Wireless Resonant Converter Engineering Review

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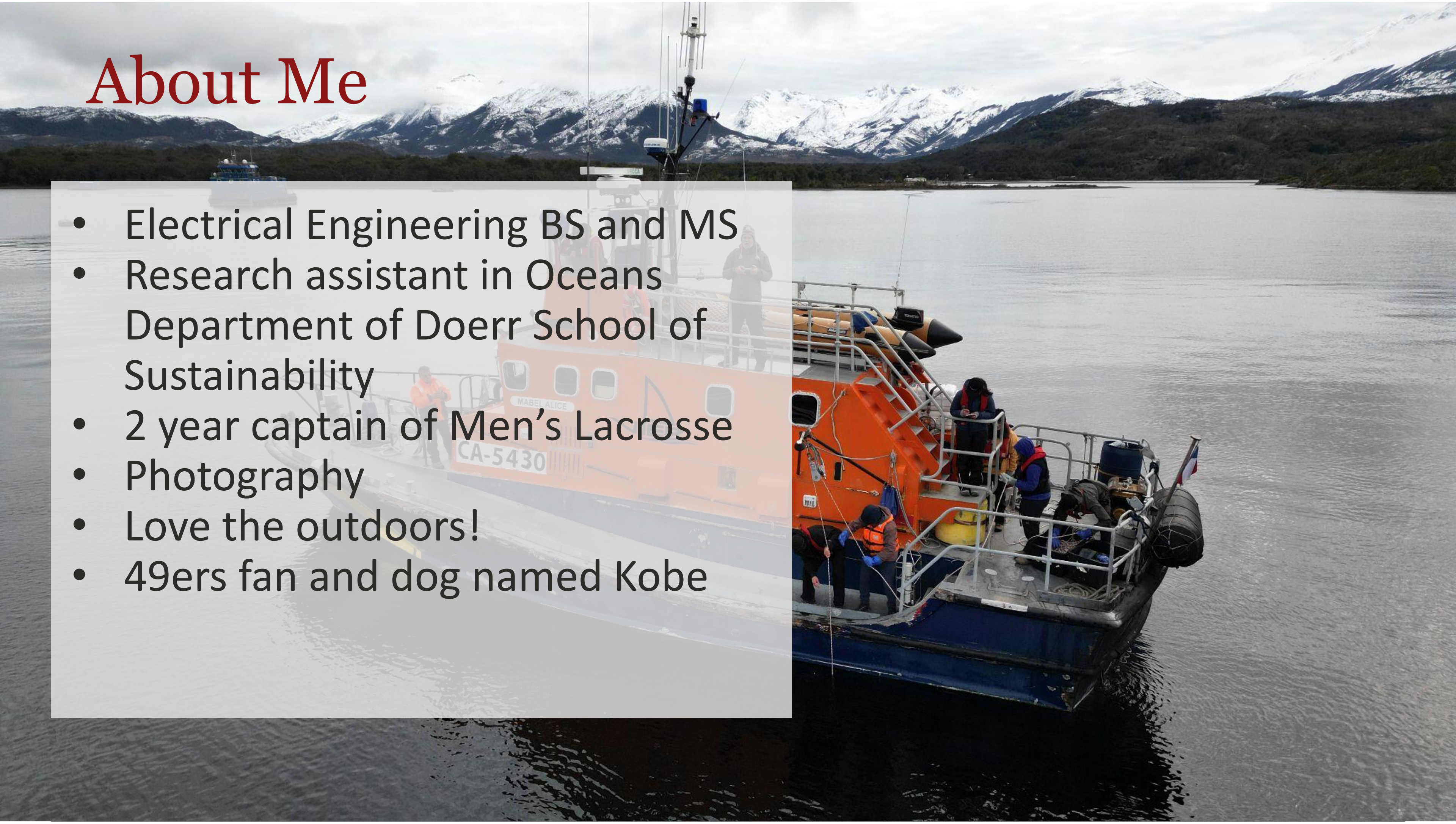
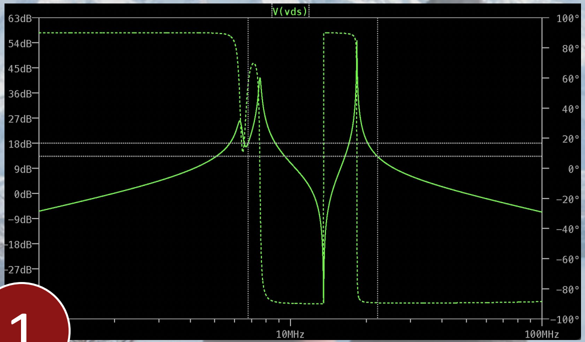
Stanford University

About Me



- Electrical Engineering BS and MS
- Research assistant in Oceans Department of Doerr School of Sustainability
- 2 year captain of Men’s Lacrosse
- Photography
- Love the outdoors!
- 49ers fan and dog named Kobe

Presentation Overview



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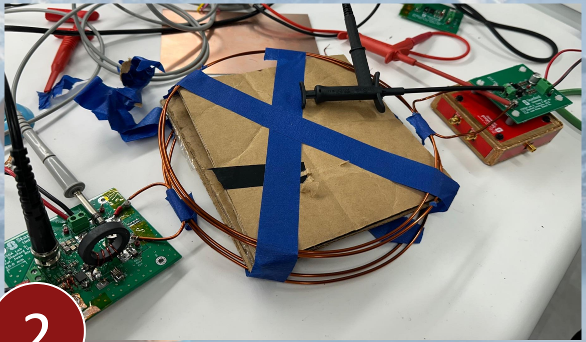
Inverter Specification and Design

- Project Requirements
- Resonant converter Overview
- Design and Strategy



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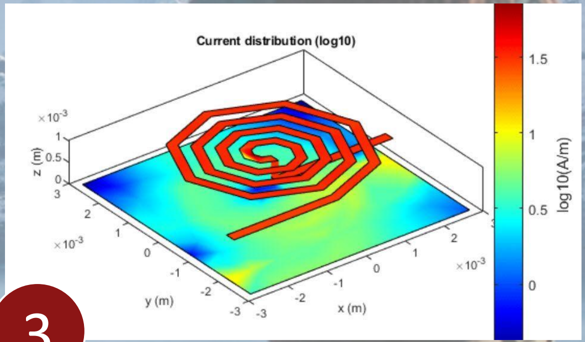
Inverter Implementation, Testing, and Results

- Inverter
- Transformer Coil
- Testing and Results



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Manufacturing and Next Steps (lessons from De-Ice)

- Reviewing main manufacturing issues
- Manufacturing Magnetics

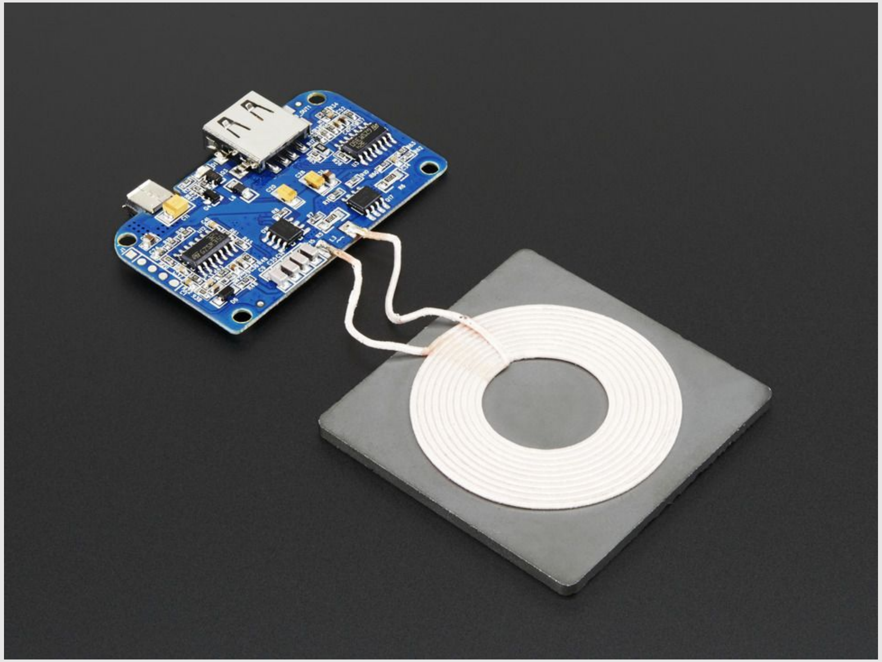
1

Inverter Specification and Design

1 Converter Requirements

EE356 Final Project Deliverables

1. Deliver 25 W of DC power
2. Operate at 6.78 MHz
3. Utilize a minimum input of 20V
4. Transmit power wirelessly (>1 in)

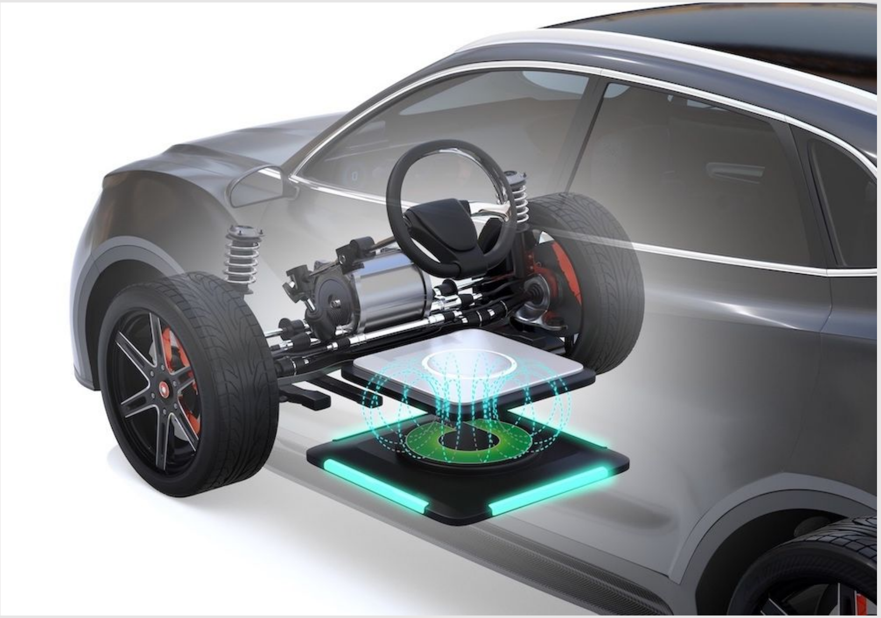


https://www.adafruit.com/product/2162?gad_source=1&gclid=CjwKCAiA75itBhA6EiwAkho9e7AlEQgyucyarSMNLOLmpIHTVSmdQLQaFAwWS8ZIf4hR8g2iSXLUUxoCBj0QAvD_BwE

1 Converter Requirements

Why would you want this?

- School design challenge for learning purposes
- Requirements aren't necessarily motivated by real life
- High frequency wireless converters may have benefits for certain applications
- Is emblematic of power electronic problems with real world applications



https://evchargingsummit.com/blog/everything-you-need-to-know-about-wireless-ev-charging/

1 Resonant Converter Review

Characteristics of DC-DC

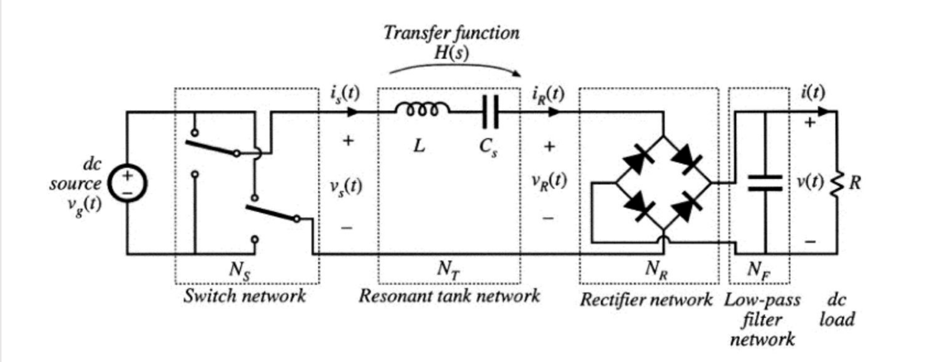
- Switch network
- Resonant tank
- Rectifier

Advantages of Resonant Converter

- Lump parasitics into design
- Diminish switching losses (ZVS or ZCS)
- Ability to easily generate high voltage, high frequency sinusoidal outputs

Common uses

- Ballasts for gas-discharge lamps
- Broadcasting
- Ionizing gas for IC plasma etching



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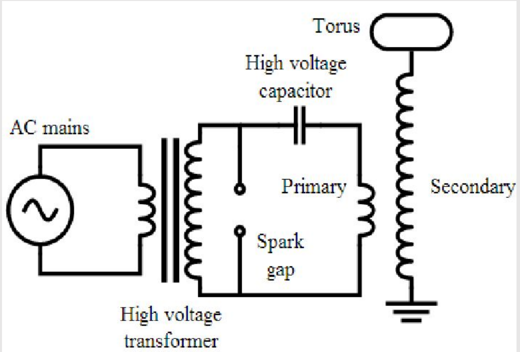


https://www.researchgate.net/figure/Tesla-coil-circuit-diagram-5_fig5_283186438

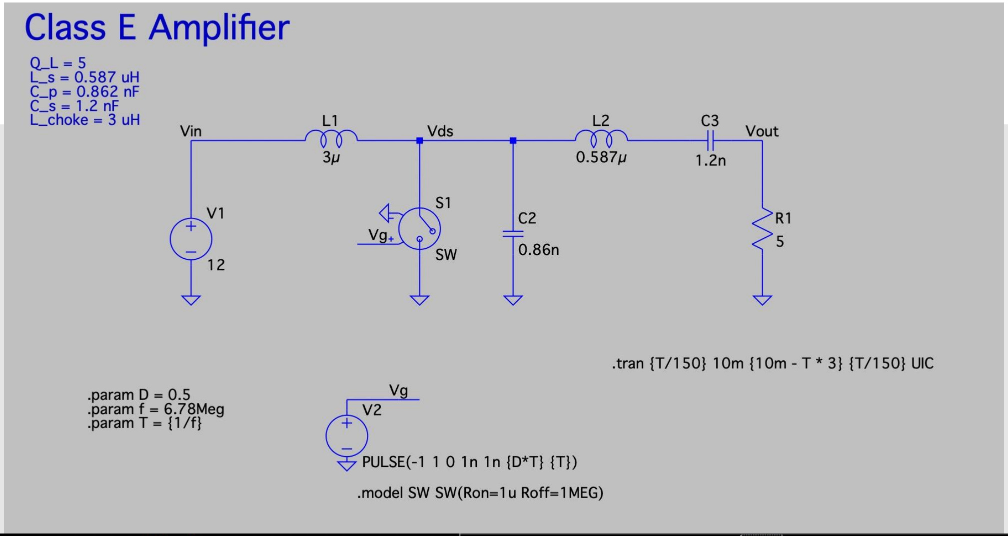
1 Design Strategy

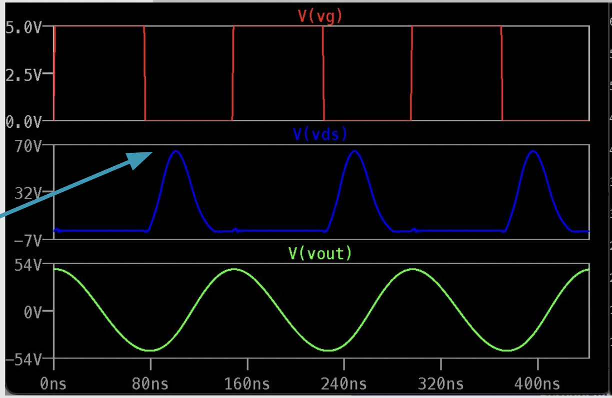
Class E Amplifier

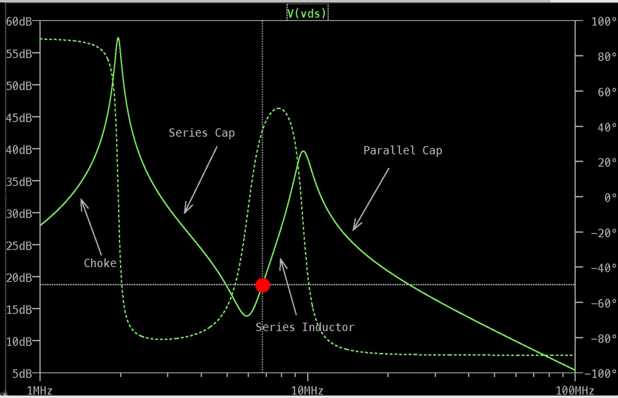
- Resonance set with LCC topology
- Lump in drain capacitance
- ZVS
- One switch!
- Large input filter

Drawbacks

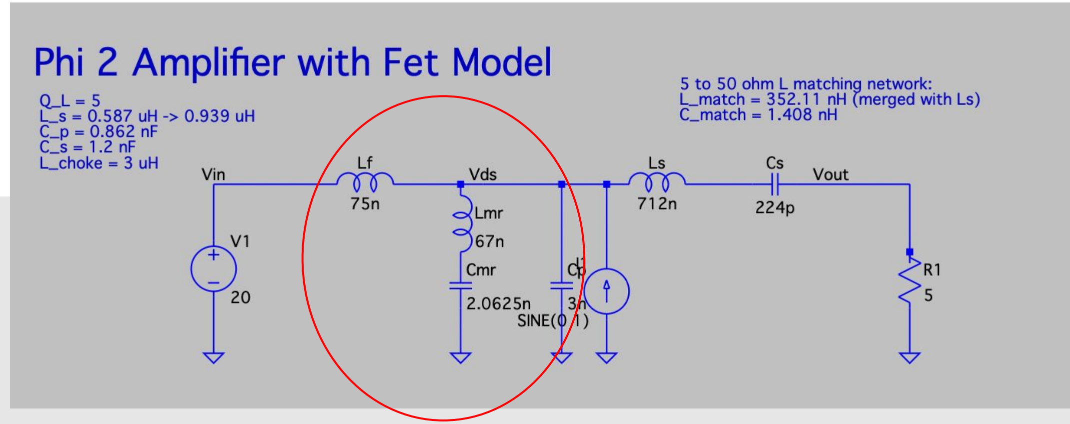
- Currently tuned to 5 ohm
- Large drain voltage
- Vd_max = 4 x Vi





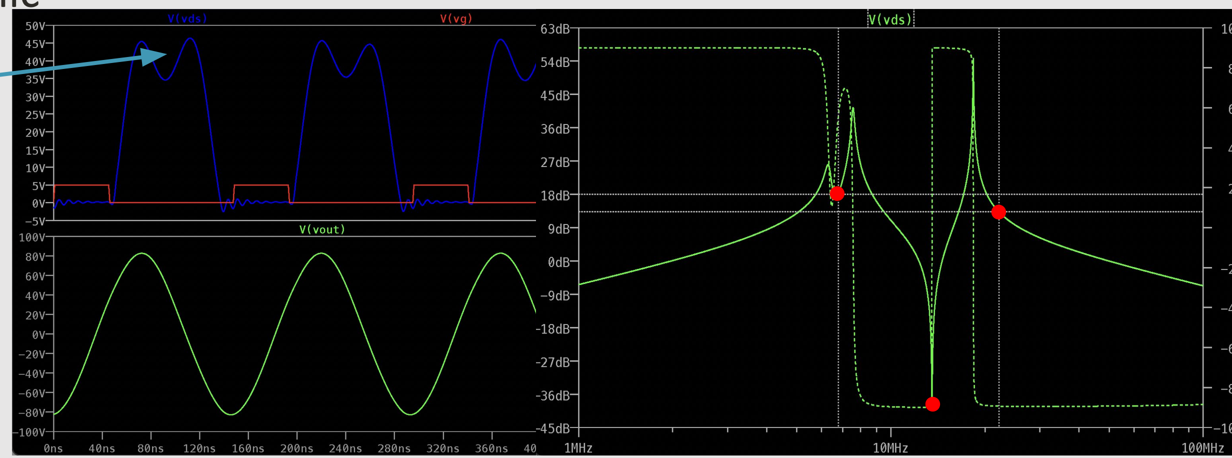


1 Design Strategy



Φ_2 Inverter

- Added "input filter"
- Eliminate second harmonic
- Still ZVS
- Vd_max = 2 x Vi



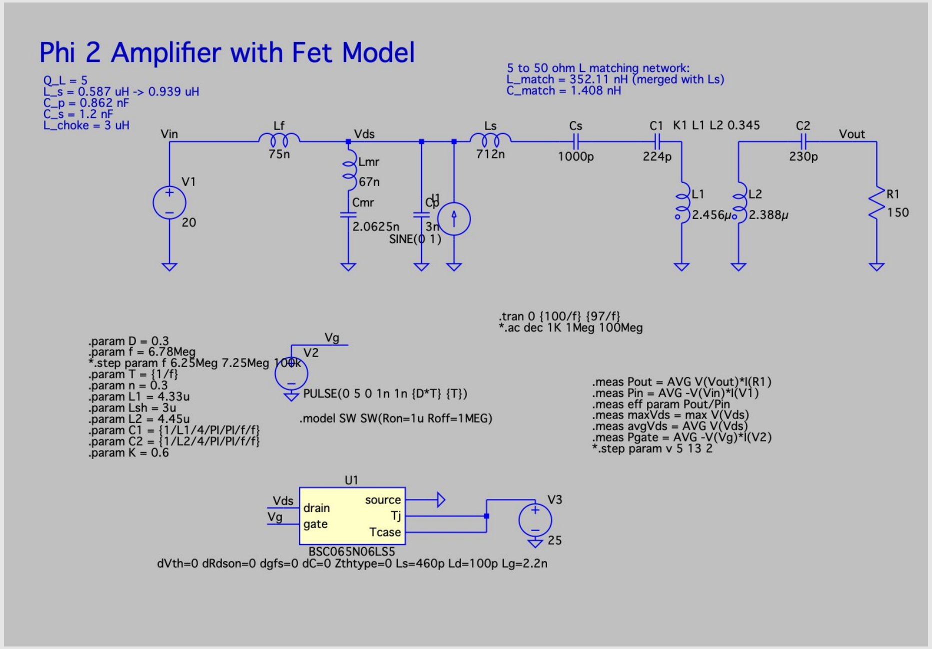
Drawbacks

- Still tuned to 5 ohm
- More magnetics!
- More resonant points!
- High transient currents in filter
- Poorer input filter

1 Design Strategy

Addressing Wireless, DC, and Power Requirements

- Design a wireless transformer
- Address impedance of transformer and rectifier
- Keep in mind high frequency considerations such as skin effect, proximity effect, radiation losses, etc.
- Choose load that can be achieved experimentally



2

Inverter Implementation, Testing, and Results

2 Wireless Coil Design

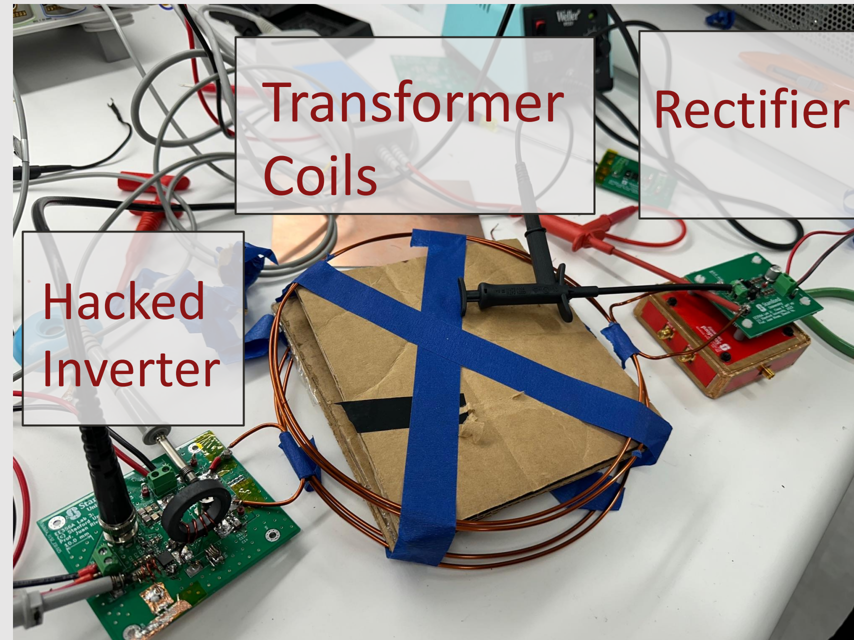
Components and Design Steps

- “Hacked” Class E Amplifier
- Characterized wireless coils with VNA
- Characterize drain impedance with VNA and compare with simulation
- Attach Rectifier and deal with non linearities
- TUNE!

Simulate

Adjust Board

Measure



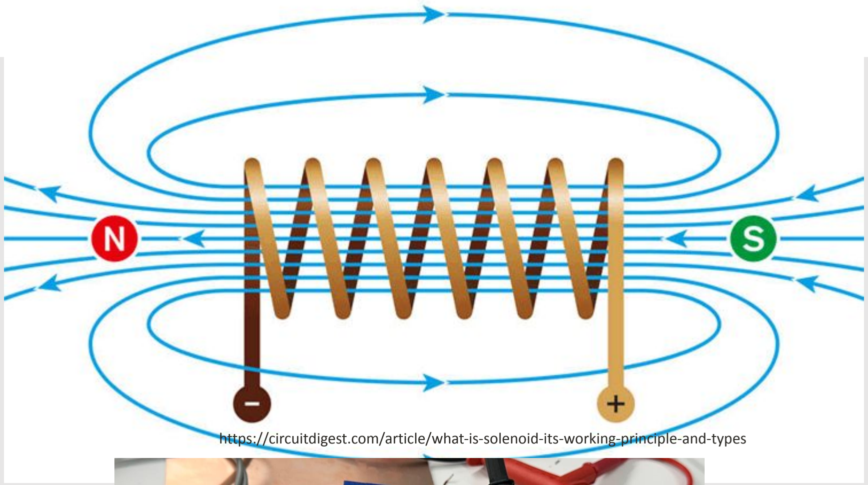
2 Our Wireless Transformer Implementation

Three main challenges

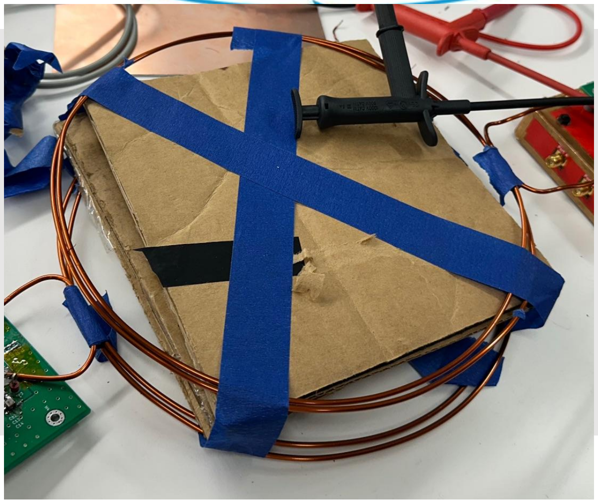
1. Avoiding self resonance
2. Achieving strong coupling between two coils
3. Dealing with large reactance

Ways to address challenges

1. Reduce number of turns
   a. But $B = \mu NI/L$
2. $\Phi = BA$
3. Cancel with series capacitors



https://circuitdigest.com/article/what-is-solenoid-its-working-principle-and-types



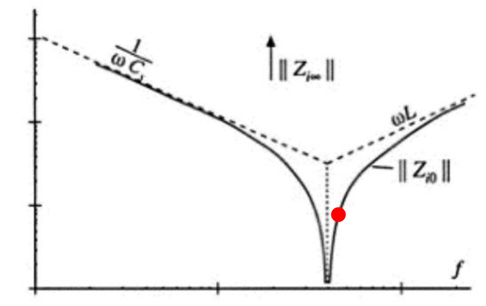
2 Testing and Results

Testing

- The discontinuities of the rectifier created a lot of issues
- Blew up a number of FETs (when not ZVS)
- Used power attenuator and tuned to 50 ohms
- Shifting frequency showed we were not perfectly tuned

Results

- Achieved required goals
- Characterized frequency, load, Vin



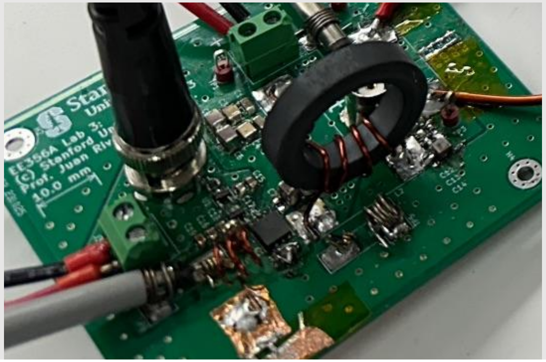

3
Manufacturing and Next Steps (Lessons from DeIce)

3 Manufacturing Considerations

Major challenges (to name a few)

EMI | Reliability | Durability | Cost

MAGNETICS



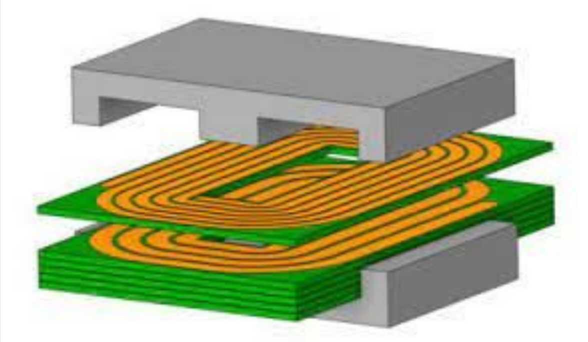
3 Planar Trace Inductors

Ferrite Core Cutouts

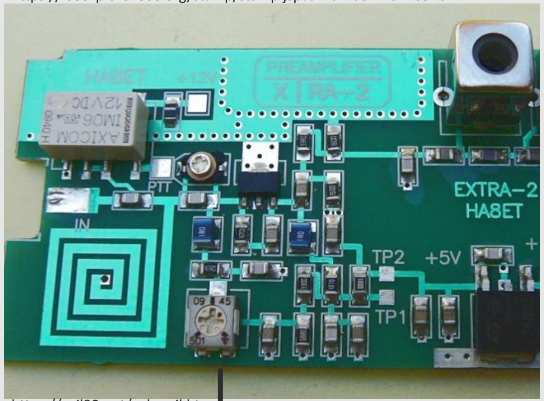
- Can achieve higher inductances ✅
- Experience saturation ❌
- Higher core losses ❌
- Fragile and take up space ❌

Spiral Inductors

- Air core
  - low losses, no saturation ✅
- Space efficient ✅
- Easier heat management ✅
- Lower inductances (harder to model) ❌
- Higher conduction losses ❌



https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=10210576

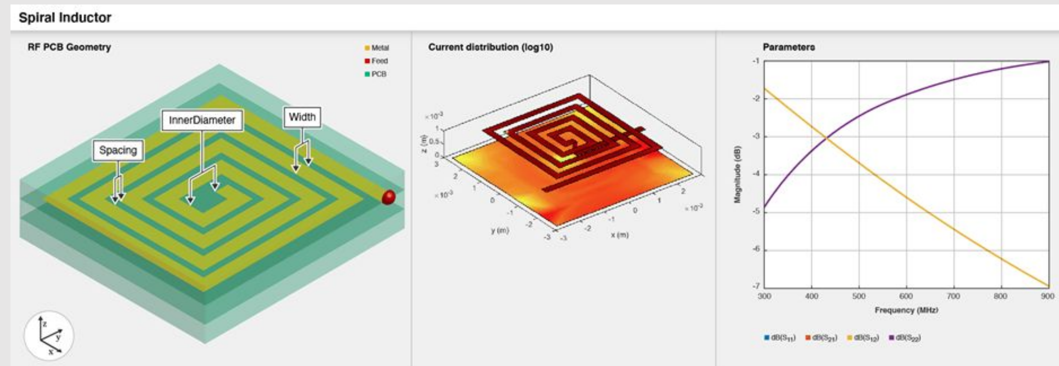


https://coil32.net/pcb-coil.htm

3 Planar Trace Inductors

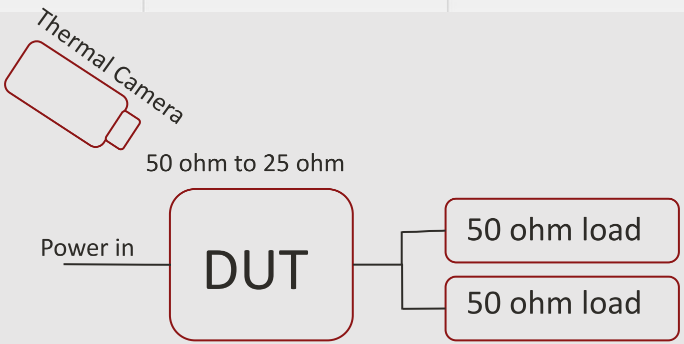
Considerations

- Geometry
  - Number of turns and shape
- Number of Layers
- Power requirements
- Power dissipation ability



Strategy

- Work with mechanical team to discuss geometric requirements and heat sink
- Simulate using finite element software
  - Use S parameters to estimate power losses
- Spin coupon boards
- Characterize and power test



3 Findings and Manufacturing Recommendations

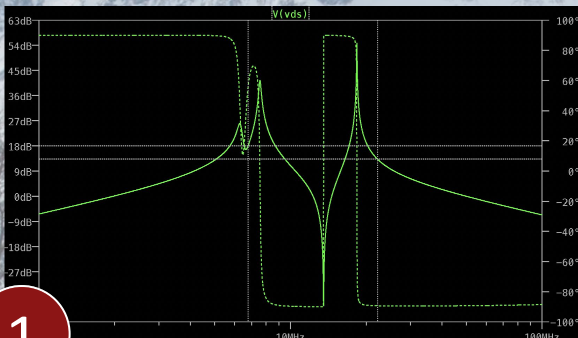
Findings

- Robust thermal interface necessary for power
- Modulating ground plane distance proved best method for tuning

Manufacturing Recommendations

- Catalog handful of inductor CAD designs
- Use washers for spacing and tuning
- Ground plane should also serve as heat sink
- Use lots of vias!

Presentation Overview



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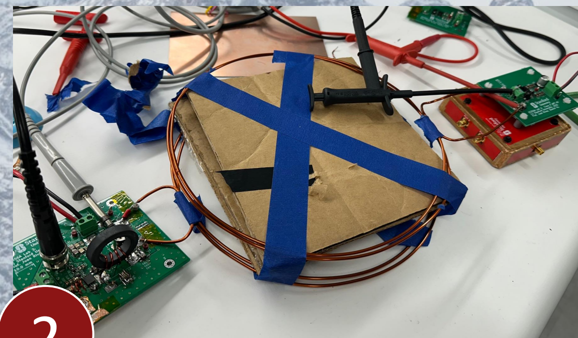

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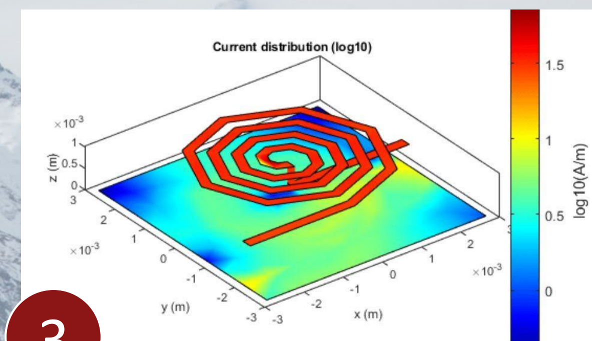

3 Manufacturing and Next Steps (lessons from De-Ice)

- Reviewing main manufacturing issues
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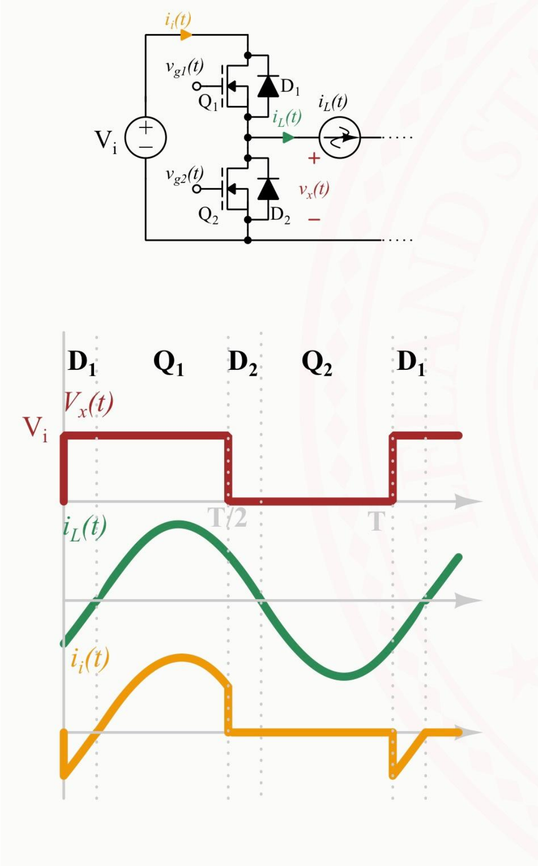
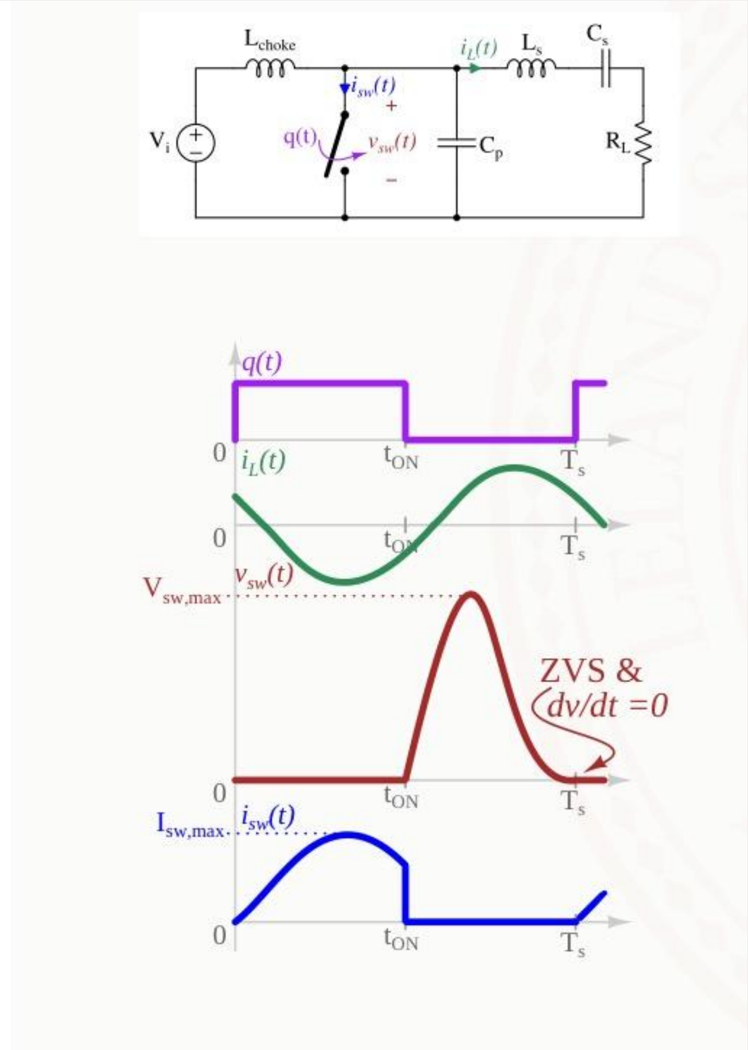
Thank You

ZVS and ZCS



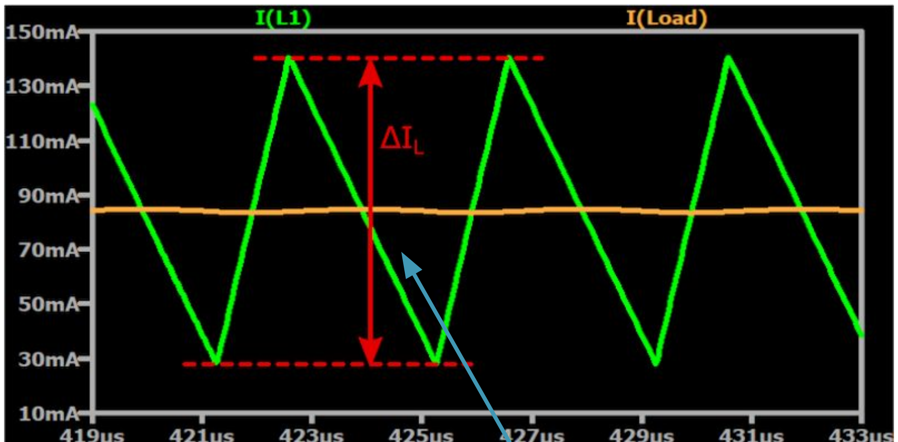
$i_i(t)$
$v_{g1}(t)$
Q_1
D_1
$i_L(t)$
$i_L(t)$
V_i
$v_{g2}(t)$
Q_2
D_2
$v_x(t)$
+
–
D1
Q1
D2
Q2
D1
$V_x(t)$
V_i
T/2
T
$i_L(t)$
$i_i(t)$



L_{choke}
$i_L(t)$
L_s
C_s
$i_{sw}(t)$
+
V_i
q(t)
$v_{sw}(t)$
C_p
R_L
–
q(t)
0
$i_L(t)$
t_{ON}
T_s
0
t_{ON}
T_s
$V_{sw,max}$
$v_{sw}(t)$
ZVS &
dv/dt =0
0
t_{ON}
T_s
$I_{sw,max}$
$i_{sw}(t)$
0
t_{ON}
T_s

Why operate at high frequencies?

Small Components



ΔV/L

But Higher Switching Losses

Energy loss in RC circuits

How much energy reaches the capacitor?

$$E_C = \int_0^\infty v_C i_C \mathrm{d}t = \int_{q(t=0)}^{q(t\to\infty)} v_C \mathrm{d}q = \int_{v_C(t=0)}^{v_C(t\to\infty)} C v_C \mathrm{d}v_C$$

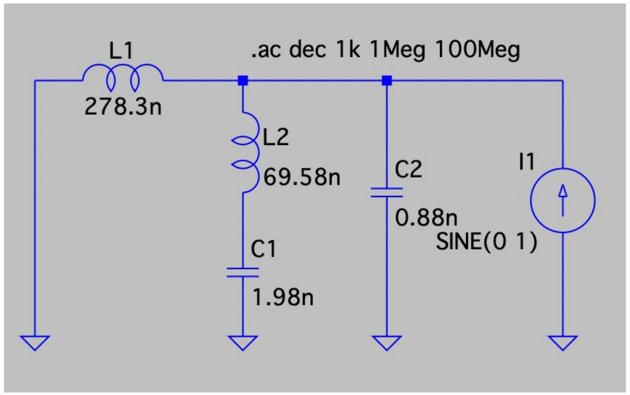
$$\boxed{E_C = \frac{1}{2} C V_i^2}$$

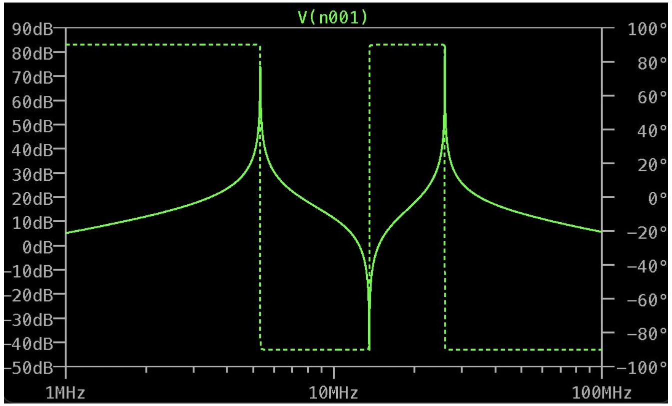
How much energy is delivered by the source?

$$E_{source} = \int_0^\infty V_i i_C \mathrm{d}t = V_i \int_{q(t=0)}^{q(t\to\infty)} \mathrm{d}q = C V_i \int_{v_C(t=0)}^{v_C(t\to\infty)} \mathrm{d}v_C$$

$$\boxed{E_{source} = C V_i^2}$$

Resonant Topologies and filtering





19.4 *Load-Dependent Properties of Resonant Converters* **731**

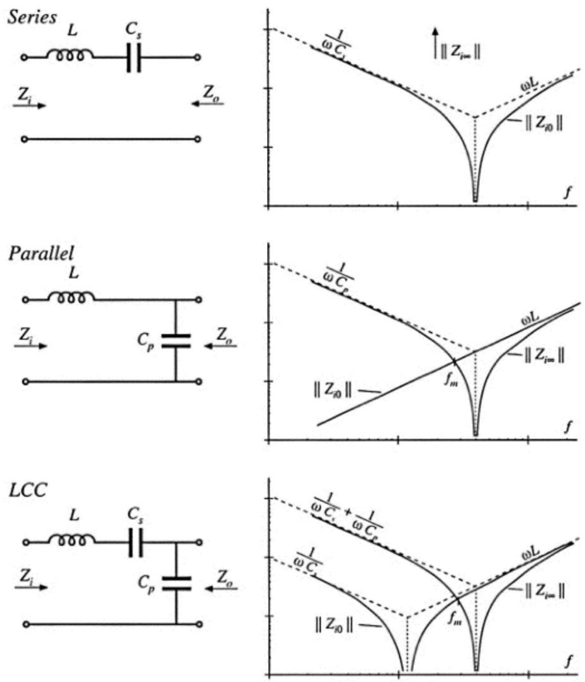
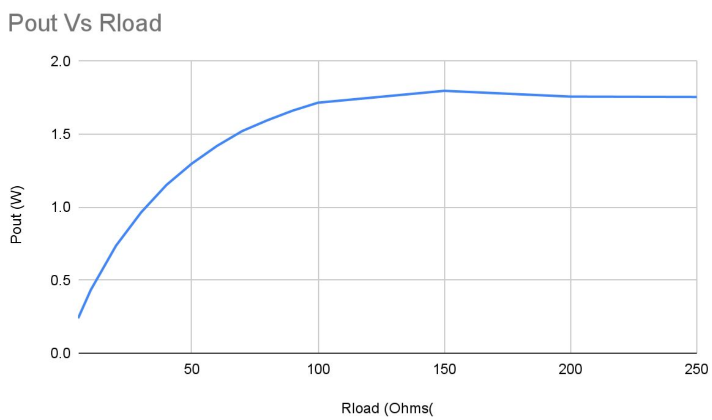
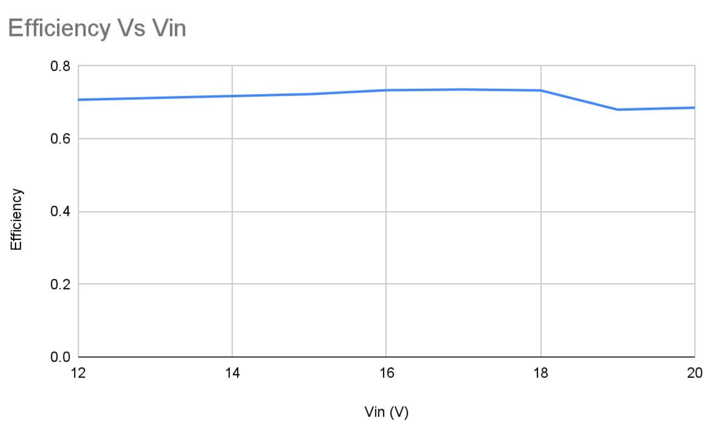
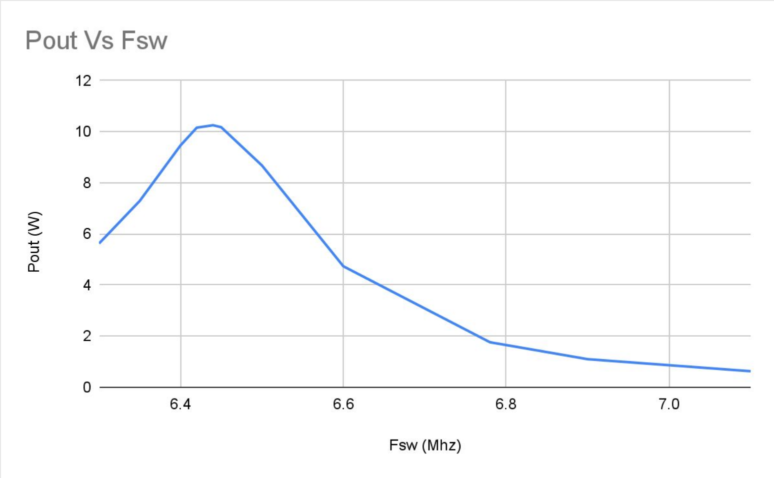


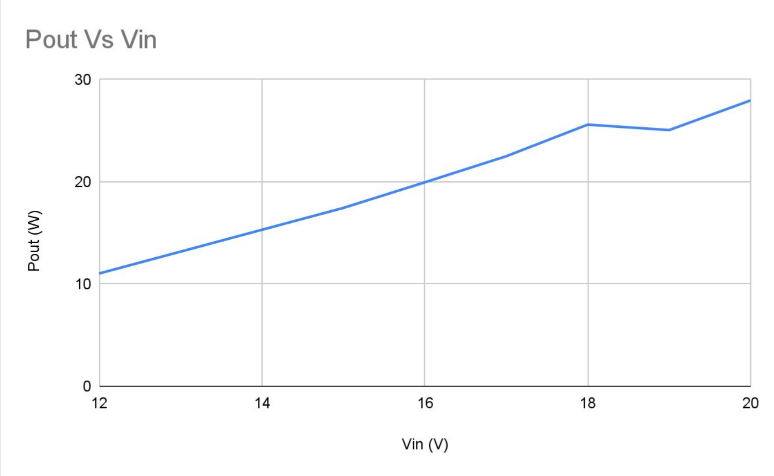
Fig. 19.34 Series, parallel, and LCC resonant tank networks, and their input impedances Z_{i0} and $Z_{i\infty}$.

Results Data









Spiral Inductor Equations

$$L = K_1 \mu_0 \frac{N^2 D_{avg}}{1 + K_2 \varphi}$$