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High Level Design - Musical Tesla Coils

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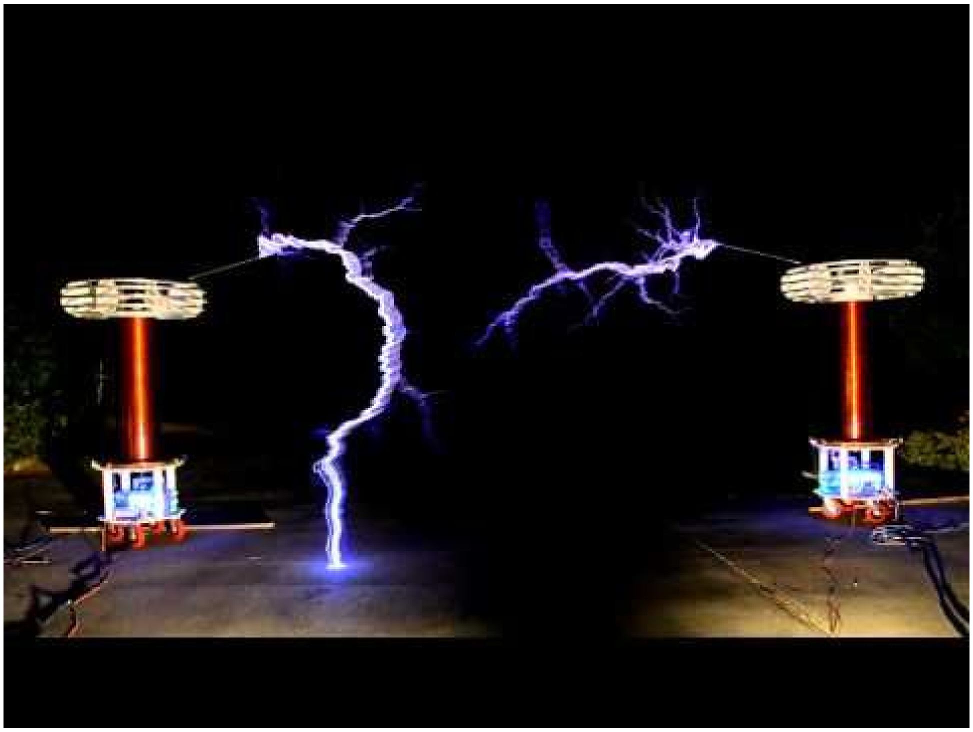
1. Introduction

A Tesla Coil is a resonant transformer circuit with a very low current, high voltage and high frequency secondary coil that is in series with a capacitor. In standard designs, the secondary coil is topped with a toroid, which is a large hollow metal ring that serves as one plate of the capacitor, the other being either the ground or a grounded external metal structure. On the toroid, the voltage gets high enough to cause the air to break down and conduct electricity, producing a large spark or electric arc as well as an acoustic wave from the air rapidly refilling the vacuum left by the plasma.

What people perceive as "music" is really just a combination of different tones put together in specific order. A tone is a sinusoidal acoustic wave at a particular frequency. Although different instruments have different amplitudes of higher harmonics (multiples of the base tone) of tones, and hence sound different, the notes produced by them can be characterized and distinguished by their base tone. Even something such as producing electrical arcs at a specific frequency could create periodic acoustic waves distinguishable as a tone and collecting a group of different tones in a specific order can produce music.

In this project, we will use our Tesla coil to create music with the produced electrical arcs from the top of the toroid and put on an amazing electrical and acoustical display.



2. Problem Statement and Proposed Solution

A traditional speaker uses mechanical drivers to push air molecules to produce an acoustic wave; however, this can also be done using the plasma sparks from the high voltage and high frequency system of a Tesla coil. Building and demonstrating this system will require the team to integrate our knowledge of electrical systems, power electronics, PCB design, programming, and electromagnetic physics. The completed system will be an example of the many capabilities of an electrical engineering degree.

The proposed solution is to create two medium-sized (~3 ft tall), solid-state Tesla coils built from scratch that are able to play musical pieces with harmonies and rhythms using square wave tones produced by a rectifier and inversion circuit. First it will be necessary to build: (1) the full-bridge rectifier, (2) the switching circuit & half-bridge inverter, and (3) the primary and secondary Tesla coils (3). Once the physical build is completed the microcontroller will be programmed to produce the tones on the Tesla coil in such a way that recognizable music is produced.

Since, ultimately, our ability to play music depends on our ability to modulate a tone at a specific frequency, this is the main problem that we need to address. Since the wall outlet is a fixed frequency at 60 Hz, we will need to rectify and invert the signal to recreate a variable frequency square wave. The full-bridge rectifier will convert the AC wall power to DC power. The switching circuitry will then take the DC power and produce a high voltage square wave using IGBT transistors regulated by a microcontroller. The control circuitry decides the tone of the note that will be produced by the Tesla coils. The power source has a fixed frequency of 60 Hz. By using the full-bridge rectifier and half-bridge inverter, we can create a square wave with a frequency corresponding to the amount of times the signal is "inverted" in a second. The control circuitry will alternate between high and low (square wave) that is at the same frequency of the note we want to play. We will control this with the use of a digital logic pin, oscillating between high and low at the same frequency of the desired note, and controlling the gates of the IGBTs in the half-bridge inverter after passing through a non-inverting amplifier to have sufficient power to drive transistor operation.

3. System Requirements

Our design will require a dedicated, well designed, and thoroughly implemented hardware component since we will be working with high voltages and currents. It will also require software in order to control the circuitry in order to actually play the song using the hardware. For analysis, we will break this section into two subparts: (1) hardware and (2) software.

(1) Hardware - questions related to all things hardware:

(a) How to power the Tesla coil- Our Tesla coil will be powered by the wall outlet mains voltage (120 V_{rms}, 170 peak) using a simple, 3 prong wall plug (with a grounding pin), which will be connected to the rest of the components through a digital breaker that will flip, thus opening the circuit, if we draw too much current.

(b) How to power the microcontroller - We were initially considering using a 9V battery to power the microcontroller and low voltage components of the board, but we decided against this since the user would need to change out the battery at regular intervals and remember to do so if any unexpected behavior were to occur. Instead, we will use a traditional “wall wart” that is readily available and affordable. The wall wart takes high voltage ac, steps it down, rectifies it, and regulates a constant, low voltage DC output that we will use to power our board. Most wall warts connect with a micro or mini usb output, which is easily available as well. Purchasing the wall wart will be economical and it will help to ensure the integrity of our build since very high quality wall warts readily exist today.

(c) How to design user interface: Since we will have 5 songs readily available for demonstration, we will need a user interface that allows the user to select the song that they want to hear. We will use a wired remote that is connected to our board with 5 buttons, one corresponding to each song. This wired remote will have a 25 foot wire for safety concerns, so that the user can stand a safe distance away from the Tesla coils while they select the song that they want to be played. We are choosing a wired remote instead of a wireless remote for various reasons. Firstly, a wireless remote can *easily* be lost especially over the course of long periods of storage. Secondly, a wireless remote will require batteries that will require charging. A wireless remote can also experience many problems that a hardwired one will not, such as interference. Since our Tesla coil system will be working with high frequencies and very high voltages, there will be a relatively large amount of electromagnetic noise in the area immediately surrounding the system. As a result, this can interfere with any sort of wireless communication to the Tesla coil system. By using a 25 foot wired remote, we can avoid all of these practical concerns while also remaining committed to the safety of our build and its longevity.

(d) Power electronics components- how the power electronics systems accomplish our goal: As seen in our high level block diagram (below), many main functional blocks of our project involve the use of power electronics and their components.

(i) Full bridge rectifier: We will take the 120 V_{rms} mains voltage from the wall and pass it through a full bridge rectifier, producing a DC signal.

(ii) Half bridge inverter: The half bridge inverter will take our DC signals (high and low) and turn it into an AC signal, specifically a square wave, with the corresponding frequency of the square wave at the frequency of the switching that will occur here (frequency of switching between high and low DC signal).

(iii) Note: The full bridge rectifier and half bridge inverter are necessary steps to complete this project. Ultimately, we need a high voltage ac signal that we can control the frequency of. Since the mains voltage from the wall has a fixed frequency, we need to rectify this signal and use an inverter to reconstruct a square wave with variable frequency that we can use our microcontroller to control.

(iv) Safety build-ins: In these two power electronics functional blocks, we will need to carefully select the components that we will use in order to handle the frequencies we will be operating at, as well as the higher voltages and currents. Specifically, our diodes will need to be carefully selected as well as our transistors in our switching circuitry. We will be using IGBT transistors, which are specifically designed for higher voltage switching circuitry. These will be specified further in our subsystem demo. These IGBT transistors will be placed on heat sinks with thermal paste to dissipate the generated heat effectively during the course of operation.

(e) The physical Tesla coils - how to build them safely and with high quality:

(i) This in itself is its own subsystem that will be calculated, constructed, and measured next semester. This includes the exact number of turns and specific wire for the secondary and primary coils and their resulting inductances and voltage step up to get the desired arc lengths, as well as the exact diameter and capacitance of the toroid.

1) In order to ensure high fidelity on this build, we will coat the secondary coil in varnish to secure it and prevent tarnishing. The PVC pipe will be fitted and glued into a flange which will be drilled into a wood board. The entire coil will be secured and sturdily built. The exact capacitance of the toroid and inductance of the coil will be measured after construction to account for how it will inevitably be slightly different than calculated, and the design will be adjusted accordingly. And, unfortunately, we will have to count turns of the secondary coil.

(ii) Secondary Coil: It will be constructed using a PVC pipe as the structural support for the windings with a flange at the base for support and to fasten it in place. The wire will then be wrapped around the pipe by fastening the pipe to the end of a drill and running the drill, spinning the pipe and rapidly wrapping the wire around it. We will stop the drill with every inch in height of wire wrapped to fix any overlap or gaps in the wire coil and count the turns. The entire coil will then be coated in a simple polyurethane varnish, available at any basic supply store (Home Depot), to secure and protect the coil and insulate it to prevent any electrical bridging between wires in the coil. The bottom end of the coil wire will go to ground.

(iii) Toroid: The toroid will be constructed with a circular aluminium air duct, available at Home Depot. It will be wrapped in a circle to form a donut shape and secured to the top end of the PVC pipe where the top end of secondary coil wire will be soldered to it.

(iv) Primary coil: The primary coil will be constructed using a thick insulated wire to account for the large current it will carry. It will then be wrapped by hand a few times around the base of the secondary coil.

(f) Safety requirements- how to design for safety:

(i) Safety is a primary concern because of the high-voltage nature of this project. Our digital breaker right at the start of our circuitry, coming straight from the wall, will be an initial line of defense against any amount of unexpected current. This will allow us to manipulate the current that we want to allow, while also making it easy to re-enable the circuitry after any potential current-drawing problem has been addressed

(ii) We presently identify two main safety problems: the proximity of the user to the Tesla coils and the potential short with a potential of 340 V through both of the IGBT transistors.

1) Proximity of user to Tesla coils: Our ten foot wired remote will be more than far enough from the Tesla coil system to avoid any sort of interaction with the arcs produced from the toroid. Given that our flashes will be on the order of 2-3 feet from the toroid, a 25 foot wired remote is going to be at minimum 20 feet from any possible interaction with an arc flash.

2) Flyback diodes: The primary safety problem with the use of our switching circuitry is a potential short through both IGBTs that could short 340 V through very little resistance. This could draw a substantial and dangerous amount of current through our circuitry. Hopefully, our digital breaker will do as designed and cut off the current if this ever occurred, however as another safety checkpoint we will be using flyback diodes in the switching circuitry. In inductive switching circuitry there is often a sudden voltage spike seen across an inductive load. The flyback diodes prevent the inductive voltage pulse which could potentially put both IGBTs in operation at the same time, thus further protecting against any potential dangerous short through both transistors.

(g) Mechanical requirements- how the system will be installed:

(i) Our dual Tesla coil system will, naturally, have two Tesla coils. Each of these Tesla coils will be built on rolling platforms for ease of transportation. Each Tesla coil will be between knee and waist high, and the subsequent circuitry for each Tesla coil will be on the respective rolling platform as well. Each rolling platform will be constructed of a thick wooden base, with four omnidirectional wheels (with locks) attached to this base. This will allow for easy movement of the system, ensuring that no lifting is required and our circuitry and coils won't get damaged in the process of transporting them.

(ii) Weight: Approximately 10 pounds each. This includes the physical Tesla coil and toroid, as well as all electrical components (circuitry, PCB). These will be built on wooden, rolling platforms that will allow for easy transportation.

(iii) Size: The size of each coil will be between knee and waist high. The circuitry will be small compared to this, and the necessary circuitry will be attached at the base of each rolling platform. The entire system, together, will be approximately 3 feet high and 4-6 feet across (each platform/coil 2-3 feet across).

(2) Software:

(a) Nature of required embedded intelligence: Our project will require two main software components: the encoded song information of the songs that we want to play, and the code that controls the switching circuitry.

(i) Song information:

1) The song information will contain the audio information of the songs that we want to play. The frequency and duration of each note, including rests (the absence of notes) will be coded. These will be coded directly, and once they are in they act as parameters (i.e. they are unchanged).

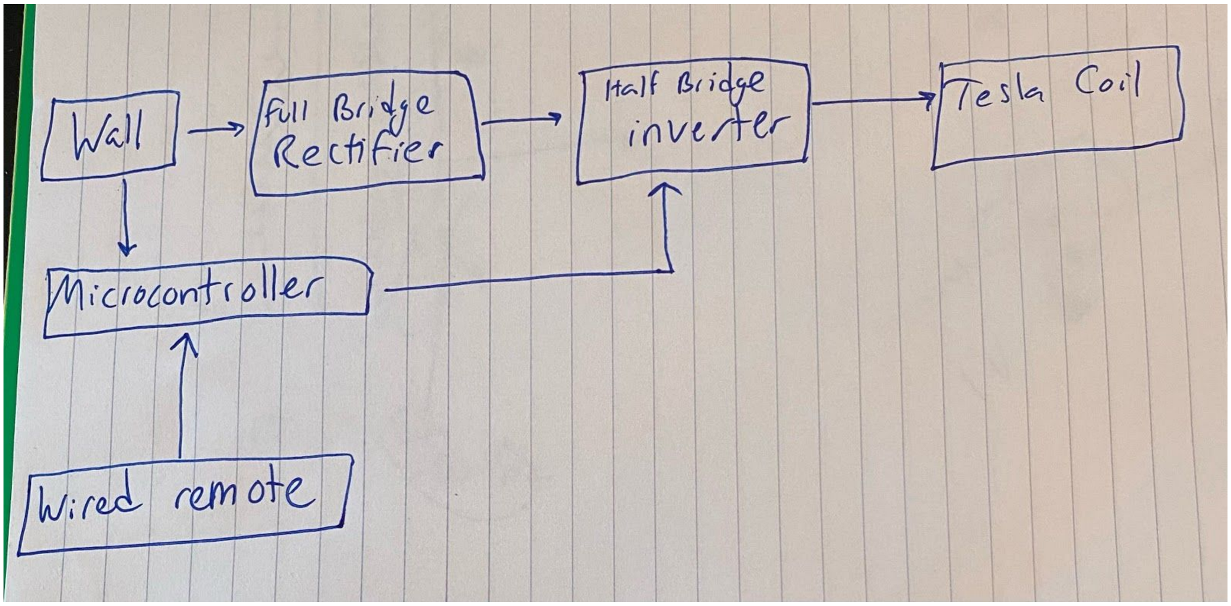
(ii) Control software:

1) The control software will need to control the switching circuitry, which is the half bridge inverter. The control software will use the

Song information and control the frequency of the IGBT transistor switching to reflect the specific note that we want to play at a given time. The control software will control a single output pin that goes high and low at the same frequency of the note that we want to play. Therefore, the IGBTs will switch at this frequency. This input signal will go into one of the transistors as is, and it will go into the other transistor inverted, which is a step to ensure that the transistors won't both be conducting at the same time. If one is conducting, the other will not be and vice versa. This is a step to prevent a short through both transistors - if they are both conducting at the same time then there will be a 340 V potential between a very low resistance. The control software simply reads the selected song information and outputs on the digital IO pin a square wave with the same frequency as the note you desire to play.

4. System Block Diagram

a. Overall System



High Level Block Diagram

These are our main functional blocks. We are starting with power at the wall outlet, and we are finishing with electrical arcs at the Tesla coil. In order to get the wall power to charge the Tesla coils and play music, we understand that we first need a usable, high-voltage DC signal which we will get from the full bridge rectifier. Then, we understand that we need to create an AC signal, a squarewave, with a variable frequency. So, we need to use an inverter, which converts DC to AC, and invert the DC signal with the same frequency as the note we would like to play. In order to control this inversion, we need a microcontroller that is a) powered and b) communicating with the IGBTs that control the inversion. We can power the microcontroller directly from the wall through use of a wall wart, and we can drive IGBT operation with an amplified output from a digital outpin pin on our microcontroller that goes high and low with the same frequency of the note we wish to play. In order to provide a practical, safe, and effective user interface, we will have a 25 foot, wired remote that communicates with the microcontroller in order to select a song.

b. Subsystem and Interface Requirements

1) Wall

   a) This is where we will get our power from. We will have two plugs: a 3 prong plug for our wall mains voltage, and a two plug wall wart to power our lower voltage components (microcontroller).

2) Full bridge rectifier

   a) The full bridge rectifier will convert the wall mains voltage into a DC signal, which will be used by the half bridge inverter to reconstruct a square wave.

3) Half bridge inverter

   a) The half bridge inverter will take these DC signal and switch from high to low at the frequency of the output signal from the microcontroller, creating a square wave at the same frequency.

4) Tesla Coil

   a) The Tesla coil is the secondary coil of a transformer. It will contain a coil (wire wrapped around a PVC pipe) and a toroid constructed from aluminum air duct. It should be able to step up the voltage from the primary coil enough to produce electrical arcs with a sufficient loudness and visual appeal (24-36 inches).

   b) The primary coil (L1) will need to be in series with a capacitor (C2), that will be chosen to match L2 *C2 to L1*C1 because L1, L2, and C2 will all be fixed.

5) Microcontroller

a) The microcontroller will simply contain the song information and subsequently control the switching circuitry based on this song information. A single digital output pin will go high and low at the frequency we want to switch at. This signal will be amplified by a simple non-inverting amplifier to sufficiently drive the IGBT operation.

6) Wired remote

a) The remote is the user interface of the entire system. It will have buttons that correspond to a particular song in the memory of our microcontroller that we would like to play.

c. Future Enhancement Requirements

Since our design will already be built with longevity in mind in terms of power supply and the quality of the build and components, the main future functionality that we believe would be beneficial is the ability to change the songs that are played. This will simply require reprogramming the microcontroller by adding the desired song information and the control code will then play it. Song information can easily be found online, and uploading this information in the song information parameter section of our code will be relatively straightforward. One will simply have to code the frequency of the notes, their duration, and the order in which they occur in the song.

5. High Level Design Decisions

1) Wall

a) It is necessary to be plugged into a wall outlet in order to have high enough voltages to feed into the primary coil of the Tesla coil transformer circuit. We are using a 3 prong plug, with the grounding pin, which adds a layer of safety since we have an earth ground in our circuit. We are choosing to avoid all battery usage so that the system will last without needing any battery changes. To this end, we will use a typical wall wart to step down and rectify the wall voltage in order to power our board, microcontroller, and other low voltage components. We will also have a digital fuse right where the wall mains voltage connects to the rest of our circuitry to prevent large or unexpected current draws that could fry our circuitry.

2) Full bridge rectifier

   a) The full bridge rectifier will rectify our wall mains voltage signal into a desired DC signal with high fidelity (low ripple factor). We will use four diodes to accomplish this, as is customary with full bridge rectifier circuits. They are efficient AC to DC signal conversion circuits and diodes perform this role well. This will be a crucial step in order to reconstruct a square wave later in the design. The input to the full bridge rectifier will simply be the wall mains voltage, and the outputs will go to the switching circuitry, where a square wave will be constructed. The high and low DC signal will be attached to the two transistors in our switching circuitry. This rectification and wiring to the transistors is simply a matter of hardware: no coding is required yet.

3) Half Bridge Inverter

   a) The half bridge inverter will receive only one input: the square wave output of the microcontroller's digital output pin. The transistors in the switching circuitry are connecting to the high and low DC signals respectively, while also connected in the middle and feeding into the primary coil of the Tesla coil transformer circuit. The only variable input the half bridge inverter will receive is the amplified signal from the output of the microcontroller, which will correspond to the frequency of the note that we want to play, and its output is a square wave with +340 potential from peak to peak that will feed directly into the primary coil of the Tesla coil transformer circuit. The wiring of the half bridge inverter is going to require some clever hardware tricks, which will be demonstrated in detail in our subsequent subsystem demo of this switching circuitry subsystem. Ultimately, the use of an independent 1:1 transformer on each IGBT, with one of the input polarities reversed, along with the use of flyback diodes will serve as protection against shorts by ensuring that the two IGBTs are never on at the same time.

b) The IGBT transistor selection for use in this half bridge inverter (switching circuitry) is very intentional. These transistors are designed for high voltage switching applications, which is precisely what we are doing in this subsystem.

4) Tesla Coil

a) The secondary coil should step up the voltage to a sufficient level from the voltage in the primary coil to produce the desired arcs. This will be done by creating a sufficiently large number of windings around the PVC pipe. Although different sources have different opinions, on average, for medium sized Tesla coils, the aspect ratio (height:diameter), is typically in the 4:1 to 4.5:1 range, with a 4” diameter, and lower for larger diameters. The thickness of the wire (gauge) multiplied by the number of turns should equal the predetermined desired height, and we will choose the gauge off of this. The coil height and PVC pipe diameter will be chosen to get a proper aspect ratio, although there are not many options for the PVC diameter.

b) There is little choice in the size and capacitance of the toroid because there are not many choices of aluminium air duct diameter.

c) The primary coil will consist of a lower gauge wire to account for the higher current, with far fewer turns than the secondary coil (<10) to provide a sufficient voltage step up. It will be placed in series with a specially chosen high voltage capacitor to match the primary coil's resonant frequency to the secondary's. Standard wall outlets are capable of sourcing around 15-20 A, so 12 gauge wire will be used because it is the smallest diameter wire that can carry 20 A.

5) Mircocontroller

a) The microcontroller subsystem in this project simply needs to store song information in memory as parameters (i.e. needs sufficient memory space), run basic programs, and perform digital IO functionality. Many PIC microcontrollers can perform this functionality, and we will be selecting the PIC32MX since we are familiar with it since we've been using it the entire semester, and it has more than enough functionality contained within the package to perform all of the necessary tasks we require, as well as having plenty of memory.

b) Positioning: the microcontroller and programming pins will be positioned in an easily accessible place that is marked clearly with some sort of colored indicator so that it can be found easily, accessed easily, and therefore updated/reprogrammed/debugged easily.

c) Power: The microcontroller subsystem needs power and it will receive power from the wall. From the wall wart, the 120 V_{rms} AC mains voltage signal will be approximately 5 V_{DC} that we can then use with a simple IC package to create a 3.3 V regulated power supply to power our board, microcontroller, and low power electronics.

d) Clock: The PIC32MX family's base clocking speed is 8 MHz, which is more than enough clocking speed for our application. We are looking to update our outputs on the order of a few hundred to a few thousand times per second (musical notes are in this range), so a chip with a nominal 8 MHz variable clock will be more than fast enough for our application. We can edit the clock value using the prescaler and postscaler as well as the PLL to tailor to our exact specifications as we get further into the low level design of each subsystem.

e) Output: Our microcontroller will simply output a digital output signal that gets amplified by a non-inverting amplifier with sufficient gain to drive the operation of the two IGBT transistors that it would be controlling. Since the clock of the PIC32MX can go much faster than what we need, our desired output frequencies will present no problem for the chip's digital output.

6) Wired Remote

a) As discussed back in section 3, we decided that a wired remote is ideal for numerous reasons. Firstly, we want it to be physically attached and inseparable from the Tesla coil system itself. This will ensure that it never gets lost. Secondly, we will use a shielded and wired connection in order to avoid electromagnetic interference that will almost certainly occur if using wireless communication, which could prevent communication altogether or at the very least introduce a lot of noise into the system. Thirdly, our wired remote will make use of a 25 foot long extension cord to ensure that the user selecting the song can stand substantially far away while maintaining control of the system. This length decision is based particularly on the safety of the user. We hope to produce sparks on the order of 2-3 feet so the user would be, at minimum, over 20 feet away from the end of the biggest sparks.

6. Open Questions

Since most of our testing and debugging can be done with circuit simulation and an oscilloscope, we don't believe that there are open questions that have to be answered. Our low level design will require extensive simulation, testing, and debugging however. The good thing is that our project is primarily a build, and we can simulate this using pre-existing circuit simulation software that will ensure, before we even start building anything, that our systems will behave as we expect them to. We can read the voltages, currents, and power dissipation at each point will allow us to understand how our circuit is behaving and to explore and experiment with any unexpected results. We can even see how the voltages will build up on the Tesla coil in the simulation because it is simply the secondary coil of a transformer circuit. Thus, the entirety of our build can be simulated in circuit simulation software so we can have a thorough understanding of our design's successes, limitations, and tweak as necessary before building anything for both safety and practical (economical) concerns.

We expect the physical construction of the Tesla coil to be difficult. Creating a high fidelity Tesla coil by hand will require a lot of tinkering and adjustment based on the measurements that we obtain for its values.

7. Major Component Costs

1) Wooden platforms (hardwood plywood) - $46
2) Wheels - $4/per * 8 = $32
3) Wood screws- $3
4) Wall wart - $17
5) 3 prong power plug - $10/per *3 = $30
6) Microcontroller - PIC32MX family $9.56
7) RLC components - ~$5
8) High voltage capacitor - ~$10/per * 4 = $40
9) IGBT transistors - $20.59/per * 4 = $82.36
10) PVS diodes- $0.37/per * 10 + $0.46/per * 0 = $8.45
11) IC package amplifiers - $0.48 * 2 = $0.96
12) PVC pipe - $15
13) PVC flange- $7 * 2 =$14
14) Secondary coil Copper wiring (26 gauge) 2lbs- $63

15) Polyurethane varnish- $19

16) Primary coil Copper wiring (12 gauge) - $15.58

17) Aluminium air ducting- $11

Total: $411.91

8. Conclusions

Musical tesla coils require a significant amount of integration of the different fields of electrical engineering, from electronics and power electronics in circuit design, to control circuitry and software, to electromagnetic physics. Our block diagram breaks down this overall design into a few distinct blocks that, when put together in the way we have designed, will help us to achieve our goal of creating working musical tesla coils that play songs with flashes of lightning. Understanding our starting point of United States wall outlet mains voltage and our finishing point at the toroid of the Tesla coil, we can outline and navigate the steps to harness this unusable wall outlet mains voltage into a usable variable frequency AC signal sent to the tesla coil that will oscillate and build in the resonant frequency transformer circuit. Our block diagram includes our microcontroller and wired remote (user interface) and how these will relate to each of our main high-level functional blocks.

The overwhelming majority of our project's works will be devoted to hardware. This will be good since we can simulate extensively before building and test with an oscilloscope after building, but difficult because interfacing hardware across different functional subsystems and making any changes once built is very challenging. We will gain experience across a wide range of fields and disciplines in electrical engineering and, when successful, we will have arguably the most important skill of all: being able to understand each subsystem that we have made while also being able to put them together to demonstrate something awe inspiring.

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What songs we are going to play:

1) Notre Dame Fighting Irish Fight Song
2) Secrets by OneRepublic
3) Levels by Avicii
4) Dance Monkey by Tones and I
5) Money for Nothing by Dire Straits

Would love some feedback from you, Prof. Schafer, on songs that you would like to hear!

Additional song possibilities/considerations:

6) Mo Bamba by Sheck Wes
7) Jump by Van Halen