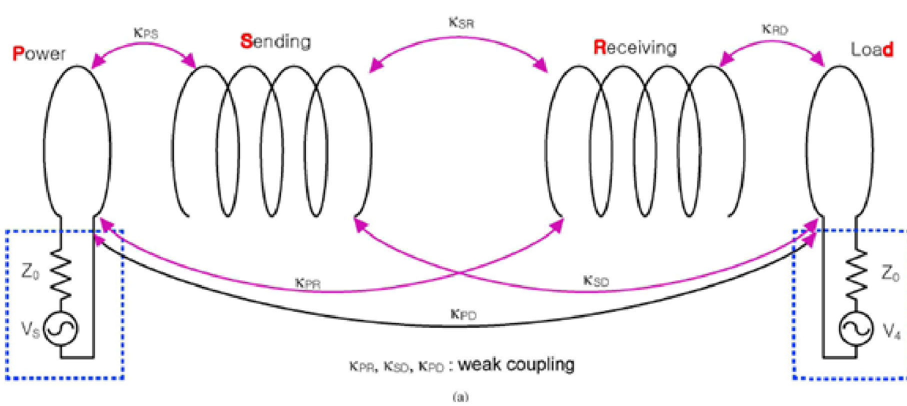


Figure 4.3.2.1 - 4-coil resonant network, from “Circuit-Model-Based Anaylsis of a Wireless Energy-Transfer System via Coupled Magnetic Resonance” presented by IEEE Transactions on Industrial Electronics Vol. 58, No. 7, provided courtesy of IEEE, Copyright 2011, Permission Pending

4.4 RF Power to DC Power

High Frequency AC to DC converters are used in everyday life with many applications toward communications and, as our project, wireless power transference. When dealing with high frequency applications much more consideration has been taken into the development and design of the circuit. This is due to the behavior of each component and how they change as a function of frequency.

Our project calls for a means of receiving the a signal ranging at 3.2 MH and once again, create a pure DC signal but this side of the grass will have requirements that differ from the first because our operating frequency. A perfect example of this would be a capacitor whose impedance is inversely related to frequency that it experiences.

The previous design called for the same implementation at a frequency in the tens of hertz. This means that the diodes acted like diodes. Diodes themselves also have a frequency response such that as frequency increases, so does their ability to exhibit internal capacitive properties. This plays a big role in their ability to go into reverse cutoff such that the reverse recovery time is longer. Since the diodes can no longer act like diodes, we must implement a different topology for switch new components for the diodes

The Schottky diode is a special kind of diode manufactured with specific properties such that that

- They have an extremely fast reverse recovery time
- The have a very low forward voltage drop
- They can operate at high frequencies with little change in capacitive properties

These specific properties can be taken advantage of in making efficient power supplies that are under high frequency conditions. Consider the Full Wave Bridge Rectifier using 1N4000 Series diodes. If we bring this implementation into the megahertz range the 1N4000's cannot keep up with the demand of the quickly changing direction in the current. This will lead to sudden voltage spikes towards a 0V instead of staying at a constant positive voltage.

Now, if the 1N4000s are replaced with Schottky diodes, they will have the ability to constantly change bias directions such that a full wave rectification can occur along with the fully and constantly charging smoothing capacitor can charge and discharge at a rate such that the output is a direct power signal.

We didn't need to use a filter capacitor specifically to rectify the signal because our design is charging an array of supercapacitors anyway. If we were to add a filter capacitor, it would do very little to rectify this circuit. Instead, whenever the full-wave rectified signal was low, the charge would immediately drain from this filter capacitor into the the supercapacitor array, so we will leave this filter capacitor out.

We ultimately went with the UC3610N Dual Schottky Diode Bridge. This rectifier bridge is ideal because it can handle up to 50V and 3A of current. If we decide to go with a higher power model in the future, we can see about upgrading these Schottky Diodes for another version that can tolerate more current, but these work well for our purposes.
This component is constructed with schottky diodes with a reverse recovery time <100ns. Since our design is going to be done with a frequency of 3.2 MHz in mind, we couldn't ask for much better in terms of frequency response. This, along with the high power tolerance, are the important elements we're looking for.

Four of these diodes within the IC are put in a standard bridge configuration to give a full-wave rectified signal to the supercapacitor array, and thus allow it to charge at a relatively quick rate without absorbing too much in forward voltage or in power. This IC is relatively small and is an ideal size for mounting on the car.

4.5 Capacitor Array

The design of our capacitor array was fairly simple. Originally, we planned to have 3 supercaps in series, and two of these 3-cap series in parallel. The 2 in series is little more than trying to store more energy; we could just as well have used 3, 4, 5, etc. of these 3-cap series in parallel to get more energy, but we ultimately went with only 1 series to avoid overloading the car with weight. However, the choice to put 3 caps in series was not a coincidence or matter of convenience.

We specifically picked 3 supercaps because 8.1V is a good value to shoot for, since each of these caps can hold a maximum of 2.7V. We want some voltage above the 6V threshold for the car with some wiggle room due to the dropping voltage of the capacitors as they lose charge. When actually designing this device, we may be able to increase the number of caps in series because we found that the car actually does not draw too much more current at higher voltage.

To allow for an even quicker charge time, without the risk of the capacitors blowing up, a warning LED was implemented using a microcontroller. Two analog inputs on an Atmega 328p were used to read the potential across the supercapacitor series, which would light an array of LEDs to display how much voltage was left. If 8V was reached, a final warning LED lit to display that charging should be ceased.

The car was detected through the use of a momentary switch. If the switch is depressed, a microcontroller on the base station allowed the VCO to operate, thus giving a signal to the amplifier. If the switch was no longer depressed, meaning the car left the station, the VCO shut off and little/no power was consumed. Certainly, this power level was low enough to cease charging.

It should also be noted that it takes even longer (in the ballpark of about two times) to charge the capacitors the first time to give them the initial charge that will provide them with their base voltages of roughly 4.2V, which the car cannot use. On the bottom of this page is a graphical representation of what our circuit will charge like.

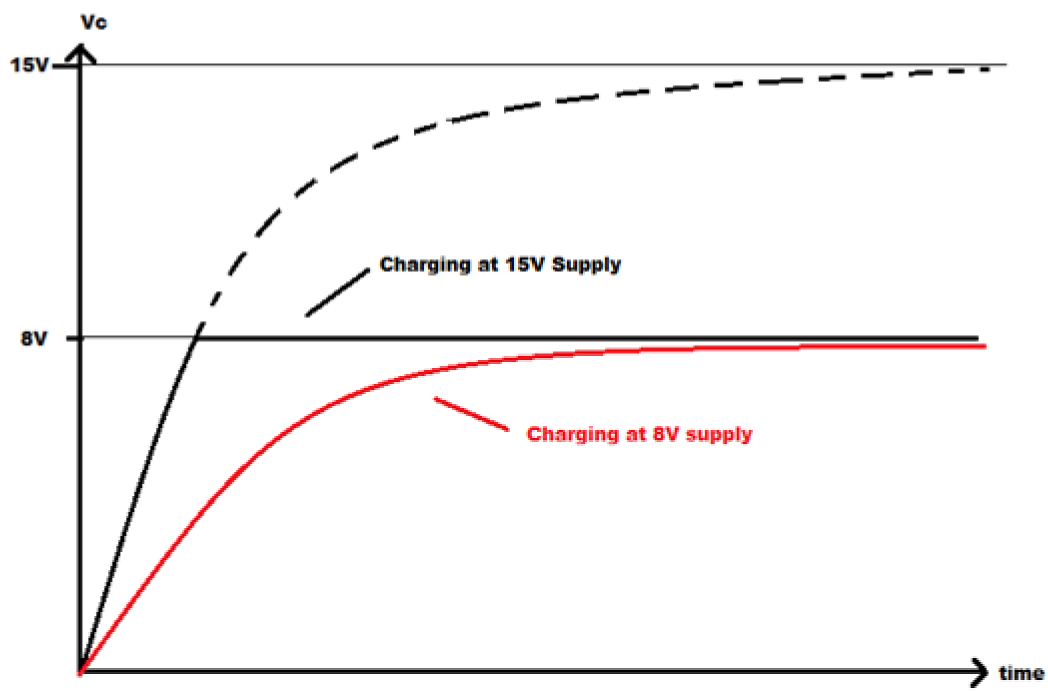


Figure 4.5.1 - Charge rate for our capacitor array

So why does this design work? This design is based around the exponential nature of capacitor charging. Capacitors build voltage as they charge until they either blow or (more ideally) reach the provided voltage value. The time it takes to reach this DC voltage value is considered asymptotic because of the vicious cycle the capacitor reciprocates.

By charging to a higher voltage, less voltage is put across the ESR the capacitor experiences, which slows the current flow into the capacitor, which slows its charge rate. The specific charge rate of each capacitor is done using a time constant, or the resistance the capacitor experiences times the capacitance (T = RC).

Generally, after 3-4 time constants, the capacitor is considered to be charged fully, but even this is time consuming. Instead, we greatly increased the supply voltage to make the capacitor shoot up to the desired voltage in less than half the time. To avoid capacitor malfunction, we've implemented a warning LED as discussed previously to avoid an overcharge.

Originally, we opted for a way to automatically shut off the charging station in a schematic like the one shown below which details an early model, but instead decided it was an unnecessary feature that would have taken time away from the production of more crucial features once we found ourselves pressed for time. Perhaps in a future implementation this will be added. One consideration was using a transistor as the "Protector", but we didn't have any readily available once we got around to this feature.

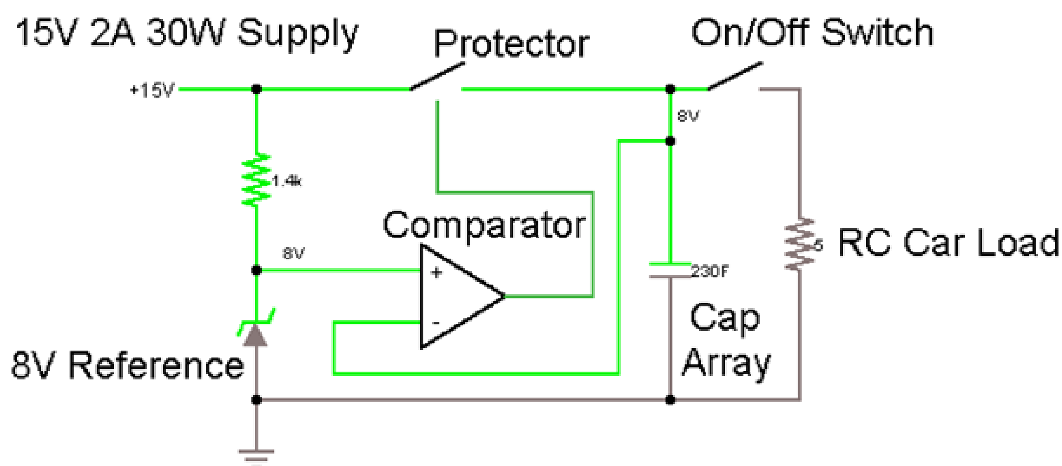


Figure 4.5.2 – Protector Circuit, A comparator shuts off the charging mechanism when the voltage is approaching dangerous levels.

When the Charging circuit is connected, and the capacitor is not fully charged, the protector switch closes and allows the capacitors to charge. However, when the cap is fully charged 8V, the comparator will open the switch and leave the capacitor strictly connected to the car.

We wouldn't have needed to worry about the comparator closing the switch again during normal operation, and it will automatically stay open when power is lost. Even if it were to leave the pad with the protector switch closed, there would be no power being transmitted to the capacitor, so there is still no danger.

One of the things we originally worried about was that at higher voltages, the capacitors would cause the car to draw more current, potentially damaging the car and causing the capacitors to run out of current much faster. However, in our testing, we discovered that the car draws a set amount of current, and that it operates well at 8V.

Below is a circuit diagram for an early analog model of a low-power warning. This was designed when we thought the car would cease to function shortly after reaching 6V. Using a voltage divider to halve the voltage read on the capacitors, when the comparator detected 3V, the low-power LED would light up to tell the user it's time to recharge. We instead implemented this with the microcontroller on the car.

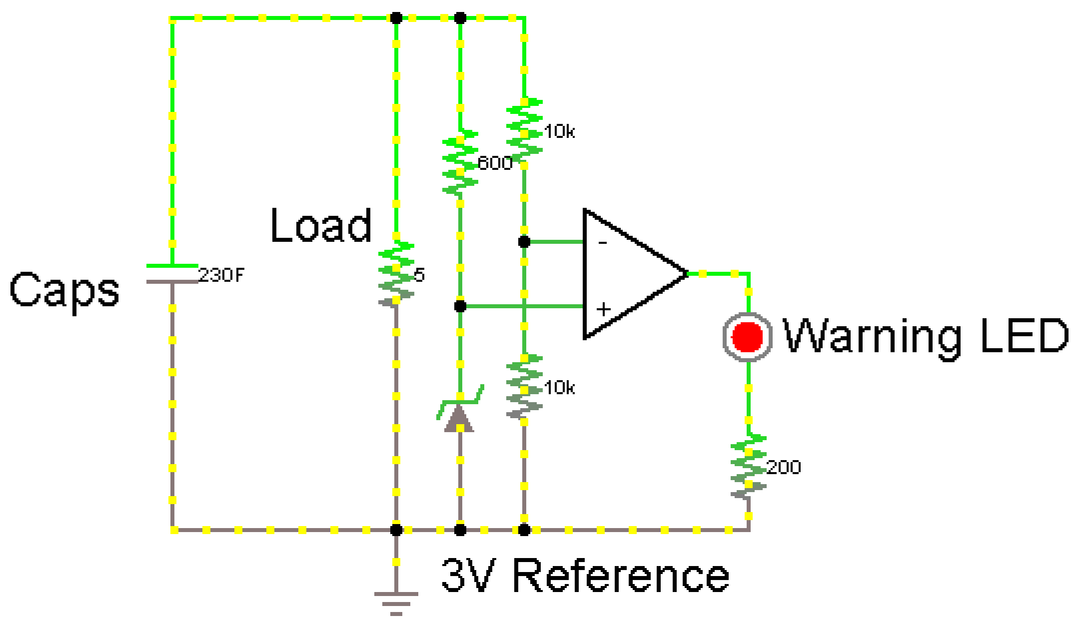


Figure 4.5.3 - LED Warning Circuit, A simple comparator circuit with a voltage divider and a voltage reference to monitor voltage

The specific capacitors we chose were 3 Maxwell Technologies BCAP0350's. These are Super Capacitors rated at 350F, 2.7V. By placing 3 of these in series, we will have an equivalent capacitor of approximately 117F and 8.1V. Below is some of the datasheet information relative to this specific capacitor model.

POWER & ENERGY	BCAP0310	BCAP0350
Usable Specific Power, P_d[5]	6,600 W/kg	4,600 W/kg
Impedance Match Specific Power[6]	14,000 W/kg	9,500 W/kg
Specific Energy, E_{max}[7]	5.2 Wh/kg	5.9 Wh/kg
Stored Energy[8]	0.31 Wh	0.35 Wh
LIFE		
High Temperature[1] (at Rated Voltage & Maximum Operating Temperature)	1,500 hours	1,500 hours
Capacitance Change (% decrease from minimum initial value)	20%	20%
ESR Change (% increase from maximum initial value)	100%	100%
Room Temperature[1] (at Rated Voltage & 25°C)	10 years	10 years
Capacitance Change (% decrease from minimum initial value)	20%	20%
ESR Change (% increase from maximum initial value)	100%	100%
Cycle Life[1,9]	500,000 cycles	500,000 cycles
Capacitance Change (% decrease from minimum initial value)	20%	20%
ESR Change (% increase from maximum initial value)	100%	100%
Test Current	31 A	35 A
Shelf Life[1,10] (Stored uncharged up to a maximum storage temperature)	2 years	2 years
SAFETY		
Short Circuit Current, typical (Current possible with short circuit from rated voltage. Do not use as an operating current.)	1,200 A	840 A
Certifications	UL810a, RoHS	UL810a, RoHS

Figure 4.5.4 Supercapacitor Datasheet from Maxwell Technologies, Functional Info, Courtesy of Maxwell Technologies, Copyright 2013, Permission Pending

We chose this specific model because we want a large capacitance in a model that isn't expensive and that will be able to deliver at least 1.4A of current. In this case, we have a shown storage of 0.35Wh per cap. Since our car battery stores 4.2Wh of energy, and each cap is 0.35Wh, 3 of these in an array will leave us with just over 1Wh, which is a fourth of the battery's energy storage. However, the useable amount of energy is only three quarters of this because the capacitors shut the car off at 4.2V. Since energy in a capacitor is relative to volts-squared:

$$E_{useable} = E_{total} - E_{remaining}$$

$$0.5*C*V_u^2 = 0.5*C*V_t^2 - 0.5*C*V_r^2$$

$$V_t = 8V, V_r = 4.2V$$

$$E_{useable} = E_{total} - 0.276*E_{total}$$

$$E_{useable} = (1 - 0.276)*E_{total}$$

$$E_{useable} = 0.724*E_{total}$$

Figure 4.5.5 - Equations to determine useable voltage within capacitor array

Applying this set of formulas to our stored energy max given on the datasheet, we can see we will only be able to use 0.76Wh of energy from the capacitors. This is about 18.1% of the energy stored in the default battery. Since the battery gave us roughly 48 minutes of constant run time, this would mean would capacitors should give us as much as 8.5-9 minutes. However, this 48 minutes was done with the car lying on its back, not having a load applied to its wheels, and both letting its wheels run and constantly applying and reapplying turning. Even then, it was a constant draw from the car, so that would be a fair simulation for the average use of the car. Since our original hope was to get 5 minutes of run time out of the car, this was more than an acceptable run time.

Also on the table is the number of recharges allowed within the cap's life cycle. At 500,000, this is a ridiculous number of recharges compared to your average battery pack, which is guaranteed to less than 1000 recharges. While building a pack of these supercaps might be expensive upfront, chances are the car is going to need replacement before your capacitor array will.

Furthermore, if the current draw should heat up the caps, or if recharging them does, they're safe at high temperatures for up to 1500 hours. If we were to factor in both recharge time, and run time, and extra time it takes for the caps to cool down after each of these types of operations, we have a liberal estimate of 30 minutes. In reality, this time would be closer to 20 minutes. Even using that 30 minute figure, that's 3000 recharge cycles, assuming the cap always gets to max temp every time.

One of the issues with the capacitors is their change in capacitance. For the demonstration of this project, this isn't an issue, but for long-term use, this becomes a problem. The capacitors will experience a 20% loss in capacitance over their lifecycle. After a few years, this makes their maximum voltage 7.2V.

For an actual product, we would mostly likely have to use a 4-cap series with 2 of these series in parallel. The total energy storage of such an array would be

2.8Wh, 66% of that of the battery pack. Applying the same formula set as the last page, where Vtotal now becomes 10.8V, we assume to safely charge the cap to 10.5V, which will give us a useable energy equal to about 82% of the total. We would be able to get more than 20 minutes of run time out of such an array, at the cost of additional space, weight, and money. It also negates the worry of capacitance change causing the array to be unable to run the car.

ELECTRICAL	BCAP0310	BCAP0350
Rated Capacitance[1]	310 F	350 F
Minimum Capacitance, initial[1]	310 F	350 F
Maximum ESR $_{DC,}$ initial[1]	2.2 mΩ	3.2 mΩ
Rated Voltage	2.70 V	2.70 V
Absolute Maximum Voltage[11]	2.85 V	2.85 V
Maximum Continuous Current ($\Delta T = 15°C$)[2]	25 A_{RMS}	21 A_{RMS}
Maximum Continuous Current ($\Delta T = 40°C$)[2]	41 A_{RMS}	34 A_{RMS}
Maximum Peak Current, 1 second (non repetitive)[3]	250 A	220 A
Leakage Current, maximum [4]	0.45 mA	0.30 mA
TEMPERATURE		
Operating temperature range (Cell case temperature)		
Minimum	-40°C	-40°C
Maximum	65°C	65°C
Storage temperature range (Stored uncharged)		
Minimum	-40°C	-40°C
Maximum	70°C	70°C
PHYSICAL		
Mass, typical	60 g	60 g
Terminals	Radial Tab	Radial Tab
Vibration	IEC 60068.2.6, SAE J2380	IEC 60068.2.6, SAE J2380
Shock	IEC 60068.2.27, SAE J2464	IEC 60068.2.27, SAE J2464

Figure 4.5.6 Supercap Datasheet from Maxwell Technologies, Physical Info Courtesy of Maxwell Technologies, Copyright 2013 (Permission Pending)

For our power draw, we can see that the caps run safely up to 34A. At room temperature, however, this maximum current draw is roughly 24A. This means that our only charge time limitation is just how powerful our charging mechanism we're using. For the scope of our project, the goal is just to get a working model for wireless power transfer, efficiency will come with future iterations.

Assuming we were able to charge the cap at 24A, though, and assuming a 15V DC charging voltage, we could charge the caps at 205 mV/s approximately, which translates to less than 20 seconds to fully charge the capacitors. 24A is an extremely large amount of current, though. In the Senior Design lab, the bench power supply was only able to supply 5.5A max. Further still, it would be nearly impossible to find an affordable set of schottky diodes to rectify a 24A signal or a MOSFET capable of withstanding high enough voltage swings generated by such a signal.

The cap is also safe to 2 years of shelf-life unused before going bad, which boasts an inactive lifespan as long as most batteries can last in an active manner. A combination of use and rest for these caps could see more than 5 years of use, while most batteries are bad after 3 years of use at most.

The caps are relatively light, weighing 60g a piece. 3 of them is a total of 180g. The previous battery pack for the RC car was about 400g, so we're actually removing weight from the car. While this won't show a significant improvement in performance, it at least means we're not presented with an issue of load on the car. Other components are fairly light, and so our circuit complied with the requirement of not obstructing vehicle's performance.

4.5.1 Capacitor Protector Circuit

While not actually implemented in our design, one of our largest considerations was the capacitive protector circuit. This circuit would ensure absolutely that the capacitors would not malfunction as a result of overvoltage. While this is something we'd like to implement in a future design due to its entirely passive nature (not to be confused with entirely passive components), we felt that it was of little priority for this iteration. We were able to implement less time-consuming measures that cost roughly the same, though they require constant user awareness. This section discusses how we would implement such a protector circuit in future iterations. Shown on the next page is what this circuit looks like again as a refresher.

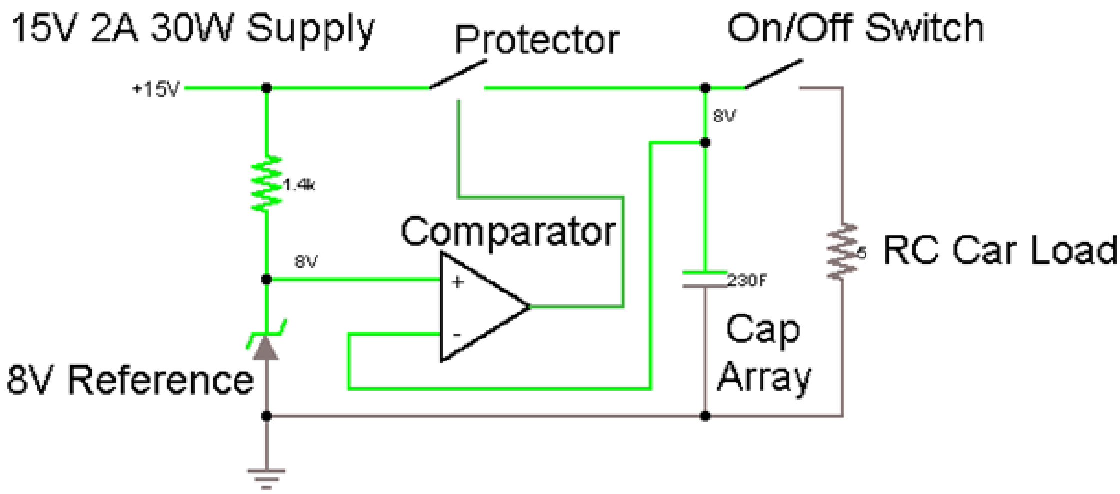


Figure 4.5.1.1 Capacitor Protector Circuit Model

We have two ways of doing the voltage reference: resistors or a precision voltage reference circuit. The advantage of the resistor-based voltage divider circuit is that it is considerably cheaper and less part-intensive. However, it merely divides the voltage, it does not guarantee the output of the branch. A reference would take twice as many resistors, and possibly an op-amp, but will be a safer option. Before we can come to a decision, we will consider both types of circuits and decide in the future which one is better for our operations.

If done with a voltage reference, we have to consider an op-amp as well. This is because there are no 8V references. There are 8.192V references, but that's still a bit high and would go over the rated voltage of our caps. Instead we can use a circuit like the one shown on the next page. This circuit just uses a 5V reference and passes it through an op-amp with a gain of 1.6 to bump it up to 8V. The 5V reference we are using is the TI LM4040A50 5V Precision Micropower Shunt Voltage Reference. The relevant information from the datasheet is below:

Recommended Operating Conditions

			MIN	MAX	UNIT
I_Z	Cathode current		(1)	15	mA
T_A	Free-air temperature	LM4040xxxI	–40	85	°C
		LM4040xxxQ	–40	125	

Figure 4.5.1.2 - LM4040A50 5V Precision Micropower Shunt Voltage Reference Recommended Operating Conditions courtest of Texas Instruments, Copyright 2009 All Rights Reserved

As we can see here, the cathode current of the voltage reference is 15mA. Planning around this, we can set the resistor preceding it in our design to supply it with the proper 15mA current using KVL. Even then, in this next table, we can see that 15mA is not required:

LM4040x50Q Electrical Characteristics

at extended temperature range, full-range T_A = –40°C to 125°C (unless otherwise noted)

PARAMETER		TEST CONDITIONS	T_A	LM4040C50Q			LM4040D50Q			UNIT
				MIN	TYP	MAX	MIN	TYP	MAX	
V_Z	Reverse breakdown voltage	I_Z = 100 µA	25°C		5			5		V
ΔV_Z	Reverse breakdown voltage tolerance	I_Z = 100 µA	25°C	–25		25	–50		50	mV
			Full range	–75		75	–125		125	
$I_{Z,min}$	Minimum cathode current		25°C		65	89		65	89	µA
			Full range			95			95	

Figure 4.5.1.3 - LM4040A50 Precision Micropower Shunt Voltage Reference Electrical Characteristics as provided courtesy of Texas Instruments, Copyright 2009 All Rights Reserved

The listed minimum cathode current is as high as 95 microamps, or about 0.01mA. This means we are able to supply our voltage reference with as low as this value and still get our precision reference. While 14mA difference might not seem like much, when it comes to waiting for our capacitors to charge, it will actually mean a 1% difference. When applied to a 10 minute wait time, it will mean our caps could charge several seconds faster. Not much of a difference in the grand scheme of things, but an improvement is an improvement. Designing this around a 15V source with a 5V reference means 10V across the resistor preceding the voltage reference. Applying ohm's law, we see that this resistor should be 10k-ohms to get our 1mA desired value for the forward current through the voltage reference.

We could also use a voltage divider to limit the supply to the op-amp to 8V instead of having to use a voltage reference, but again, you run into the issue of having to adjust it if the supply voltage goes over 15V. Instead of having to worry about any of that, we just went with the following circuit:

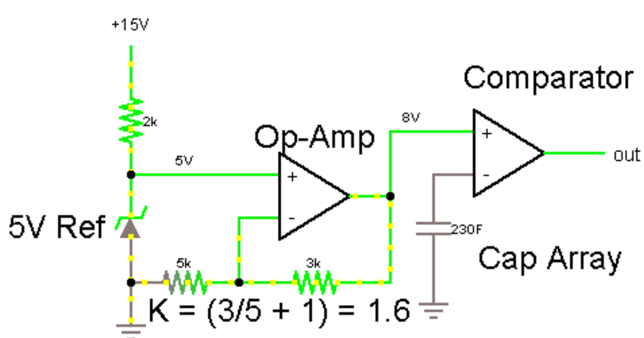


Figure 4.5.1.4 Voltage Reference circuit using Op-Amp

Note that there is a 2k-ohm resistor preceding the 5V reference. This is because this simulation software assumes the voltage reference requires a 5mA forward current to be precise. The 8V reference provided by the combination of the 5V reference with the Op-amp, goes to the + input of the Comparator. The output of the comparator will trigger a power MOSFET that allows for the power supply to deliver current to the cap array. The - input of the comparator monitors the voltage of the Cap Array and shuts it off once 8V has been reached.

If we do decide to make our design solely with resistors, our voltage reference is to be done with a simple voltage divider circuit. This is because comparators have an extremely low input current, especially when compared to how much current could be passed reliably through a resistor. Rather than using a precision voltage reference as per the circuit shown previously for the protector, we are going to use a voltage divider circuit. This is because a voltage divider circuit would require more components and is unnecessary. Considering we want resistors that are inexpensive and going to allow us to skip using a voltage reference, we need resistors that aren't so high in value that their low current will make voltage division inaccurate due to the small, albeit existent, input current of the comparator. At the same time, if the resistance is too low, then they consume power as well as heat up. However, before considering which resistors to pick, we first looked at exactly what our input current would be on our comparator.

The comparator we picked is the TI LM397 Single General Purpose Voltage Comparator. It is a low-power comparator, which is important considering our design needs all the power it can get. On the next page is the relevant information from the datasheet for the LM397. The beauty of using a comparator like this is that it can be used to power a power MOSFET later, which will act as our switch. This is good because the voltage being supplied can be manipulated to allow more current to flow. This comparator will also require a pull-up resistor, but that's something we'll cover in another section.

Absolute Maximum Ratings (1)(2)

ESD Tolerance (3)	Human Body Model	2KV
	Machine Model	200V
V_{IN} Differential		30V
Supply Voltages		30V or ±15V
Voltage at Input Pins		−0.3V to 30V
Storage Temperature Range		−65°C to +150°C
Junction Temperature (4)		+150°C
Soldering Information	Infrared or Convection (20 sec.)	235°C
	Wave Soldering (10 sec.)	260°C

Figure 4.5.1.5 LM397 Maximum Rating Information courtesy of Texas Instruments, Copyright 2008 All Rights Reserved

As shown above, the comparator will work for up to +30V reference. Since our comparator will not need a negative low output, this means we can later configure our device to work with more power if we so desire. It also means that it's completely within our current voltage supply value. The comparator is also resistant to heat, which shouldn't present a problem but is a nice bit of added security. The input voltages are also well within our range. We should only have up to 8V on both input pins, so the 30V input allowance is plenty.

Operating Ratings (1)

Supply Voltage, V_S		5V to 30V
Temperature Range (2)		−40°C to +85°C
Package Thermal Resistance (2)	5-Pin SOT-23	168°C/W

Figure 4.5.1.6 LM397 Operation Ratings Information courtesy of Texas Instruments, Copyright 2008 All Rights Reserved

From this information, we can see that the LM397 will operate well within our temperature range. At 85 degrees celsius, we would have a larger concern for other components malfunctioning before the comparator did. The supply voltage values are also nice. If we decide we need to lower the output voltage for whatever reason, we can lower the supply voltage down to 5V to limit the output to 5V as well.

Electrical Characteristics

Unless otherwise specified, all limits are ensured for T_A = 25°C, V_S = 5V, V^- = 0V, V_{CM} = $V^+/2$ = V_O. **Boldface** limits apply at the temperature extremes.

Parameter		Test Conditions	Min (1)	Typ (2)	Max (1)	Units
V_{OS}	Input Offset Voltage	V_S = 5V to 30V, V_O = 1.4V, V_{CM} = 0V		2	7 **10**	mV
I_{OS}	Input Offset Current	V_O = 1.4V, V_{CM} = 0V		1.6	50 **250**	nA
I_B	Input Bias Current	V_O = 1.4V, V_{CM} = 0V		10	250 **400**	nA
I_S	Supply Current	R_L = Open, V_S = 5V		0.25	0.7	mA
		R_L = Open, V_S = 30V		0.30	2	
I_O	Output Sink Current	V_{IN}^+ = 1V, V_{IN}^- = 0V, V_O = 1.5V	6	13		mA
$I_{LEAKAGE}$	Output Leakage Current	V_{IN}^+ = 1V, V_{IN}^- = 0V, V_O = 5V		0.1		nA
		V_{IN}^+ = 1V, V_{IN}^- = 0V, V_O = 30V		1		µA
V_{OL}	Output Voltage Low	I_O = −4mA, V_{IN}^+ = 0V, V_{IN}^- = 1V		180	400 **700**	mV
V_{CM}	Common-Mode Input Voltage Range	V_S = 5V to 30V (3)	0 **0**		V_S - 1.5V **V_S - 2V**	V
A_V	Voltage Gain	V_S = 15V, V_O = 1.4V to 11.4V, R_L > = 15kΩ connected to V_S		120		V/mV
t_{PHL}	Propagation Delay (High to Low)	Input Overdrive = 5mV R_L = 5.1kΩ connected to 5V, C_L = 15pF		900		ns
		Input Overdrive = 50mV R_L = 5.1kΩ connected to 5V, C_L = 15pF		250		
t_{PLH}	Propagation Delay (Low to High)	Input Overdrive = 5mV R_L = 5.1kΩ connected to 5V, C_L = 15pF		940		µs
		Input Overdrive = 50mV R_L = 5.1kΩ connected to 5V, C_L = 15pF		440		ns

Figure 4.5.1.7 LM397 Electrical Characteristic Information provided by Texas Instruments, Copyright 2008 All Rights Reserved

The offset voltage is also very low, up to 10mV. Considering the voltages we're dealing with, this isn't much. The offset current is also extremely low, as high as 250 nA. The input bias current was our main concern with this. Too high, and it would mean we would have to have more current in our voltage divider reference branch for the comparator. However, it is as low as 10nA. Even if we were to use 15k-ohms total in our reference branch, this is still only a variation by

0.001%. At that point, resistor precision is the bigger concern. Propagation delay isn't as important for us, mainly because this circuit isn't being designed to change much, let alone at a high enough frequency to be an issue. Still, low delay is nice. The gain could be higher, it would mean less rise time, but it's still not much of a concern since the capacitor takes so long to gain voltage compared to the switch time.

The main reason for choosing this one specifically is its low power requirements and its low bias/offset currents. This will help to ensure that our voltage reference stays accurate. Accuracy is crucial here because of what it means to the capacitor array that's being charged. If the reference is too low, the capacitors don't charge as long as they could, so operating time is reduced; too high, and the capacitors overcharge, which could be disastrous to the project or whoever's operating it. Seeing as we now have a good comparator to use, now we'll look at what resistors we want to use. First, let's consider a few things.

We know the resistors need to be the right value. As stated before, too low and they will heat up too much. Too high, and the bias current will start to interfere. The power they consume isn't much of an issue, since this is coming directly from our source. Later, there will be another voltage reference circuit using voltage divider where power consumption is an issue, but we'll cross that bridge when we come to it. The reference needs to be 8V, and we're planning around a 15V supply. So, given 2 resistors, R1 and R2, we'll need R1 to be 7/8ths of R2. At 1mA of current, the entire branch itself would only experience 15mW of power, well within the range of even 8th-watt resistors. If we can guarantee the DC supply is 15V at this stage, we could easily just use those proportional resistor values.

The "switch" in our circuit will actually be a power MOSFET. Voltage is provided at its gate when the comparator is high, which will only happen when the cap needs more charge. Once the cap is "full", the comparator shuts off the MOSFET and stops supplying current to the caps. This MOSFET must adhere to a few conditions. First, we are picking a FET for this application because a BJT is current controlled, and a comparator will only emit so much current. However, we can manipulate the output voltage of the comparator to just turn on the MOSFET and let it try to pump as much current as possible into the caps. Extra current would only mean the caps would charge faster, which is always a plus. The MOSFET must therefore also be able to handle a large flow of current, something that can handle >3A would be ideal. Fast switching speed isn't necessary, and can be sacrificed in this case. We also need the MOSFET to have a maximum drain-to-source voltage of at least 15V, preferably closer to 30V. If the source is attempting to conduct to the caps with nothing present, the 15V is going to be consumed by the FET itself, therefore we need a Vdss greater than that to avoid the FET breaking when the charger is on but not charging. Given these criteria, we picked the SI2300 N-Channel MOSFET. Relevant information is as follows:

ABSOLUTE MAXIMUM RATINGS T_A = 25 °C, unless otherwise noted				
Parameter		**Symbol**	**Limit**	**Unit**
Drain-Source Voltage		V_{DS}	30	V
Gate-Source Voltage		V_{GS}	± 12	
Continuous Drain Current (T_J = 150 °C)	T_C = 25 °C	I_D	3.6[a]	A
	T_C = 70 °C		3.0	
	T_A = 25 °C		3.1[b, c]	
	T_A = 70 °C		2.5[b, c]	
Pulsed Drain Current		I_{DM}	15	
Continuous Source-Drain Diode Current	T_C = 25 °C	I_S	1.4	
	T_A = 25 °C		0.9[b, c]	
Maximum Power Dissipation	T_C = 25 °C	P_D	1.7	W
	T_C = 70 °C		1.1	
	T_A = 25 °C		1.1[b, c]	
	T_A = 70 °C		0.7[b, c]	
Operating Junction and Storage Temperature Range		T_J, T_{stg}	- 55 to 150	°C
Soldering Recommendations (Peak Temperature)[d, e]			260	

Figure 4.5.1.8 SI2300 N-Channel Power MOSFET, Datasheet information provided courtesy of Vishay Siliconix, Copyright 2011 All rights reserved

As shown on the datasheet, the Vds max of this FET is 30V, well above our required voltage. The max continuous drain of the FET is 3.1-3.6A, again, above our requirements. Lastly, the FET will only consume up to 1.7W, which means it's also not consuming too much wattage. These stats mean that this is a good MOSFET for our general purposes, now let's see how well it will interact with our other components. Below is the relevant information from the datasheet provided by Vishay Siliconix.

SPECIFICATIONS T_J = 25 °C, unless otherwise noted						
Parameter	**Symbol**	**Test Conditions**	**Min.**	**Typ.**	**Max.**	**Unit**
Static						
Drain-Source Breakdown Voltage	V_{DS}	V_{GS} = 0 V, I_D = 250 µA	30			V
V_{DS} Temperature Coefficient	$\Delta V_{DS}/T_J$	I_D = 250 µA		21		mV/°C
$V_{GS(th)}$ Temperature Coefficient	$\Delta V_{GS(th)}/T_J$			- 3.2		
Gate-Source Threshold Voltage	$V_{GS(th)}$	V_{DS} = V_{GS} , I_D = 250 µA	0.6		1.5	V
Gate-Source Leakage	I_{GSS}	V_{DS} = 0 V, V_{GS} = ± 12 V			± 100	nA
Zero Gate Voltage Drain Current	I_{DSS}	V_{DS} = 30 V, V_{GS} = 0 V			1	µA
		V_{DS} = 30 V, V_{GS} = 0 V, T_J = 55 °C			10	
On-State Drain Current[a]	$I_{D(on)}$	$V_{DS} \geq 5$ V, V_{GS} = 10 V	10			A
Drain-Source On-State Resistance[a]	$R_{DS(on)}$	V_{GS} = 4.5 V, I_D = 2.9 A		0.055	0.068	Ω
		V_{GS} = 2.5 V, I_D = 2.6 A		0.070	0.085	
Forward Transconductance[a]	g_{fs}	V_{DS} = 15 V, I_D = 2.9 A		13		S

Figure 4.5.1.9 SI2300 N-Channel Power MOSFET Static Specs provided on datasheet, courtesy of Vishay Siliconix, Copyright 2011 All rights reserved

This table shows a threshold voltage that can be supplied by our comparator, so our design will work. The FET is also a very low resistance, which is good. We don't want the fet to take up too much power. The FET also only supplies 1-10 microamps of current when it's off, which is acceptable. This means the caps are not building voltage, and would in fact be losing it faster than they are gaining it through this leakage, seeing as the leakage current of our caps is 0.3mA. For these reasons, we are using the SI2300 N-Channel MOSFET as our protector switch.

As this section details, there is a lot of consideration that must go into designing such a passive circuit, and should explain why we opted for using a microcontroller to implement a warning system. One semester doesn't afford us much time, so more crucial components were considered first and an acceptable substitution was made to prevent capacitor malfunction. Something else to consider is that current electric vehicles do not use capacitors, so such a system isn't even necessary on a full-sized electric vehicle if this system does become modular.

4.5.2 LED Low Voltage Warning

Similar to our high-voltage warning system, we attempted to implement a passive low-voltage warning system to let the user know when to begin recharging. For the same reasons, we decided to instead implement this in the microcontroller. However, if we are attempting to avoid using a microcontroller altogether, this could accompany the previous circuit to help avoid the need for one while performing the same tasks. This circuit was implemented into the microcontroller by flashing the lowest LED of the array which displays remaining voltage. Below 4.4V, the last LED of the array flashed to let the user know the car will die in short order. This section discusses the circuit considered to implement this in a design which does not utilize a microcontroller, which is also something we may consider in future iterations. It takes into account the fact that the supply voltage of the capacitor is constantly lowering with time.

In the case that the voltage of the caps is reaching a value too low for normal operation, we originally attempted this advanced-notice warning light. The 3V reference may be adjusted to a slightly higher value, such as 3.1V, to alert the user before the car is about to stop functioning, or it can be left at 3V to let the user know when the car has stopped functioning simply because the voltage is too low and not due to some other malfunction. This plays well into the nature of these capacitors, which is that they will have quite a bit of leftover charge after the car can no longer function, and instead uses this to directly notify the user to recharge the array. LEDs consume very little power, as do comparators, so this system can remain active well after the car has died.

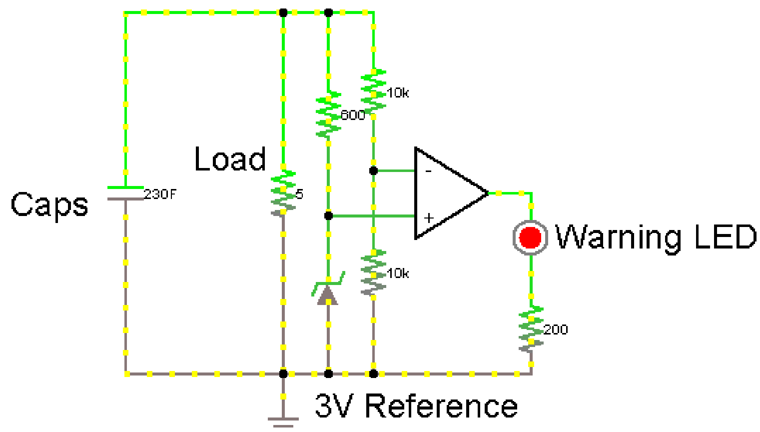


Figure 4.5.2.1 - LED Low Voltage Warning Equivalent Circuit

The comparator used would be the same as it was in the protector circuit, the LM397. We would need to choose an acceptable LED, though. The LED should be low power, but we have a lot of power left to dissipate, so low power isn't as important. Since the car will most likely be used outdoors, we want an LED that is bright, and therefore easy to see, even with a lot of ambient light. We would also need one that will be able to operate on a voltage of <5V, since that is the lowest the LM397 Comparator can run on while still giving an output. Given these requirements, we would choose the RL5-R8030 Super Bright Red LED from SuperBrightLeds.com. Red LEDs naturally have a much lower forward voltage, and are a relatively alarming color. This is the relevant information:

Part Number: RL5-R8030 - Super-Red LED (AlGaInP)			
absolute maximum ratings: (TA=25°C)			
PARAMETER	SYMBOL	RATING	UNIT
Power Dissipation	PD	80	mW
Continuous Forward Current	IF	20	mA
Peak Forward Current (1/10th duty cycle, 0.1ms pulse width)	IFM	50	mA
Reverse Voltage	VR	5.0	V
Operating Temperature	TA	-40~+85	°C
Storage Temperature	TSTG	-40~+85	°C
Reverse Current (VR=5V)	IR	10	µa
Lead Soldering Temperature (3mm from body) 260C (for 3 seconds)			

optoelectric characteristics:					
PARAMETER	SYMBOL	MAX	TYP	UNIT	TEST
View Angle of Half Power	2ø1/2		30	Degree	
Forward Voltage	VF	2.6	2.2	V	IF=20mA
Peak Emission Wavelength	ÿ P		630	nm	IF=20mA
Luminous Intensity	IV		8000	mcd	IF=20mA

Figure 4.5.2.2 RL5-R8030 Super Bright Red LED Specifications List, provided by SuperBrightLeds.com, Copyright 2013, permission pending

The LED only requires 2.2V Forward voltage with 20mA forward current, both of which are well within our requirements. Despite this, the LED is able to supply 8 candelas of luminosity, which literally hurts the eyes if observed directly in a dark room. Fortunately, LEDs have a very narrow viewing angle, so anyone not directly staring into the LED will be fine. Reverse voltage is not a concern because the LED will never experience a voltage rise, only a voltage drop. Lastly, the power consumption is good, with only 80mW of power being consumed. Given that the LED will be active as long as the capacitor array has a voltage of less than 6V and greater than 5V, this LED will have a supply of almost 2kJ at its disposal before the comparator will shut off. With this much energy, the LED can run for more than 20000 seconds, or more than 4 1/2 hours. Needless to say, this is an ample amount of warning time for the client.

The resistor for the LED needs only to hold between 3.8V and 2.8V, since the LED should consume a constant 2.2V. The LED, however, is still a diode, and will begin to consume more and more voltage as its current is higher. To avoid its forward current reaching or even exceeding its maximum rated voltage of 2.4V, we want the LED to experience no more than 20mA. To ensure that 20mA is its maximum, we must select a resistor that limits the branch to 20 mA at the maximum voltage, which is going to be 3.8V. Using ohm’s law, we can see that this is going to be 190-ohms. Since there is no standard resistor of 190-ohms, we would use the next best highest resistor, which is 220-ohms.

This will supply the LED with 17.3mA of current. At a low end, the resistor experiences 2.8V, which will mean a forward current of 12.7mA for the LED. This is actually a good thing, because the LED will actually dim as the capacitor runs out of power, acting as a way to show the user that the capacitor array is slowly running out of power. The 220-ohm resistor will experience a maximum power dissipation of 65.6mW, so an 8th-watt resistor will work just fine, though it may begin getting hot. A quarter-watt resistor might be a better idea here, just to be on the safe side.

In the case that the LED is too bright, a higher-value resistor could be used in place of the 220-ohm resistor. 17mA is a lot of current for an LED, especially a super bright one. It may be damaging to the eyes of the user. If our later testing confirms this, we can make the 220-ohm resistor a sufficient value to reduce the current enough in order to reduce the brightness. One of our members has worked with super bright blue LEDs that worked well at less than 1mA, so there is a wide range of options.

We would also need to consider the 3V Reference being used in this circuit. Similar to the one we used in the protector circuit, we will be using the LM4040A30 3V Precision Micropower Shunt Voltage Reference. The operating conditions for this reference are similar to the 5V model, but with a slightly lower minimum operating forward current. It still retains the 15mA maximum current though. Specifications for the LM4040 series maximum ratings can be seen in Figure 4.5.1.2. The specifications for the 3V model are displayed below:

LM4040x30Q Electrical Characteristics

at extended temperature range, full-range T_A = –40°C to 125°C (unless otherwise noted)

PARAMETER		TEST CONDITIONS	T_A	LM4040C30Q			LM4040D30Q			UNIT
				MIN	TYP	MAX	MIN	TYP	MAX	
V_Z	Reverse breakdown voltage	I_Z = 100 µA	25°C		3			3		V
ΔV_Z	Reverse breakdown voltage tolerance	I_Z = 100 µA	25°C	–15		15	–30		30	mV
			Full range	–45		45	–75		75	
$I_{Z,min}$	Minimum cathode current		25°C		47	77		47	77	µA
			Full range			82			82	

Figure 4.5.2.3 - LM4040A30 3V Precision Micropower Shunt Voltage Reference Electrical Characteristics as provided courtesy of Texas Instruments, Copyright 2009 All rights Reserved

The 3V model also operates at the same current range as the 5V model, but with slightly lower minimum cathode current. Arbitrarily, we picked 1mA as the minimum reference current. In doing so, the resistor preceding it in the circuit diagram needs to consume at least 3V, and will consume as much as 5V, because the reference will always take 3V, and the capacitor will have a low of 6V with a high of 8V to pass across this branch. The minimum condition here is when the resistor takes 3V, and thus must be 3k-ohms to provide the necessary 1mA current to the voltage reference. At 5V, this same resistor will cause the reference to experience approximately 1.7mA of current, well within the operating range of forward currents.

This 3V reference is going to be the + input of the comparator, and will act as a reference for the capacitor. The - input of the comparator uses a voltage divider circuit. An arbitrary value of 10k-ohms was picked, as long as both of the two resistors are the same value. This means the 3V precision reference can be checked with half the voltage. The purpose of this design as opposed to directly connecting a voltage reference to the capacitors or using a 6V model is because the capacitors are the only supply of power within the car. If the capacitor cannot give off more than 6V, the reference will only take what it can get, and may drop to a value insufficient to turn on the LED.

The value of 3V wasn't selected out of specific need, rather just an easily calculable value. If it's half of the low-end voltage, then we can just use a voltage divider with two identical resistors to check what half the voltage of the capacitor array is without having to worry about resistor proportions or trying to find some obscure value to precisely make this calculation.

Since the - input is half of the capacitor array voltage, it will have a high value of 4V and steadily decline to 3V, at which point it will light the LED. Fortunately for us l, the comparator can run as low as 5V, so the LED will be powered long after the car has shut off. For this reason, we can just get a single IC with 2 of these comparators on it, saving us space on the board as well as time needed to find another IC.
Similar to the high-voltage protector circuit, there is a bit of complexity to this circuit, and it isn't of great importance to the function of this system; it is an added feature. As a result, it was also replaced with a simpler microcontroller-

based solution. However, the components used are cheap, and if mass-produced, this passive route would cost less than implementing a microcontroller on every car.

4.6 Design of Data Acquisition

To design the microcontroller and its constituent network, some important basic requirements needed to be filled. But first, what needed to be designed:

- Microcontroller configuration and board
- High voltage sensor configuration
- Wireless communication network
- Display real-time data
- Regulate load discharge output
- Short circuit charging process
- Alert low voltage in capacitors

For each of these the responsibility at hand will be described in specific detail, which will bring in competitors who can fulfill this responsibility, then apply a design solution which can fulfill the needs of this project.

4.6.1 32-bit Compatible Microcontroller

This component served as the processor of this project by monitoring voltage levels, ascertaining control outputs from said sensor data, communicate wirelessly, and output to a visual display for oversight of the project in functionality.

A 32-bit controller is best after researching them due to the flexibility a 32-bit controller affords. They can be readdressed to configure to smaller needs, provide easier construction as the programmer can be prepared more so to code in a 32-bit instruction set, and that there are many which can fit the cost effectiveness of many lesser sized packaging while harboring more capabilities. The architecture may seem to begin with being less efficient with hardware, but all aspects of this chip can be utilized with proper programming.

What can be searched for from these companies are a few parameters like cost, instruction size compatibility, RAM, memory, clock rate, I/O, operational voltage, connectivity, peripheral compatibility, comparators, analog to digital resolution, and physical tolerances. All of these parameters can be discussed from the observation of a datasheet, with the obvious exception of pricing. For ease of use on this project and from fleshing out a lot of the basics on this project, only the best 32-bit processors will be analyzed from each of these companies for their feasibility as a useable microcontroller and software suite. From their packaging will be discussed upon determination of which chip to use later in this paper. Then, high voltage sensor configuration, display of real-time data, discharge regulation, short circuit charging, and how to alter for low voltage will all be discussed in that order, again, later in this paper.

To list important parameters, there are some parameters that are needed for determining the brains of this operation. Here after researching companies, there are four different, competing, and viable chip producers to work with, the first being NXP, an industry workhorse; Atmel, a company with an expansively large fan-base; Texas Instrument, and their starting expansion; and Microchip, who has been around since the beginning.

4.6.1.1 The Contenders

1. NXP offered, at the 32-bit compatibility level, their LCP4000 line of microcontroller as its contender with model LPC4088FET208 at $12.30 for the MCU as a manually surface mounted device (SMD) in ball pin configuration.

2. TI did not provide a microcontroller dedicated specifically at the 32-bit level for the MSP430 architecture unfortunately, but under the Hercules TMS470M in 32-bit. But this offering is aimed at automotive uses. Their best offering thus far was difficult to find under all the different types of MSP430’s out there. So after searching, their best controller was for this projects use was the 16-bit MSP430F67791X at $6.48 for the MCU alone at surface mount level.

3. Atmel offered many different microprocessors for the purpose of project utilization. Of their 32-bit variants their ARM inspired ATUC256L4U was a viable option as microcontroller candidate for the use of this project and sticking with the 32-bit size flexibility and with the benefit of a common instruction set. It was offered in a less basic packaging like a starting kit; but, as a single chip, it was offered at around $6 in a 48 pin package SMD.

4. Microchip offers in this format the PIC32MX795F512L which has an impressive amount of users behind them. Their chip is not exactly available in the stand alone package unfortunately, as it is not feasible, for the hobbyist, to tinker with one on such a small scale at surface mount level. But if it is desired, the chip is offered at the price-point of $11 in a 100 pin package at the SMD level.

With each of these choices decided upon as their prime candidates, they were placed side-by-side to determine which of them would best suit the needs of this project. It is important to note that of these models of their specific architectures, the major consideration was that they are the most complex of their architectures with regards to datasheet statistics. In values on the table of the following figure 4.7.1-1 describe some important aspects of each of their designs in a comparative set-up.

	LPC4088	MSP430F67	ATUC256	PIC32MX7
Clock(MHz)	180	25	50	80
Pin Count	208	100	48	100
Packaging	TFBGA208	100 PZ	TQFP	TQFP
CPU	Cortex-M4	MSP430	32-bit AVR	MIPS32 MK
RAM(kB)	96	32	16	128
EEPROM(B)	4096	0	0	0
I/O	165	62	36	83
Memory(kB)	512	512	256	512
EMC Bus	32-bit	None	None	None
I2C	3	2	2	5
SPI	1 (SPIFlash)	6	1	4
UART	5	4	4	6
Display	Yes	Yes	No	Yes
Timers	4	3	6	5
Comparator	2	3	8	2
A/D res.	12-bit	10-bit	12-bit	10-bit
A/D count	8	7	8	16
D/A count	1	2	0	0
Temp. (C)	-40 to + 85C	-40 to + 85C	-40 to + 85C	-40 to + 105C
V operation	2.4V to 3.6V	1.8V -3V	1.62 to 3.6	2.3V-3.6V
Cost ($)	13.50	6.48	6.00	11.00

Ethernet	Yes	0	No	0
USB	Yes	1	0	1
CAN	2	0	No	1
Debugger	Yes	Yes	Yes	Yes

Figure 4.6.1-1 Parallel comparison of four leaving 32-bit and 16-bit designs

As can be seen, each chip has a specialization in some special application, like NXP's LPC4088 series with more port adaptability towards industrial applications requiring multiple sensor inputs and outputs, or MSP30 geared for lower power consumption with lower RAM and sampling rates but an impressive for its size memory.

4.6.1.1.1 Competition I

Unfortunately, the compatibility of the MSP430 towards this project is compromised when its clock rate is seen as remarkably low as compared to Texas Instruments competitors. Albeit a low power requirement and price point, the equipment itself did not meet the physical fit of the projects needs for displaying of data quickly in real-time or maintain enough interfacing for the amount of sensors necessary. What also played a large hindrance upon choosing MSP430 for the project purpose also is the fact that the software would be significantly prices. Complementary coding can occur up to a 16Kb memory size on the MSP430's software Code Composer, but beyond this size, a big deciding factor was that to release a full version of CCS would require a $445 Single License version. To tack onto this, to prototype with this board would be an additional 50-dollar drop for the starter kit which allows for easy and preset-for-project-use format.

4.6.1.1.2 Competition II

Next to the chopping block would be Atmel's ATUC256L4U with its low clock speed and RAM. 16Kb of RAM is even lower than the RAM found in the MSP430 translating in a traditionally slower processing of instructions and data. Count on top of this, the fact that the chip is incapable of integrating a visual display; it immediately lost the possibility of use ability to this project. It is enticing to test with this microcontroller since the software is complementary to the user and compatible with the use of the MIPS32 language, but it did not outweigh the high processing capabilities necessary for this project.

4.6.1.1.3 Competition III

NXP’s LCP4088FET208 comes as a strong contender for viability on this project’s with its numerous I/O, A/D resolution, impressive memory and connectivity potential, it falls short in the department of cost effectiveness and complexity.

The benefits for this are that it could be useable in even larger scale projects in observation of many more different nodes and output control of even more nodes. It can handle a complex screen inherently and could be useful for the use of this project. Wireless can be handled as another I/O Device as well as the ADC being possible for use in the measure of the voltages at specific nodes. There would be the possibility of the chip being overkill because of the many input and outputs on this microcontroller for the scope of this project. It would be more suited for its intended purpose of industrial applications on a more complex machine needing observation at strategic positions on the manufacturing line (which this is not a manufacturing application but a proof of concept). We aim to not waste space on this microcontroller

Hardware wise, aside from the microcontroller, both debugger and development boards tend to be pricey and not economically viable for this project. The debugger could be potentially bypassed though through a JTAG (Joint Test Action Group) based debugging tool. Officially, these devices can cost as much as $395 directly from ARM. But off brand possibilities are fully possible at considerably marked down cost of $39. This could allow for cost effective utilization of NXP, but the development board intended for the LCP4088FET208 costs in the neighborhood of $273, highly costly and nearly the same prices as the rest of the components found on this project. Software for this line of MCU comes from ARM directly since they utilize the architecture of ARM. Their software comes in an all-inclusive and convenient development pack. The main issue with this comes from the fact that the software costs in upwards of $2.7K with their KEIL-MDK-ARM-B - ARM Development Kit, Basic, Node locked; falling far beyond the hobbyist’s pocket book or the projects budget by leaps and bounds. The only way this would be feasible is if it were donated to our use.

4.6.1.1.4 Microcontroller of Choice

By the designing phase of this project, we decided to go with a significantly simpler microcontroller, utilizing no longer an SMD package chip, but a chip that was in a 28-DIP package and 28-pin socket. This was to streamline the project after realization of the simplicity of the requirements of the project which was simple digital signalling. there ended up being two different microcontroller models utilized in the project. the PIC32MX250F128B and the ATMEGA328P-PU.

The PIC32MX250F128B is utilized on the station for the input and output abilities. The PIC was attached and wired to the circuit to be powered, grounded, take in two digital inputs and finally to output signals of being powered , charging and in position to charge. Challenges arose when implementation of the ADC's was necessary on the car side of the microcontroller. PIC, being as configurable and controllable as a chip, was difficult and not straightforward to implement. Primarily, software limitations were the key issue of using the PIC on the car, where the ADC was absolutely necessary. Again, an issue arose with PIC software as implementation of UART is not so straightforward as well.

The ATMEGA328P-PU is utilized on the car side of control. This chip comes paired with the Arduino software and prototyping package which is why we utilized this chip. It makes use of ADC, digital input and output extremely simplistic on the software side with extensive arduino libraries . This was to be originally connected to wireless communication which would be simplistic to implement with the arduino software.

The greatest benefit of both of these microcontroller choices was by far though the packaging, making testing simplistic and untedious. The following are the primary specs for the chips used.

	PIC32MX250F128B	ATMEGA328P-PU
Clock(MHz)	50	20
Pin Count	28	28
Packaging	28-PIN DIP	28-PIN DIP
CPU	MIPS32 MK	8-BIT AVR
RAM(kB)	32	0
EEPROM(B)	0	1024
I/O	19	23
Memory(kB)	128	32
EMC Bus	0	0
I2C	2	0
SPI	2	2

UART	1	1
Display	Yes	Yes
Timers	5	3
Comparator	5	1
A/D res.	10	10
A/D count	9	8
D/A count	0	0
Temp. (C)	-40 to 105	-40 to 85
V operation	2.3-3.3	1.8-5.5
Cost ($)	4.38	4.32
Ethernet	No	No
USB	Yes	No
CAN	No	No
Debugger	Yes	No

4.6.2 High Voltage Sensor configuration

For the project, it was opted that high voltage sensing was done using simple voltage dividers scaled to the input maximum voltages allowed by the chip pins at 5V. To be safe, they were further scaled to 4V to allow for safe functionality. These values scaled were then incremented to appropriate ADC values and configures to be read as such by the MCU to allow for accurate interpretation.

4.6.3 Wireless Communication Network

This section is dedicated to determining how the microcontroller will talk with the wireless sensors on the car. The issue for one thing here is that the wireless is not embedded into the microcontroller, so an external accessory is necessary.

Unfortunately, the addition of wireless communication was deemed unnecessary by design and more of an additional feature so this was not implemented in final design. But for additional efficiency, utilizing the product that follows this section would allow for easy implementation with the hardware of the charging station.

4.6.3.1 XBee

So to choose, a familiar wireless communicator was chosen, the XBee-Pro. This small device fits a standard form factor from its predecessor, the XBee, and communicates in its traditional instance using the IEEE 804.15.4 standard. The RF receiver is also capable of Zigbee, DigiMesh, and 802.11bgn standards. Because of such compatibilities, it is the preferable choice as over Bluetooth which uses proprietary frequencies and standards. Their built form the ground up to be low cost and low powered wireless network sensors.

They have for their functionality respectable cost, good range and flexibility, allowing for I/O connection as well as operate on standardized frequencies. Without additional programming, these little bees are capable of analog to digital conversion and well as digital I/O at up to a 10-bit resolution which is the same as the resolution of the PIC32MX795F512L. Quintessentially, these little things are able to act as direct leads. For testing purposes, it may be important to test compatibility beforehand by use of a simple Xbee compatibility kit which will hook up easily to a PC via a USB connector.

Power requirements for these are low at max using only 340 microamperes of power at 3.3V. In case of necessity, they come with free configuration software, as it is in technicality a microcontroller of its own right. The Xbee is ideal for use on this project as the need for remote sensing is important for the charging and discharging of the capacitor array.

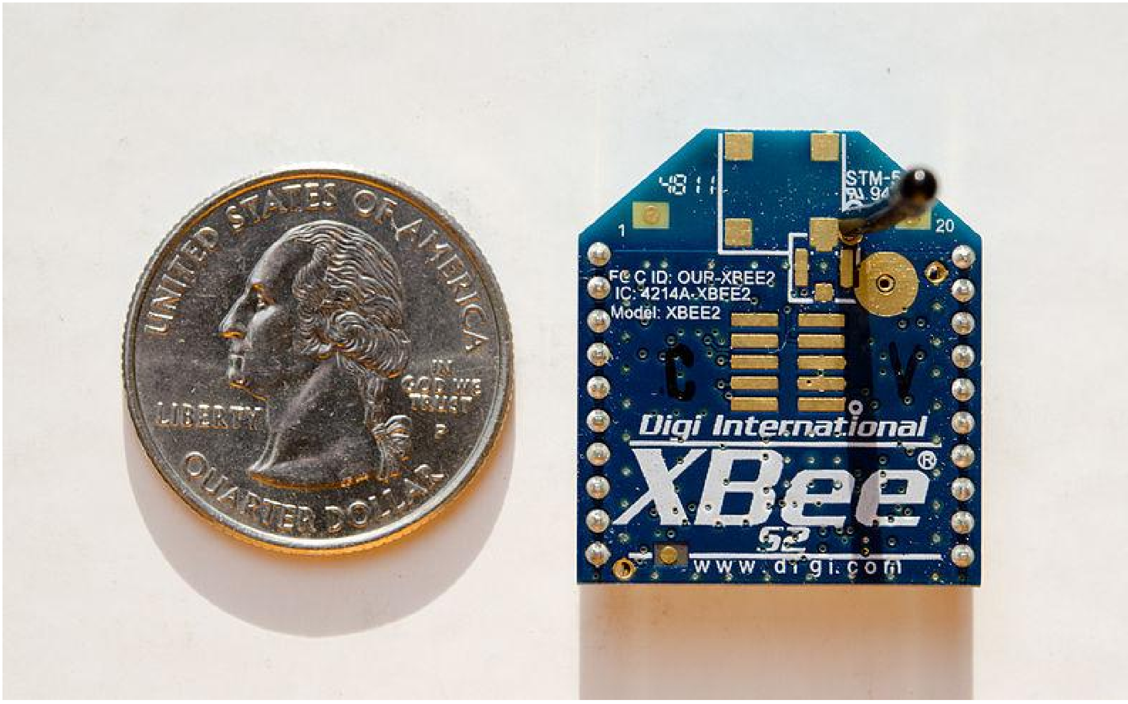


Figure 4.6.3-1 Visual representation of the XBee form factor (Permission: Wikipedia)

4.6.4 Display real-time data:

It is important to be able to observe the data flow of this project in order for the control signal to the charge and discharge regulators have the proper actions in this system. This is not only important for the protection of the circuits, but also the efficiency of the project. The best way to observe and know the project is running properly is when these values can be observed. To do this, an analogue concept can be implemented, more easily in a display system like a series of LEDs, or nixie tubes.

Analog system would have been difficult at this point when it requires ADC already, to then go digital to analog conversion (DAC) would be redundant. Although this may be the most cost effective, it would also not be the most aesthetically pleasing nor complex beyond the DAC.

Nixies tubes are an old system and would be similar to that of the analog circuit that displays but use a transistor based switching system to control the output of the nixie tube. These also require tremendous amounts of voltage, the likes of which are not possible easily driven by todays digital control standards. They still exist in normal use due to old equipment which still utilizes nixie tubes. Because of their relative age as a technology and incompatibility with the digital control, they are not a useable candidate.

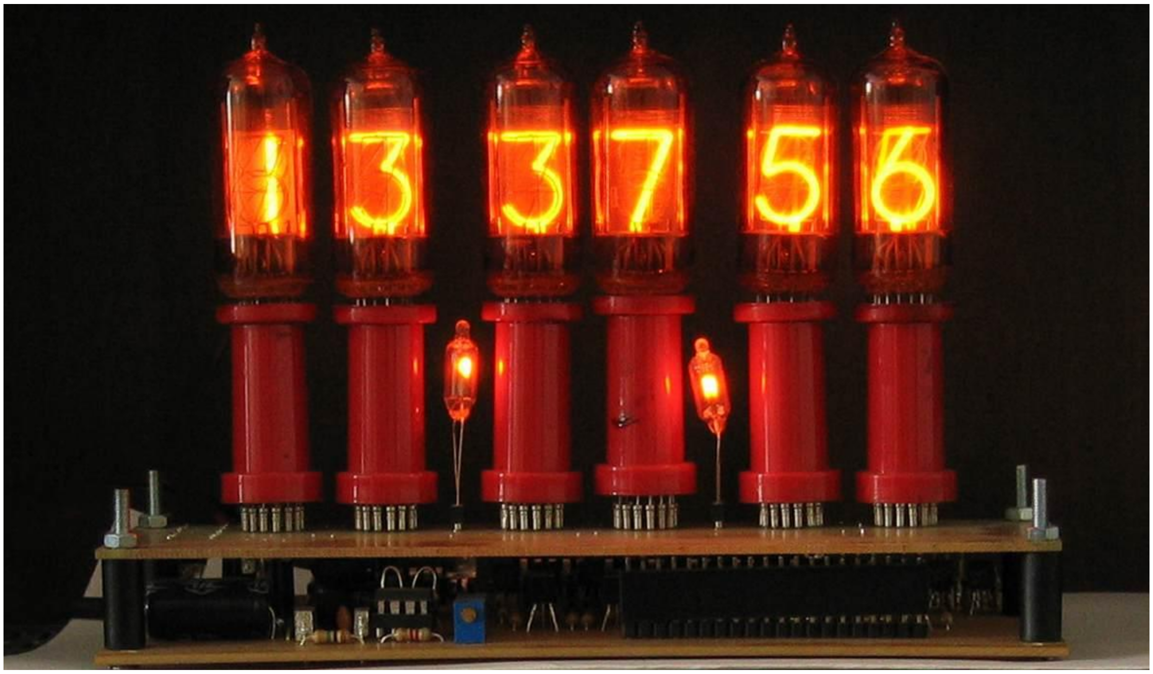


Figure 4.6.4-1 Nixie Tubes

So an LED array is the best, and simplest way to display the functionality of charge capacity whilst still indicating when charging is complete or entering critical stages.

Implemented, the LED's would display charge level accompanied by an LED array that ranges from zero percent of useable charge to 100% useable charge in a series of 9 LED's. At the charging station, a series of LED's would be used to indicate simply the powering of the MCU, charging and car positioning.

4.6.5 Regulate load discharge output:

To regulate the load discharge, the LED's would provide visual indication of immediate voltage status of the capacitors. This would then be used to regulate the charging of the capacitors, as the voltage levels of the capacitors are what are important for safety of this project. The visual indicators are then what were used to regulate discharge output.

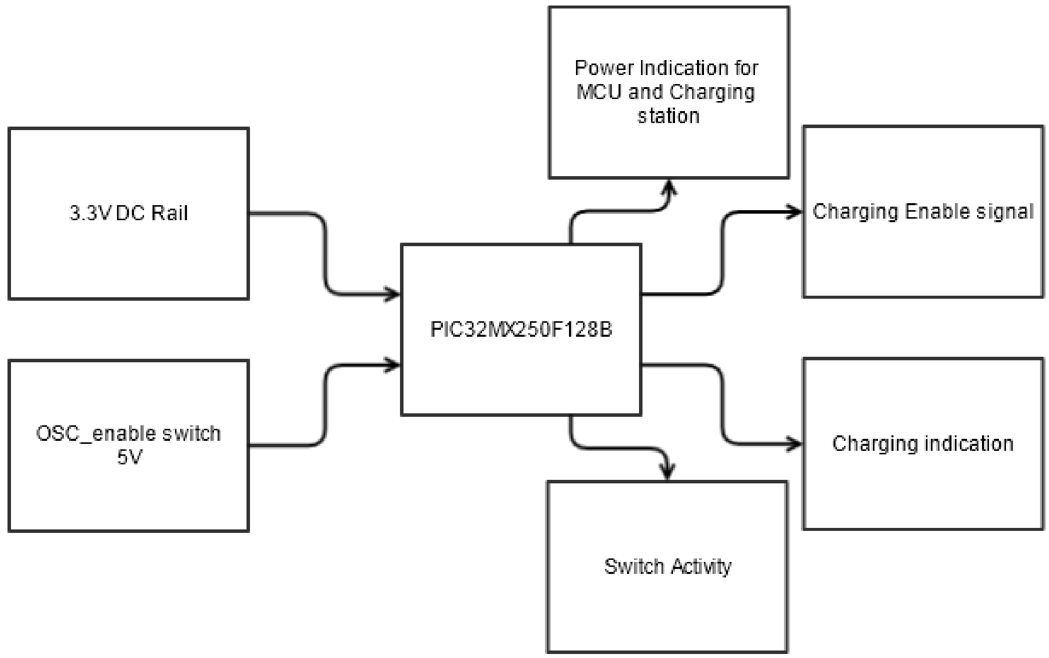


Figure 4.6.5-1 Block diagram of Data Flow on Charging Station

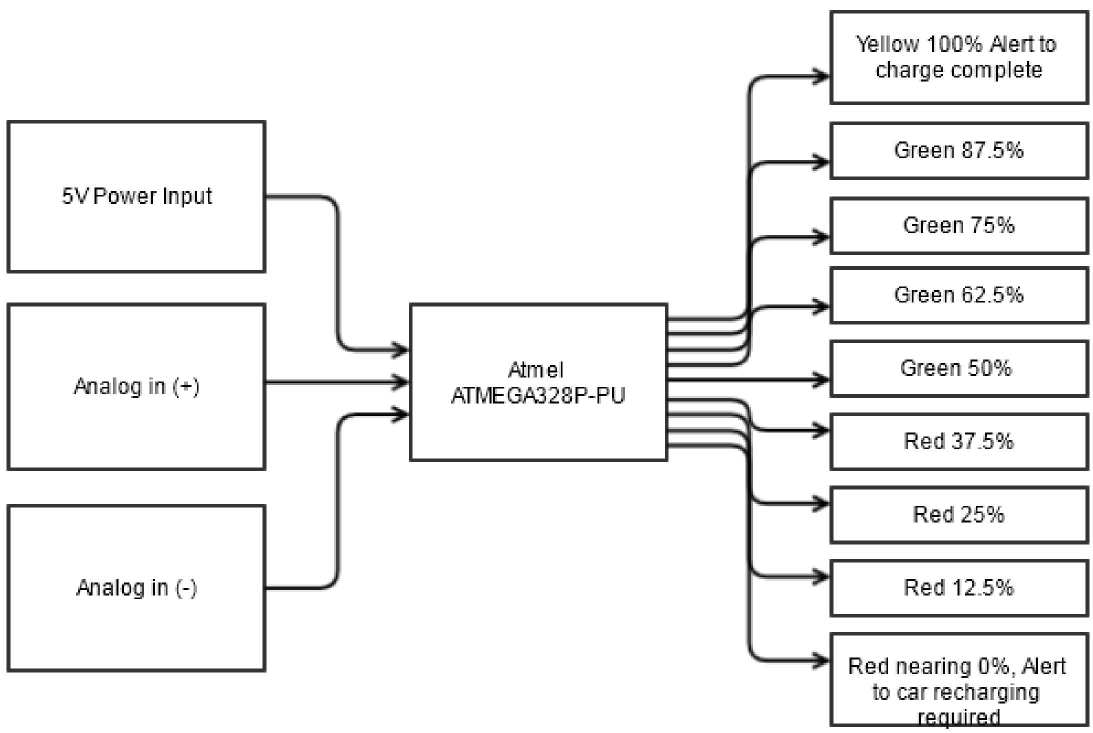


Figure 4.6.5-2 Block diagram of Data Flow on Car

4.6.6 Alert to voltage in capacitors:

Fortunately, the alarm system can be very simple since there are two methods to use for this application. 1 can be controlled through an analog circuit which activates when nearing a specifically determined voltage level and another would be by blinking an existing LED to alarm that it is reaching near overvoltage or undervoltage. Solid lights indicated everything in between these two extremes.

4.6.7 Data Acquisition Budget:

Category	Part	Parts Designation	Cost	Quanitity
Microcontroller	DP32 ChipKit	DP32 ChipKit	26.99	1
	Arduino Uno	Uno	39.99	1
	PIC32MX250F128 B	PIC32MX250F128B	4.86	2
	PICkit™ 3 De. Exp.	DV164131	52.49	1
	Adruino Software	Adruino Software	Free	1
	MPLAB IDE	MPLAB IDE	Free	1
	28P DIP Socket	DIL28P	0.39	2
Wi. Comm	XBee 900 MHz	XBP09	40.00	2
	Xbee Adapter Kit	Xbee Adapter Kit	10.00	2
	Xbee U.FlAntenna	66089	2.64	2
LED	5mm LED’s	5mm LED’s	0.05	14
Power	3.3V Lin. Reg.	LM33V	2.50	1
	5V Lin. Reg.	TI7805	2.50	1

Figure 4.6-1 Budget from Data Acquisition

5. Design Summary

5.1 Power Supply

5.2 RF Power Signal Generator

In developing the RF Power Signal Generator, we determined that the best course of action was be to first generate a small signal of the desired frequency with an oscillator, then we amplifed that small signal to levels required for the right amount of coupling of the resonators as well as enough power to quickly charge the RC car.

For our oscillator, we chose to utilize a voltage controlled oscillator to generate the small power, high frequency signal that we will later amplify. We chose the VCO because it was extremely easy to adjust with a potentiometer, operated at a wide range of frequencies, and was relatively cheap and easy to implement.

The VCO that we chose was the SN74LS624 from Texas Instruments. The relevant specifications of the DS1077 are shown below in figure 5.2-1

	SN74LS624N	
Price	$3.92	
Frequency Range	1Hz - 20 MHz	
Supply Voltage	5	v
Supply Current	0.2	mA
Load Capacitance	45	pF
Operating Temperature Range	0 to 70 degrees	C
Package	PDIP-14	

Figure 5.2-1 SN74LS624N Specifications

In order to amplify the high frequency signal generated from the DS1077 programmable oscillator, we explored a wide variety of amplifier options. After exploring all of the common RF frequency amplification options, we determined that a class E amplifier best suited our project because they have very high efficiency ratings, operate well into the RF range, and can effectively amplify a signal to the current levels that we need.

Our class E amplifier employed at it's heart a IRF510 FET by Vishay, which has a high drain current, can operate at RF frequencies, has a low on resistance, and is much cheaper when compared to RF Power MOSFETs of comparable specifications. The relevant specifications of the IRF510 are shown below in figure 5.2-2.

	IRF510	
Price	$0.98	
Max Vds	100	V
Max Vgs	10	V
Max Id	5.6	A
Ciss	180	pF
Coss	81	pF
Crss	15	pF

Figure 5.2-2 IRF510 Specifications

The output LC tank circuit of the class E amplifier, which is critical for the class E operation of the design, was determined by measuring the inductance of the MRC network and choosing a capacitor to resonate with the MRC network at the frequency we found the MRC to best couple at. We determined the best coupling frequency of the MRC network to be 3.2MHz, and the MRC network to be equivalent to a 66.46uH inductor. With this information, we calculated the capacitor to be 42pF.

With these components, the final schematic of the class E amplifier, with placeholder components are shown in figure 5.2-8.

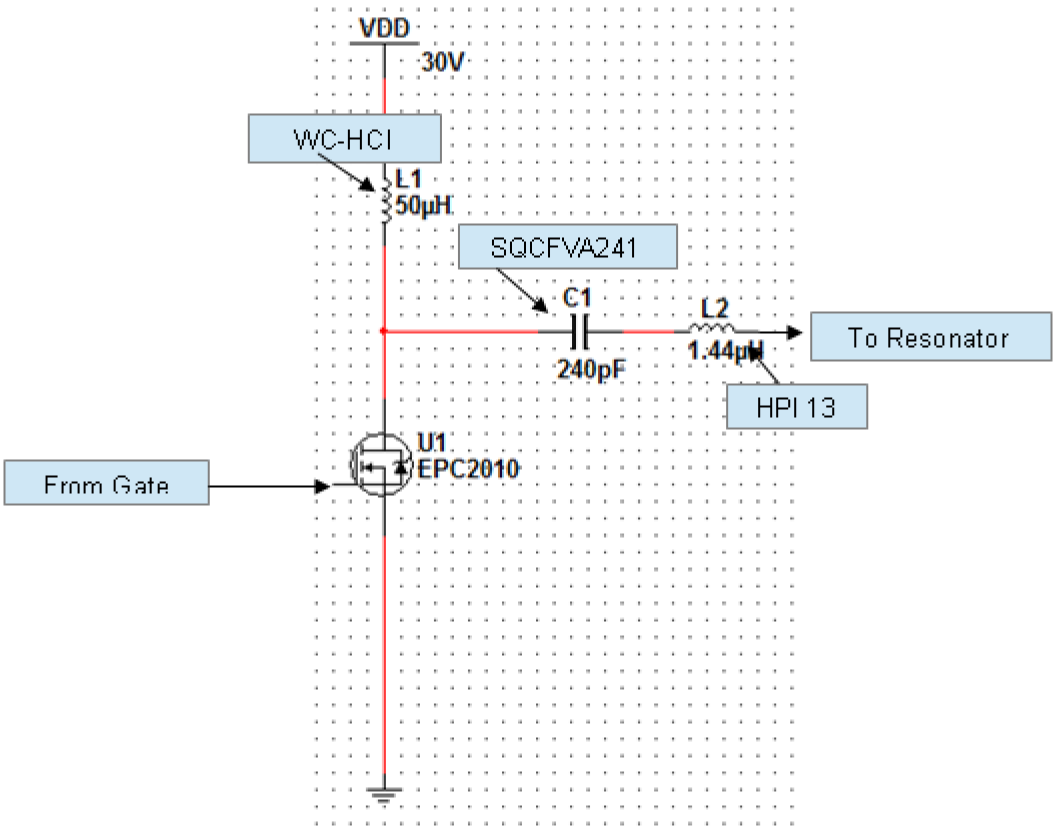


Figure 5.2-8 Class E Schematic With Components

One last key consideration in the RF Power Signal Generator is the driving of the FET into ‘on’ and ‘off’ mode at high frequencies. The small signal from the VCO does not carry enough current to fully turn the IRF510 FET on and off at such high frequencies.

After exploring many options such as using class A amplifiers to step up the small signal from the VCO to current levels able to switch the IRF510 FET at high enough frequencies, I determined that the best course of action was to utilize a gate driver, which is specifically designed for taking small signals from IC’s such as a programmable oscillator or microcontroller, and outputting that signal at current levels high enough to drive high power RF FETs into ‘on’ and ‘off’ modes at high frequencies. The specifications we set for determining the correct gate driver for our design are:

1. Delay Time below 50ns (equivalent to 20MHz)
2. Current peak above 1A
3. Inverting or Non-inverting input type
4. Availability
5. Price
6. No more than 2 outputs; only one needed

With these specifications, we determined that the IXDN604PI is best suited for our design at it's price point. It's relevant specifications are shown in figure 5.2-9.

	Input Type	Delay Time	Current-Peak	Number of Outputs	Price
IXDN604PI	Low-Side	9ns	4A	2	$1.28

Figure 5.2-9 Gate Driver Specifications

5.3 Magnetic Resonant Coils

The MRC network is able to be modeled as a transformer network, and was be treated as such. The only difference is that we did not directly implant resistors in our network, and instead used the ESR of the components in series for our calculations. The lower the ESR, the higher the Q factor and thus the better the transmission, so naturally we wanted ESR to stay low. The capacitors we used were simple ceramic capacitors. We had originally considered high-Q caps, but found them to be both costly and unnecessary.

As stated in the design section, we used 18AWG standard wire to wind our coils. Recall that inductors do not link through electric fields, rather through magnetic flux. While not the most ideal permittivity, the wire propagated the fluctuating magnetic field well and was easily able to tolerate the amount of current drawn. Plus, they are extremely cheap to make. It should also be noted that when constructed, the very nature of this design will cause a small amount of capacitance that is to be measured before attempting to select a capacitor for impedance matching. This parasitic capacitance comes from the spaces between the coils on the inductors.

For specific capacitances to be used within the MRC, we had to first determine the inductance of our coils, which we were able to test by using them in a high-pass filter configuration of a resistor in series with the coils. From there, we found the resonant frequency of our coil network, an inherent property to the mutual inductance of the coils combined with the distance of separation. Using this desired frequency, found to be 3.2MHz, we calculated what capacitance we would need to make our resonant networks, which was 136pF.

As mentioned before, we were considering using high-Q caps, specifically ones from muRata Americas. Below is a listing of their ERB series of capacitors, designed for RF applications and able to tolerate up to 1GHz. Beyond 1GHz, most passive components become too small since their relative size decreases with an increase in frequency. While these would have worked, we felt it both unnecessary and bothersome to have to use SMT capacitors when ceramic caps work well enough, are cheaper, and are easier to manipulate.

Features:

- Size: 0603, 0805, and 1210
- Voltage: 50, 100, 250, 300, 500VDC
- Cap Range: 0.5 to 1000pF
- Internal Electrode: Pd/Ag
- Termination: Pd/Ag + Ni/Sn plating
- ESR: Low
- Power: Medium Power (5-15W)
- Frequency Range: 1MHz – 1GHz
- Tolerance: Tight Tolerance Available ([W]=+/-0.05pF for <=5pF, [[B]=+/-0.1pF for 5 - 9.1pF, [C]=+/-0.25pF for 5 - 9.1pF, [F]=+/-1% for 10 - 20pF)
- Temp. Characteristics: C0G (-55°C to 125°C with 0 ±30ppm/°C)

Figure 5.3.1 - ERB Series Capacitor features courtesy of muRata Americas

5.4 RF to DC Power

For our RF to DC power supply we will be using a basic bridge configuration, but we won't need to use a filter capacitor. This is because we are charging to a capacitor array anyway, so the capacitor array acts as a slowly-filling filter capacitor.

We selected the UC3610N for our 4-diode full-wave rectification diode, . This is because this specific model of diode has a quick switching speed, high voltage tolerance, and a high current tolerance. It also consumes considerably less voltage than a standard diode, which means it will consume less power. This is ideal since less power consumed will mean more transfers to the capacitors, and thus charges them quicker.

We made sure that the diodes are able to tolerate our operating frequency of 3.2 MHz. We also made sure that it would be able to handle our current of 2A and voltage of 20-30V AC. It met all of these specifications without issue, and is thus the model we will be working with. The diodes also come as a surface mount model, which means we can easily place it on a small PCB to fit flush with the car's chassis.

5.5 Capacitor Array

Something nice about the rated value that Maxwell Technologies has done is that they have given a rated value below the absolute maximum voltage, which means the voltage we aimed for were even safer. According to the datasheet, we would be safe up to 8.25V, and we were only charging the caps to 8V.

These capacitors are rated at 3.2m-ohms of ESR. While this is still a very low resistance compared to our load (which is 5-ohms), and the rest of our circuitry, it is still fairly high for a capacitor, which usually has tenths of milliohms if not hundredths of milliohms of ESR. For our current design, this wasn't an issue since we weren't drawing a large amount of power. However, it would become an issue should we decide to increase the power of our source, as the caps will begin to heat up to much greater temperatures.

The capacitors also have a relatively low leakage resistance. Rated at 2.7V with a leakage current of 0.3mA, these caps have a leakage resistance of approximately 9k-ohms, well below the desired mega- or even gigaohm range. However, considering the large amount of charge they can hold, this isn't an issue. The caps lose less than 1 micro-volt per second at this rate. This is still the maximum leakage current rate, and only applies when the cap is fully charged and left alone. it would take more than 15 million seconds to fully discharge one of these caps, or roughly 180 days, which is about 6 months. Not only does this easily beat the average discharge time of most batteries out there, which is about 2 weeks to 1 month, but it would be far less painful to recharge one of these caps for roughly 30 minutes to 1 hour than to recharge a battery pack for 3-4 hours.

Lastly, we see that the cap is safe up to a short of 220A, Listed in Figure 4.5.6. We had no plans for the caps to ever reach such a current, but it is still a great feature to have. The problem a lot of people have with RC cars is that turning while moving can sometimes put a great deal of stress on the battery pack because performing both functions under load at the same time is often too much for a battery pack. With caps, this would no longer be an issue, since the caps would be able to supply this type of current immediately. As a matter of fact, this load would be well within the 24A safe continuous current draw.. We actually found small capacitor banks available to RC car enthusiasts that will store a temporary charge to negate such a problem. Now the client wouldn't need to purchase an after-market array.

5.6 Design Summary of Data Acquisition

In short, the design of the data acquisition system had many parts which require synchronizing from sensors to controllers and finally the brain which needs to coordinate all of them together. A major hurdle alone was to find a brain chip compatible with the needs of the project. It needed many peripheral functions and access points as well as being advanced enough for the ability of a low budget project like this wireless energy transfer project to 50 MHz be able to access such powerful computational power of an embedded chip. The PIC32MX250F128B in the DP32 ChipKit turned out to be a marvelous find which will be a great addition to the project. It will include the express debugger for fast and easy start up of this project.

To add to this, the ADC sensors on the car MCU were connected using the ATMEGA328P-PU due to software simplicity. By this, implementation was achieved very easily within one afternoon.

For wireless autonomy, it was deemed to be an unnecessary feature being that it would complete a simple task of a single transmission one way to alert for or against charging. In conclusion, wireless communication was omitted.

The LED array is simple to implement by wiring each pin output to a specific ADC reading that is scaled to their respective LED and output desired. These were scaled by use of testing which will be defined later. The LED array was chosen over the LCD screen.

The MCU was also decided to be powered separately on the car as to not drain the supercapacitors more than necessary. This is because the MCU requires a constant 5V rail since the ATMEGA utilizes a 5V rail. The microcontroller was decided to be supplied using a 9V battery.

To manage load discharge, what was most important is to understand just how imperative it is to find the right way to implement when deciding to go with simplicity or autonomy. Since the system is continually monitored, for this project it was decided to use the LED array be the indicator to load discharge, as to not over discharge the capacitors or overload the capacitors.

5.7 Printed Circuit Board

We determined that the best PCB manufacturer for our project was 4pcb.com. The reason was chose 4pcb.com is because it is the only PCB manufacturer that offered a student discount, and quite a good one as well! It’s only $33 for a 2-layer PCB board and $66 for a 4-layer PCB board. For our project we only needed 2-layer PCB boards, so this was an easy decision.

A big consideration we took into account when ordering with 4pcb.com was that they have a 5 day turn around time, which we need to consider with our deadlines, and that does not include the shipping, so we felt it would be wise to save 2 weeks when considering arrival time of the PCB to make sure that it is on time as expected, and to account for any possible delays. Originally, we thought we would need to order them to be shipped to the school to maintain the student discount, but found that we could ship to residences as well.

For our design software, we chose EAGLE. Probably the most popular PCB software in the market right now is EAGLE, and this is simply because it’s a very powerful, well documented piece of software, and best of all, it’s a freeware license, and therefore it’s completely free. It also outputs in all of the popular PCB layout file types that many PCB manufacturers use, and is has a massive component library available online. It has a huge following, and therefore a lot of support, documentation, and tutorials can be found online.

6. Testing

6.1 Power Supply

The testing for the AC/DC power supply involved placing the components on a breadboard, and using two oscilloscope probes to ensure that the bridge rectifier is properly functioning, then applying a 100 mF capacitor for smoothing. A simulated load is attached (Power Resistor) and the voltage is measured across it. Once its functionality has been ensured, the class E amplifier is placed in cascaded with the power supply and verified that the amplifier can properly function using our power supply.

6.2 RF Power Signal Generator

For our design, it's not possible to test and finalize the signal generator because it's driving an inductive load, and therefore this load will affect the operation of the signal generator immensely when connected. However, we can test certain aspects of the signal generator to verify that they are acting appropriately.

6.2.1 Functionality Testing

The methodology I chose to test the signal generator was to test the functionality of each stage of the generator to ensure that particular stage was working properly, and then add on successive stages and test those.

The first stage of the signal generator is the voltage controlled oscillator. I used a lab power supply, a function generator, and a potentiometer to test and measure the operation of the VCO. Then I adjusted the potentiometer to make sure that the frequency of the VCO changed appropriately. This was confirmed to work as expected.

The next stage would be the gate driver, so I connected the input of the gate driver to the output of the VCO, applied a 10V power supply, and measured the output of the gate driver. The gate driver acted appropriately.

The next stage would be the amplifier stage, and I chose to first test it with a purely resistive load and to observe the output. Using a 15Ohm 50W power resistor, a VDD of 10V, and a 50mH choke inductor, I tested the amplifier with the VCO and gate driver and got a very nice signal across the resistor; everything operated very well up to 20MHz. Once we began testing with the inductors of the MRC network we began having a lot of reflectance into the FET, causing a lot of power dissipation into the FET, which is not what we want. Since the amplifier worked so well with a purely real load, I determined that we should design the output to have no imaginary component at the resonant frequency of the MRC network. So using the measured inductance of the MRC network, we used the equation for resonance (w0 = 1/sqrt(LC)) to determine the capacitor we should put in series with the MRC network at the drain of the FET. Once we put this capacitor in there, we got very little reflectance into the FET, with it just barely getting warm, so there was very little power dissipated across it, and a very nice signal at the output of the MRC network.

6.3 Magnetic Coupled Resonators

In order to test our MCR network, we had several key features that must be examined. First, we had to make sure that the MCR network is properly transmitting power between the transmitter and the receiver, which it did. Next, we tested to make sure that the MCR network operates at the resonant frequency we have set by the system. While this was mostly accomplished by the first test, this secondary test would help us fine-tune our circuit. Once that was done, we had to test that this network works at the distance at which we need it to be, which it did. After that, we needed to examine ways of making it more efficient. This mostly came down to ensuring the coils were the same diameter and number of turns. Finally, we had to test to make sure we can successfully utilize the power it is transmitting, which also succeeded.

To test proper transmission, we constructed two crude coils as shown below. We were able to get the signal to transmit and receive a 10MHz signal. The resonant coil picked up roughly 60% of what the transmission coil sent out, which proved to us that these coils do not need to be well-made to pick up a transmitted signal. However, as the photo displays, these were made hastily and with little consideration to exact dimensions beyond turn number and an approximate diameter. Later iterations of these coils, which were wound to tighter specifications, proved to be more efficient.

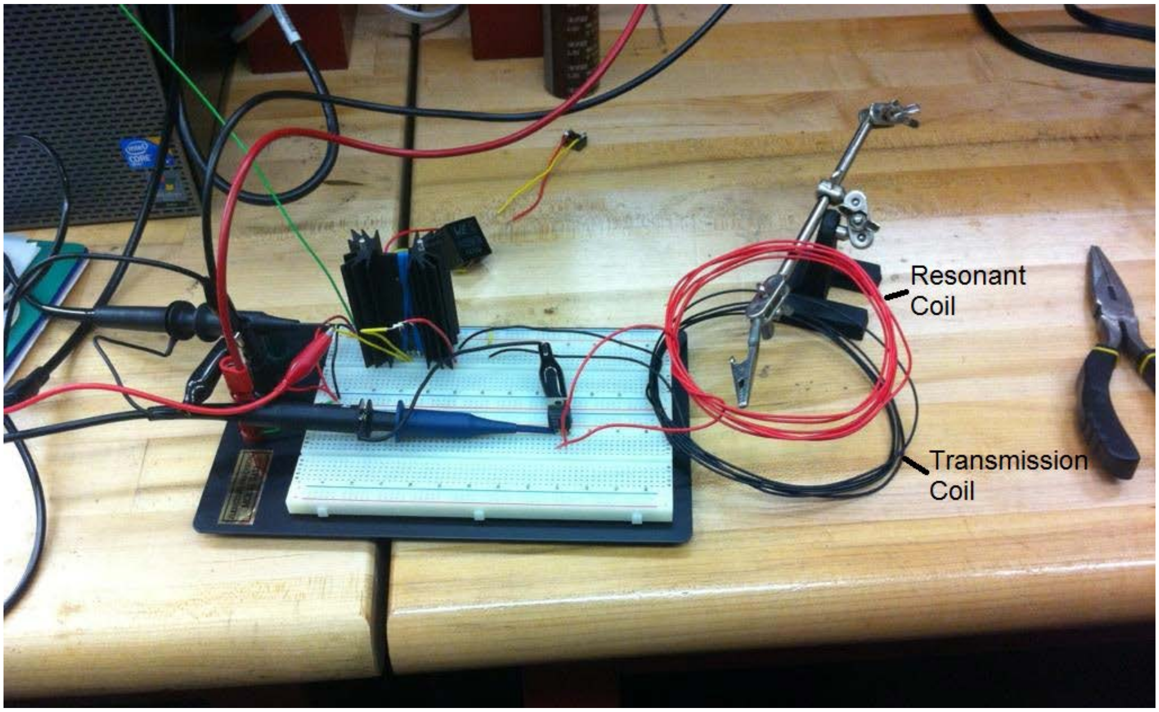


Figure 6.3.1 - Initial coil testing.

Once better coils were made and finalized, we began testing their resonant frequency. To test resonant frequency, we set the function generator to 10MHz and observed the efficiency of the system. From there, we lowered the frequency and fine-tuned it until we found one with the greatest received amplitude. We found this frequency to be 3.2MHz

To avoid having to retest the coils at the separation distance between the car and the ground, we simply performed the previous tests at that distance, found to be 1.5 inches. Since the coils have thickness, bear in mind this 1.5 inches is the separation from the top of the receiver coil to the bottom of the transmission coil.

Next we began efficiency testing. After verifying that the current in and out was identical, we compared the peaks of the transmission coil to the received coil. We found that the receiver coil was picking up roughly 90% of what the transmission coil was sending out.

Finally, to ensure this system worked, we connected our supercapacitors to the RF diode bridge mentioned in the next section following the receiver coil. The transmission coil was connected to our working amplifier. After all components were put in place, our system was successful and began charging the supercapacitors wirelessly at the distance we desired.

6.4 RF Power to DC Power

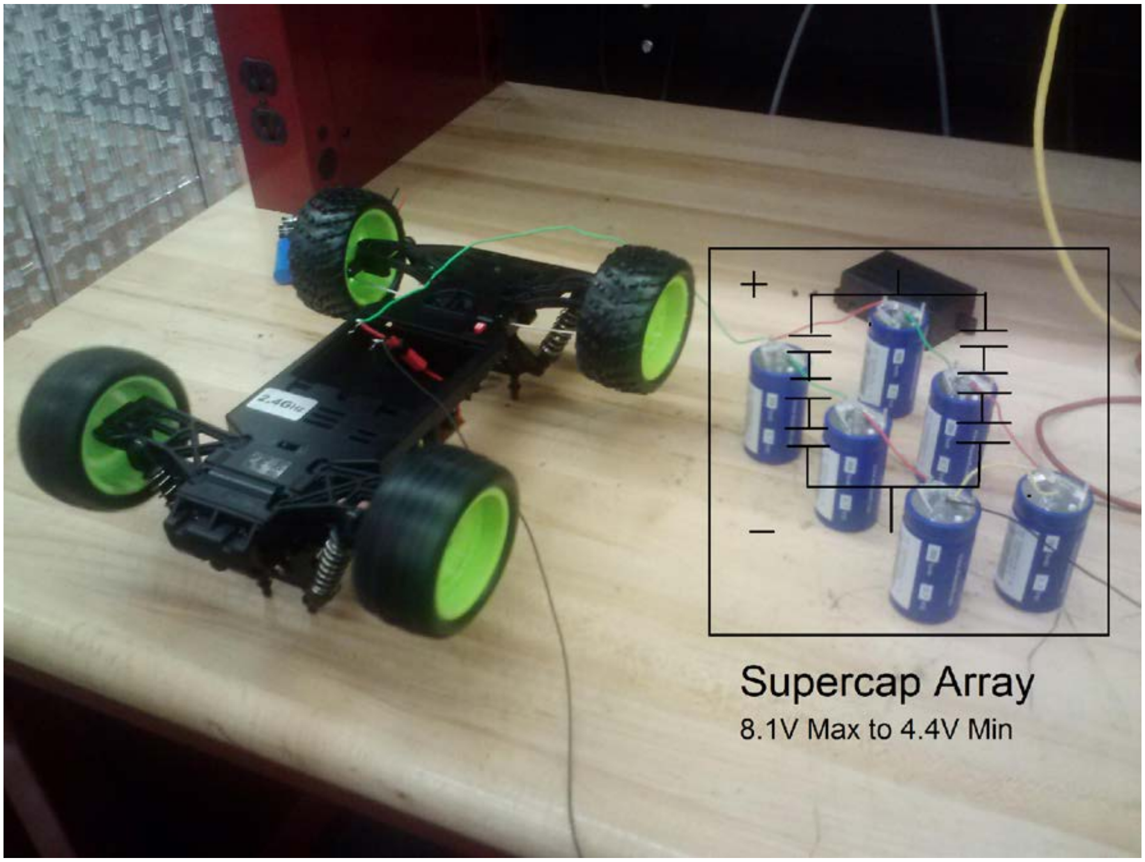
To test the RF Power to DC power converter, we first obtain through a function generator a 3.2 MHz signal and observe its true value through and oscilloscope. Once this has been achieved we double check to make sure that our circuit configuration is correct and connect the function generator to the input of the converter. Using the oscilloscope, we observed the output of the converter by measuring the voltage signal across the parallel load. The expected signal should be and is a clear and reliable DC power signal with minimal noise.

In addition, we have mimicked the load of the charging capacitor array with another load in series with another power load. This is done using a resistance comparable to the the capacitor array and its designed circuitry. This load should has a current draw of 3 A max. This is enough to charge the capacitor array fast enough to meet the specifications and requirements of the next component which is the Capacitor Array.

6.5 Capacitor Array

For our capacitor array, we needed to make sure that the capacitors were safe up to 8V for normal operation. This came from a “burn-in” test of sorts. We charged the capacitors to 8V, left them for an a while (about an hour), and allowed them to dissipate naturally. This allowed us to see the charge retention of the supercaps, which was found to be acceptable. In charging the caps, we were also able to test another feature, which was the low ESR we desired. Since our bench supply could charge at 5.5A, and the ESR of the caps was 3.2 milliohms each (about 10 milliohms with 3 in series), this means our caps would experience a combined total of about 51mW, or 17mW each. For caps this size, this is negligible. Sure enough, the capacitors were not even warm to the touch, therefore the ESR had to be low.

Third, we needed to test that the car is able to handle effectively the current coming from the capacitor array. For this test, after testing the capacitance and ensuring they charge/discharge as they should, we connected the capacitors, and only the capacitors, to the car in place of the battery pack. We then ran the car until it was no longer running. From there, we measured the voltage remaining on the capacitors. We were able to test yet another important feature here, which was how low of a voltage the car could run at, which was found to be roughly 4.3V before shutoff. In future tests, we were able to get the car to run as low as 4.1V. Below is what this test setup looked like.



6.5.1 - Supercapacitor array connected to car.

After the operating test, and following the successful implementation of all the other important features, the test to see if the warning LED circuit worked, as well as the LED array displaying remaining power. For this test, we connected the capacitor array to the analog inputs of the microcontroller and checked that the LED array lit up properly to the desired level. We verified the voltage with a bench multimeter, but found that the analog read value actually changed slightly when connecting the DMM in parallel. This was most likely due to the high resistance we used in our analog read-in acting in parallel. This conclusion makes sense, because the LED display would always indicate a lower voltage level, which is the expected behavior of adding a resistor in parallel with a resistor in a voltage divider network: the equivalent resistance, and thus the voltage received by both parallel resistors, should go down.

The previous test also tested if the low-voltage warning light worked, which it did. The low-voltage warning simply flashed the lowest LED in the array at a low voltage by triggering a delayed toggle on all of the LEDs in the circuit when voltage was critically low. Since the only LED on at this point is the lowest LED, only it would blink.

After all of that, we tested to see that this worked on the charging station as well. After ironing out some bugs in our code and adding an averaging algorithm to eliminate fluctuation on the analog reads, the LEDs did properly display remaining voltage.

6.6 Testing Outline on Data Acquisition:

Testing needed to be done in sections and in phases.

1. The first phase was to determine if we have a satisfactory brain for use on this project. For that to be done, test codes and simple tasks were run through the microcontroller prototyping kit. This is what determined that the PIC32MX795F512 was too powerful for our project and the PIC32MX250F128B was chosen over it.

2. Some simple tests had to be done to determine of the single source ADC voltage sensors are viable and will not destroy the circuitry that makes this a relevant addition to the project. This is when we determined that, software wise, the ATMEGA328P-PU was the best choice to use for ADC implementation as the code was mere lines rather than tens of lines of code.

3. LED's were next to be implemented as to see if software was correctly configured to output what the true voltage levels were within the Supercapacitor array.

4. Charging controls were be tested next on the instance of whether there needs to be something more exhausting than a shunt required. A shunt itself is an analog part, but a diversion circuit might be necessary for our power consumption. It was tested without the microcontroller to begin with, to see the physical limit of the shunt, and then go to something more controllable afterwards.

5. Integration testing was the final step as all of these functionalities needed to be able to work together on the board at one time.

7. Construction/Parts Acquisition

In the following sections we will be discussing the development of our final fully built wireless power transfer system, with the ability to power a radio controlled car wirelessly. We will go over the materials we have deemed necessary to acquire, our plan of acquirement, our method of PCB board development, final assembly, and any other key considerations relevant to our project.

7.1 Budget

The total cost of the project is as follows:

Part Number	Description	Quantity	Manufacturer	Vendor	Unit Cost($)		Total Cost($)
IRF510	Power MOSFET	1	Vishay	Digikey	0.93		0.93
SN74LS624N	Voltage Controlled Oscillator	1	Texas Instruments	Digikey	3.92		3.92
Project Box	Project Box	1		Amazon	24		24
WE-HCI	Inductor	1	Wurth	Digikey	6.83		6.83
HS380-ND	Heat Sink	1	Aavid Thermalloy	Digikey	1.73		1.73
IXDN604PI	Gate Driver	1	IXYS	Digikey	1.28		1.28
LM2574N-5GOS-ND	5V switching regulator	1	Texas Instruments	Digikey	1.65		1.65
SRR1206-331KLCT-ND	330uH Inductor	1	Bournes Inc.	Digikey	0.84		0.84
DV164131	PICkit3 Express Debug	1	Microchip	Microchipdirect	69.99		69.99
PIC32MX250F128B	chipKIT Max32™ Prototyping Platform	1	Digilent	Digilent	23		23
1/10 size RC car	RC car	1	Various	eBay	40		40
PCB Boards	PCB Boards	1	4pcb.com	4pcb.com	33		33
PB5006-E3/45GI-ND	Diode Bridge	1	Vishay Siliconix	Digikey	3.78		3.78
SI2300	N-Channel MOSFET	1	Vishay Siliconix	Digikey	1		1
BCAP0350	Supercapacitor	3	Maxwell Electronics	Mouser	10.95		32.85
Arduino Uno	Development Kit + Atmega 328p	1	Atmel/Arduino	Radio Shack	28		28
UC3610	Schottky Diode Bridge	1	Texas Instruments	Digikey	6		6
LN7805	5v Linear Regulator	1	Radio Shack	Radio Shack	3		3
Transformer	12.6V 3A Transformer	1	Radio Shack	Radio Shack	12		12
LM33V	3.3V Regulator	1	Texas Instruments	Mouser	2		2
Perferated Board	Perferated Board	1		Skycraft	3		3
Various components	Caps, resistors, LEDs, sockets, wire, etc.	1	Various	Various	20		20
						Grand Total:	318.8

Figure 7.1.1 - Final Project Budget

The budget wound up coming in at just over $300 total. The most expensive components were the development kits for our microcontrollers (contributing to over $100 alone) and the supercapacitors at $11 each. The enclosure also contributed $24 to the total, excluding shipping.

7.2 Procurement of Parts

Utilizing the vendors given in the Budget, we began procuring parts this summer and early fall semester in order to begin initial development and testing of our designs for the project. If the parts that we've selected became suddenly difficult to obtain, we will attempt to procure those parts from other various venders. For instance, if a part is out of stock at Digi-Key, we attempted to procure it from Mouser. If we were unable to obtain the part from a reputable vendor, it was then necessary to find a suitable replacement for the part unable to be obtained. Fortunately, this was rarely an issue, if at all. We were also able to salvage some components from the Senior Design lab, graciously (and involuntarily) contributed by previous teams.

We also needed to consider in the procurement of our parts the amount of time that it would take a particular vendor to deliver our order. In many situations, we found that part vendors tend to take longer to deliver parts than normal consumer stores such as Amazon. However, thanks to USPS Priority Mail we were able to get our parts within 3-4 business days for little cost on shipping.

We also adopted the habit of purchasing an excess of parts cheap enough to be deemed worthy. This was to ensure that we had spares for most of our parts. With these spares, we could be sure that we will not have to panic and overnight parts if a component were to suddenly malfunction during construction. We were trying to make sure to minimize any opportunity for negative situations to crop up in our project construction; we wanted it to be as straightforward and as easy of a time as possible. On several occasions, we were able to avoid catastrophe by having spare parts lined up after several of our components malfunctioned in testing.

7.3 PCB

Originally, we had planned on ordering one PCB for the base station and one for the car. We instead just stuck to a PCB for the base station, since it had so many parts. On the car itself, we used perforated board since it was much cheaper. We would still need to plan how to acquire a PCB for our design. We first explored different PCB manufacturers to see who would give us the best deal while remaining compliant. Then we considered different PCB design software.

7.3.1 PCB Manufacturing Company

In considering which company to choose when we were ready to manufacture our PCBs, there are a few considerations to take into account. First, we didn’t have to worry too much about the quality of the PCB board, as most reputable PCB manufacturers produce reliable products, and we felt that we could be sure that our PCB board will be up to par as long as we chose a reputable dealer.

With that in mind, Price is was the biggest concern with our choice in a PCB manufacturer. We had to take into account that we only needed one board and most PCB manufacturers operate by selling in bulk, so they generally charge extra fees for single boards. We felt we should be on the lookout for PCB manufacturers that are friendly to small quantity customers, or even provide student discounts, since that would be applicable to us. Aside from price, we also needed to consider the types of development software that they accept or if they require their own development software.

Taking into account the considerations laid out above, we determined that the best PCB manufacturer for our project is 4pcb.com. The reason we chose 4pcb.com is because it is the only PCB manufacturer that offered a student discount, and quite a good one as well! It’s only $33 for a 2-layer PCB board and $66 for a 4-layer PCB board. For our project, we only needed a 2-layer PCB, so this was an excellent option.

A big consideration we took into account when ordering with 4pcb.com was that they have a 5 day turn around time, which we need to consider with our deadlines, and that does not include the shipping, so we felt it would be wise to save 2 weeks when considering arrival time of the PCB to make sure that it is on time as expected, and to account for any possible delays. Originally, we thought we would need to order them to be shipped to the school to maintain the student discount, but found that we could ship to residences as well.

7.3.2 PCB Software

When choosing which PCB software we were going to use when developing our PCB, our first consideration was what PCB EDA tools our preferred PCB manufacturer accepts. Lucky for us, our prefered PCB manufacturer, 4pcb.com, accepts all of the major PCB layout formats, as well as they have their own PCB CAD tool called PCB Artist, which has a large amount of parts already on file and ready to be routed. PCB Artist was certainly an option to consider when determining which PCB software we want to use for our project.

For our design software, we chose EAGLE. Probably the most popular PCB software in the market right now is EAGLE, and this is simply because it’s a very powerful, well documented piece of software, and best of all, it’s a freeware license, and therefore it’s completely free. It also outputs in all of the popular PCB layout file types that many PCB manufacturers use, and is has a massive component library available online. It has a huge following, and therefore a lot of support, documentation, and tutorials can be found online.

After comparing the two best options for developing the PCB in software, we felt that EAGLE was the best option for us. It’s long history gives it much more documentation and tutorials than PCB Artist would, and it’s such a popular platform that pretty much any component is ready to be implemented into EAGLE with all of the support that it has online. It’s this support that made it the better choice over PCB Artist.

7.4 Assembly

Once we fully tested the functionality of all of the components of our project, then had PCB boards made and components soldered, and finally had those PCB boards and components tested for the correct functionality, we began to finalize the project by affixing the PCB and its connected components (such as the transformer) to the project box, as well as the receiver coil, capacitor array, and perforated board with the microcontroller to the car.

We first needed to modify the project box to properly hold all of the base station components. We removed a hole for an AC Mains connector, followed by holes to mount the transformer with screws, then holes to mount the PCB on standoffs, and lastly holes for the button to detect the car and to feed to the coil on top of the box. Once all of these were done, we attached the components securely to the box.

Once the base station had been assembled and checked that it is still working correctly, we began modifying the RC car for our project. We were able to find a sheet of acrylic to mount its respective components to, and attached the receiver coil to the bottom of the car. We drilled holes in the sheet to allow us to hold the perforated board in place with screws. Everything else was held in place with glue.

Once everything was in place and fully assembled, we double checked that everything maintained proper functionality. Thankfully it did, and our project was deemed a success at this point.

Appendix A: Permissions

Wikipedia:

Description	**English:** An XBee Series 2 radio with a wire whip style antenna, placed next to a US quarter.
Date	7 June 2012
Source	Own work
Author	Mark Fickett

Licensing [ed

UBM LLC (DesignNews.com):

Vishay Siliconix:

Texas Instruments:

On the High-Voltage Signal Conditioning for Differential ADCs by Pete Wilson PE:
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www.ti.com/broadband
Interface interface.ti.com Digital Control
www.ti.com/digitalcontrol
Logic logic.ti.com Military
www.ti.com/military
Power Mgmt power.ti.com Optical Networking
www.ti.com/opticalnetwork
Microcontrollers microcontroller.ti.com Security
www.ti.com/security
Telephony www.ti.com/telephony
Video & Imaging www.ti.com/video
Wireless www.ti.com/wireless

Appendix B: Figures

Appendix C: References

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