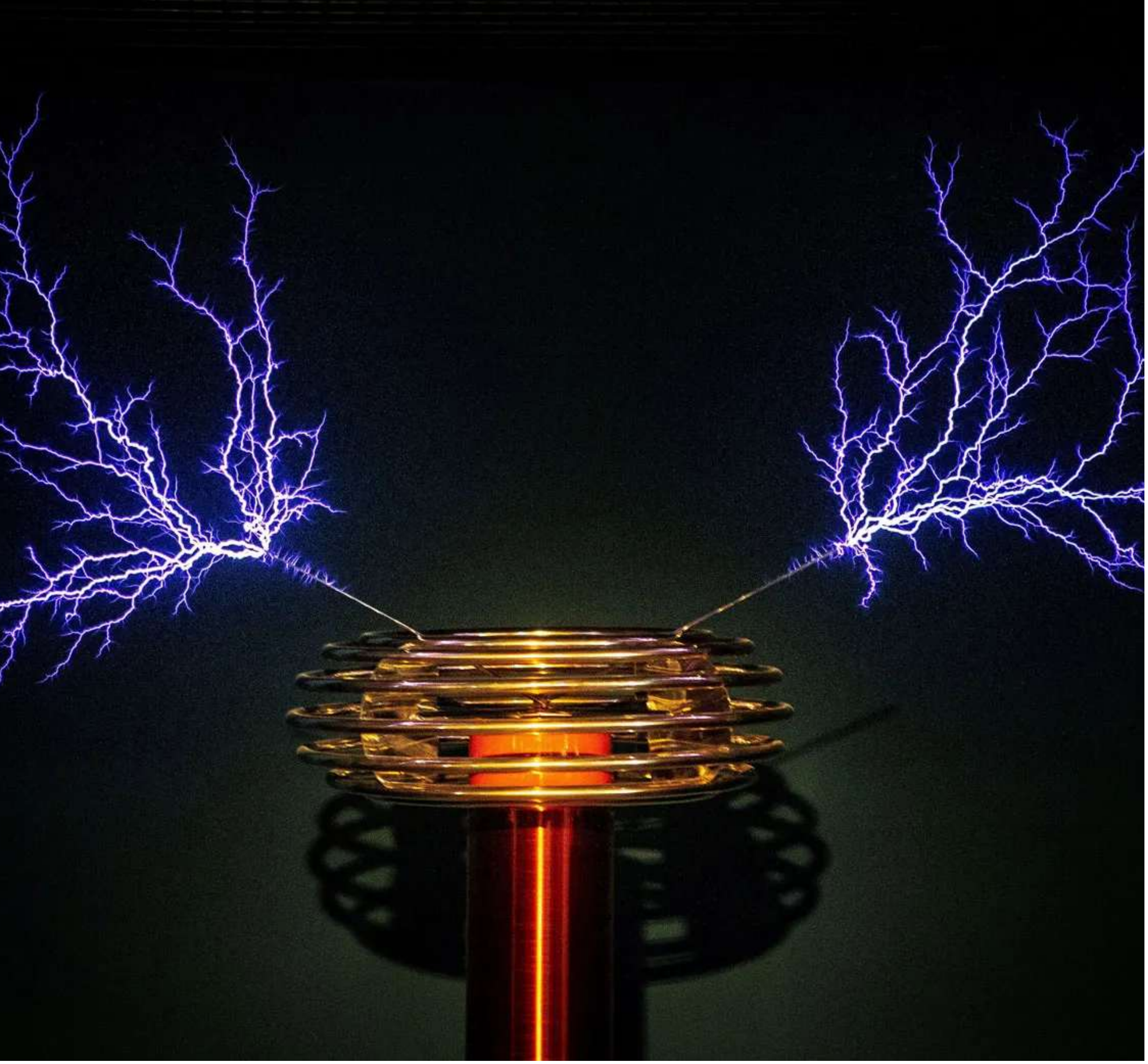


Solid-State Musical Tesla Coils: Architecture, Educational Uses, and High Voltage

Alex Kowalewski
&
Zander Selleseth

Research conducted at NC State University under Dr. David Ricketts

Introduction

About Me

- Callsign: KR4ESQ – General
- BS EE, NCSU, May 2025
- MS EE, NCSU, May 2026
- RF circuits + Analog Electronics

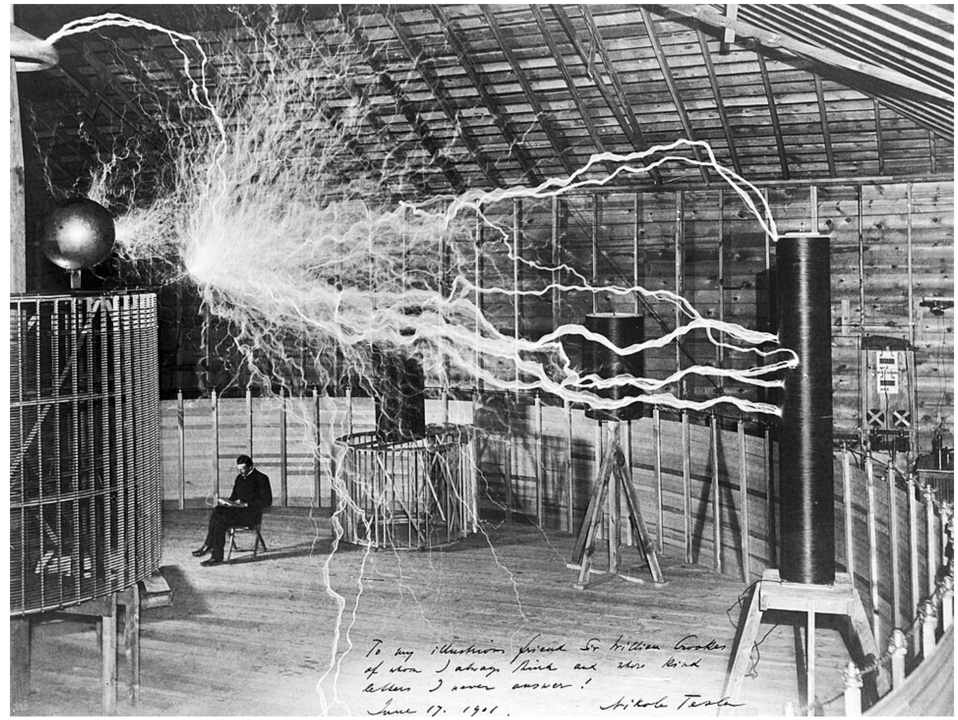
Past Work

Past Work

What is a Tesla Coil?

- A cool demo of EM concepts?

- Air-core resonant transformer driven by an oscillator
    - Typical resonant frequencies (F_{res}): 10s of kHz to 1MHz
    - Typical output voltages: 50kV to several million volts!

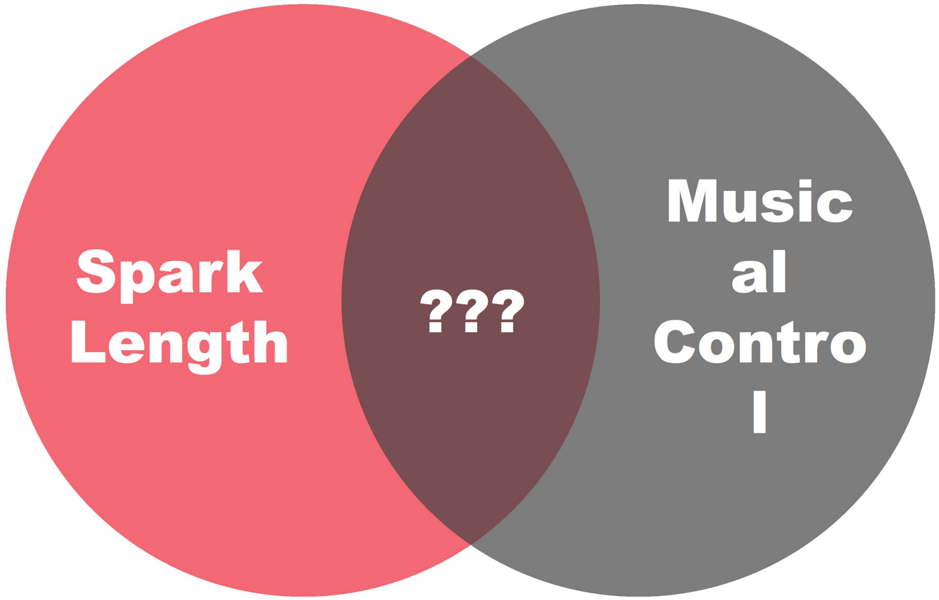


Nikola Tesla in his Colorado Springs lab circa 1899.
Fun Fact: this famous image is a double-exposure!

Types of Tesla Coils

Spark Gap (SGTC)

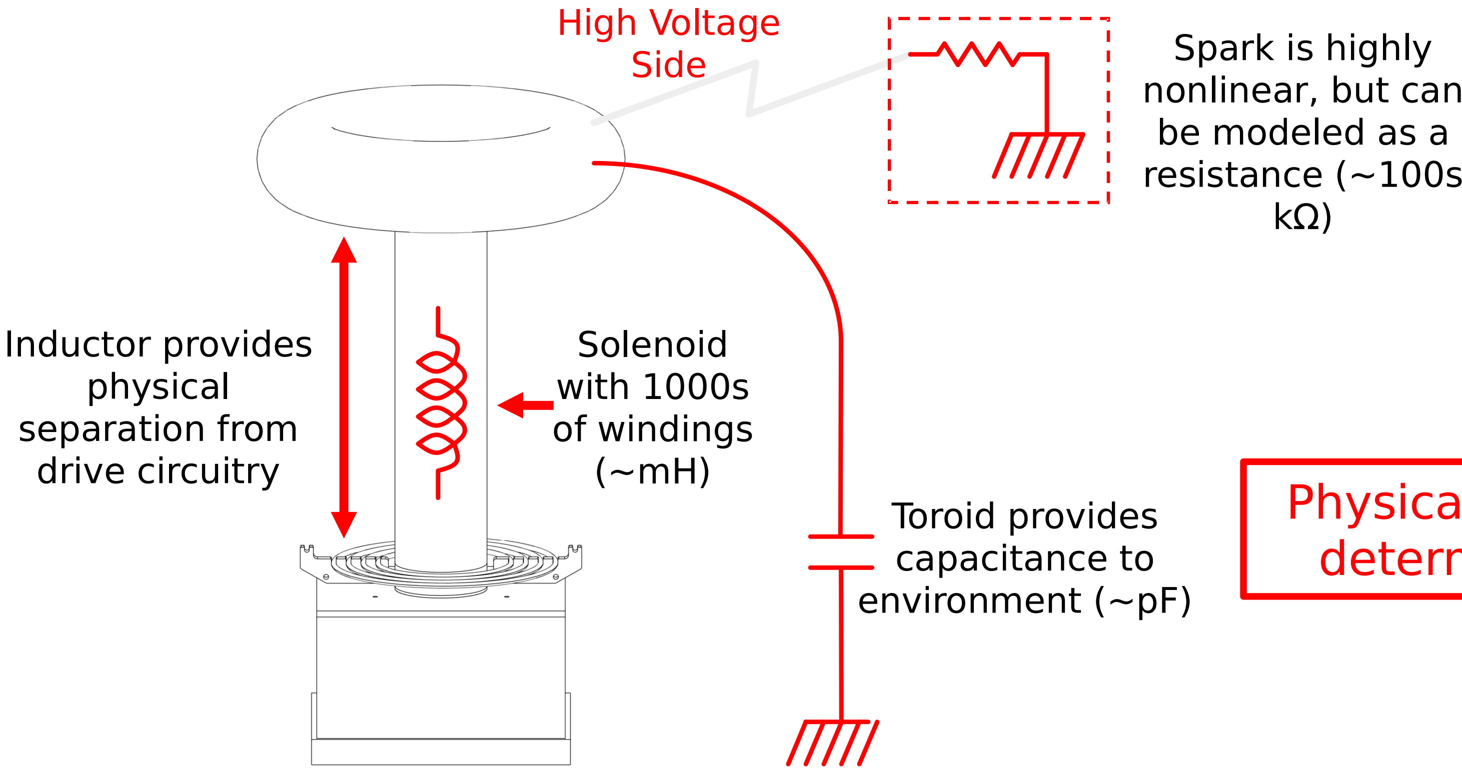
Griffith Observatory, Los Angeles



Early Solid State Tesla Coils (SSTC)

Loneoceans Laboratories

The Tesla Resonator – The "Heart" of the Tesla Coil

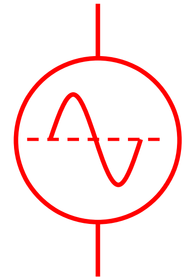


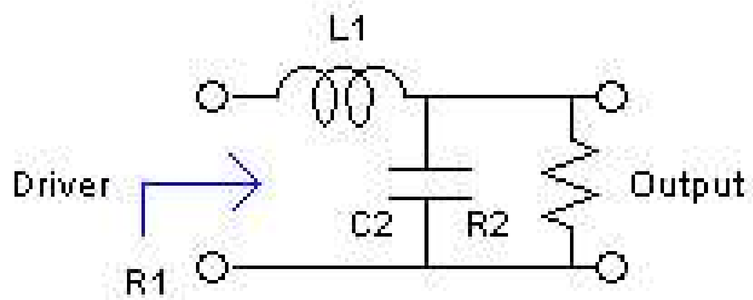
Physical geometry determines F_{res}!

Resonant Network Design

- Driver: circuit able to excite network at F_{res}
  - R1 set by desired drive voltage/current (typically 100s of V and A → R1~ Ω's)

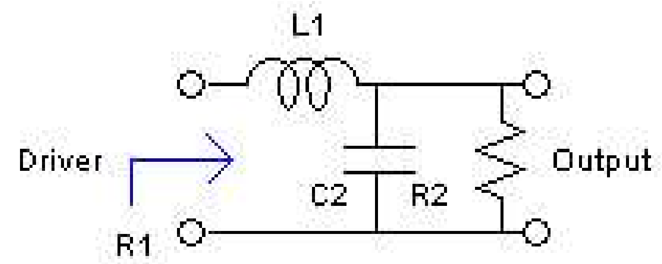
- <u>Goal:</u> Transfer maximum power to spark
- Helpful to think of design as an impedance matching problem.
  - Driver (Ω's) → Spark (100s kΩ's)





Designing a Solid-State Tesla Coil, Antonio Carlos M. de Queiroz

Simple L-Match

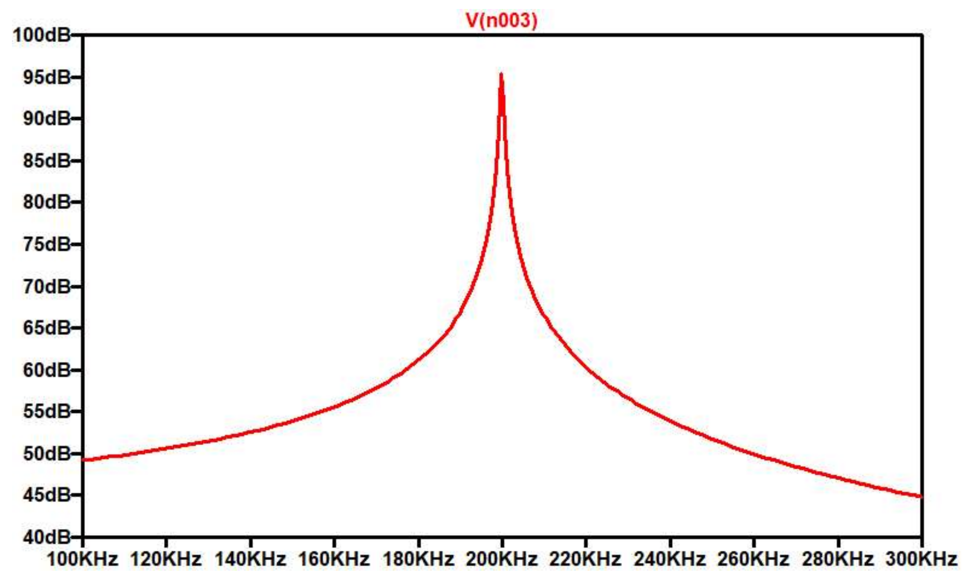


Pros:

- Simple, closed form solution
- No additional matching components

Cons:

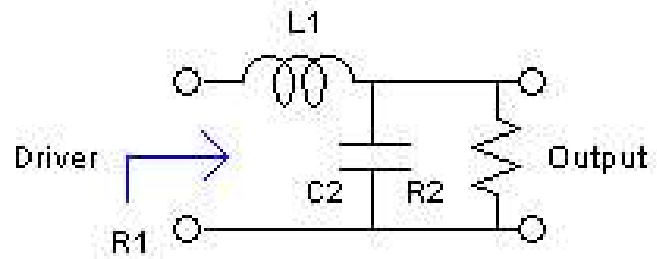
- Sensitive to changes in R2 (R1 no longer purely resistive)
- Very high Q



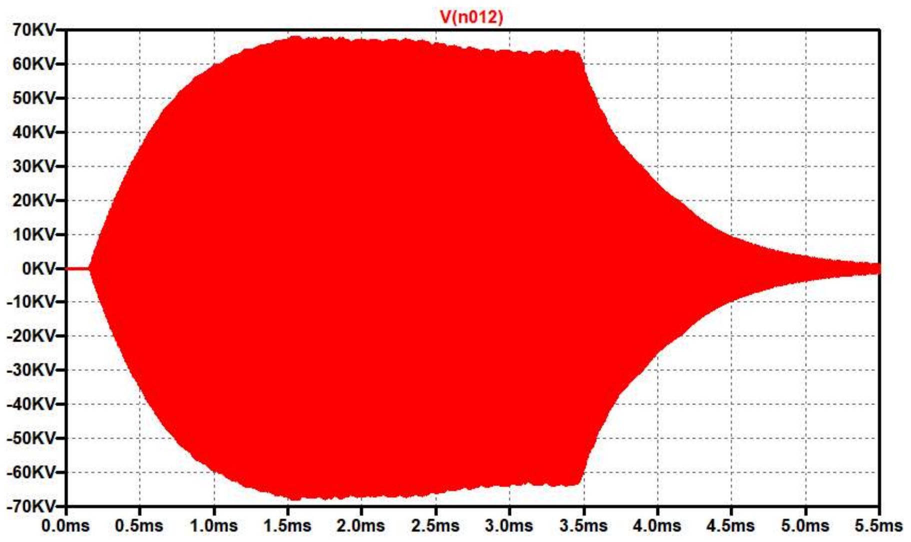
Output voltage of example L network (dBV),
F_{res} = 200 kHz

Designing a Solid-State Tesla Coil, Antonio Carlos M. de Queiroz

Impact of Q



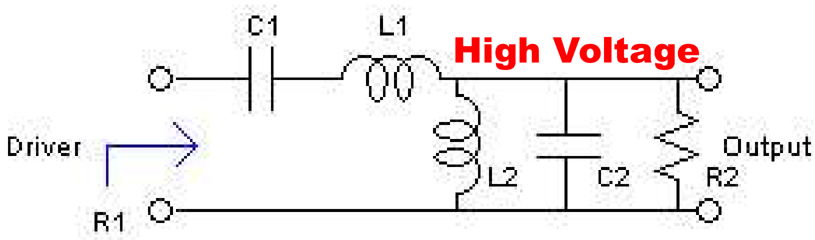
- High Q causes long ring-up time
  - Takes approx. Q cycles to reach steady state (~ms)
  - Challenging to build necessary driver
- Q set by R1 and R2
- If R1 is varied → Q proportional to voltage gain
  - How can we lower Q but maintain voltage gain?

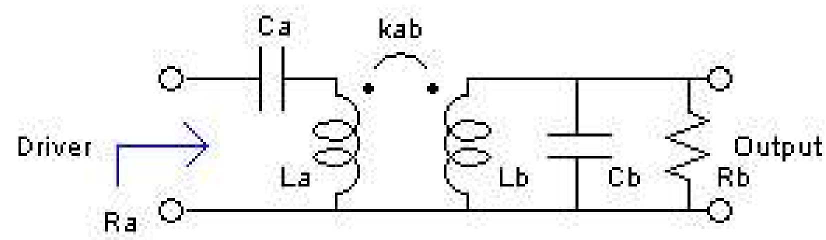


Resonant ring-up of example L network, F_{res} = 200 kHz,
Q = 588

Designing a Solid-State Tesla Coil, Antonio Carlos M. de Queiroz

Controlled Q Impedance Matching





Bandpass Butterworth filter

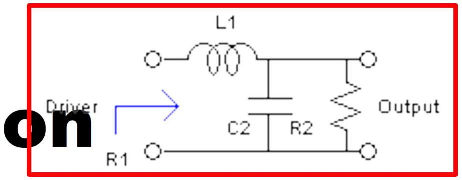
- Offers precise control over bandwidth (and therefore rise time)
- Challenging to fabricate (due to HV)

Designing a Solid-State Tesla Coil, Antonio Carlos M. de Queiroz

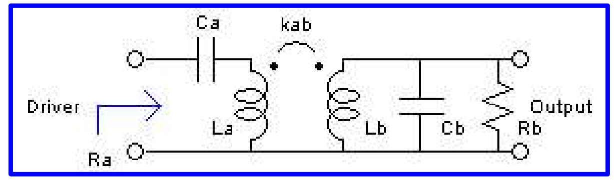
Tuned Transformer

- Mathematically equivalent response
- k_{ab} typically 0.1-0.2 (loose coupling)
- Two LC Tanks → “Dual Resonant Solid State Tesla Coil” (DRSSTC)

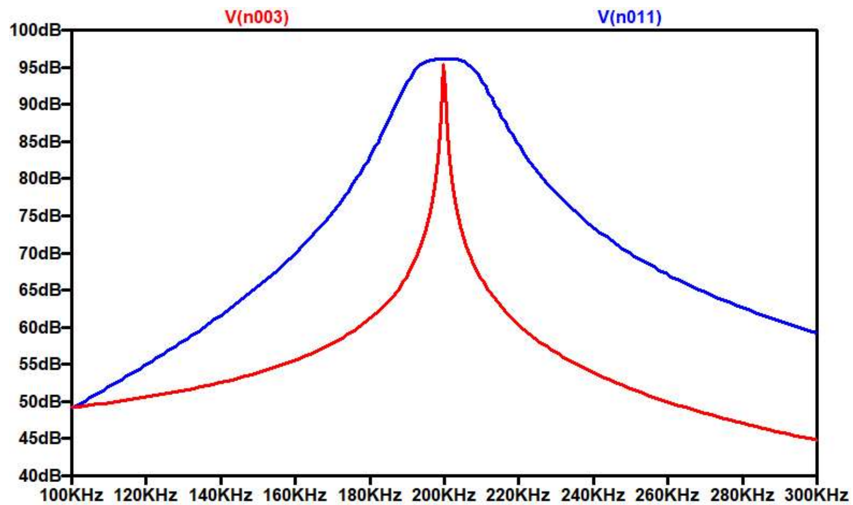
Performance Comparison



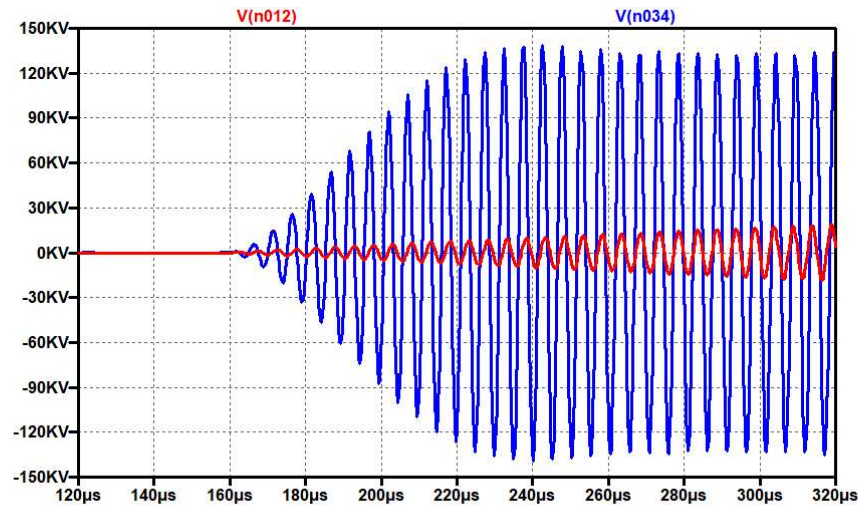
Q = 588



Q = 10



Output voltage of example L and tuned transformer networks (dBV), F_{res} = 200 kHz

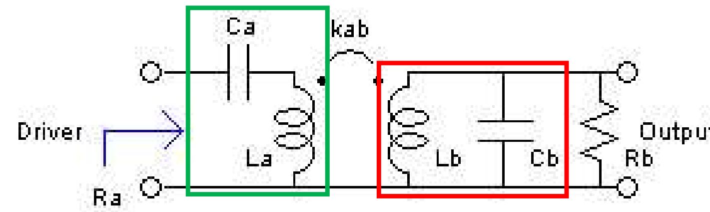


Resonant ring-up of example L and tuned transformer networks, F_{res} = 200 kHz

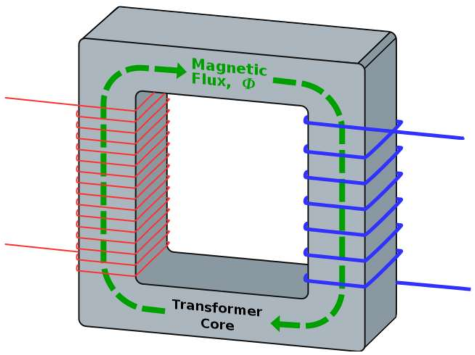
Tuned transformer achieves faster response without compromising gain!

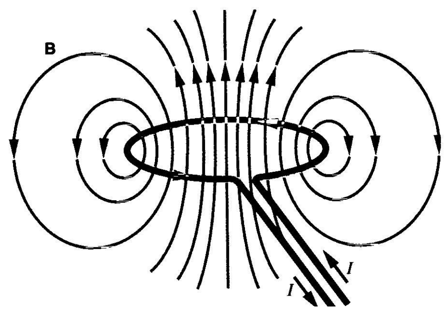
Designing a Solid-State Tesla Coil, Antonio Carlos M. de Queiroz

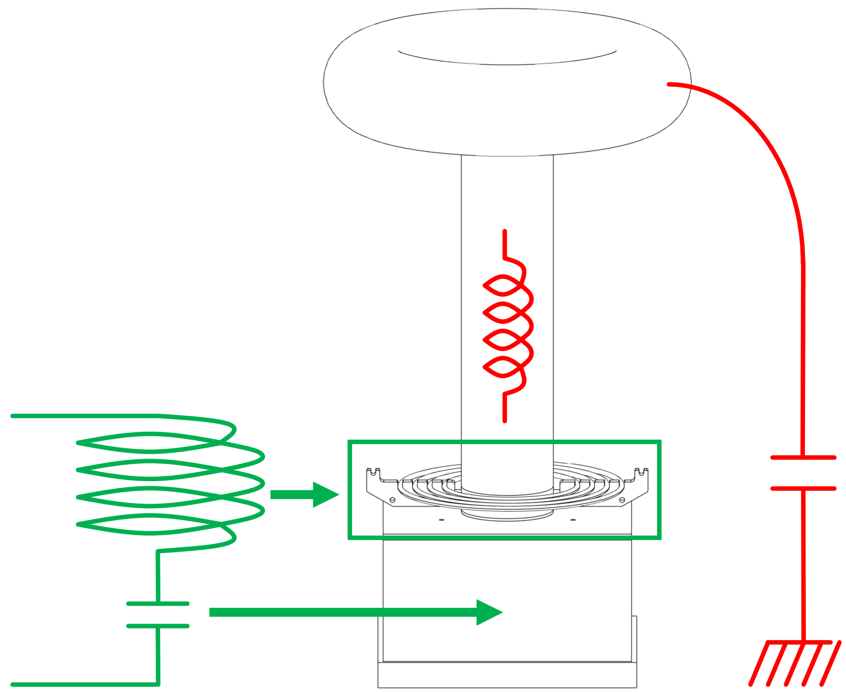
Physical Construction



- Stacked inductors
- k_{ab} controlled by coil size/spacing
  - Remember: typically only 0.1-0.2 (loose coupling)

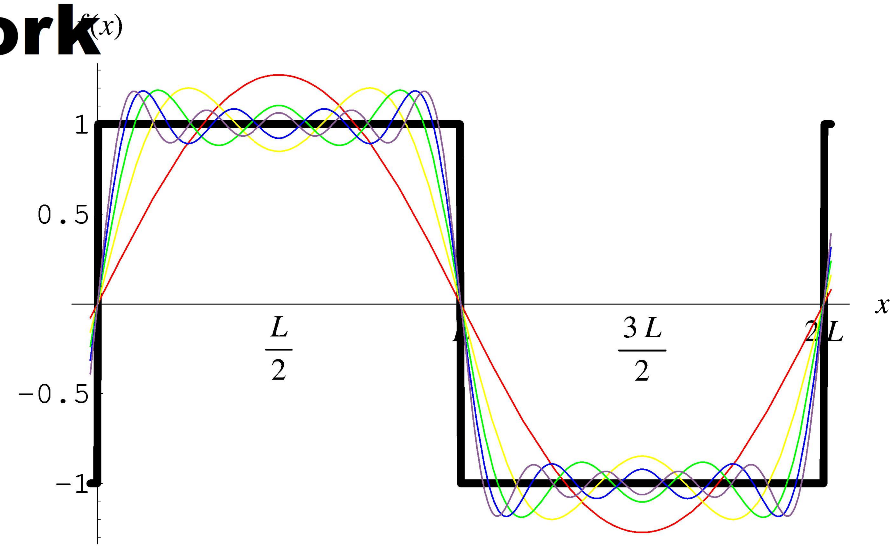






Driving the Resonant Network

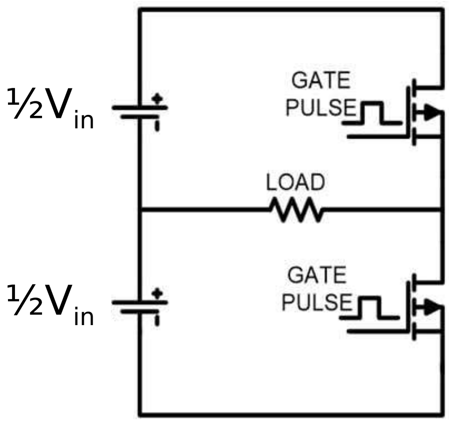
- Driver: circuit able to excite network at F_{res} (implied sinusoid)
- What if we use a square wave?
  - Narrowband network only passes fundamental frequency
  - Coefficient of $\frac{4}{\pi}$ → "free" gain!



$$f(x) = \frac{4}{\pi} \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{n} \sin\left(\frac{n \pi x}{L}\right).$$

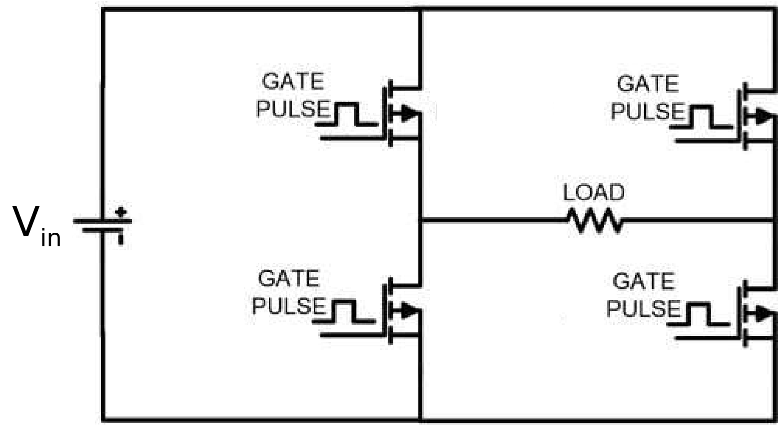
Fourier Series--Square Wave, Weisstein, Eric W., From Wolfram Mathworld

Bridge Topologies



Half Bridge

- $V_{out} = \pm ½V_{in}$
- 2 switching elements (lower cost)



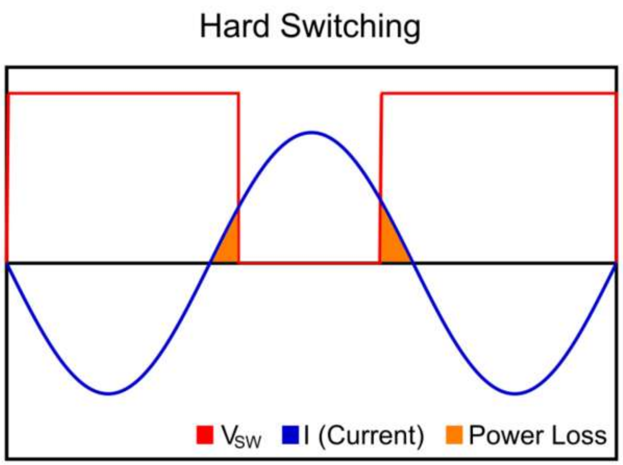
Full Bridge (H-Bridge)

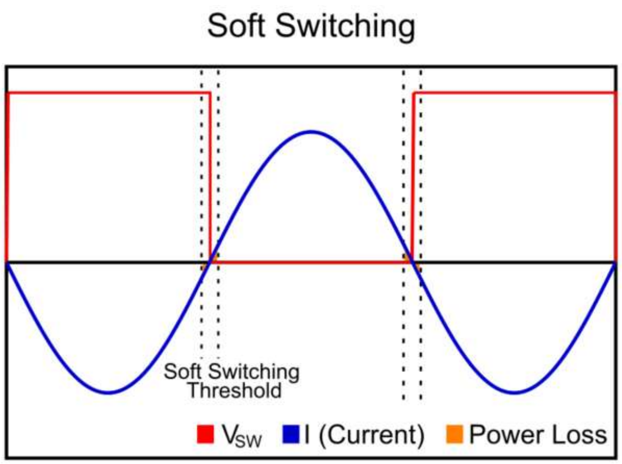
- $V_{out} = \pm V_{in}$ (higher power)
- 4 switching elements

Single Phase Half Bridge and Full Bridge Inverter using MATLAB, Ravi Kansagara

Minimizing Losses

- **Hard Switching:** device switched abruptly during high voltage/current condition
- **Soft Switching:** device switched at near-zero voltage/current to minimize losses
  - Zero Voltage/Current Switching (ZVS/ZCS)
  - Crucial…remember we are conducting 100s of Amps!

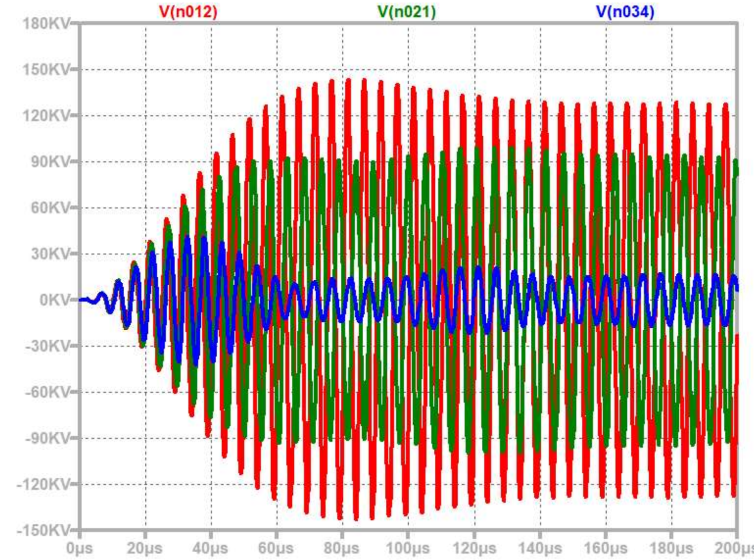




Practical ZVS/ZCS Implementation

- How can we switch at exact zero-crossings?
- **Solution 1:** Oscillator at our calculated F_{res}
  - F_{res} depends on environment, spark length, etc. → challenging to predict!
- **Solution 2:** Use feedback!
  - Current transformer/antenna
  - Can be taken from either LC tank
  - Driver adapts to F_{res}

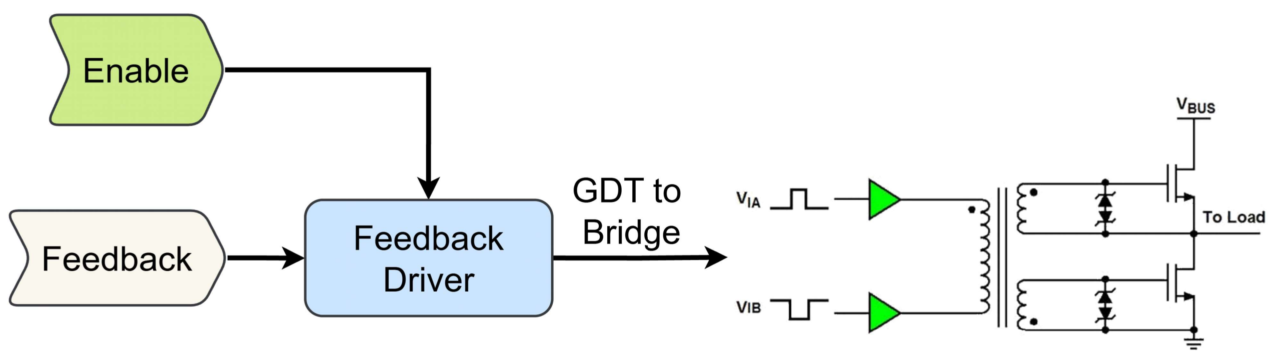
Impact of Driving Frequency on Output Voltage



Coil driven at F_{res} (200 kHz)
Coil driven at [F_{res} – 10 kHz]
Coil driven at [F_{res} – 20 kHz]

Feedback Driver

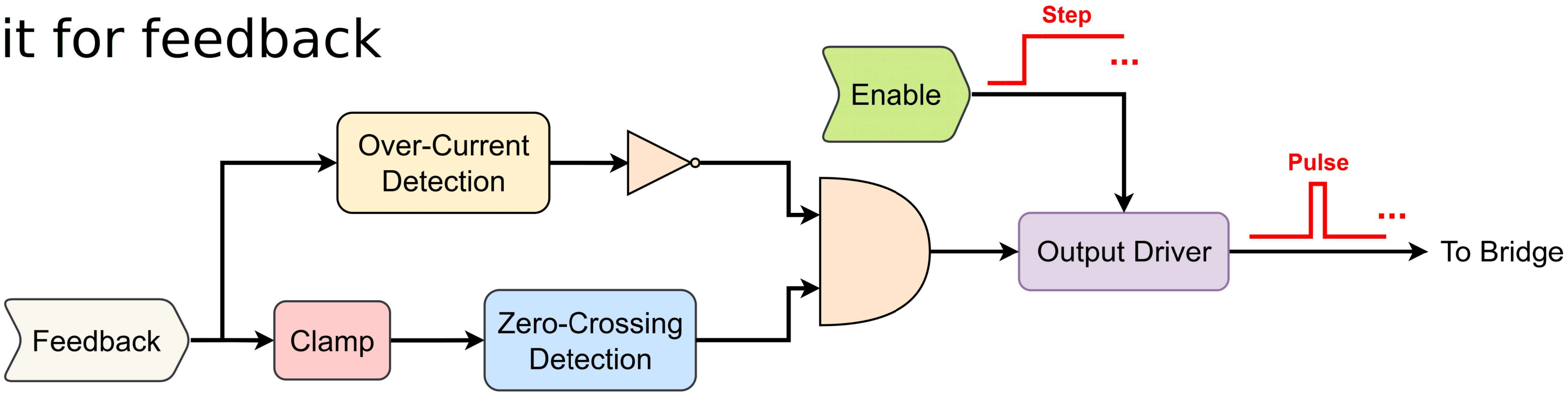
- Uses feedback to switch bridge at zero-crossings
  - 3 stages of operation



Feedback Driver

Stage 1: Startup

- Upon enable signal, "kickstart" resonant network with pulse
- Wait for feedback

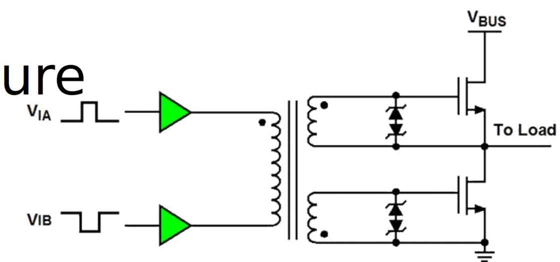


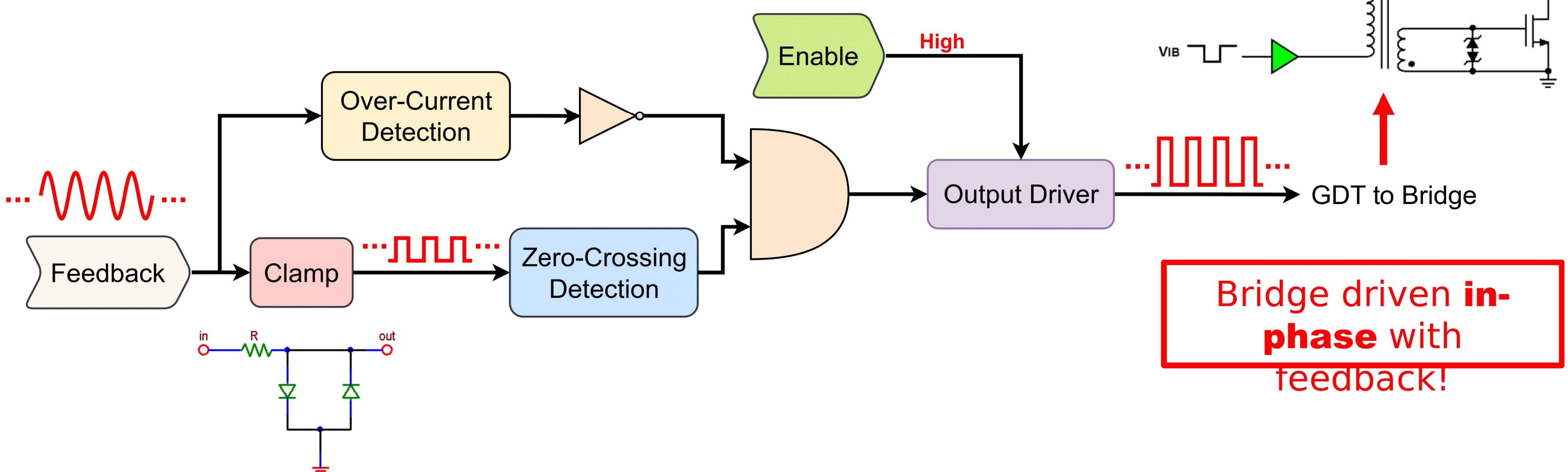
Front-end circuitry bypassed

Feedback Driver

Stage 2: Receiving Feedback

- ➢ Clamped feedback signal fed into comparator
- ➢ Over-current protection used to prevent bridge failure

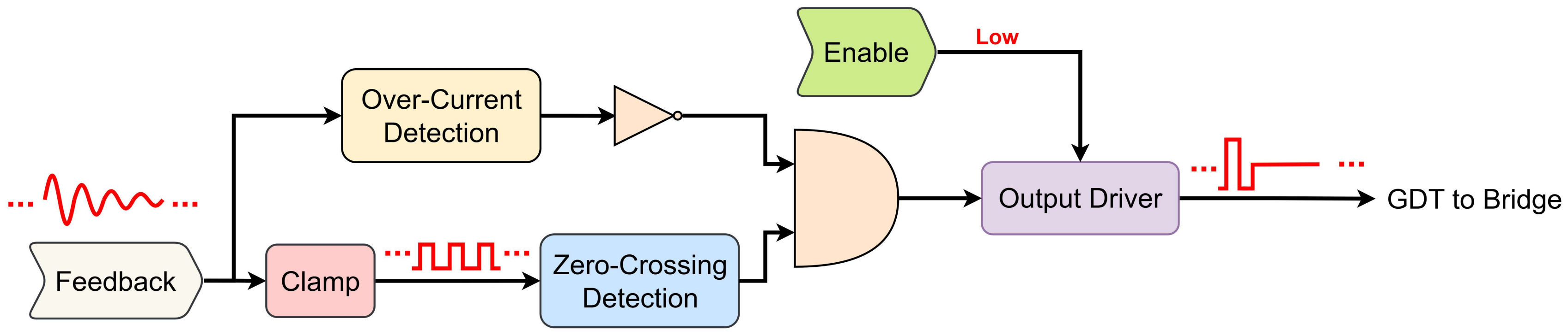




Feedback Driver

Stage 3: Turnoff

- Output disabled at next zero crossing
- LC tank begins ring-down period



Front-end circuitry bypassed

Audio Modulation

- Switching enable signal at audible frequency allows coil to play notes!
  - Audio frequencies: 20 Hz – 20 kHz
  - External **"interrupter"** circuit pulses enable signal
- Similar to on-off key (OOK) modulation

1 enable = 1 spark

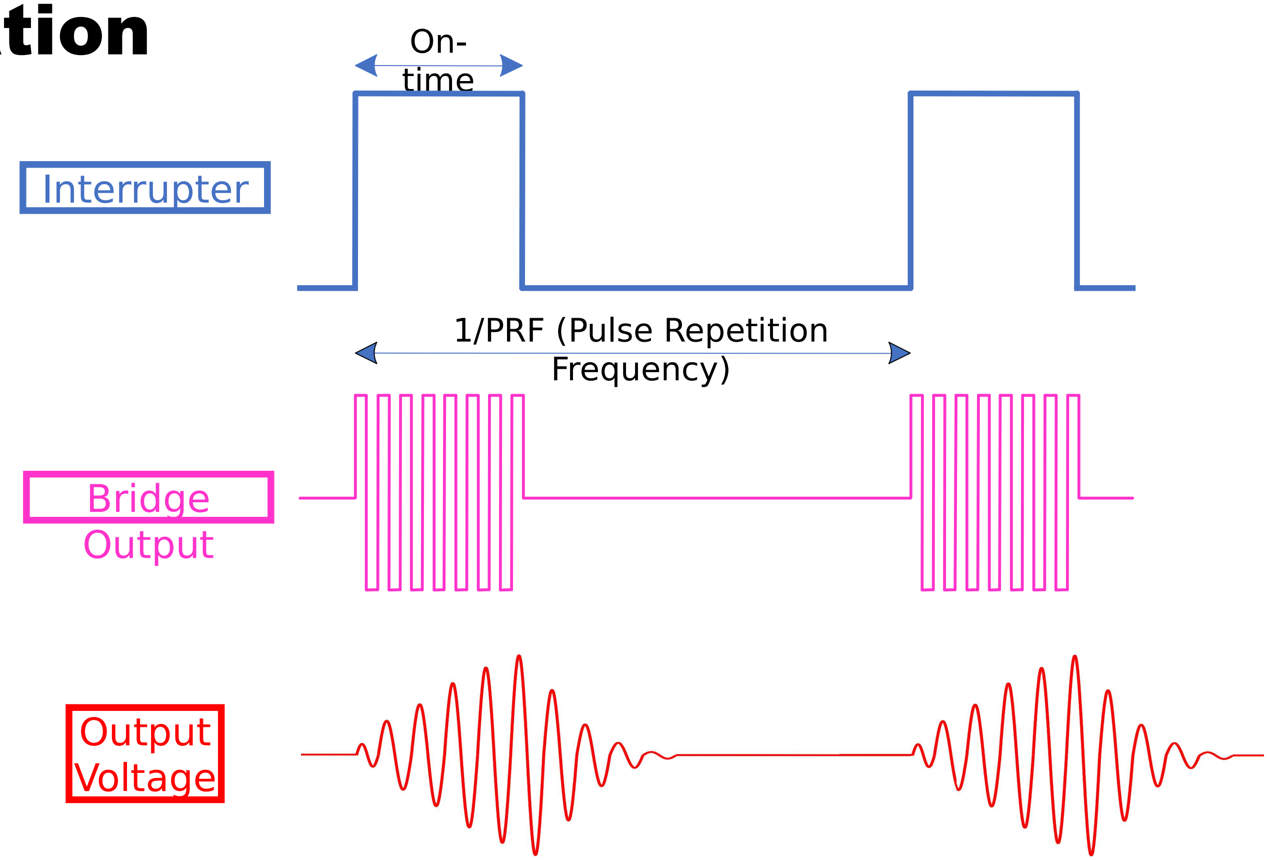
100 enables/second = 100 sparks/second = 100 Hz tone

Parallel sparks from a modulated DRSSTC,

Loneoceans Laboratories

Interrupter Operation

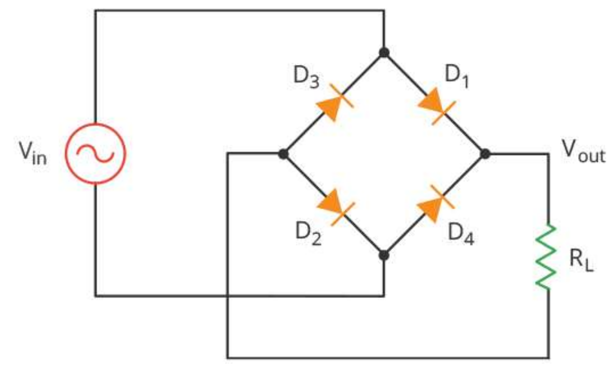
- Pulse repetition frequency (PRF) controls tone
- On-time controls duration of spark growth
    - Longer = louder
    - Practically limited to ~5% duty cycle by thermals



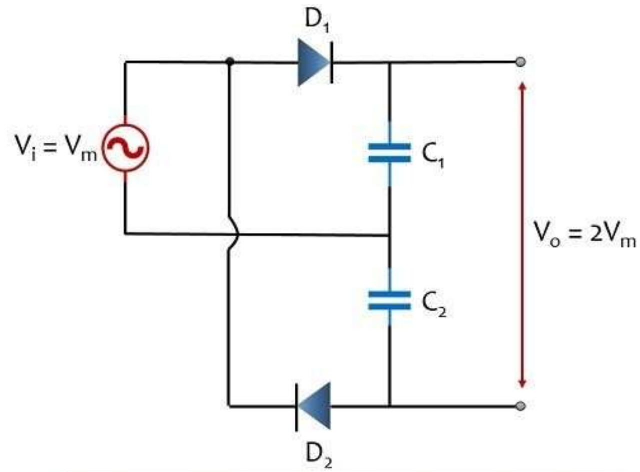
Front-End Power Stage/DC Bus

- Common to simply rectify mains power
  - Full Bridge (170V) or Doubler (340V)
  - May be influenced by target spark length: $V_{out} = \sqrt{Rb * I_{peak} * V_{in}}$
- Large bus capacitance (~1000s of μF)
- Power factor correction (PFC) can improve efficiency
  - ~0.6 → ≥0.95 with active PFC

Power Factor Correction for High Power Inverters, Kaizer Power Electronics

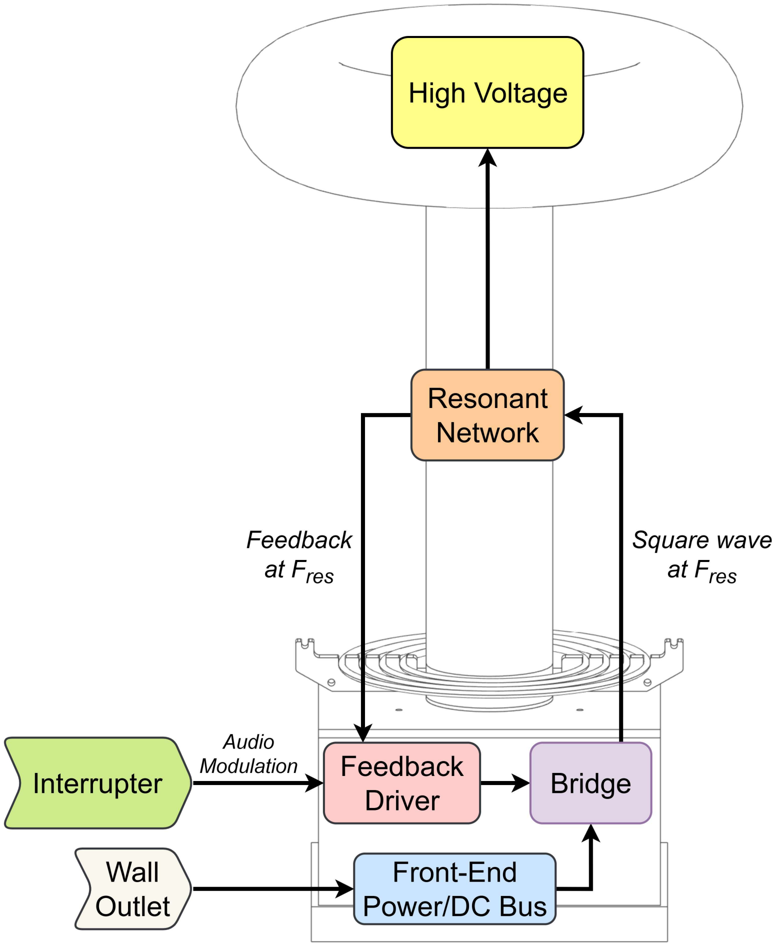


Full Bridge Rectifier



Full Wave Doubler

Full System Diagram



Educational Benefits

Building a Musical DRSSTC requires knowledge of:

- Resonant Circuits and Q Factor
- Impedance Matching
- Frequency Domain and Bode Plots
- Mutual Inductance and Electromagnetism
- Signals and Systems (Fourier Analysis)
- DC→AC and AC→DC Conversion
- Power Semiconductor Devices and Switching Losses
- Thermal Management
- Feedback/Digital Logic/Controls
- Microcontrollers
- Modulation Techniques
- **Making practical design decisions!**

By building a Tesla coil, students can get hands-on experience before they get to industry!

Future Plans

Problem:

- Traditional approaches of teaching EM are math-heavy and abstract
  - Students struggle to gain a “practical” understanding of key concepts

Solution:

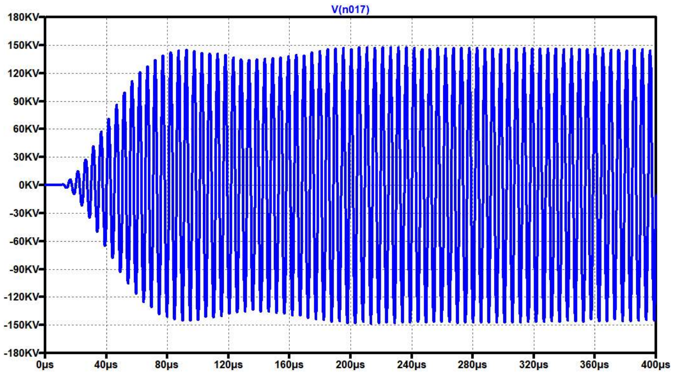
- One-semester course in which students build Tesla coil
  - Every 1-2 weeks focuses on one concept, lab, and sub-system build
- Target release: Spring 2026, NC State University

Common Reactions:

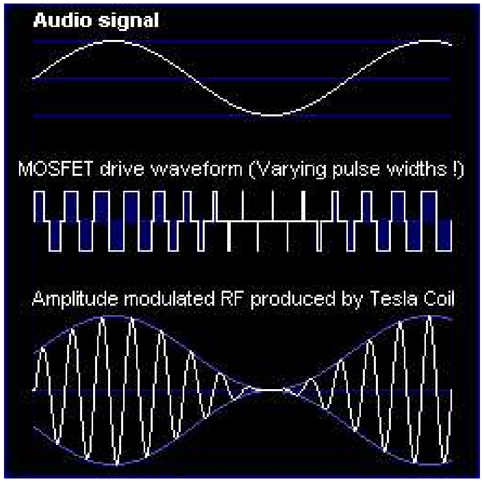
- “That’s really cool!” *walks away*
- “Have you ever been shocked?”
- “Would it kill you?”
- **“Are there any real-world applications?”**
  - **Well… yes!**

CW/AM Operation

- DRSSTC's generally limited to pulse mode by high primary currents
- Reduced currents → continuous wave (CW) operation possible; "steady state"
- PWM of bridge output → AM spark output
  - ~Buck converter at frequency $F_{res,}$ resonant network acts as filter



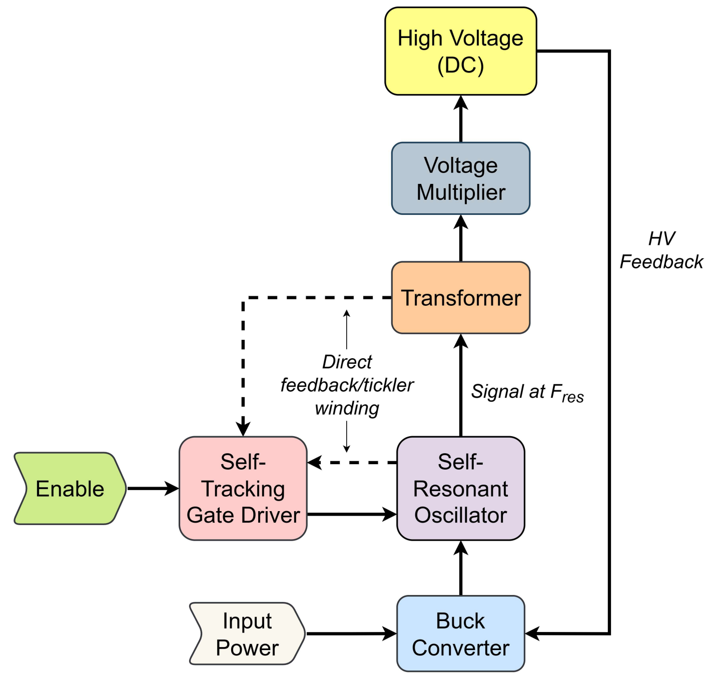
Resonant startup for CW operation



Amplitude modulation of a CW SSTC,
Richie Burnett

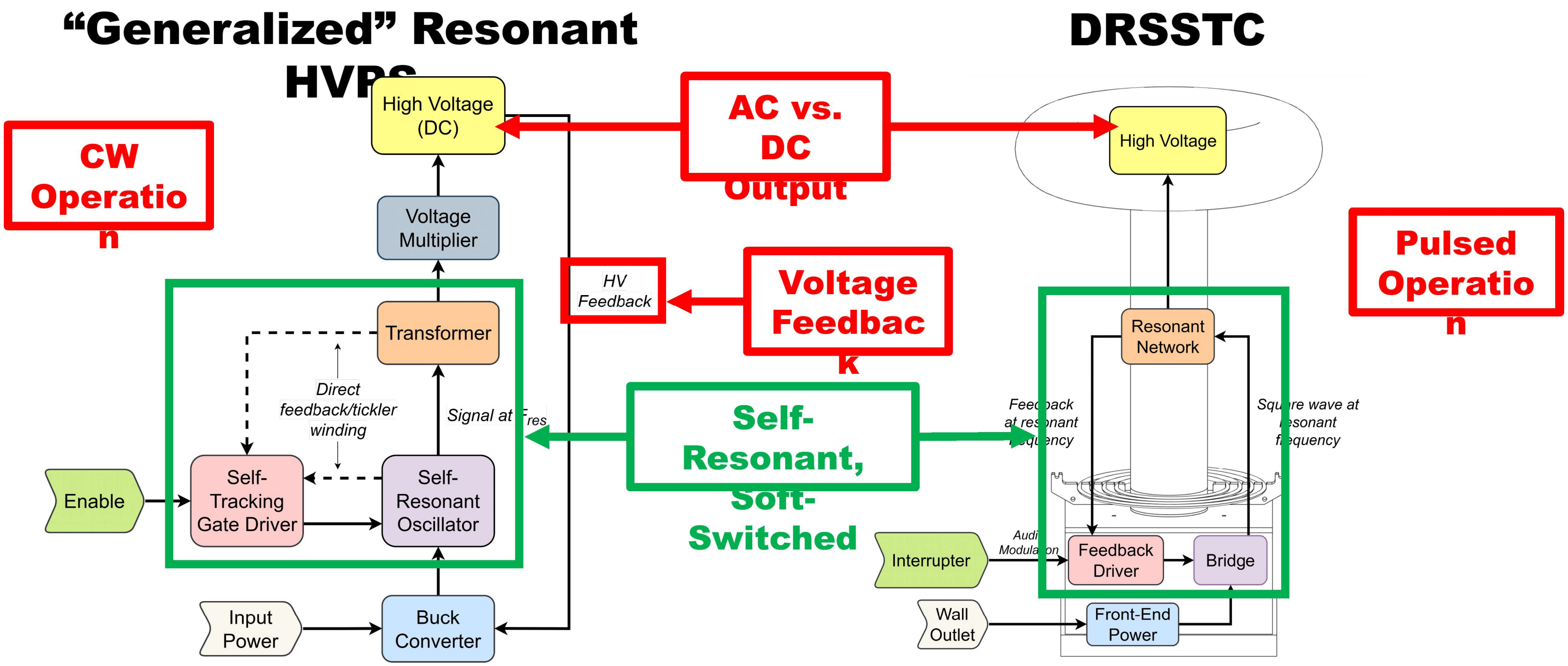
Wait. This seems familiar...

- ➢ Steady-state, controllable AC output
- ➢ Rectify/filter → stable HVDC output
- ➢ This is essentially just a resonant power supply!
  - Needs feedback to be self-regulating



"Generalized" Resonant HVPS Architecture

Architecture Comparison



Questions?