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Senior Design Proposal

1. Introduction

A Tesla coil is a resonant transformer circuit that produces high-voltage, low-current, high-frequency A/C electricity. We will build and demonstrate a interrupted solid-state Tesla coil (ISSTC). On top of the Tesla coil is a toroid with a surface voltage on the order of hundreds of thousands of volts. This voltage is so large that it can ionize the air around it (tearing electrons from the atoms in the air—oxygen and nitrogen—causing a flow of charge), which produces a spark. These sparks modulate the air at a particular frequency, which generates an acoustic wave that is heard. By modulating the voltage in the coil at specific frequencies, we can produce audible sound waves recognized as tones. Since each tone has a corresponding frequency (A4 is 440 Hz), we can play a string of these tones to produce a song.

2. Problem Description

A standard speaker uses mechanical drivers to push air molecules to produce an acoustic wave; however, this can be done using the plasma sparks from high voltage, high frequency systems. Building and demonstrating this system will be a serious challenge that will require us to integrate our knowledge of electrical systems, power electronics, PCB design, programming, and electromagnetic physics, allowing us to produce an incredible display that mechanical engineers could only dream of.

3. Proposed Solution

The proposed solution is to use two medium-size, solid state Tesla coils constructed from scratch to recreate musical pieces with harmonies and rhythms using the tones produced from the coils. The coils will be powered by a standard 120V A/C wall outlet and controlled by a microcontroller. Our design will have four main block diagram components of the physical build: (1) the full bridge rectifier, (2) the switching circuitry and half bridge inverter, (3) the interrupter, and (4) the primary and secondary Tesla coils. These 4 blocks are the crux of our project and will be further discussed in detail in section 6 of this proposal. The last thing is to program the microcontroller to control the entire system.

The full bridge rectifier will convert the AC wall power in DC power. The switching circuitry will then take this DC power and with high voltage IGBT transistors regulated by a microcontroller producing a high voltage square wave. The control circuitry is how we are actually controlling the frequency of the note that we want to play. One cannot just simply pass a sinusoidal wave to the tesla coil using the control circuitry because this would not allow us to modulate the frequency. The mains voltage sine wave has a fixed frequency of 60 Hz. In order to control the frequency, we need a wave that we can control the frequency of. By using a full bridge rectifier and half bridge inverter, we can create a square wave with a frequency corresponding to the amount of times we “invert” the signal in a second. Therefore, our control circuitry will alternate between high and low (a 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. This digital logic output pin will control the two IGBTs in the half bridge inverter. By designing our control system in this way, the half bridge inverter and the interrupter will be combined. Since neither transistor is always on, they will not be continuously conducting current. Thus, the current entering each transistor will be interrupted at regular intervals. This is necessary to prevent fatally high temperatures that occur in transistors under continuous, uninterrupted operation.

4. Demonstrated Features

The final version of our project will be able to play numerous (ideally about five) selectable songs for demonstration. Each song will include use of both coils playing in harmony or with syncopated rhythms. The coils will be portable, built on a rolling platform. We will perform an electrical concert with arc flashes of at least nine inches as the instruments.

5. Available Technologies

Since our project is primarily a “build”, we will be spending a significant portion of our $500 budget on the PCB, the materials for the primary and secondary coils, and the necessary electrical components for all of the control circuitry.

The toriod of the secondary coil will be handmade, using aluminum ducting, and the coil out of thin copper wire wrapped around a PVC pipe. The wire will be coated in a varnish to prevent arcing from windings of the coil. The primary coil will be made using a thicker wire with only a few turns to carry a large current that will be stepped down significantly into the secondary coil.

- PCB & Microcontroller ($50)
- Physical Materials for Coils (~$150)
    - Wood, PVC, Aluminum ducting, wire, nails, etc.
- Electronic Materials for Build (~$200)
    - HV capacitors, IGBT transistors, resistors, inductors, potentiometers, diodes, op-amps, fuses, and power cables

6. Engineering Content

As mentioned earlier, this project will have four main functional blocks that we will design and build. The full bridge rectifier, switching circuitry, interrupter, and primary and secondary coils will all require design, testing, and building. We will design and simulate our circuits using circuit simulation software, and build our system by hand. A significant amount of debugging and testing, with the use of an oscilloscope and logic analyzer, will be required to understand how our circuits are behaving. We will break down each of the four main functional blocks:

(1) Full bridge rectifier- We will be using the voltage from a regular wall outlet (120 V_{AC} rms) to power this system. In order to use this, we need to pass the sinusoid through a full bridge rectifier that will give us two outputs: a positive and negative DC voltage of 170 V, which will be necessary signals for our switching circuitry. These will eventually be used to create a square wave (through the use of an inverter and interrupter with IGBTs) that will control the frequency of the audible note that will be played.

(2) Switching circuitry - This circuitry will use IGBTs, diodes, resistors, and high voltage (HV) capacitors to switch the input to the primary coil from high to low at a given frequency, corresponding to the musical note that will be heard. Designing and implementing this control subsystem is a crucial step in the project. This half bridge inverter will convert our two DC signals (high and low) to a square wave that is passed to the primary coil of the transformer.

(3) Interrupter - An interrupter is another important part of this project to ensure the security and integrity of the build over a period of time. A Tesla coil operating continuously will put significant stress on the transistors in the circuitry, which will eventually heat up to a fatal temperature. The interrupter will turn the transistors on and off at a certain frequency, which will prevent the transistors from reaching this fatally high temperature since they are not continuously operating. By implementing our half bridge inverter with a proper control system, we will achieve an interrupted current that prevents the transistors from continuous operation.

(4) The primary and secondary coils - This final block is the transformer and Tesla coil itself. The primary coil is directly connected to the switching circuitry and interrupter, and the secondary coil (the Tesla coil) is separated by air and connected to the toroid on top, which is where the flashes are visible. This final step will require us to consider the resonant frequency of the RLC circuits that we are designing and building in order to create the voltage necessary to produce arc flashes from the toroid.

A large concern is a potential short between the two DC signals coming from the full bridge rectifier. We will have these outputs, +170 V and -170 V DC signals, separated by the two IGBT transistors. If both of these transistors are on at the same time there will be a 340 V potential difference connected through a very small resistance, which could easily fry our transistors. In order to safeguard our transistors and the transformer, we will be using a 1:1 transformer with two independent secondary coils. The primary coil of this 1:1 transformer will receive our on-off signal (square wave) from our microcontroller at the frequency of the note we want to play. These independent secondary coils will be attached to the gate of the IGBT transistors, and the bottom secondary coil (the one that is connected to the transistor attached to the -170 V supply) will be flipped so that the signal on the bottom transistor is always opposite to the one on the gate of the top transistor (attached to the +170 V supply). Therefore, only one transistor can be on at a time, avoiding a potential short since the switching of transistors is not instantaneous. Since the output of the microcontroller will be very small compared to the voltages on the transistors, we will amplify the output of the microcontroller pin using an op-amp so that it is sufficient enough to drive the transistor operation. Flyback diodes will also be used on the secondary coils of this 1:1 transformer to further protect against a possible short through the IGBTs. These flyback diodes are a defense against inductive voltage pulses that occur in switching circuits that use inductors, which could potentially activate an IGBT that isn't supposed to be on, shorting the +170V and -170V.

We will also need to be able to choose an appropriate microcontroller for the design. It will need to be programmed to modulate the signal at the desired frequencies for a desired sequence of notes. And, it will need to be integrated into the high voltage system using operational amplifiers.

Resonant frequency is a major consideration in our design. When an LC circuit operates in resonance, the amplitude of the energy stored in the circuit increases. We will need to match the resonant frequency of the primary coil circuit with that of the secondary coil. In order to do this, the product of L_1C_1 (inductance and capacitance of primary coil) = L_2C_2 (inductance and capacitance of the secondary coil). This is a crucial consideration because if our circuit is not at resonance then we will not be able to build up a voltage high enough to produce the flashes from the toroid, which is responsible for playing the sound. Since the inductance of the secondary coil will depend primarily on the amount of turns (N = ____) and the capacitance will be a characteristic of the toroid, we will then need to calculate the resonant frequency of this circuit. We will then need to fix values (the inductor and capacitor of the primary coil) to match this resonant frequency. The reason we must do the secondary coil circuit first is so that we can have a very precise value for the resonant frequency, since one cannot calculate the exact values of inductance and capacitance of the L_2 and C_2 without building them and testing directly.

The largest challenge in this project will be constructing the two Tesla coils so that they are well-built enough to produce a clean, recognizable tone. Further, the control circuitry will be a significant challenge. If we do not carefully pass the signal through the full bridge rectifier and fine tune the control circuitry our signal will not be a high fidelity square wave. We will need to very carefully select each component in our circuitry, including resistors, capacitors, inductors, and op amp packages, that can meet the high voltage requirements of the circuit without breaking down or experiencing unexpected behavior. To protect our circuitry, we will be using a fuse located close to the original mains voltage source (wall outlet) so if too much current is drawn during operation the fuse will blow and protect our circuit and its components.

7. Conclusions

This project is a very hardware and power electronics intensive design that will test our ability to program and integrate low voltage microcontrollers into a high voltage system, utilize rectifiers to convert AC to DC voltage, construct and operate transformers, use operational amplifiers, and calibrate according to resonant frequencies all while taking intensive precautions to avoid frying our more sensitive electronics. When our project is successful, it will be a unique and awesome display of what is possible with electrical engineering.