ECE 445

Gentle Giant: A Power-Factor-Corrected Musical Tesla Coil

Project Proposal

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Introduction

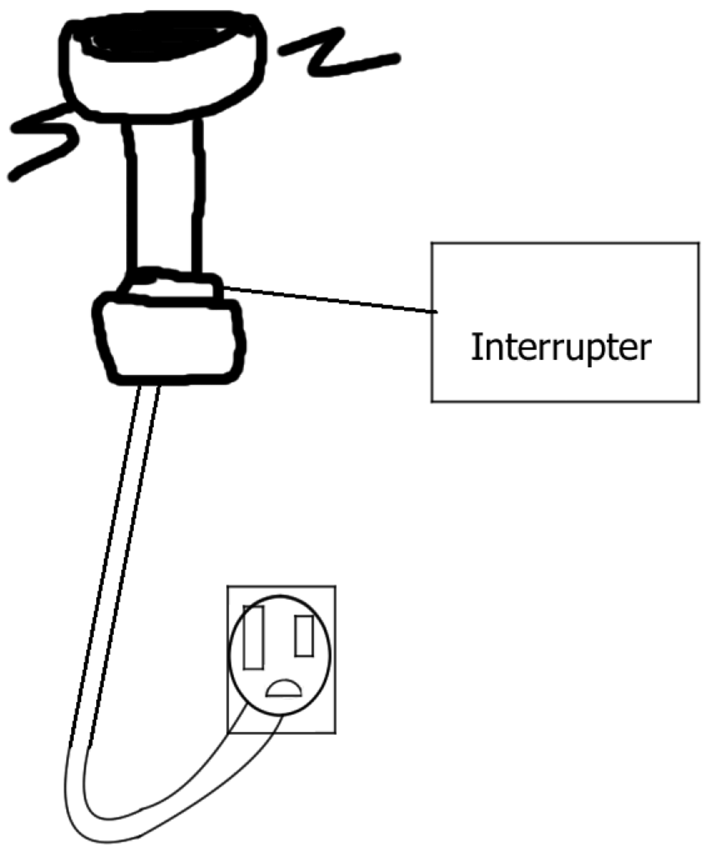
Tesla coils are impressive visual and auditory devices; some can create a surprising range of sounds using arc discharges, and thus have found uses as display pieces in entertainment and STEM education. A particularly large one is permanently mounted to a ceiling inside the Museum of Science and Industry in Chicago. However, for the majority of their existence, they have been crude instruments. Their design and operation typically results in a suboptimal use of AC power, also known as a poor power factor, and even with the advent of "solid-state" Tesla coils (SSTCs) that use power semiconductors, the situation has not improved. Areas with lower-voltage mains like the United States are often at a disadvantage due to details in many of these implementations. Further, when scaling up to large Tesla coils for use in performances, they can place significant strain on electrical grids and suppliers. Addressing these challenges could enhance the efficiency and portability of all Tesla coils, making them more practical for a wider range of applications.

Solution

We aim to build, for a comparatively low cost, a Dual-Resonance Solid State Tesla Coil (DRSSTC) with an active Power Factor Correction (PFC) front end. The combination of these two systems, the latter of which has never been done before on a Tesla coil, puts our design at the very forefront of Tesla coil power electronics technology, and solves several technical issues with other modern designs.

Tesla coils are effectively giant transformers, with a secondary winding that has many times more turns than the primary. Conventional SSTCs operate by first rectifying mains AC to a high-voltage DC, then using a half-bridge or full-bridge of power semiconductors to switch the primary of the Tesla coil. This results in a very large voltage being generated in the secondary, which causes it to release arc discharges. A major benefit that DRSSTCs like ours bring over SSTCs is that it operates more like a resonant converter. In the design phase of the transformer, the primary and secondary must be tuned to have close LC resonant frequencies. During operation, feedback from the primary is used to switch it at its resonant frequency, which results in more energy being built up in the system and more impressive arc discharges. This energy buildup must be stopped intermittently by an external PWM signal called an interrupter (which can simultaneously be used to modulate musical sounds into the arc discharges). The primary feedback also enables zero-current switching (ZCS), reducing thermal losses in the power stage to near zero.

We choose to improve even further by designing a digitally controlled boost-type active PFC to create the high-voltage DC rail. This brings with it several benefits of its own, like improving system power factor and making the system agnostic to mains voltage and frequency. With a higher power factor, larger arcs can be generated for the same apparent power, or arcs of the same size can be generated for less apparent power. This is a great all-around benefit for Tesla coil efficiency and viability at large scale.



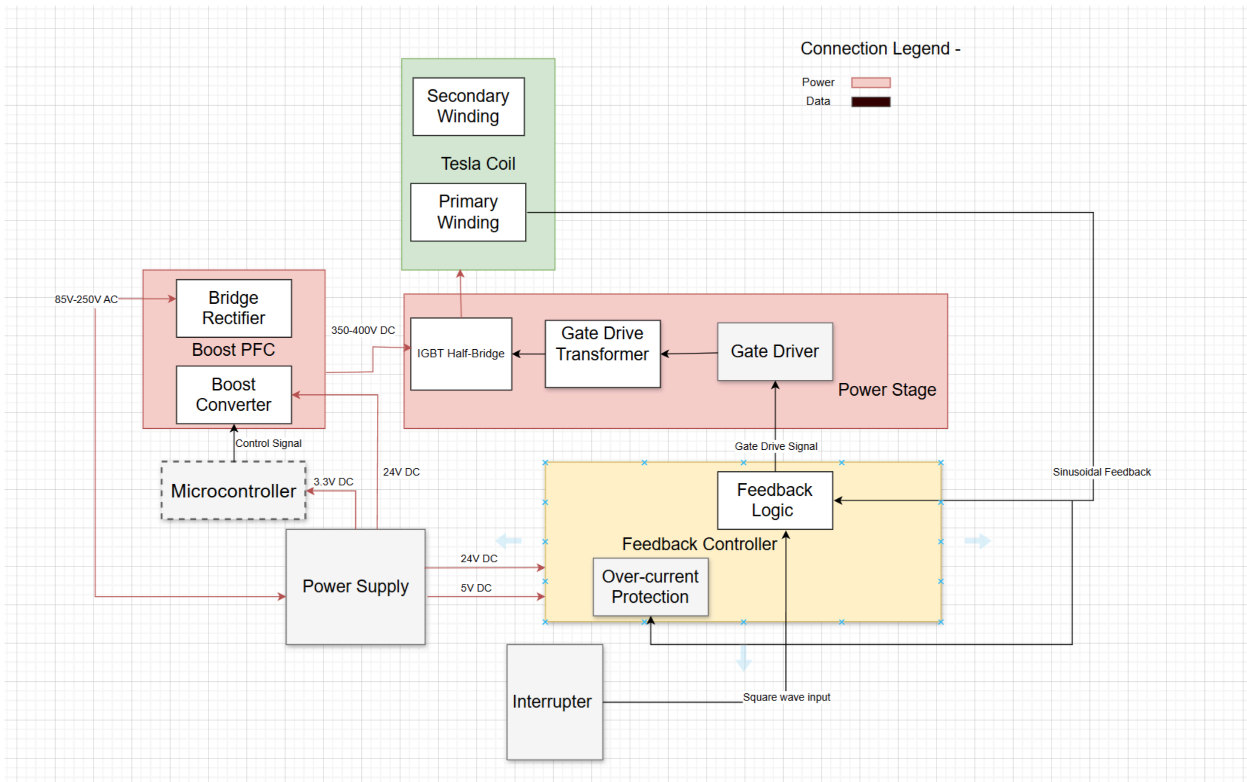
As our main focus will be the boost PFC used in the Tesla coil, users will not immediately see any visual differences from other Tesla coils. However, a measurable metric can be provided in the form of the device’s power factor and power consumption.

Project–level Requirements

- The measured power factor has to be above or equal to 0.95 when operating at the US mains level of 120VAC.
- Arc discharge length has to be at least 1 foot, to demonstrate working of the Tesla coil.
- The apparent power drawn during operation should be no more than 1000VA.

Design

Block Diagram



Feedback controller

This subsystem implements a simple ZCS feedback controller using comparators and digital logic chips, and utilizes a long cable to safely and remotely play simple musical notes via PWM (this is the interruptor signal). There must be absolutely no conduction measurable with a multimeter between the interrupter device and the Tesla coil. Thus, the interrupter signal receiver we use will be an Industrial Fiber Optics IF-D95T, which is an inexpensive fiber optic device that has been highly proven in Tesla coil design history. Though in theory the microcontroller could also perform the logic task, we felt that it would not have low enough latency. The feedback itself is provided by a current transformer made of a Fair-Rite #77 ferrite core, which feeds into a burden resistor. Microchip MCP6561 comparators perform the zero crossing detection, and 74HCT logic chips manipulate the signal, combine it with the interruptor signal, and create gate drive waveforms for the power stage.

Power stage

The power stage simply consists of a half-bridge of two power semiconductors to which the primary LC is connected. The switches are driven by a gate drive transformer (GDT) to save cost and complexity versus developing a solution with isolated gate drive ICs. GDTs have been by far the leading solution to drive SSTC power semiconductors, and there is little incentive to do otherwise. Its gate drive signals are provided by the feedback logic, and it should drive the primary at its resonant frequency. In order to achieve smooth operation with the PFC and Tesla coil, the IGBT half-bridge must withstand at least a 400 VDC voltage input with headroom to spare, and the IGBTs must have a t_{on} and t_{off} low enough to operate at a minimum of 300kHz without excessive switching loss. We choose to use 60N65 IGBTs, and a UCC27423 to drive the GDT which then drives the half-bridge.

Transformer/Tesla coil

This is the Tesla coil itself; electrically, it is an air-core transformer. It will stand at around three feet tall once completed, and we estimate that the frequency will be around 200kHz. It has no electronic components, but its physical design places some constraints on the power stage and boost PFC. The physical placement and shape of the windings determines the coupling coefficient, which must be kept low (below 0.3) for a slow ramp-up. Calculating the stray capacitances in both the primary and secondary is necessary to keep the real resonant frequencies close. The math behind this is indeterminate due to how the plasma in the arcs affects the secondary LC's capacitance, so it is difficult to come up with strict requirements for this subsystem, but we will be using a popular community tool called JavaTC to help us meet good specifications.

Boost PFC stage

The PFC stage must output between 350-400 V DC for use in the power stage's DC rail. It is digitally controlled using an STM32F103 microcontroller, which allows it to compensate for different mains voltages and frequencies.

This subsystem consists of a bridge rectifier and a boost converter structure (which can be further broken down into an input inductance, an output capacitance, a FET and a diode). Specifically, we plan to use a Panjit KBJB bridge rectifier, the same 60N65 IGBT as the power stage, and an STMicroelectronics STPSC12065D SiC diode. A Texas Instruments UCC5710x gate driver powered from the 24V supply can be used to allow the STM32F103 to drive the FET, and it must be able to operate at a switching frequency of 100kHz.

Tolerance Analysis

Programming the embedded microcontroller to perform the PFC is one of the main challenges we expect to face, as digital power is a relatively new technology. We plan on getting started early to familiarize ourselves with the microcontroller's functions, and building a small-scale test bed to experiment with lower voltages.

Ethics and Safety

Responsibility to Public Welfare (IEEE/ACM Code of Ethics)

This project involves high-voltage electricity, which poses risks of injury or fire if not properly designed and controlled. Misuse or accidental exposure could harm individuals or damage property. To mitigate this, we will adhere to the IEEE Code of Ethics principle of prioritizing public safety and welfare by ensuring the design includes safety features such as grounding, insulation, and fail-safes to prevent accidental harm. In addition, clear labels on the device with warnings will provide sufficient instruction for safe operation.

Transparency and Honesty (IEEE/ACM Code of Ethics)

Misrepresenting the capabilities or safety of the Tesla coil could lead to misuse or overconfidence in its safety. We aim to be transparent about the risks and limitations of the device, and will document all design choices, safety measures, and potential hazards.

Environmental Impact (IEEE/ACM Code of Ethics)

High-voltage discharges generate ozone and other byproducts, potentially harming the environment or human health. The Tesla coil should and will only be operated in well-ventilated areas.

Preventing Misuse (IEEE/ACM Code of Ethics)

The Tesla coil could be intentionally misused to cause harm, such as by interfering with electronic devices or creating public panic. It will be kept out of reach of children, and any instructions for use will be accompanied by warnings of the ethical and legal implications of its misuse.

Electrical Safety

High-voltage discharges pose risks of electric shock, burns, or even death, so in order to minimize injury we will adhere to the following electrical safety standards and best practices.

NFPA 70 (National Electrical Code): Ensure proper grounding, insulation, and circuit protection.

OSHA Standards: Use personal protective equipment (PPE) such as insulated gloves and safety goggles during testing.

Campus Policies: Adhere to university lab safety protocols, including supervision (presence of at least one other person in the lab) and restricted access to high-voltage equipment.

FCC standards for Electromagnetic Interference (EMI): A Tesla coil is, by nature, a large emitter of broadband EMI, potentially disrupting nearby electronic devices or communication systems. We will operate a safe distance from any sensitive electronics.

Auditory and Visual Safety: Loud noises and bright flashes from the Tesla coil could cause hearing damage or eye strain. We will maintain a safe distance during operation to mitigate any potential harm.

Legal Responsibilities

Failure to comply with state or federal regulations could result in legal liability. We will review and adhere to:

State and Local Regulations: Take Illinois Electrical Equipment - General admin code and Champaign noise ordinance laws into consideration while building and testing the coil.

Federal Regulations: Ensuring compliance with the aforementioned FCC and OSHA standards.

Industry Standards: We will follow guidelines from organizations like the IEEE for high-voltage circuit design, particularly with respect to safe clearances.

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