Who We Are

• Tesla Orchestra is a team of engineers and artists who make music with lightning
• Founded in 2009 by Ian Charnas
• Most members are Case students, alumni, or staff, ranging from freshman undergraduates to seniors in industry
• Funded by various sources:
  – Private donations
  – Case funding
  – Show fees
  – Sears undergraduate lab resources
• Performed for thousands of people, including two shows in Europe
• A short example
Who We Are
Safety disclaimer

Working on or around Tesla Coils, and other high power/high energy/high voltage systems is lethally dangerous. Every year both hobbyists and professionals lose their lives. This presentation is not a guide on the safe construction or operation of Tesla Coils. Such experiments should only be conducted under carefully controlled circumstances, in the presence of experienced engineers. We never work alone, and someone always knows CPR.
Tesla coil basics

- Invented by Nikola Tesla (1856-1943)
- Commonly defined as a resonant air core transformer
- Uses resonant circuits and loosely coupled transformers to convert between high currents and high voltages
- Tesla intended them to be used for wireless transmission of electrical power in the upper atmosphere
- Even geniuses have bad ideas
- Now used for entertainment and education
Circuit theory: resonance

- A system is said to be resonant when it tends to store, absorb, or transfer energy at one or more particular frequencies.
- In electronics, resonant circuits are often made of inductors and capacitors.

**Capacitor impedance:**

\[
X_C = \frac{1}{j \omega C}
\]

**Inductor impedance:**

\[
X_L = j \omega L
\]
Parallel resonance

- When driven in parallel, a LC circuit’s impedance will approach impedance at the resonant frequency.
- When driven with a current, it will accumulate voltage.

\[
Z = \frac{X_L \cdot X_C}{X_L + X_C}
\]

\[
f_C = \frac{1}{2\pi \sqrt{LC}}
\]
Series resonance

- When driven in series, a LC circuit’s impedance will approach zero at the resonant frequency.
- When driven with a voltage, it will accumulate current.
- Also the midpoint will amplify voltage.

\[ Z = X_L + X_C \]

\[ f_c = \frac{1}{2\pi\sqrt{LC}} \]
**Baby’s first transformer model**

**Ideal transformer model:**

\[
N = \frac{N_S}{N_P} \\
V_S = V_P \cdot N \\
I_S = \frac{I_P}{N}
\]

**Impedance transformation:**

An impedance on the secondary will be “reflected” on the primary as an impedance lower by a factor of \( N \) squared.

\[
Z_P = \frac{Z_S}{N^2}
\]
Magnetizing inductance

- All transformers have some finite magnetizing inductance which appears in parallel with an ideal transformer model.
- Current flowing through magnetizing inductance $L_m$ is called magnetizing current, and induces magnetizing flux.
Coupling and leakage inductance

• The primary and secondary windings are not perfectly coupled
• Some magnetic flux “leaks,” and manifests itself as leakage inductance in series with the primary and secondary windings
• The fraction of the flux from winding that is coupled to another winding is called the coupling coefficient $k$, where $0 < k < 1$.

\[ L_{Lp} = (1 - k) \cdot L_{Mp} \quad \quad \quad L_{Ls} = (1 - k) \cdot L_{MP} \cdot N^2 \]
The Tesla Coil: coupled resonances

• By adding capacitors to the primary and secondary of a loosely coupled transformer, we get a basic Tesla Coil circuit.
• The two coupled resonances, together with a large turns ratio N in the transformer, causes huge voltage gain when driven and “tuned” correctly.
• Coupling two LC circuits with the same $f_r$ gives rise to peak splitting. The coupled system will have a double resonant behavior with two peaks centered around the original $f_r$.
• The frequency gap between the two peaks is generally $f_r \times k$. 
The topload

- A Tesla Coil’s secondary is normally connected to earth ground at one end
- The other end is usually connected to a topload
- The purpose of the topload is to allow higher voltages to be reached before breakout occurs
- Also increases secondary capacitance. The topload acts as one plate of a capacitor, while the earth acts as the other.
- May also have a breakout point, which gives a preferred path for corona discharge
Spark gap tesla coils (SGTC)

- Need a way to excite the resonant coil from conventional power sources (50/60HZ AC, 120-240Vrms)
- Circa 1900: no transistors yet, vacuum tubes were just being invented
- Spark gaps are the best way to switch high current circuits quickly and reliably
- Spark gaps conduct when the voltage between them exceeds its breakdown potential
- The gap will continue to conduct until current ceases long enough for the arc to extinguish
SGTC operation

• 60Hz AC service is stepped up with HV transformer
• Line filter prevents high frequency currents from feeding back into service

Image courtesy of Richie Burnette
http://www.richieburnett.co.uk/tesla.shtml
SGTC operation step 1

• Spark gap is initially open
• Primary capacitor Cp is charged to high voltage through step up transformer T1
• Energy is accumulated on primary side

Image courtesy of Richie Burnette
http://www.richieburnett.co.uk/tesla.shtml
SGTC operation step 2

- When $C_p$ voltage rises above breakdown point of spark gap, the spark gap closes, creating an effective short circuit.
- $C_p$ resonates with $L_p$ at its resonant frequency.
- Choke $L_1$ prevents the spark gap from completely shorting out the AC line.

![Diagram with labels: L, N, 240 VAC, RFI FILTER, T1, L1, Cp, Lp, Ls, Cs.]

**SPARK GAP CLOSES**

$C_p$ discharges into $L_p$ through conducting spark gap. (Damped oscillation at 200kHz.)

Image courtesy of Richie Burnette
http://www.richieburnett.co.uk/tesla.shtml
SGTC operation step 3

• As $C_p$ and $L_p$ oscillate, energy will transfer to the secondary side.
• If there is enough energy, the voltage at the topload will rise enough to cause corona discharge.

Image courtesy of Richie Burnette
http://www.richieburnett.co.uk/tesla.shtml
SGTC operation

• Energy will transfer between primary and secondary circuits, creating peaks and notches in voltage and current
• Energy will continue to circulate until it is dissipated in corona discharge, or in ohmic losses

Image courtesy of Richie Burnette
http://www.richieburnett.co.uk/tesla.shtml
Solid State Tesla Coils (SSTC)

• We want a way to control the coil using modern solid state switches
• Must be able to drive coil at its resonant frequency (20KHz-2MHz)
• Switch must not be latching (like spark gaps and SCRs)
The H bridge inverter

- Common topology for generating AC waveforms from a DC bus
- Four switches are driven out of phase to deliver square wave to load
- Switches are usually MOSFETs or IGBTs
Basic SSTC

• Primary of the Tesla Coil is driven directly by H bridge
• Only a single resonant system
SSTC operation

- Feedback from the secondary current, or toplod electrical field, is used to make the circuit self oscillate
- System operates in “continuous mode”
The DRSSTC

- Huge improvement over SSTC
- Primary capacitor is added in order to cancel out primary leakage inductance
- Allows dual-resonant behavior like SGTC
DRSSTC operation

- Usually uses primary current feedback
- Zero current switching on primary drastically improves efficiency of H bridge
- When tuned properly, operates in “burst mode”
Reality check
From sparks to music

- Anything that disturbs the air can be modulated to make tones
- Each arc heats the air, causing it to expand and generate sound waves
- Repeating the arc at a certain frequency will produce a sound of the same tone
Our Coils

- World’s largest and most powerful twin musical Tesla Coils
- Stand 14 feet high and output up to 12KW each (so far)
- Capable of up to >13foot arcs (so far!)
Secondary coil

• Wound on 12” diameter, 6’ long PVC pipe
• Wound with ~2300 turns (1.37 miles) of 21 AWG magnet wire
• Coated in clear epoxy
Primary coil

• Primary is a flat spiral of 7/8” OD copper pipe, ~6 turns
• Can be tapped anywhere for tuning of inductance and coupling
• Height of primary can be changed with standoffs
Topload 1.0: The sphere

• First topload was made with a spherical shape, 54” OD
• Sphere is approximated by a set of aluminum rings
• Sphere is gives large topload capacitance
• But gives undesirable electrical field shape; lots of primary strikes
Topload 2.0: The toroid

- The toroid is a much more common topload shape
- Directs highest electrical field to outer edge, not bottom
- Slightly lower capacitance
Primary capacitor

Current generation
• 35KV, 0.94uF, 40A Maxwell pulse capacitor
• Pretty good, but not enough

Coming soon:
• 8x16 array of small pulse capacitors
• Overall specifications: 16KV, 1.0uF, 175A
The H bridge

• Driven by four CM600HA24 IGBTs
• Cooled by custom aluminum water cooled heatsink
• Laminated bus structure with 1/8” copper sheet
• 8x2 capacitor bank for DC bus: 24mF, 900VDC
H bridge
H bridge
Controlling the beast

• The driver board is housed with the H bridge
• Drives the H bridge and takes primary current feedback in order to drive the coil
• Takes measurements on peak primary current, oscillation frequency, heatsink temperature, DC bus voltage
• Communicates info back to operators via fiber serial
• Receives audio interrupter signal via fiber
Controlling the beast

Telemetry board
Converts USB serial to fiber serial for telemetry

Sound board
Converts MIDI interface from computer to PWM signals over fiber

Both interface to Macbook, which runs telemetry GUI and runs all audio tracks. Each coil can play one MIDI track. No polyphonics, just single tones.
Feeding the beast

• Need to convert various AC services to DC bus voltage
  – 50/60Hz line frequency
  – 208V or 240V voltages
  – Split phase, three phase, delta, wye, etc...

• Initially used large 30A variacs
  – Large, heavy, no fault protection
  – 30A isn’t much...

• The Jonny Box contains all line filters, transformers, and breakers
More Jiggawatts: The PFC

• Wanted more power with good regulation, fault protection...
• Decided on power factor corrected (PFC) boost converters
• First attempts were discouraging...
PFC 2.0

• John Kacunich shows up with the serious silicon
• PFCs are eventually capable of 100Arms input each
• PF>0.98, η>0.95 at heavy load
• Vout adjustable between 370-800VDC
• Built in current limit, safety interlocking, temperature measurement, etc.
Other issues

• Tesla coils generate an incredible amount of EMI
• All control signals to the coil are fiber optic
• All electronics are shielded if possible
• Cables get ferrite chokes

Things that really do not like Tesla Coils:
• Macbook offline chargers
• Digital audio amplifiers
• Smart lighting
• DSL modems
• Small flying animals
The Faraday suit

• Aluminum chain mail suit covering the entire body
• Specially designed for HV work
• Worn with insulating clothing layer between suit and skin
• Creepy mask
The Faraday cage
Future goals

- Increase power delivery to >20KW per coil
- Extend audio bandwidth to 1KHz
- Explore polyphonics, tone modulation, other audio effects
- Add more elements to the show
  - Need other instruments. Fire organ??
  - Hire professional performers and choreographers
Resources for the curious

- Tesla Orchestra youtube channel: [http://www.youtube.com/user/teslaorchestra](http://www.youtube.com/user/teslaorchestra)
- Steve Ward, expert on solid state Tesla Coils: [http://stevehv.4hv.org/](http://stevehv.4hv.org/)
- Richie Burnett, various Tesla Coils and other high energy stuff: [http://www.richieburnett.co.uk/tesla.shtml](http://www.richieburnett.co.uk/tesla.shtml)
- Antonio Carlos M. de Queiroz, detailed analysis of Tesla Coil theory [http://www.coe.ufrj.br/~acmq/tesla/drsstc.html](http://www.coe.ufrj.br/~acmq/tesla/drsstc.html)

Interested in joining?