Resonant Magnetics for Capacitive Wireless Power Transfer

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Penetration of Electric Vehicles

- EV sales growing - though not fast enough
- Hurdles in widespread adoption due to limitations in battery technology:
  - Limited range
  - Long charging times
  - High cost
- High EV penetration requires widely deployed public charging infrastructure

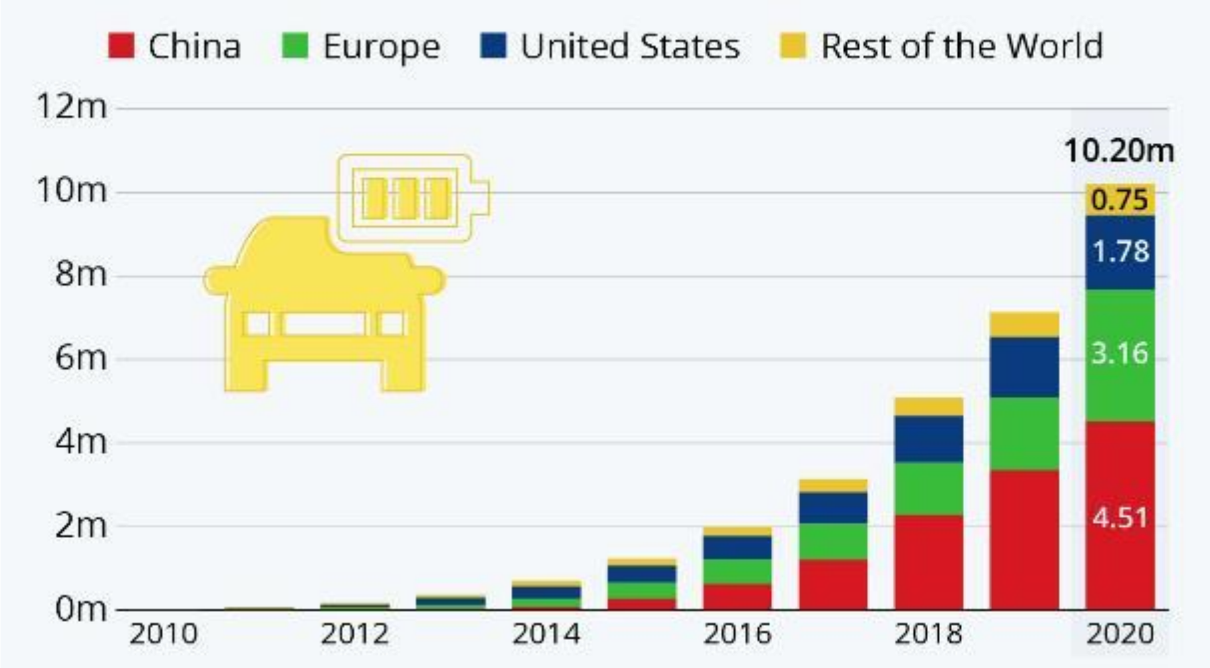
Global vehicle sales in 2022

Total: 66 million

EV: 7.6 million (11.5%)

Global EV Stock (2022)

23 million (1.5%) out of 1.5 billion vehicles



Dynamic Charging

- Minimize onboard energy storage
- Instead deliver energy to moving EVs from the roadway

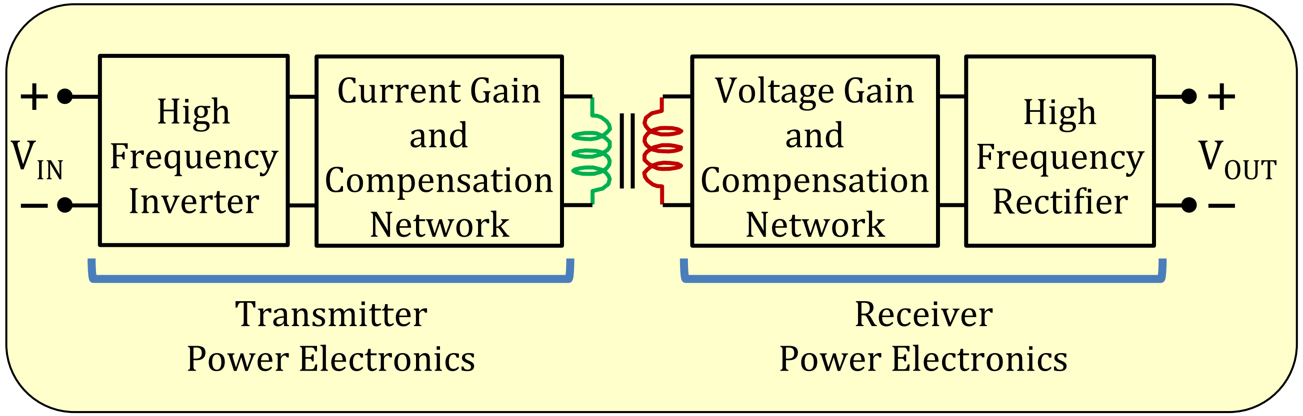
Overhead Catenary Lines

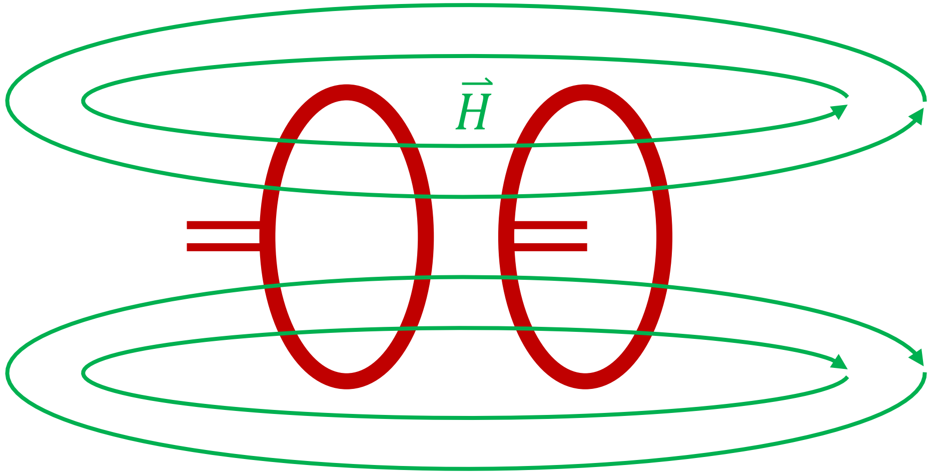
Conductive Rails

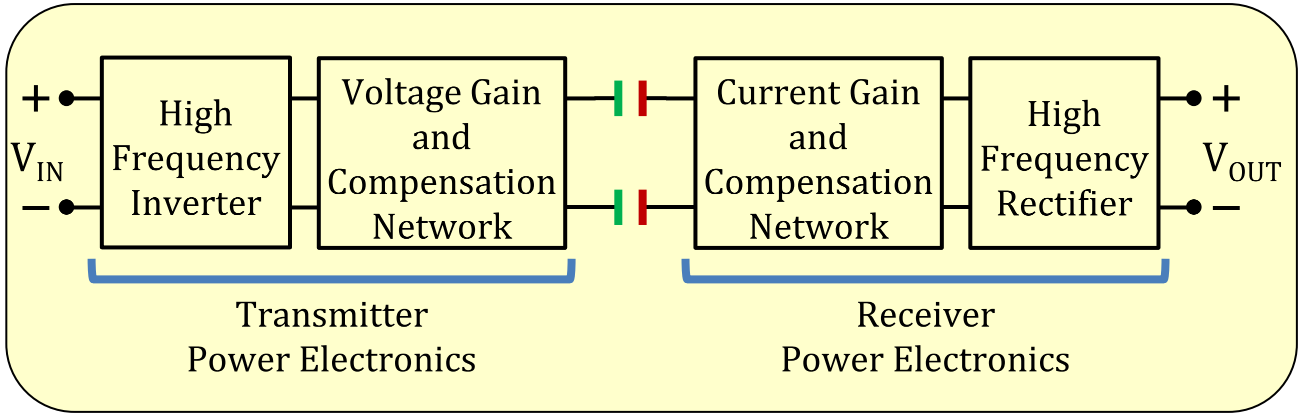
Dynamic Wireless Charging

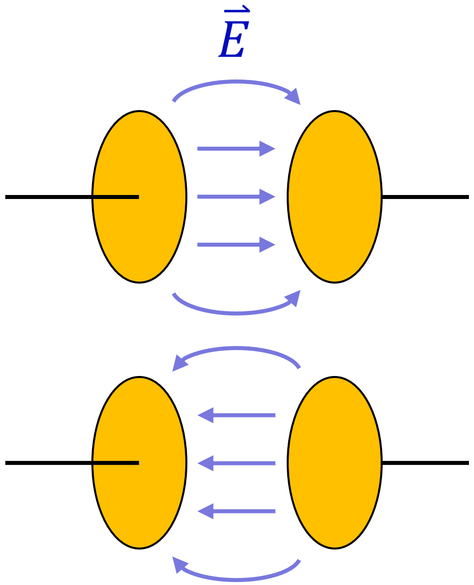
Dynamic wireless charging could be viable way to drastically reduce batteries in EVs

Inductive vs. Capacitive Wireless Power Transfer (WPT)

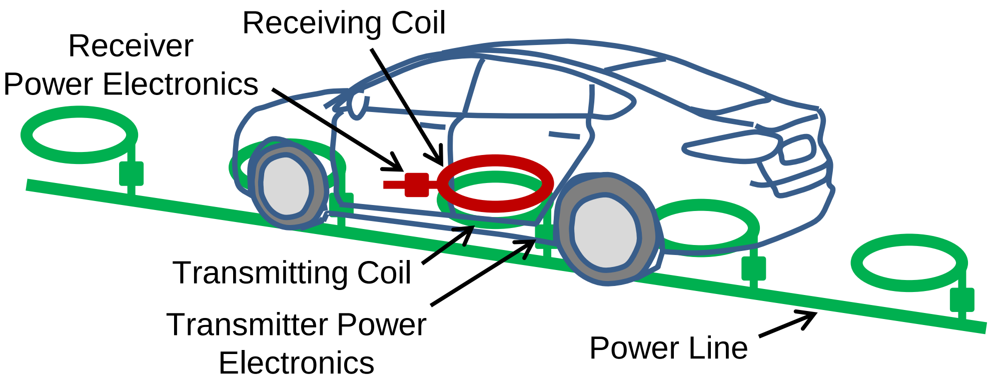


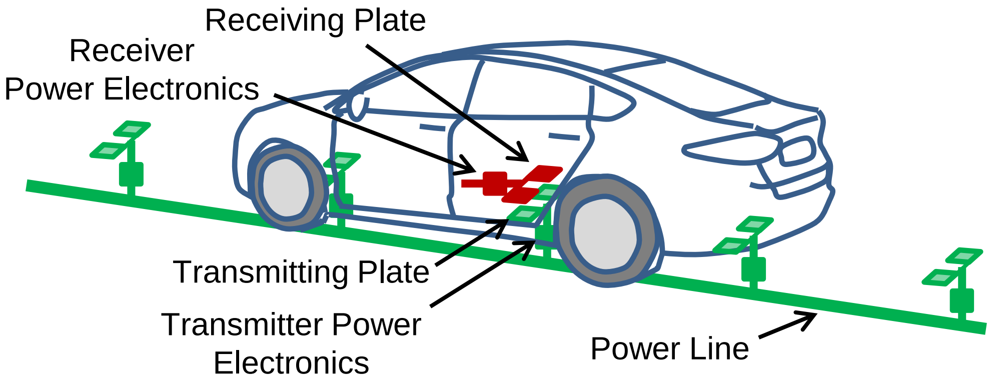




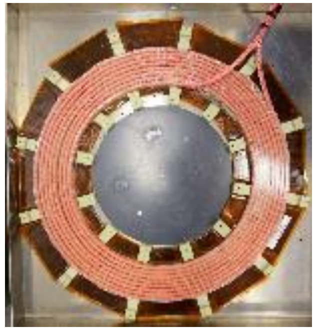


Advantages of Capacitive Wireless Charging





- Inductive systems require Litz wire and ferrite cores for magnetic flux guidance and shielding
  - Expensive
  - Fragile and difficult to embed in roadway
- Inductive systems operate at relatively low frequencies to limit ferrite losses
  - Large and heavy
- Inductive systems have low misalignment tolerance and induce eddy currents in nearby metallic objects



- Capacitive systems simply use conductive plates, the fields are naturally directed (no ferrites or dielectrics), can operate at high frequencies, so can be:
  - Less expensive
  - Easier to embed in roadway
  - Smaller, lower profile and lighter
- Capacitive systems have high misalignment tolerance and do not induce eddy currents in nearby metallic objects

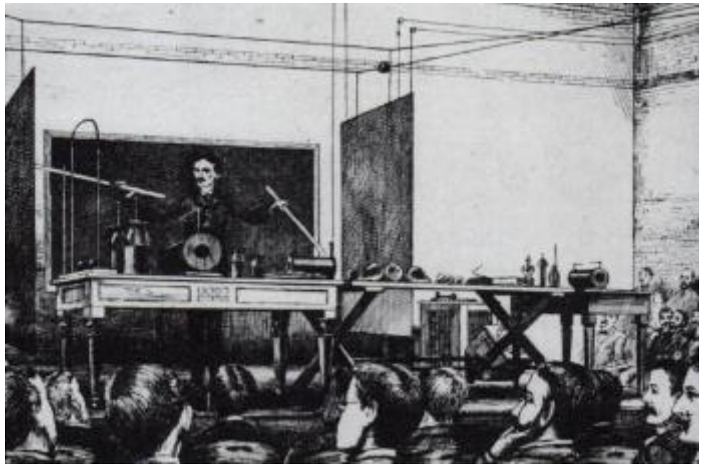
Conventional Wisdom Regarding Capacitive WPT

Source:
Toyohashi University of Technology

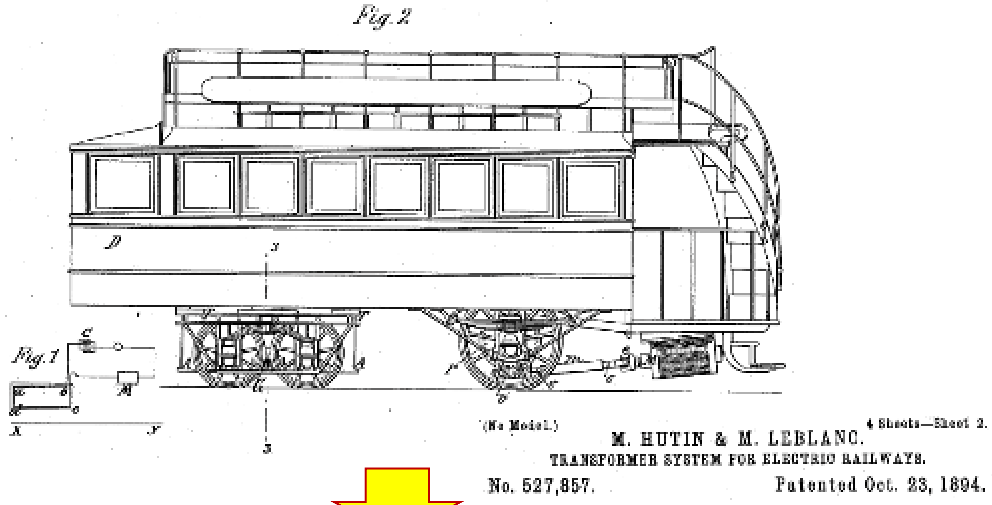
- Capacitive WPT usable for low-power small-gap applications
- Capacitive charging of EVs through tires has been tried
  - Low efficiency due to carbon black filler
  - Inadequate power transfer due to limited area

History Behind Our Capacitive WPT Work

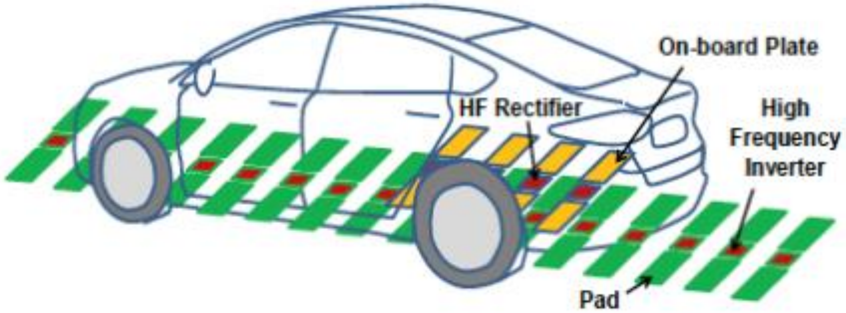
Nikola Tesla (1891)



M. Hutin & M. Leblanc (1894)

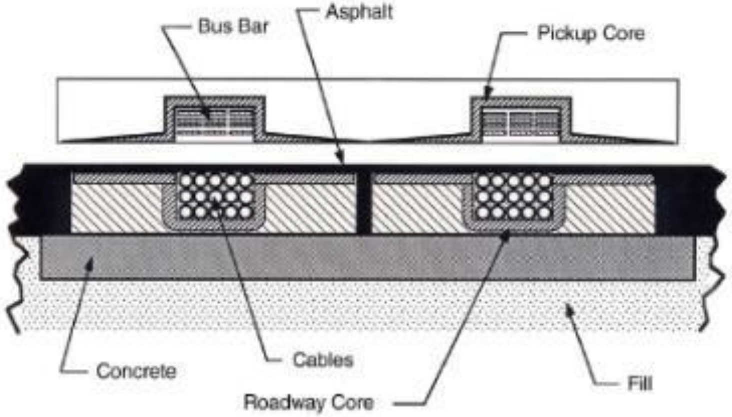


Kumar, Pervaiz, Chang, Korhummel, Popovic & Afridi (2015)

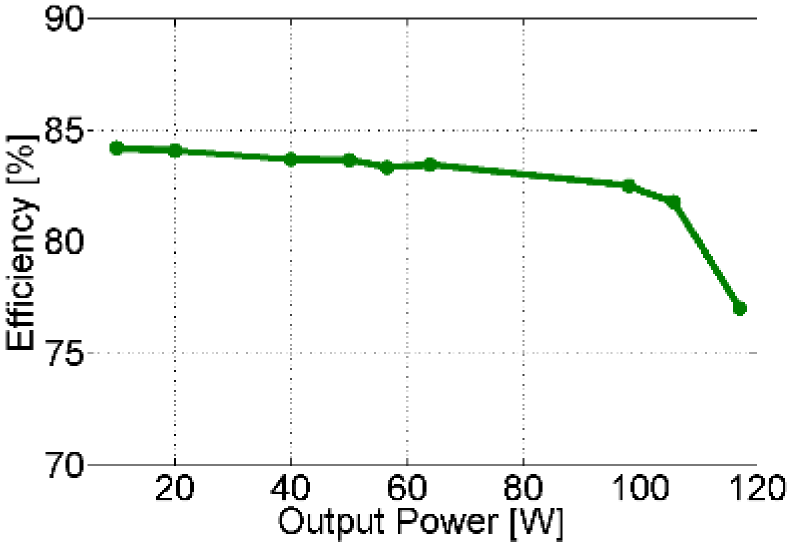


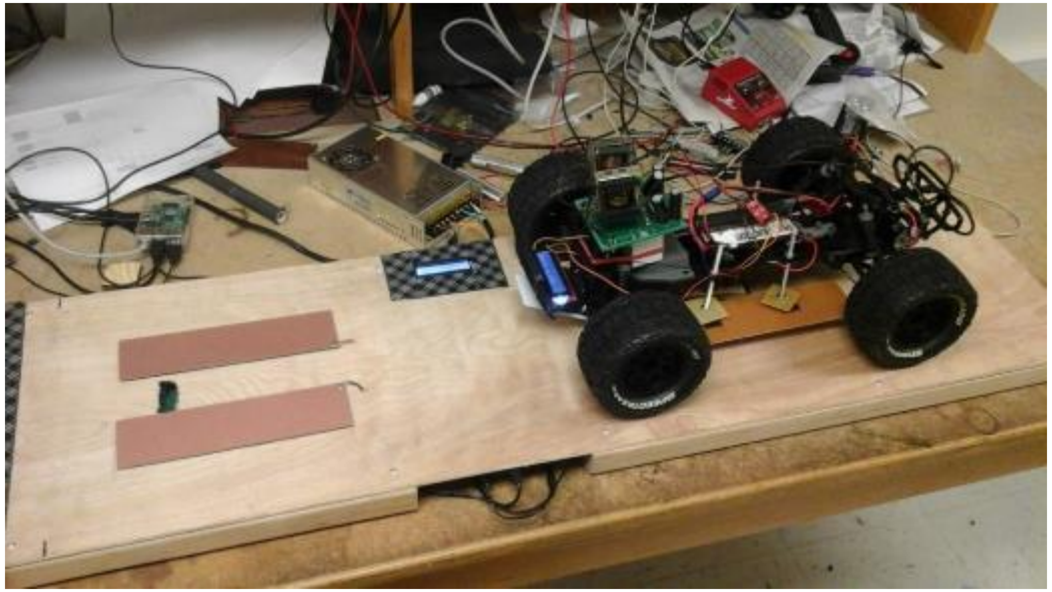
2015 IEEE Wireless Power Transfer Conference

UC Berkeley PATH - RPEV (1994)



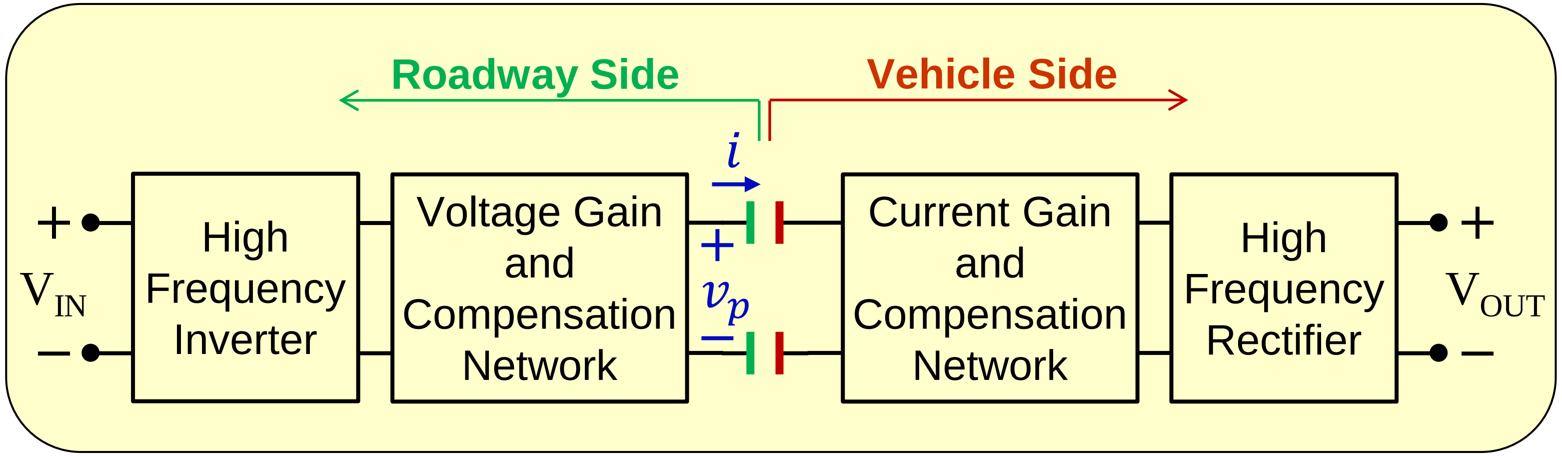
Our Early Experiments with Capacitive WPT

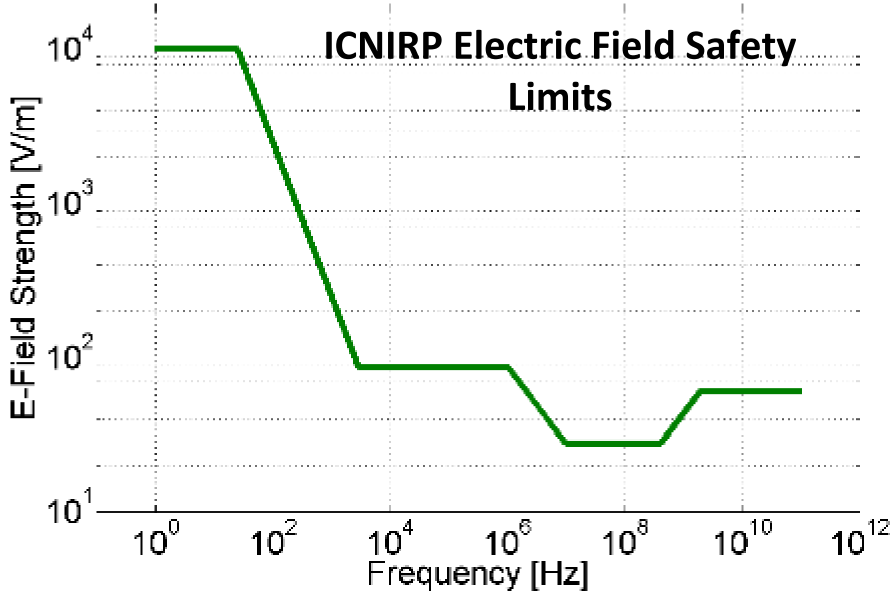




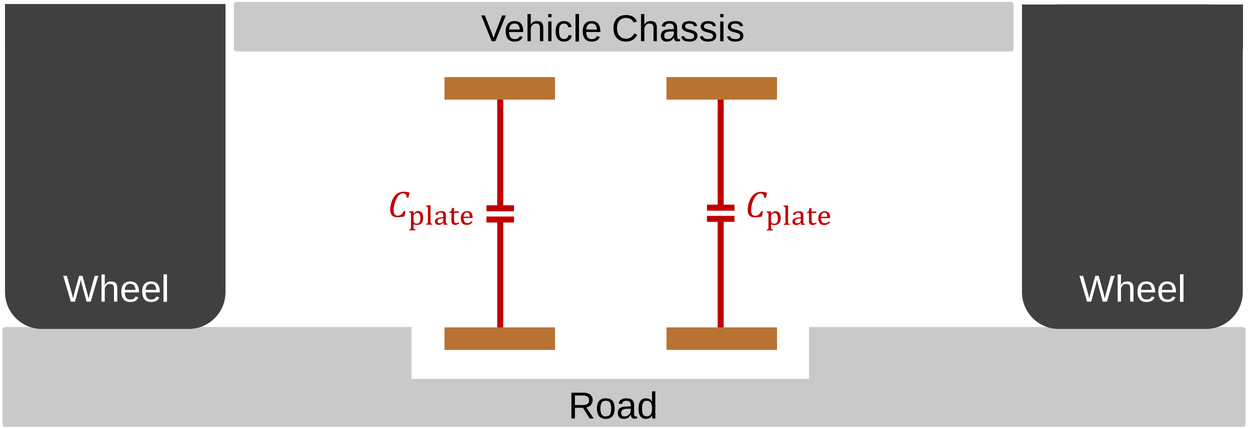
Challenges in Capacitive Wireless Charging

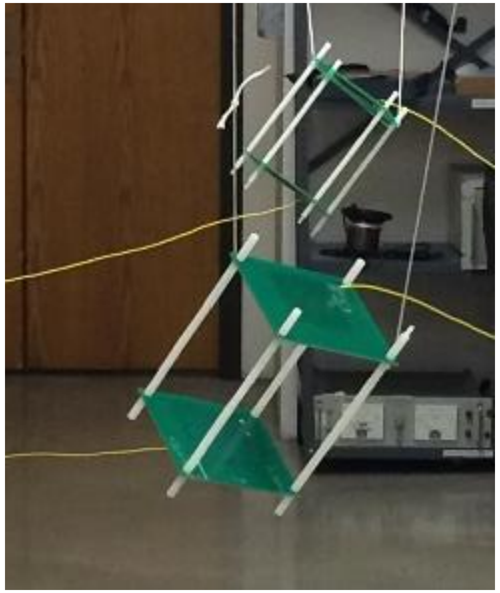
- Small coupling capacitance due to large gap between road and vehicle
- Need high frequency operation to achieve high power transfer levels
- Need high voltage/current gain to limit fringing fields and meet safety limits
- Need large reactive compensation



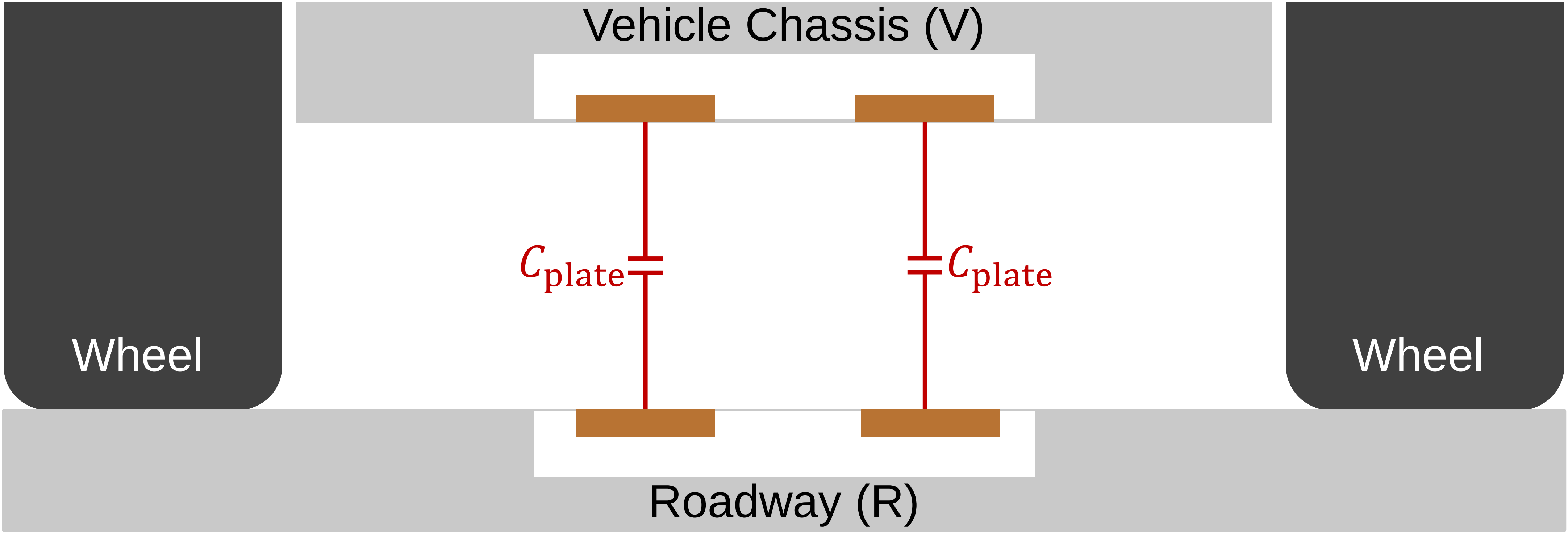


Large-Airgap Capacitive Wireless Power Transfer

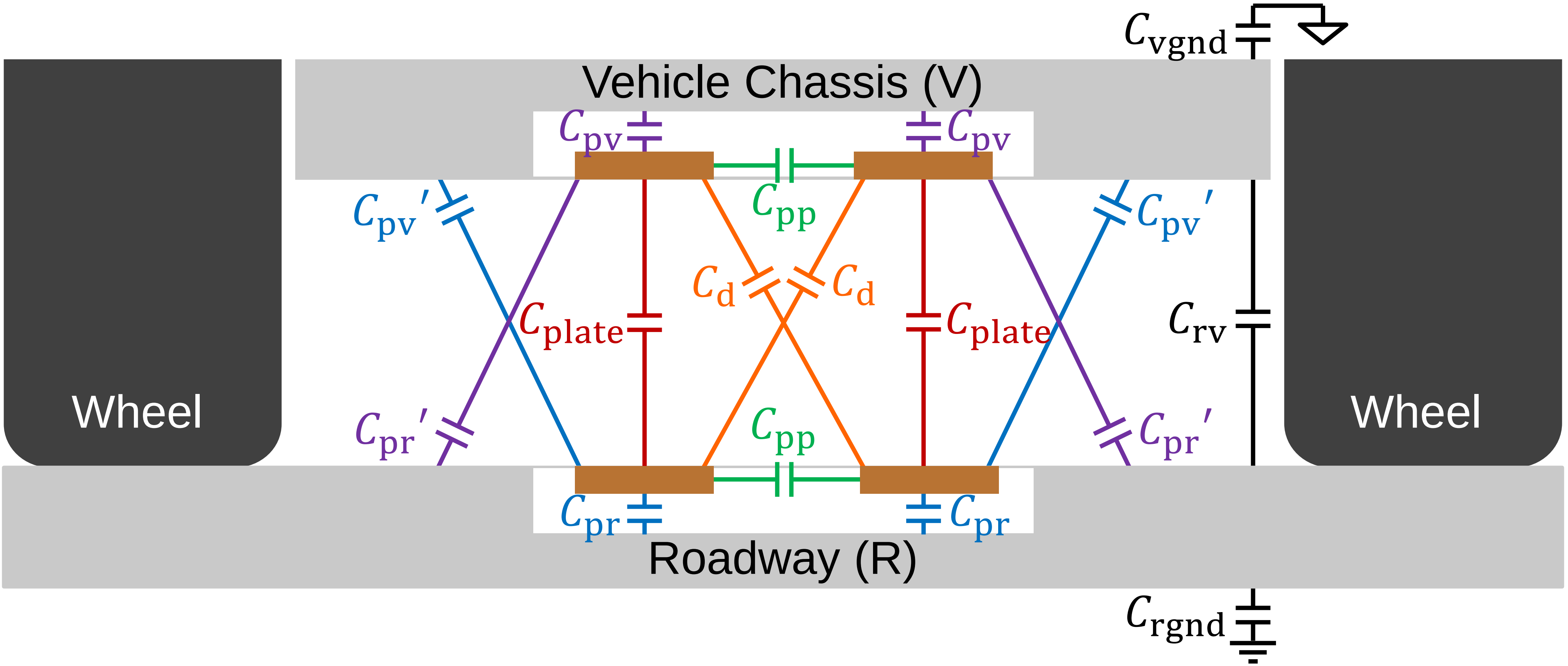




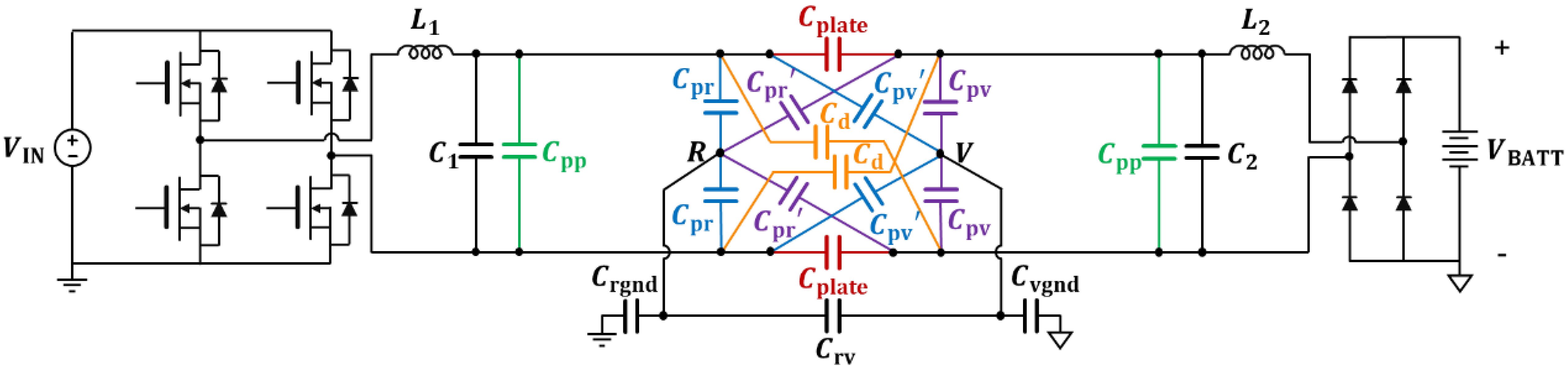
Electric Vehicle Charging Environment



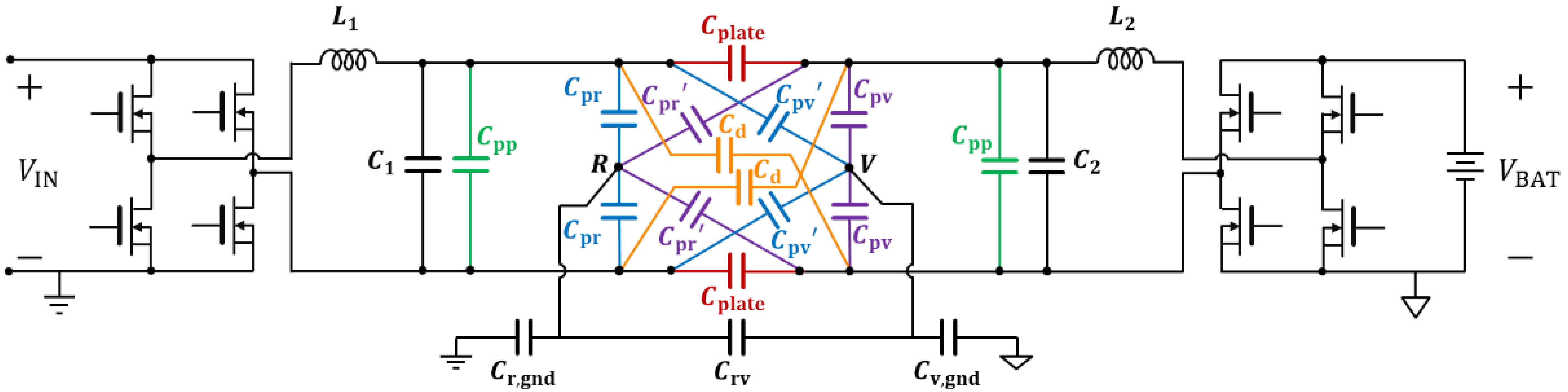
Overwhelming Parasitic Capacitances

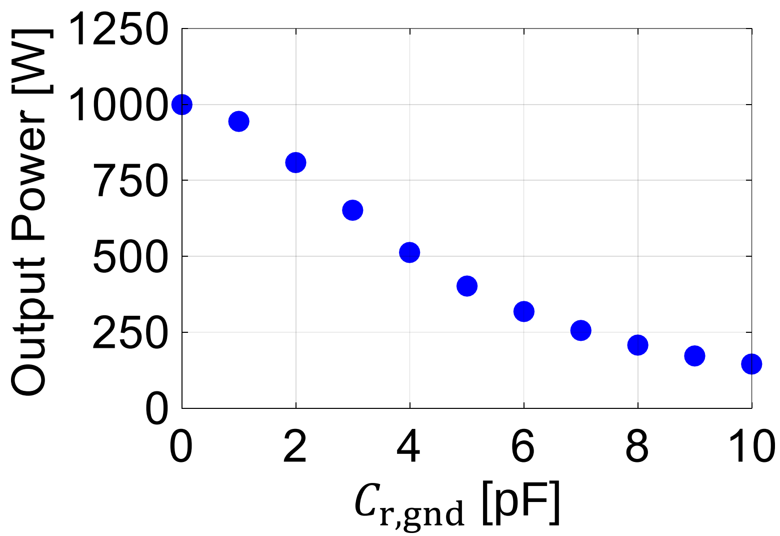


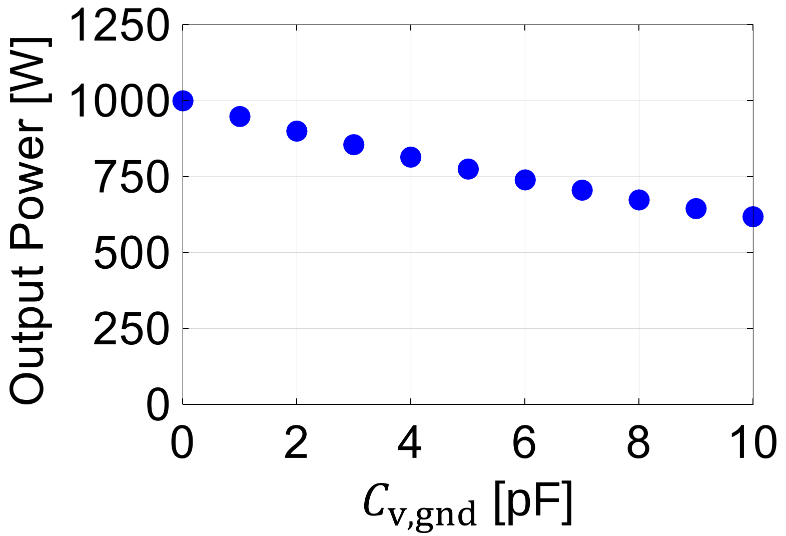
Circuit Including Parasitic Capacitances



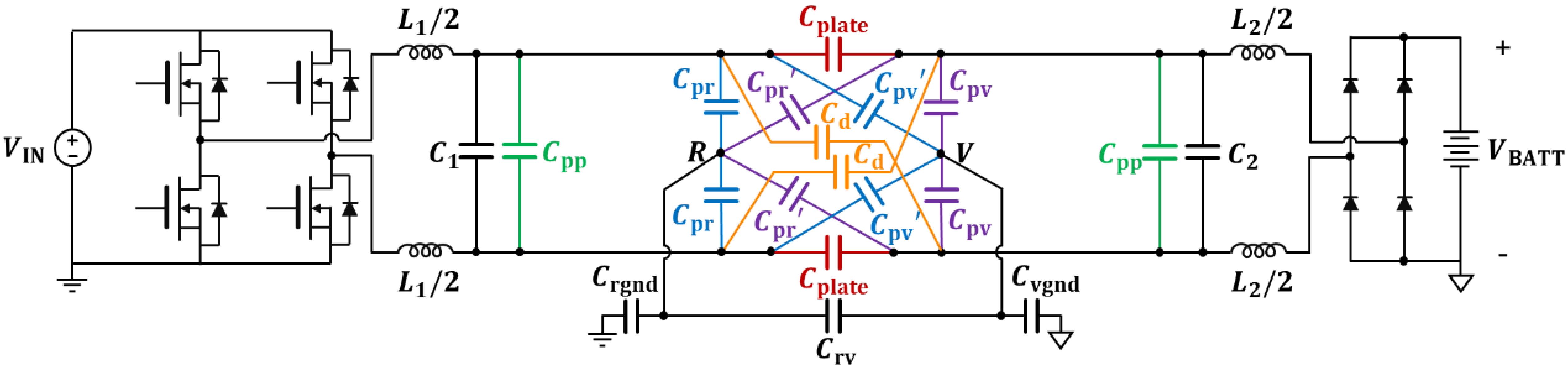
Effect of Parasitic Capacitances



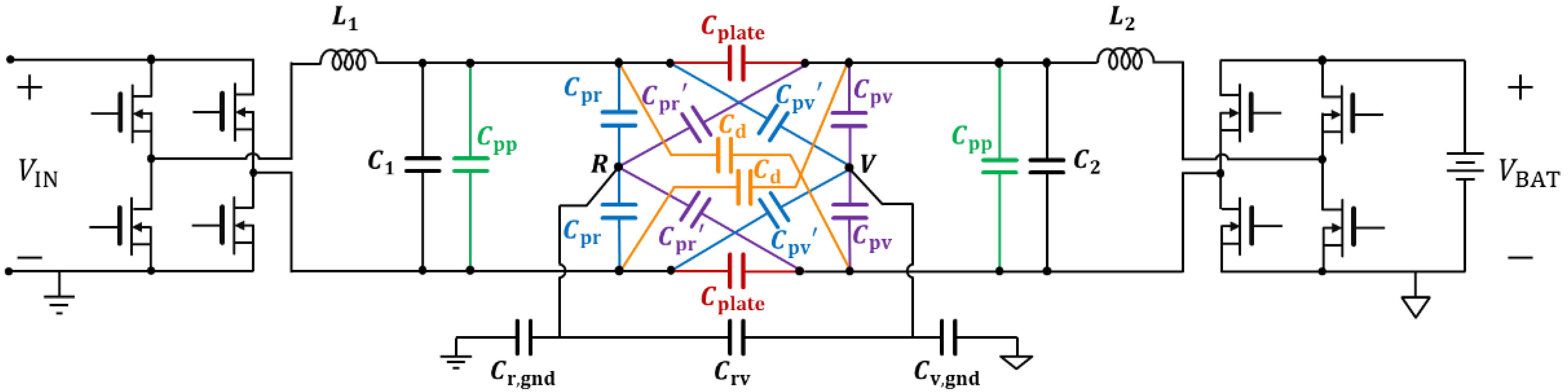


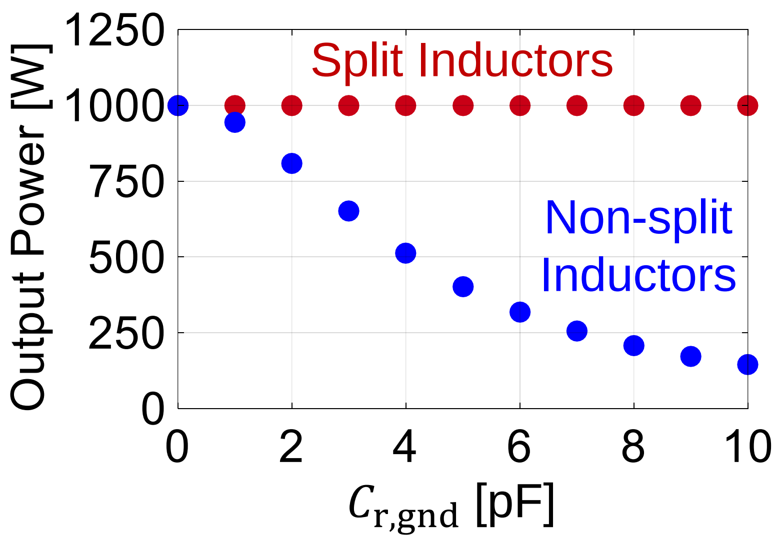


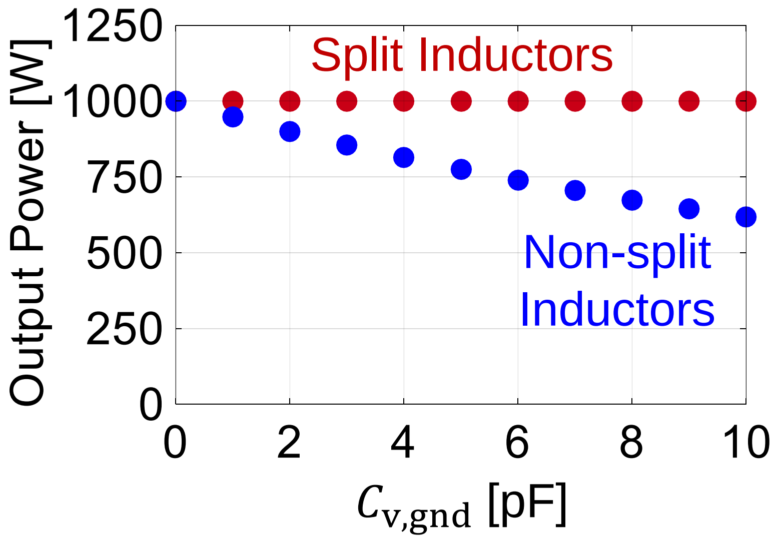
Split-Inductor Matching Network



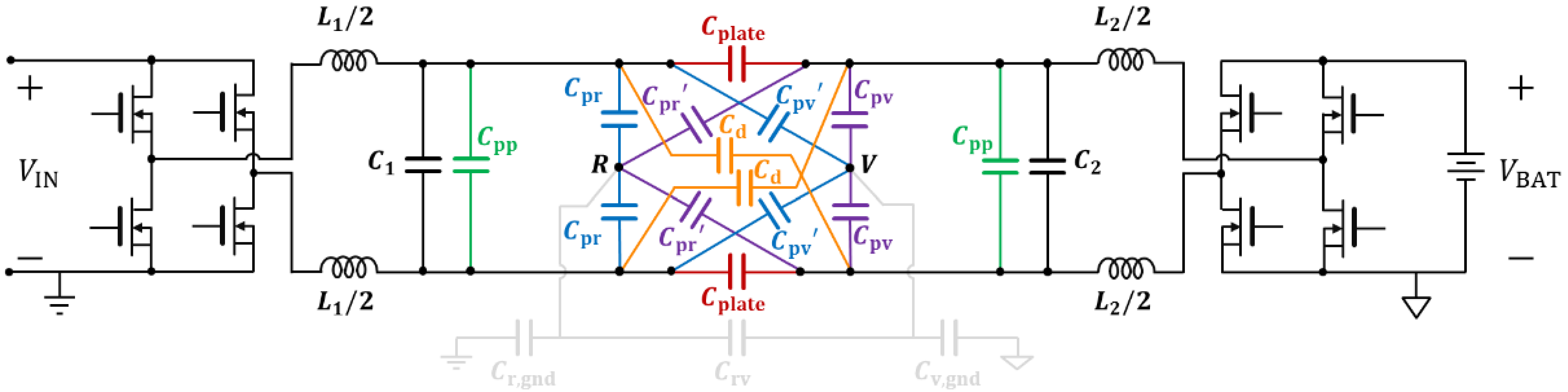
Effect of Parasitic Capacitances with Split-Inductor

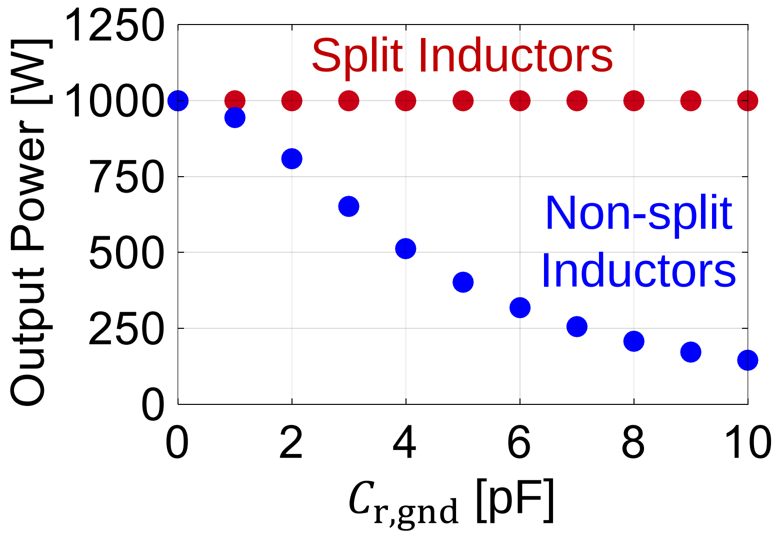


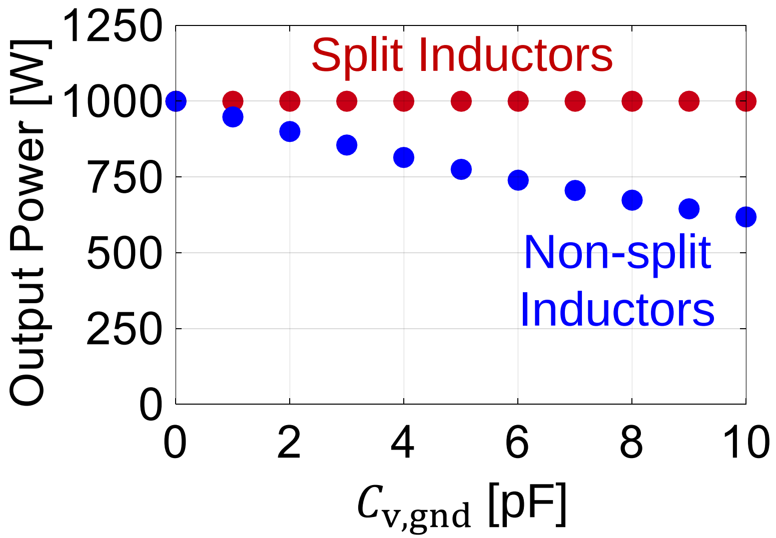




Effect of Parasitic Capacitances with Split-Inductor







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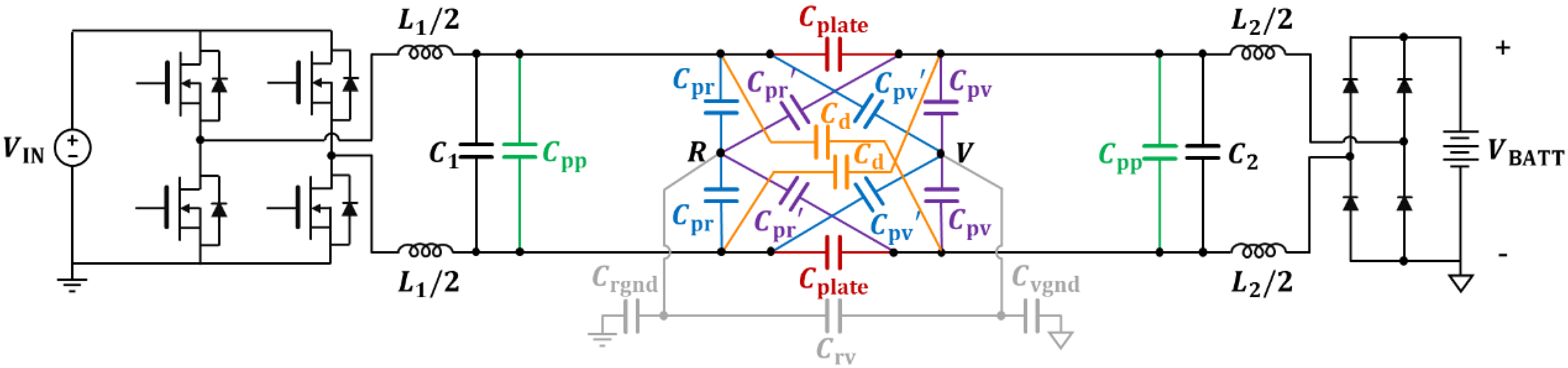
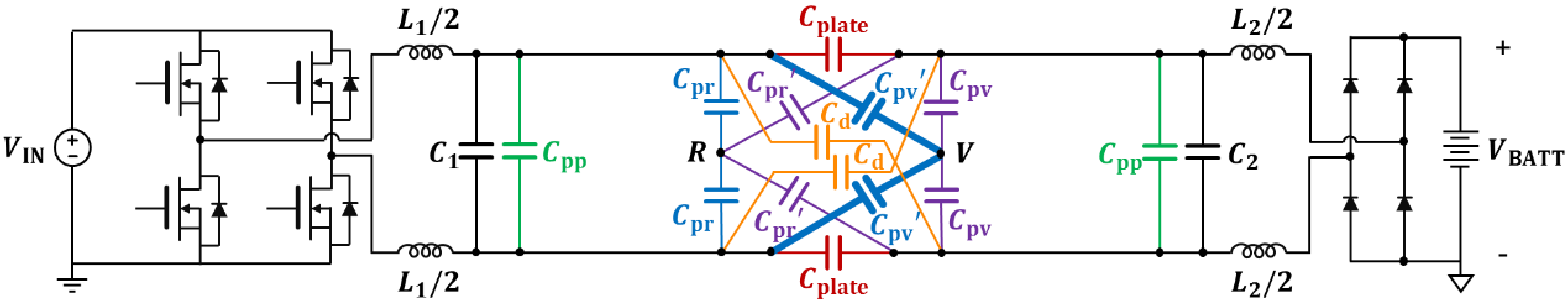


Capacitance Network Simplification



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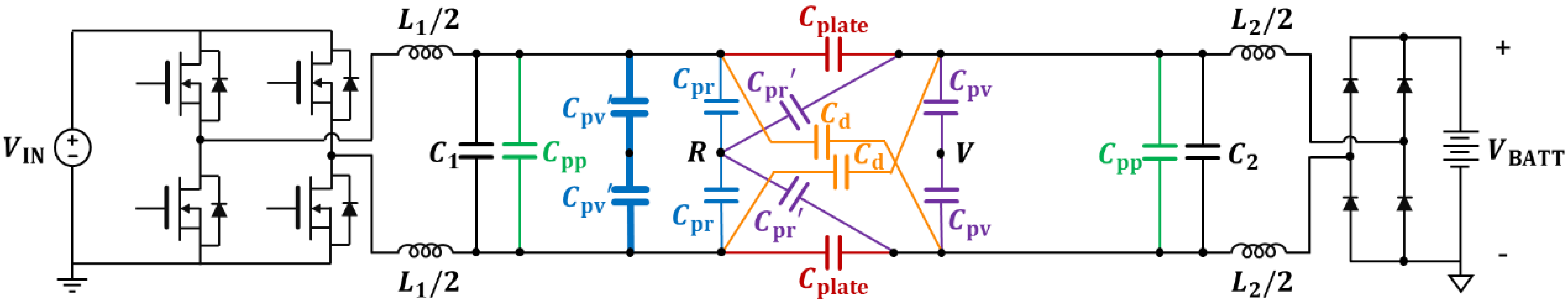

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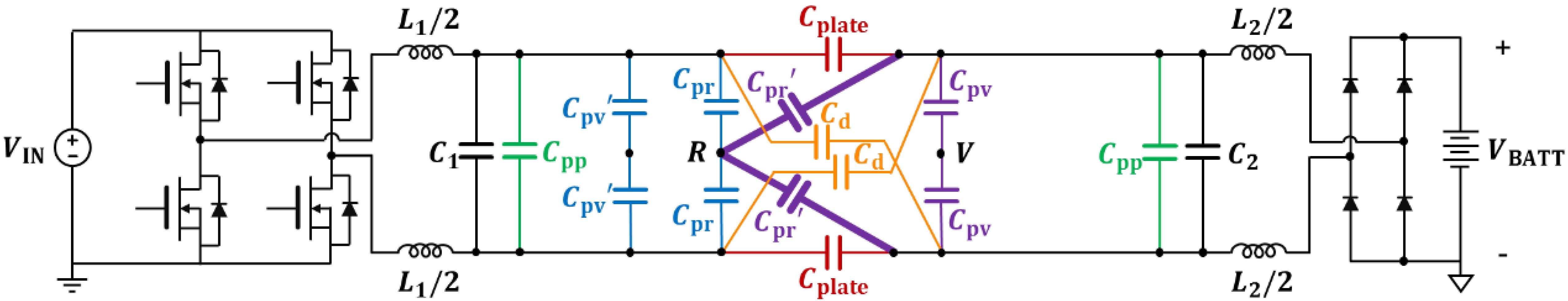

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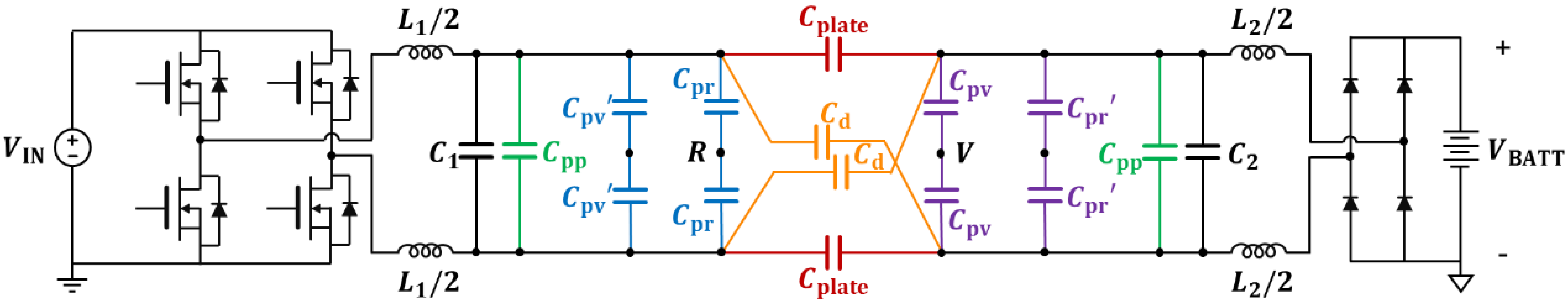

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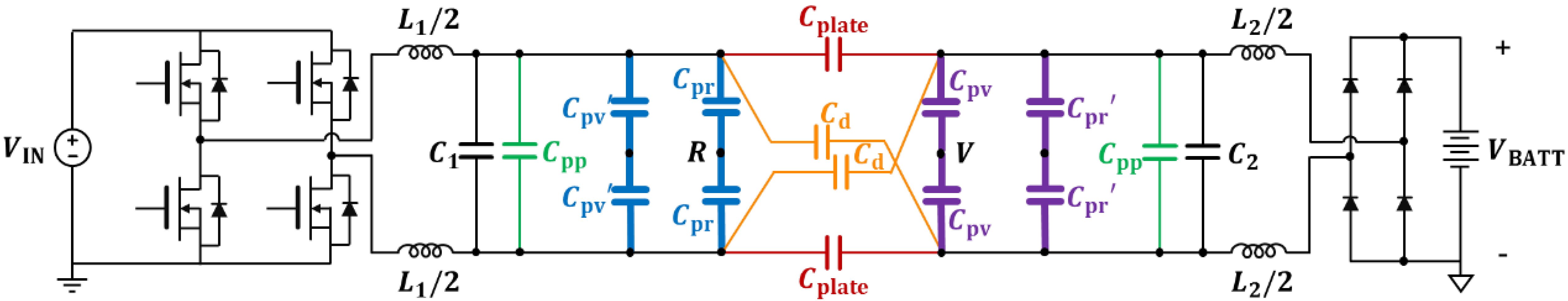

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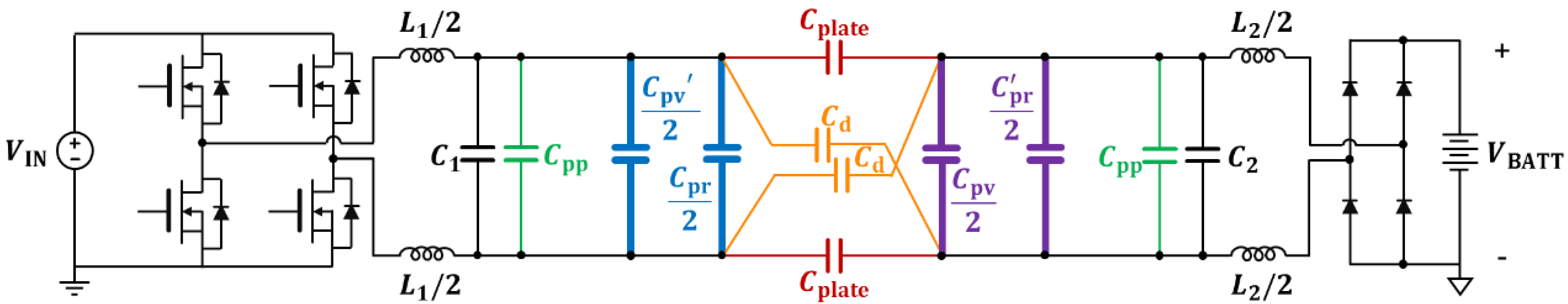

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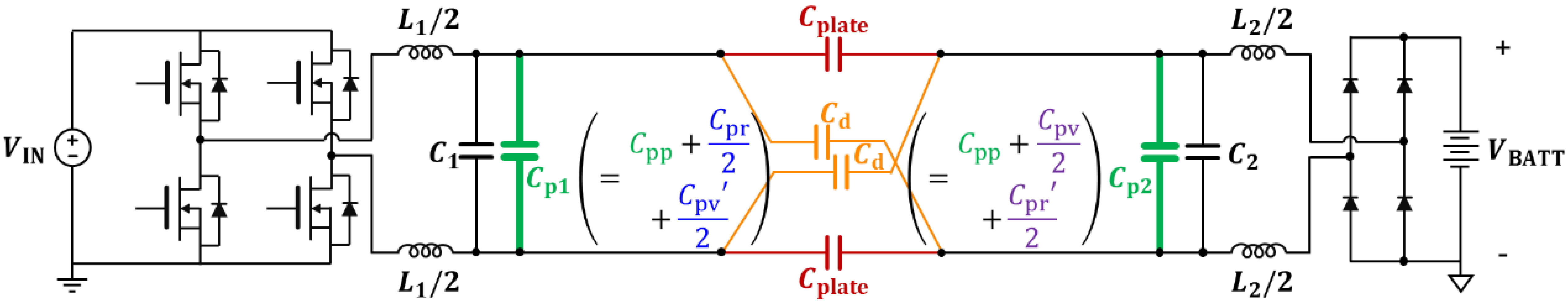

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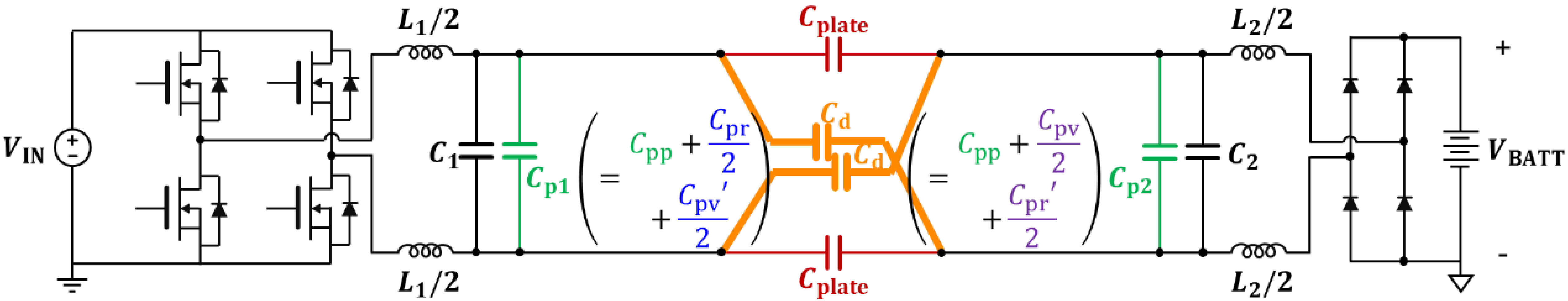
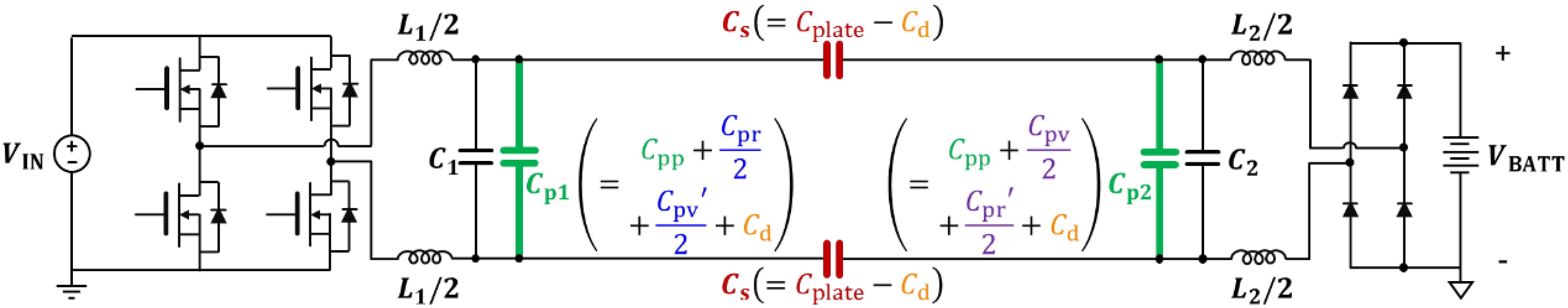
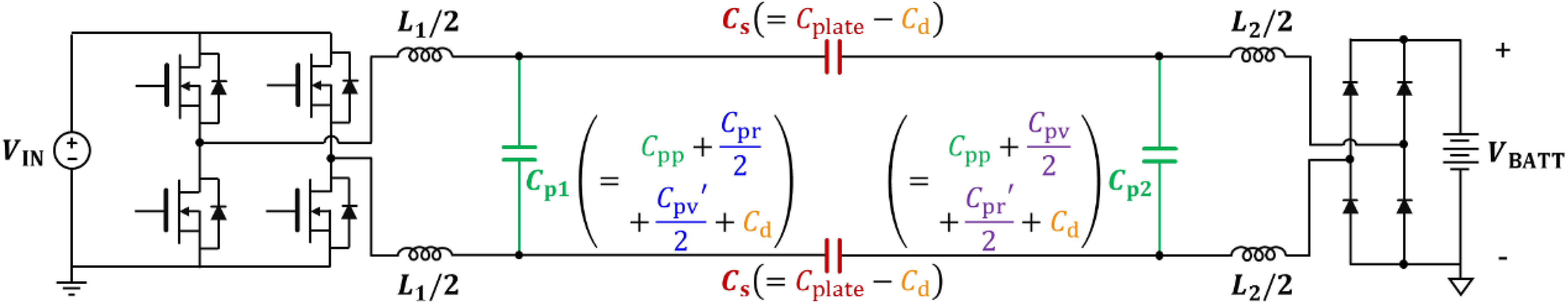


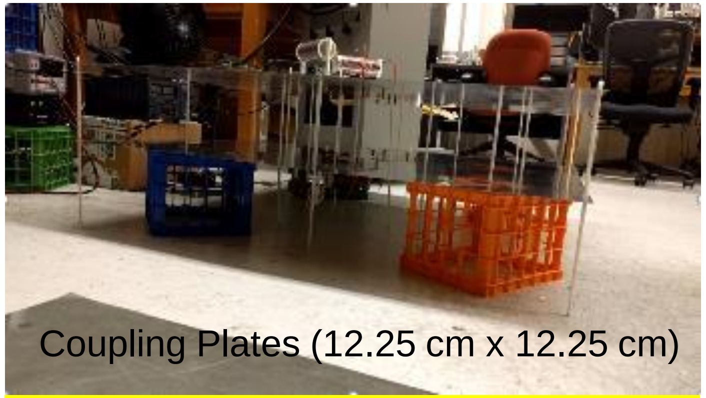
Capacitance Network Simplification



Capacitance Network Simplification

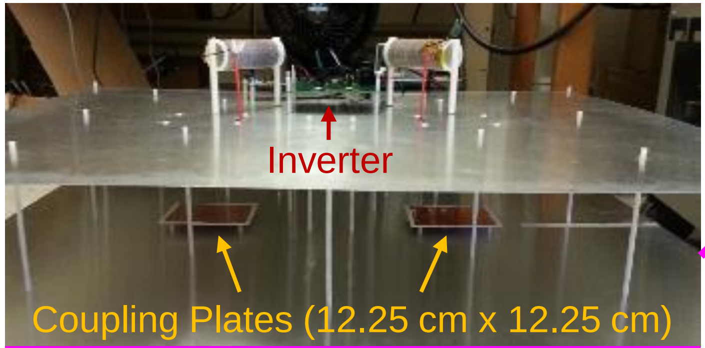


6.78-MHz Capacitive Wireless Charging Systems



Gen-1 System

Output Power: 146 W

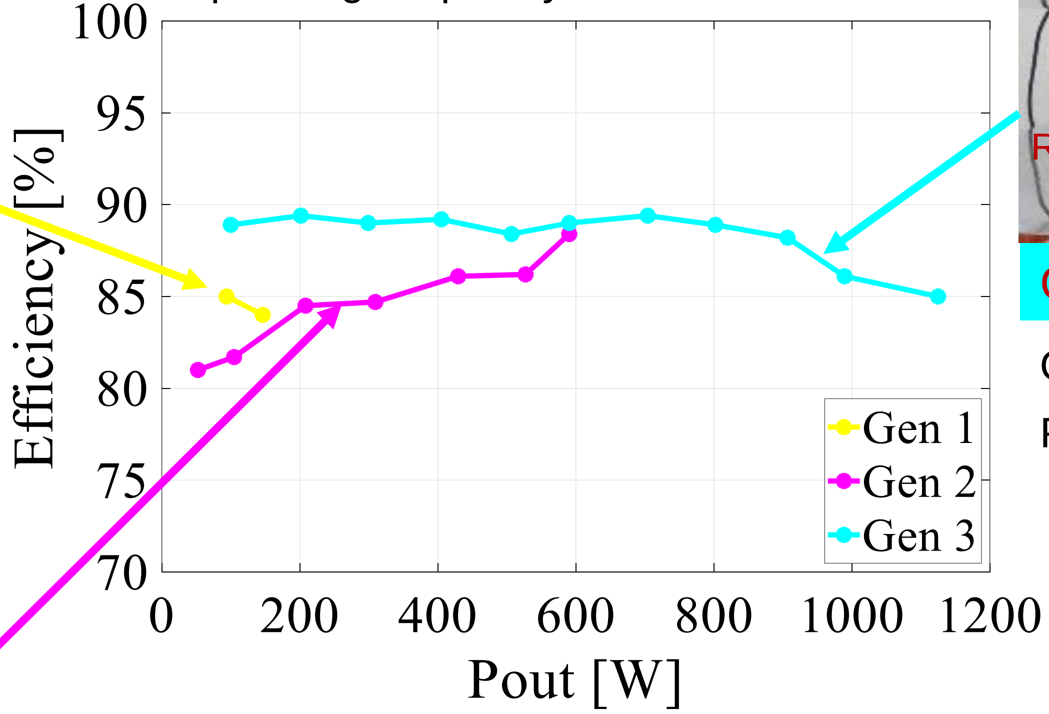


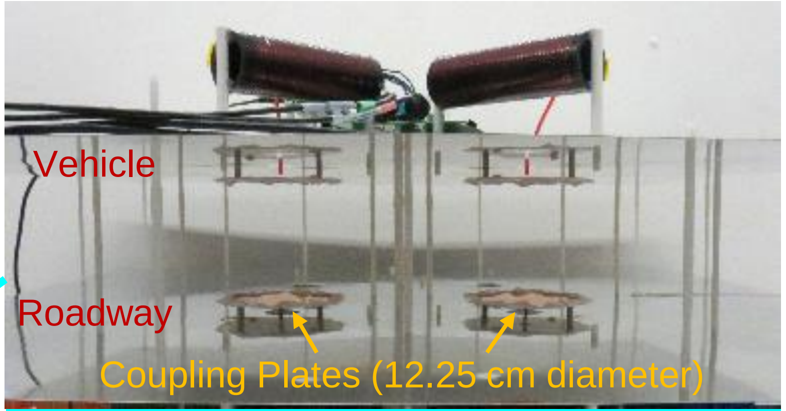
Gen-2 System

Output Power: 589 W

Air gap: 12 cm

Operating frequency: 6.78 MHz



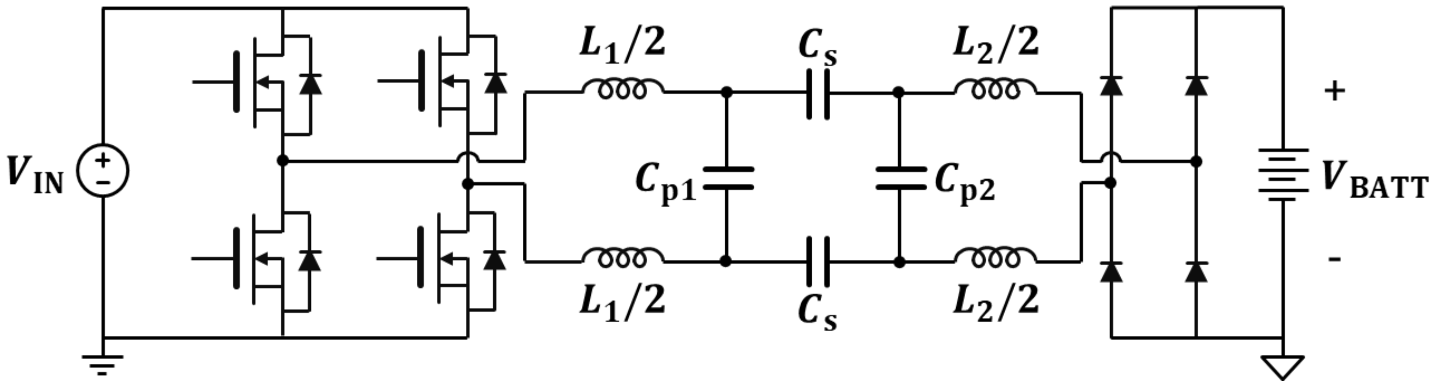


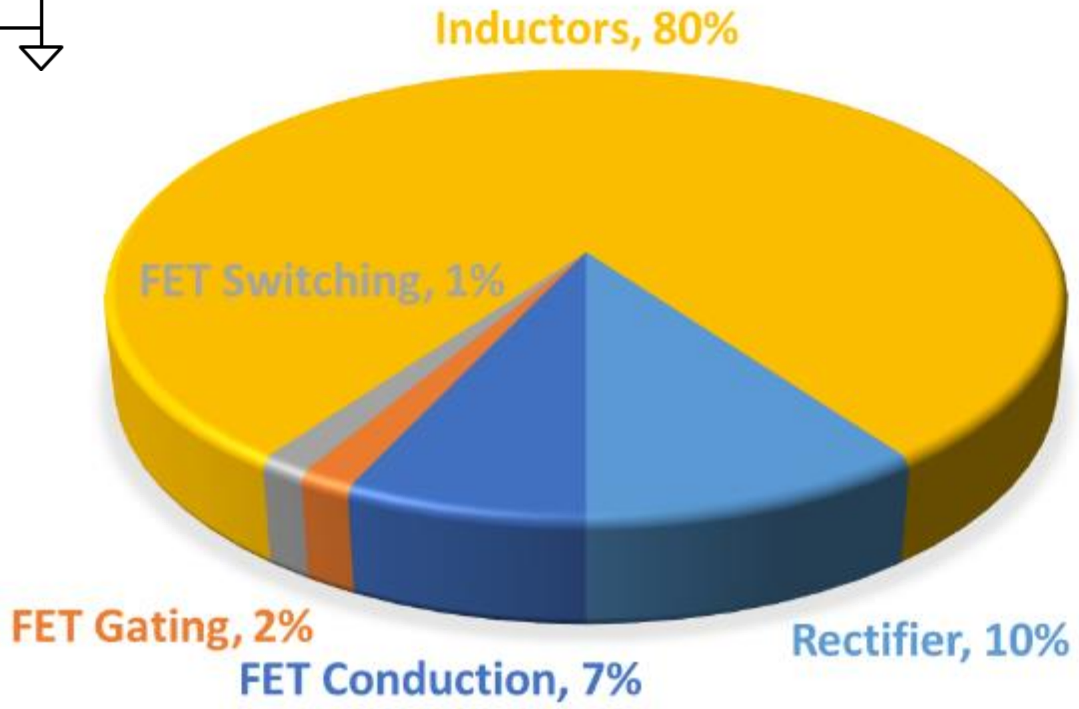
Gen-3 System

Output Power: 1216 W

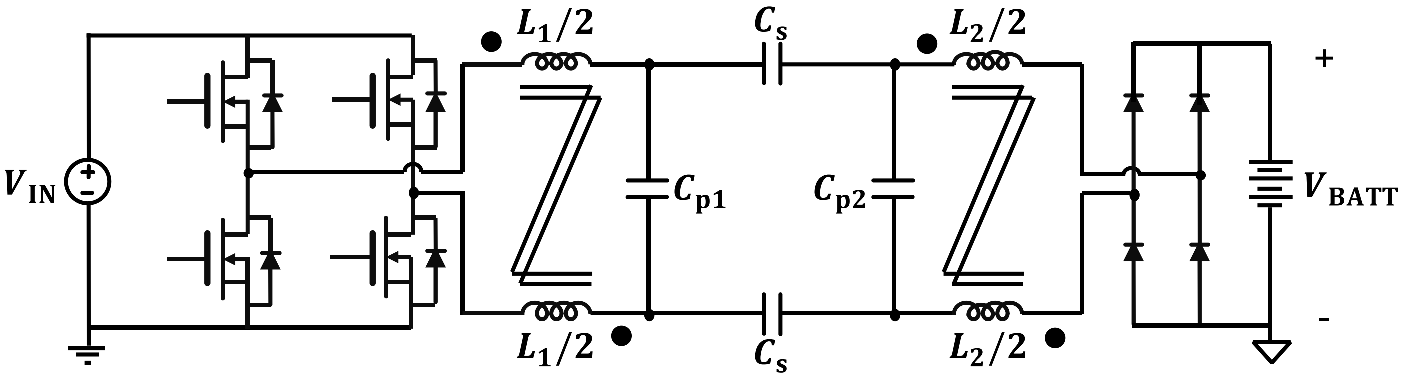
Power Transfer Density: 51.6 kW/m^2

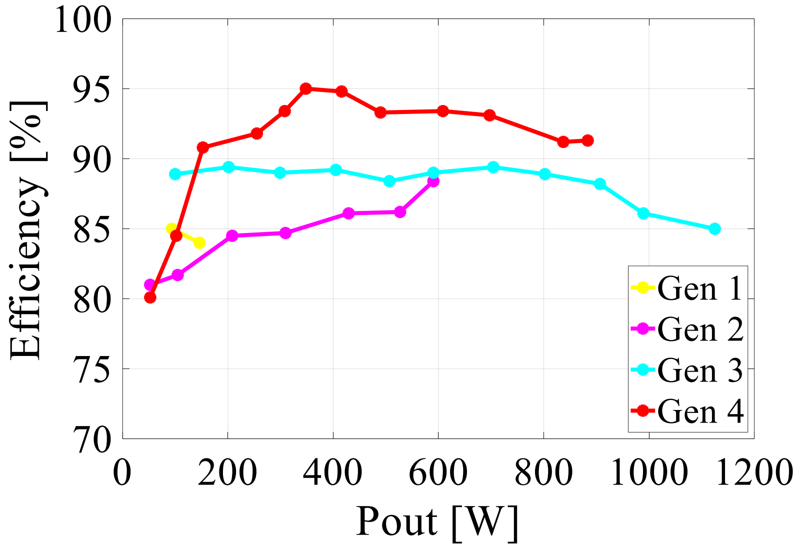
Loss Breakdown Analysis





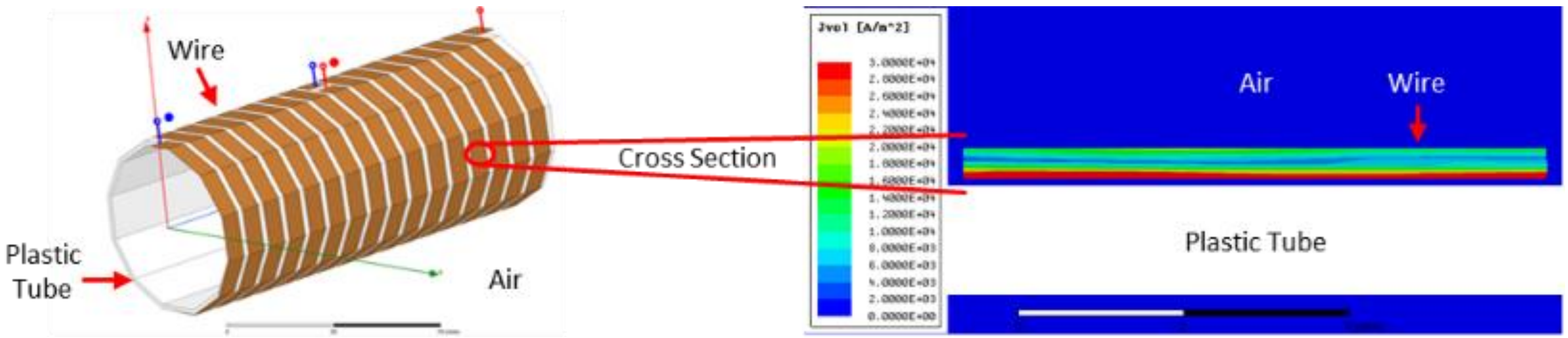
Coupled Inductors and Higher Frequency Operation



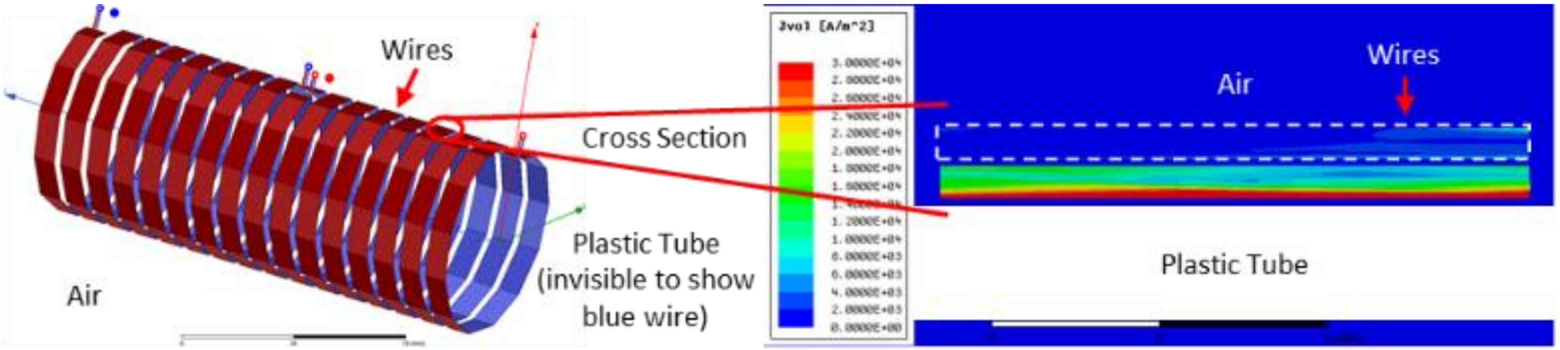


Optimizing Coupled Solenoidal Inductors

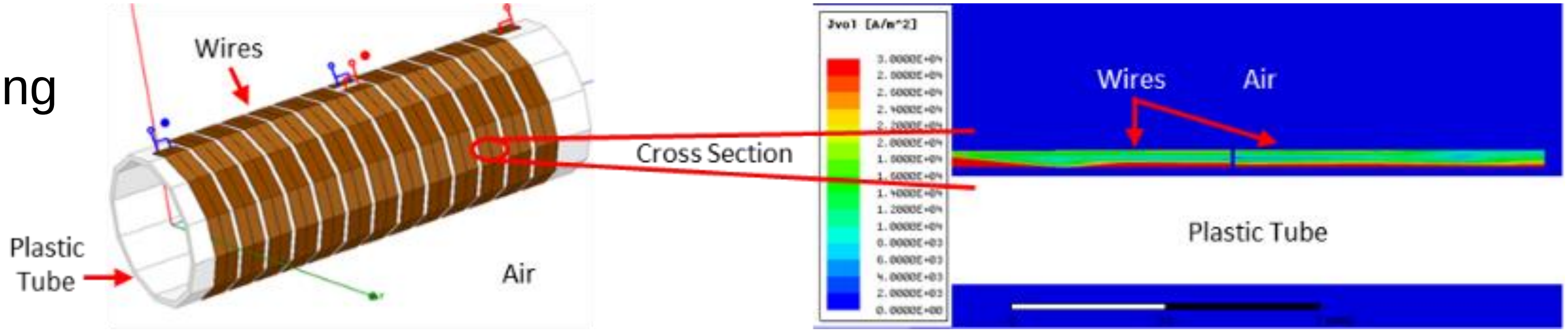
Single Winding



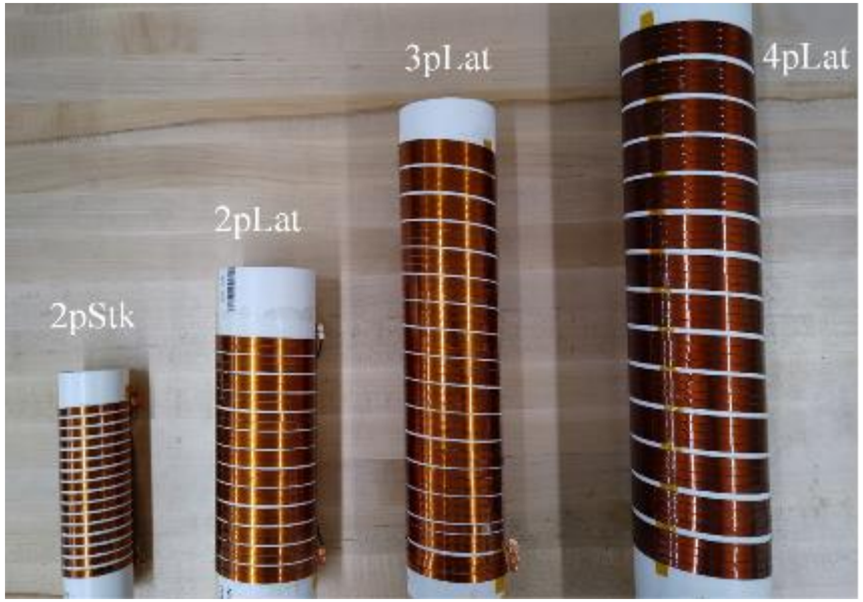
Stacked Parallel Winding

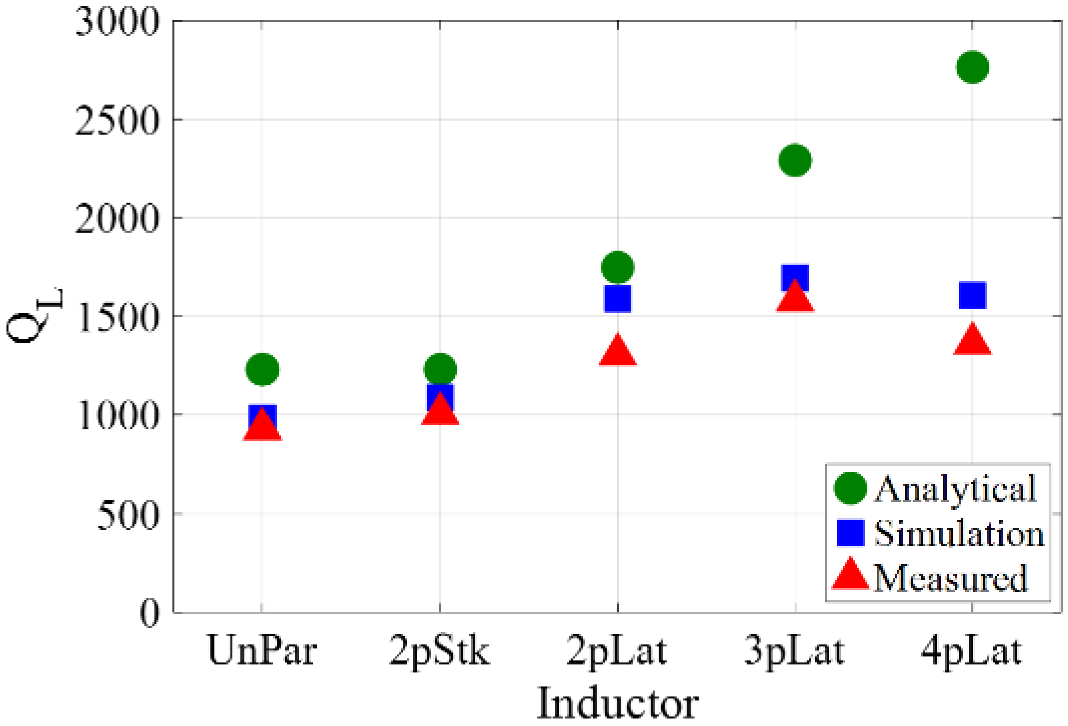


Laterally-Adjacent Parallel Winding



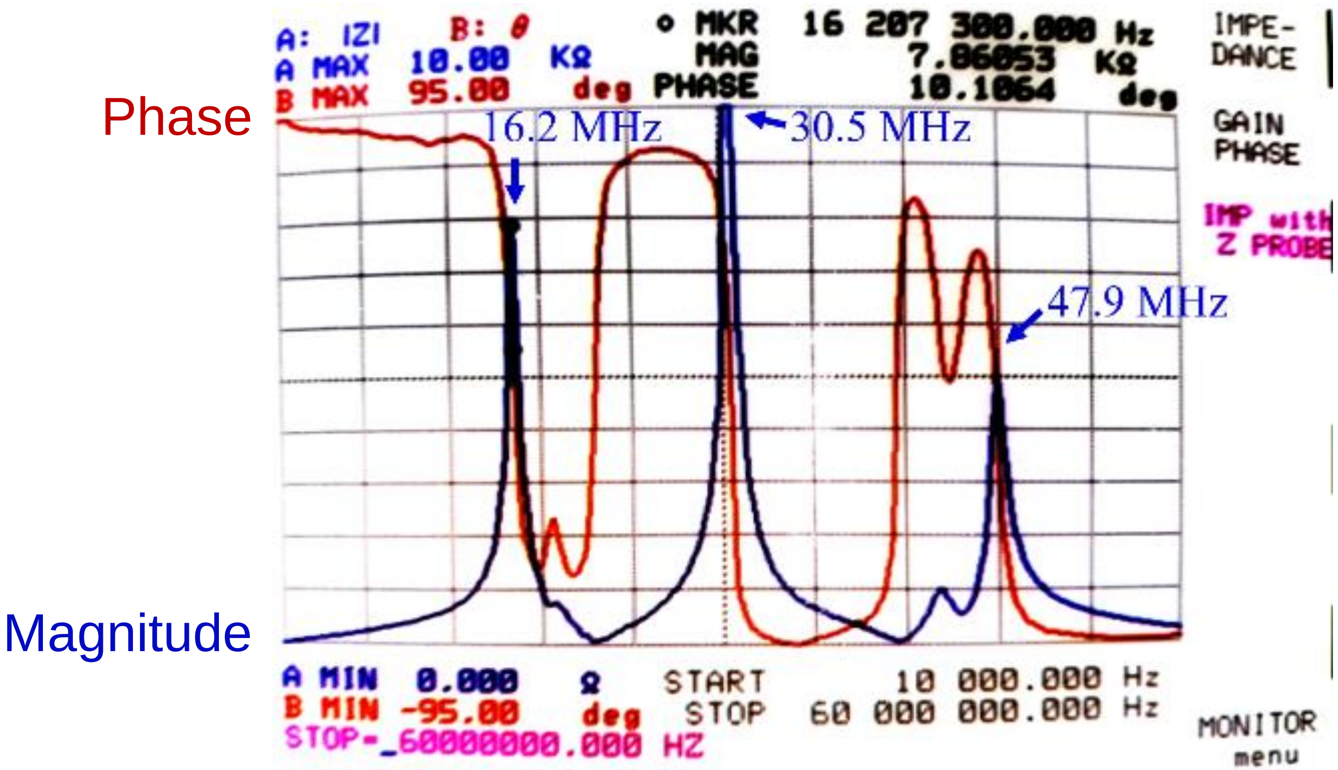
Solenoidal Inductor Quality Factor Comparison





$$Q_{\mathrm{L}} = \frac{2\pi f L}{R_{\mathrm{ac}}}$$

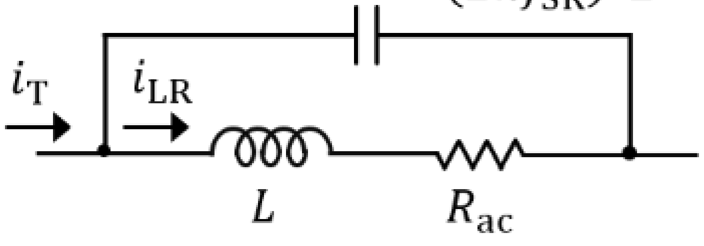
Impedance of “4pLat” Solenoidal Inductor



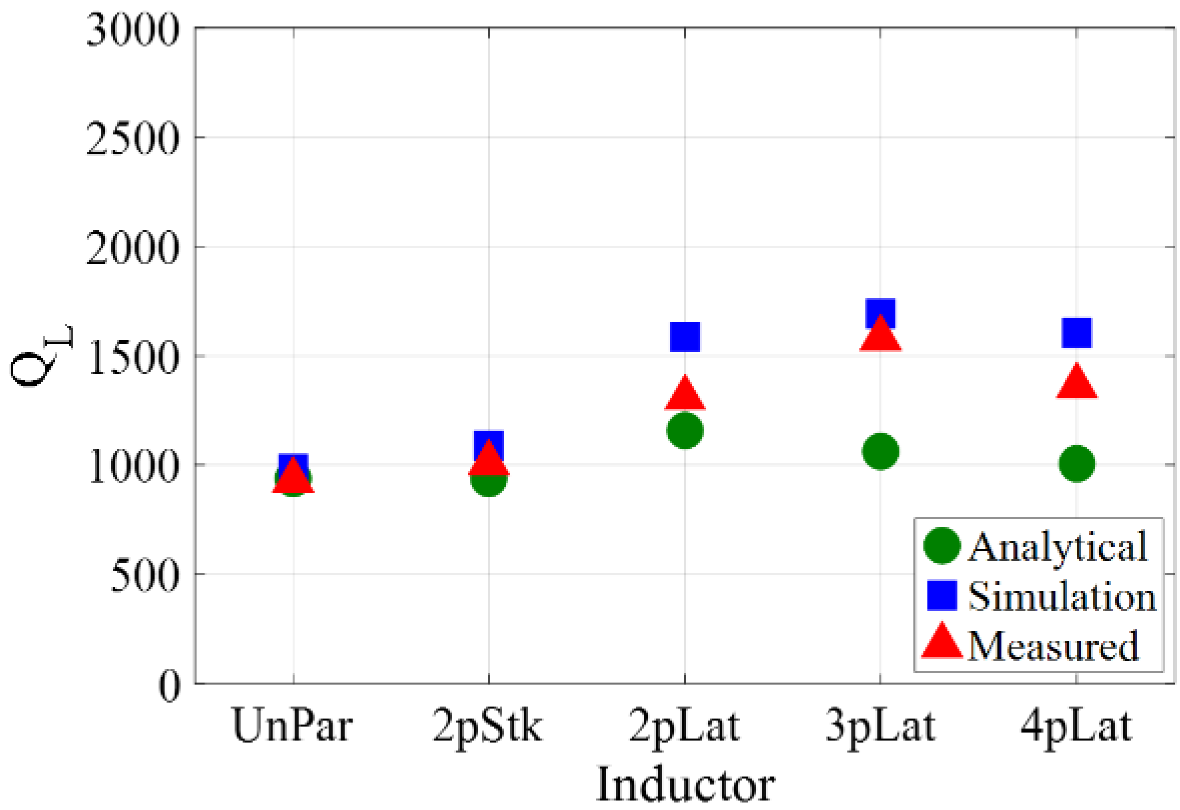
Self-resonance frequency is only slightly higher than operating frequency

SRF-Inclusive Quality Factor

$$C = \frac{1}{(2\pi f_{\mathrm{SR}})^2 L}$$

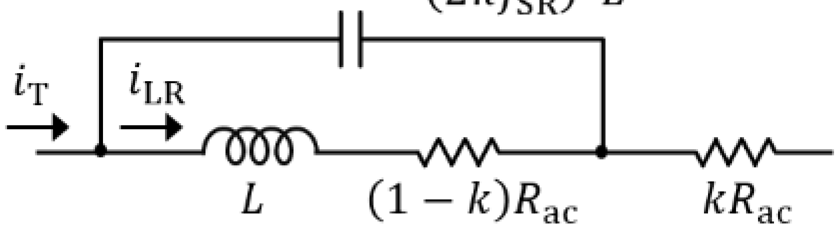


$$Q_{\mathrm{L,SR}} = \left| Q_{\mathrm{L}} - \left(\frac{f}{f_{\mathrm{SR}}}\right)^2 \left(Q_{\mathrm{L}} + \frac{1}{Q_{\mathrm{L}}}\right) \right|$$

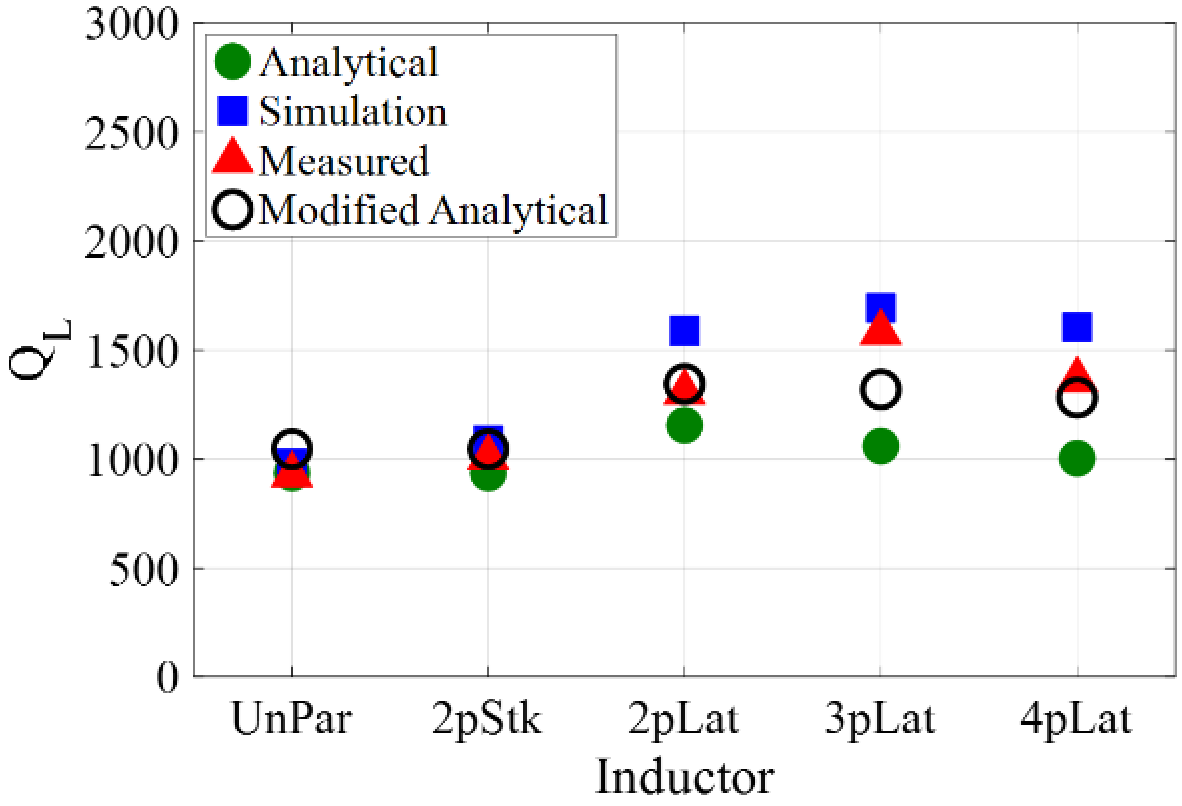


Modified SRF-Inclusive Quality Factor

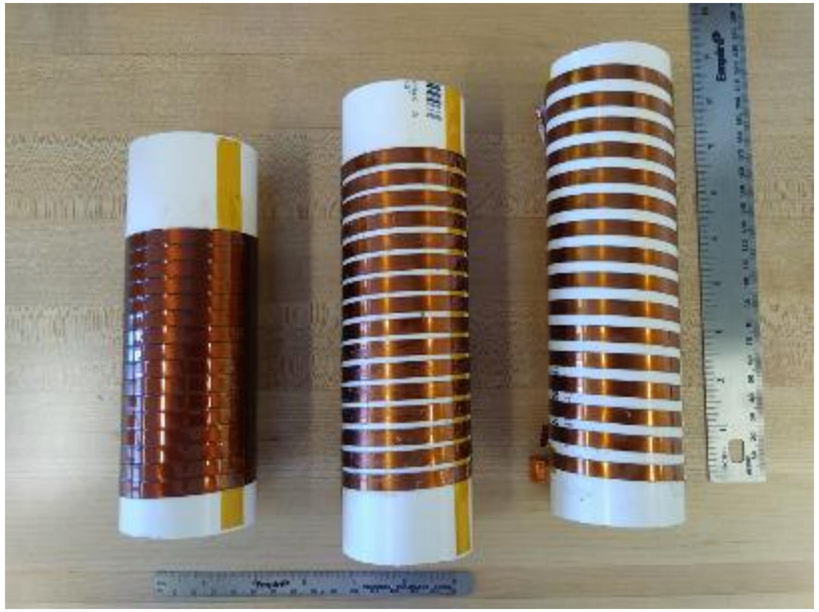
$$C = \frac{1}{(2\pi f_{\mathrm{SR}})^2 L}$$

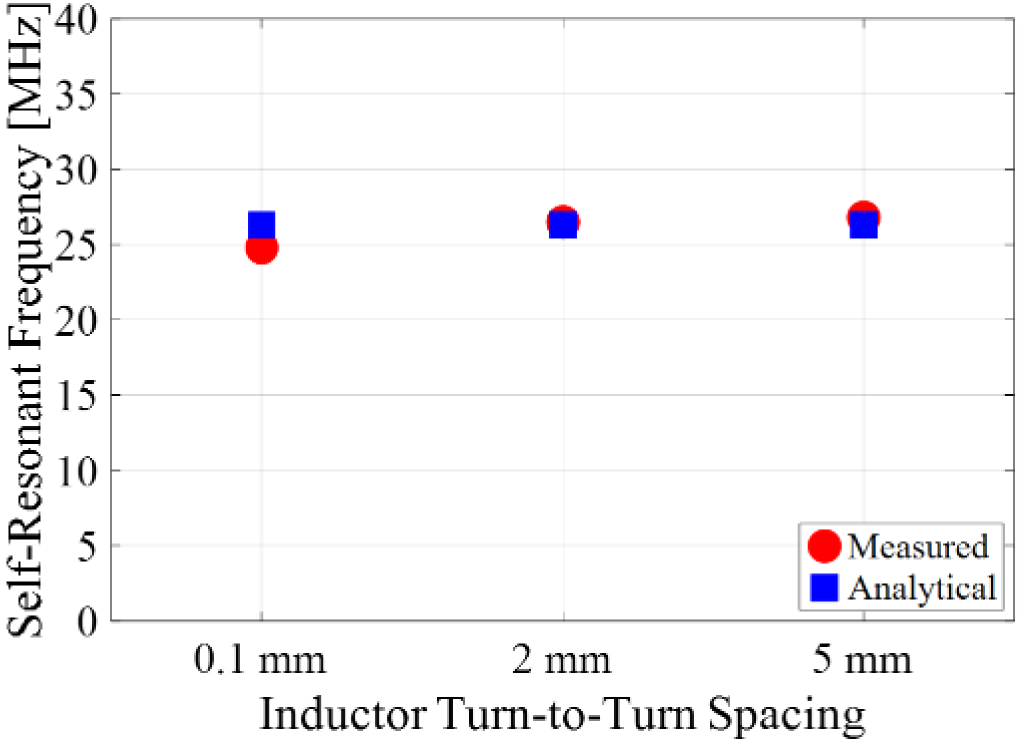


$$Q_{\mathrm{L,SR,m}} = \frac{\left(1-\left(\frac{f}{f_{\mathrm{SR}}}\right)^2\right) Q_{\mathrm{L}} - \frac{\left((1-k)^2\left(\frac{f}{f_{\mathrm{SR}}}\right)^2\right)}{Q_{\mathrm{L}}}}{1 + k\left(\frac{f}{f_{\mathrm{SR}}}\right)^4 - 2k\left(\frac{f}{f_{\mathrm{SR}}}\right)^2 + \frac{\left(k(1-k)^2\left(\frac{f}{f_{\mathrm{SR}}}\right)^4\right)}{Q_{\mathrm{L}}^2}}$$

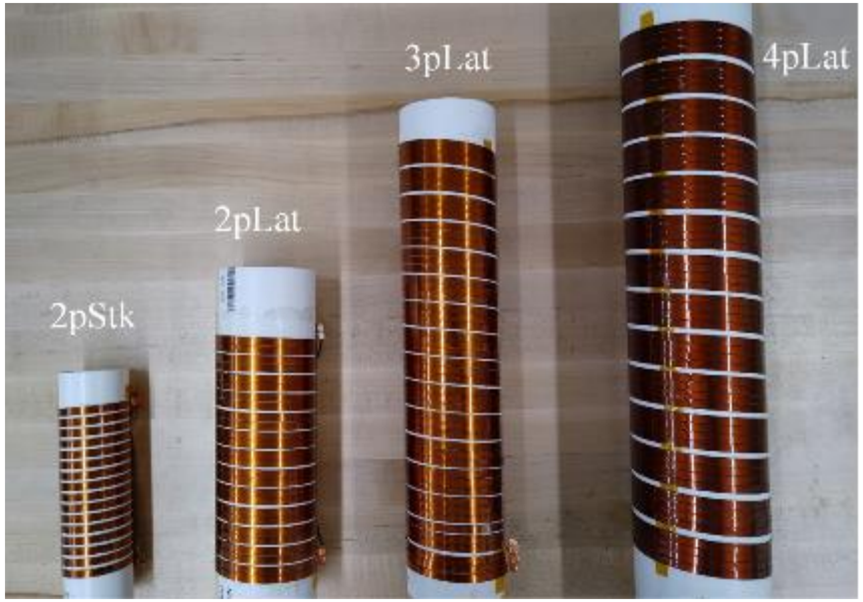


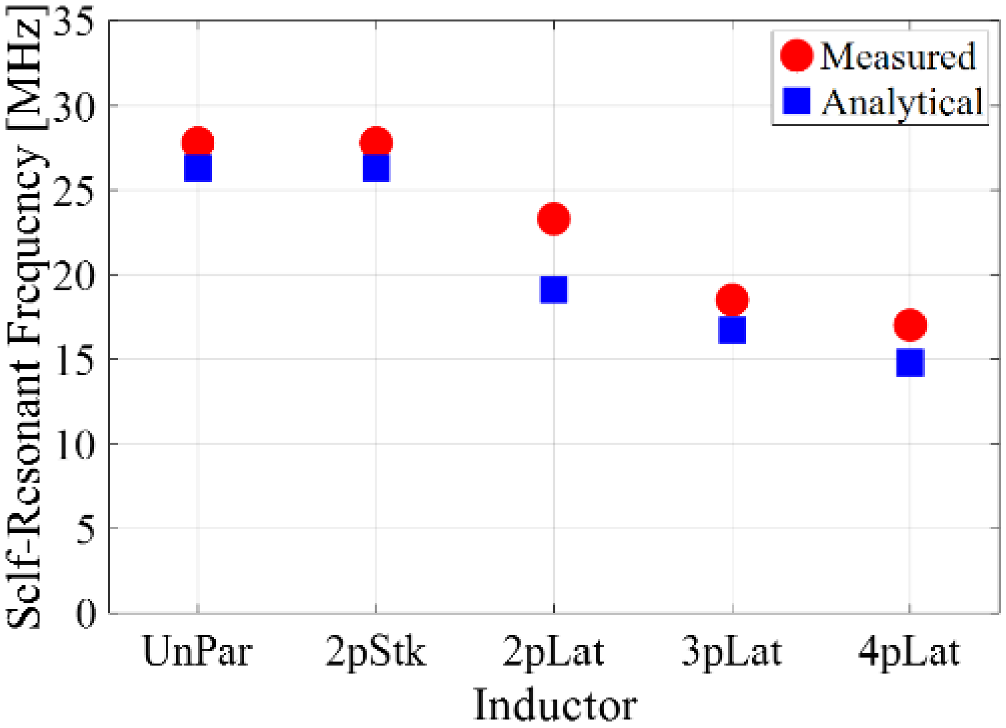
Self-Resonant Frequency Modeling





Solenoid Inductor Self-Resonant Frequency

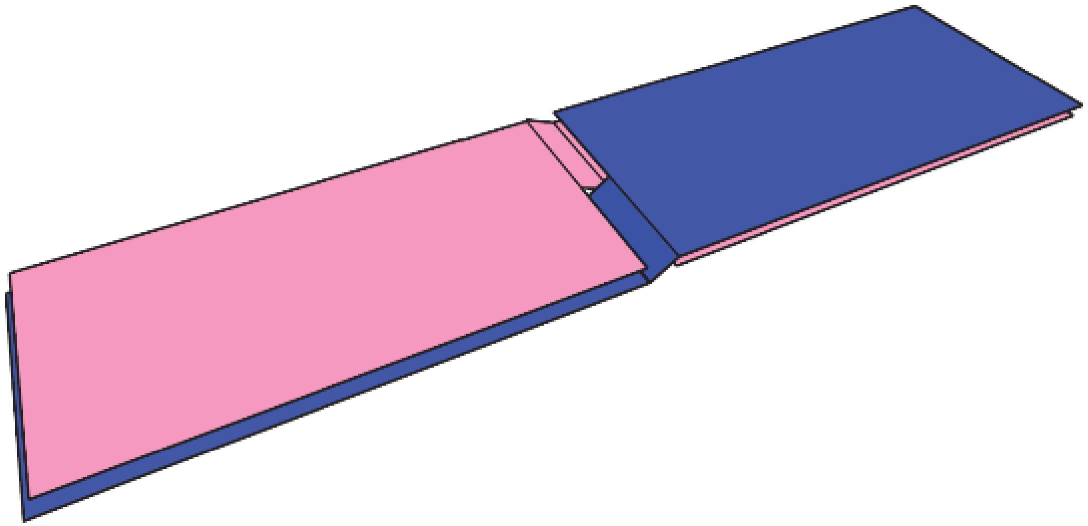




$$f_{\mathrm{SR}} = \frac{c}{4 l_{\mathrm{w}}}$$

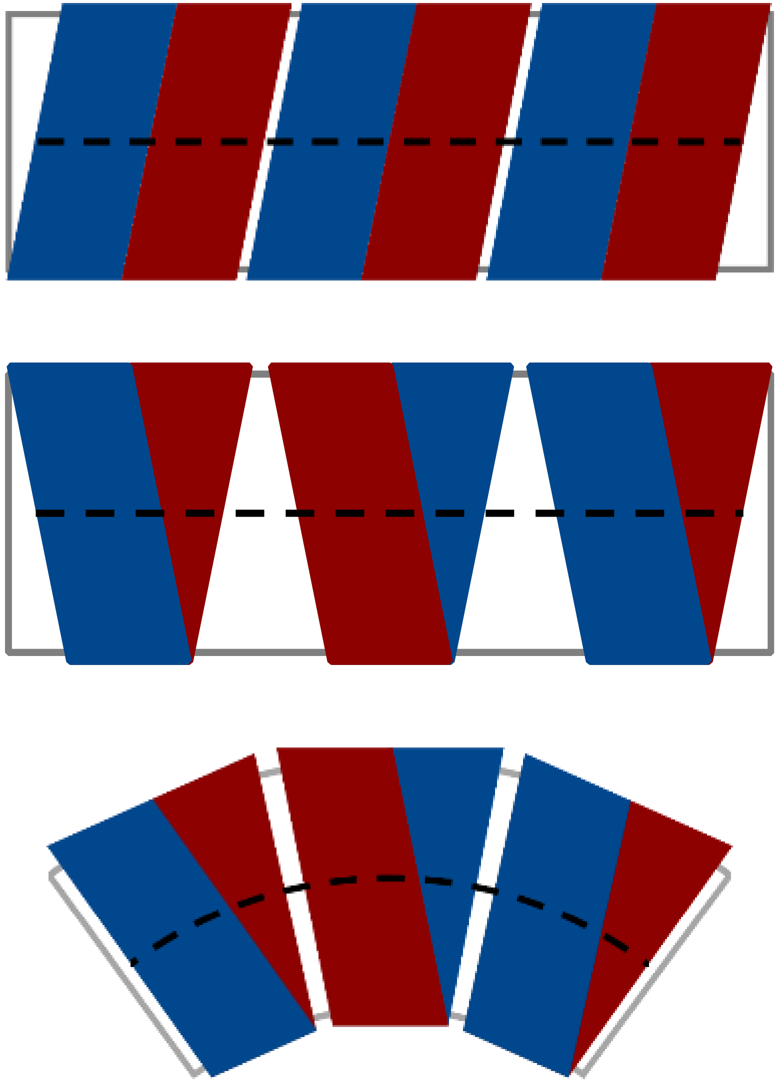
$$l_{\mathrm{w}} = N\sqrt{D^2\pi^2 + (mw + s)^2}$$

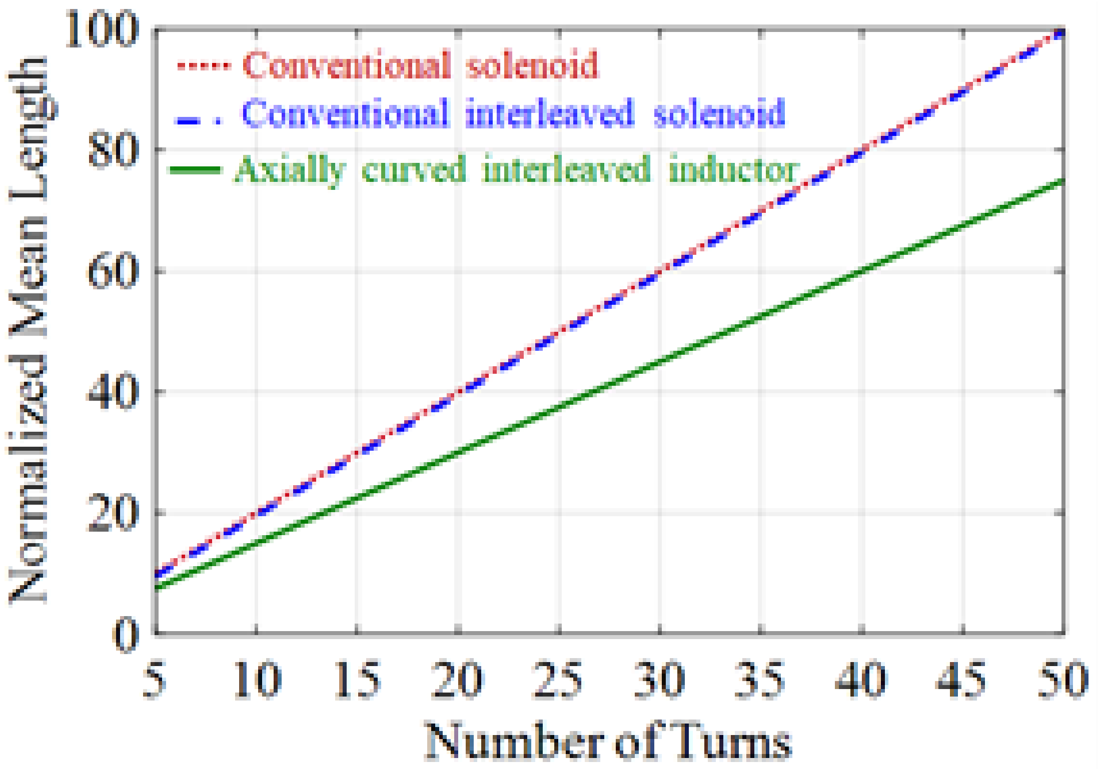
Quality Factor Improvement using Layered Foil



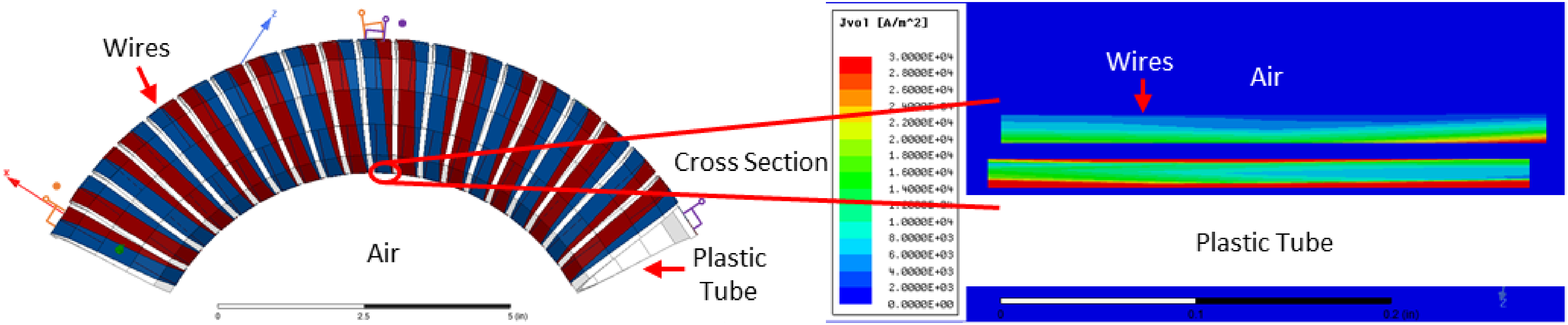
C. R. Sullivan, "Layered Foil as an Alternative to Litz Wire: Multiple Methods for Equal Current Sharing Among Layers," *Proceedings of the IEEE Workshop on Control and Modeling for Power Electronics (COMPEL)*, Santander, Spain, June 2014.

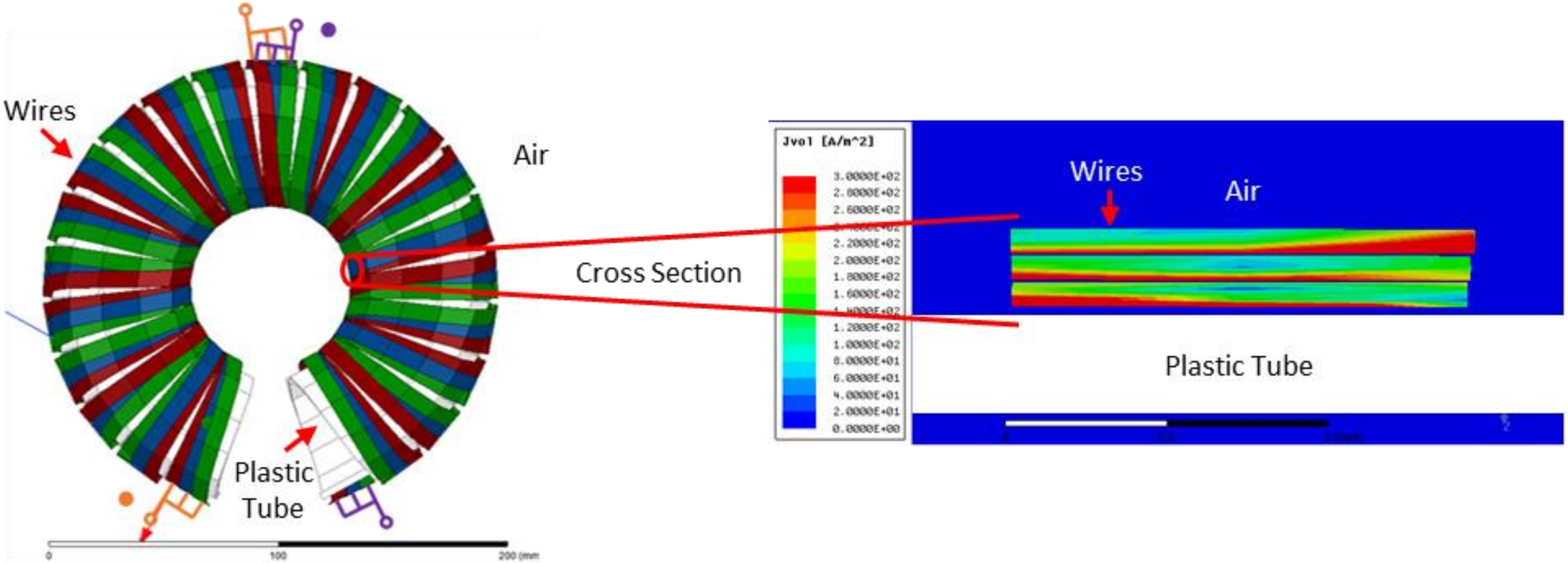
Interleaved-Foil Inductor





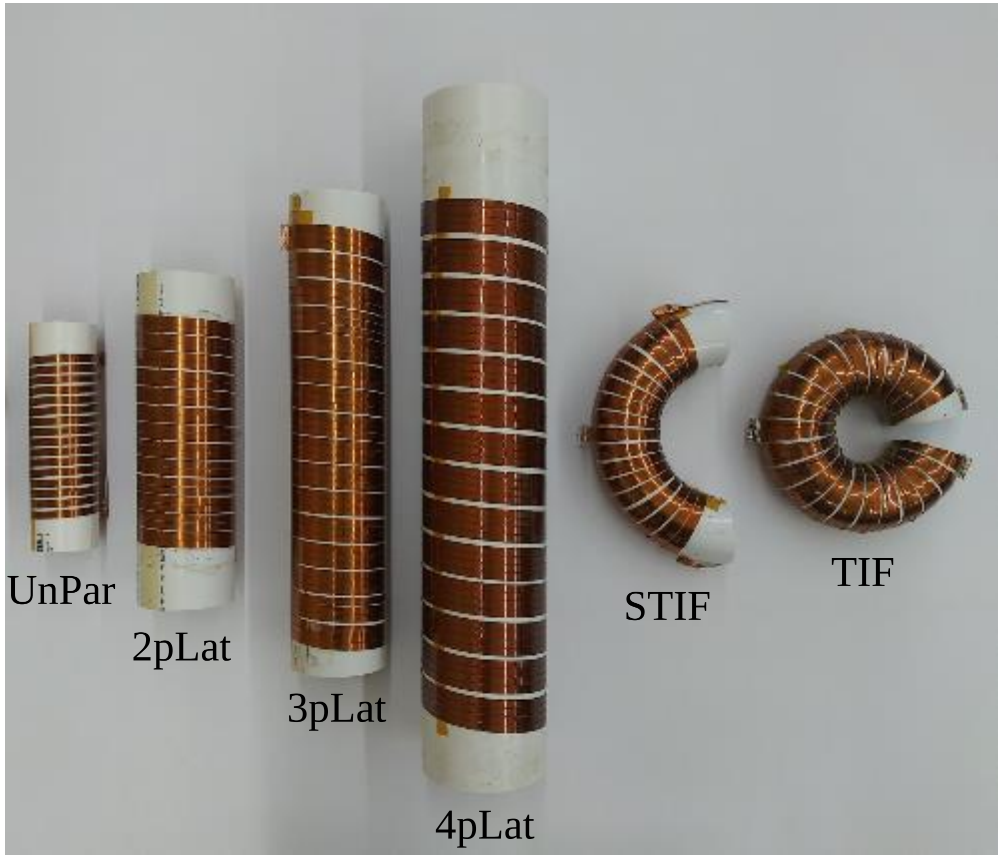
Semi-Toroidal Interleaved-Foil (STIF) Coupled Inductor

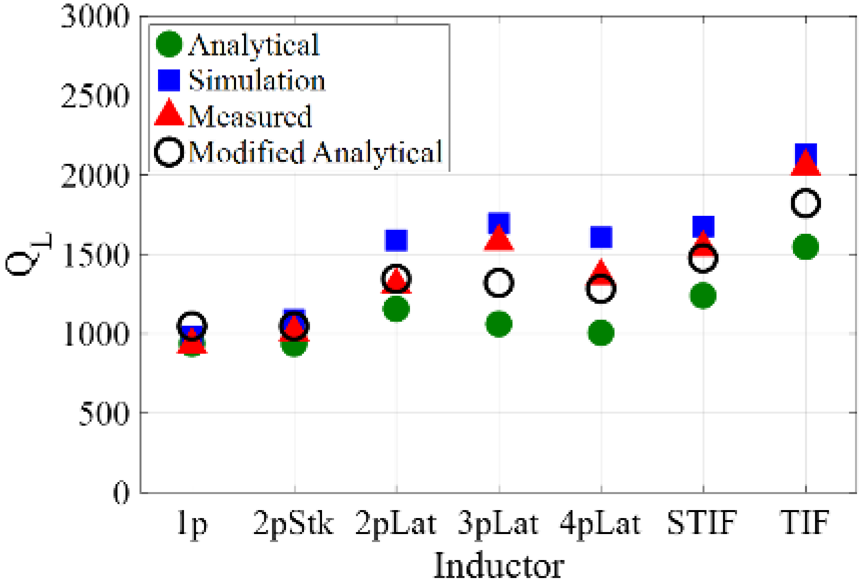


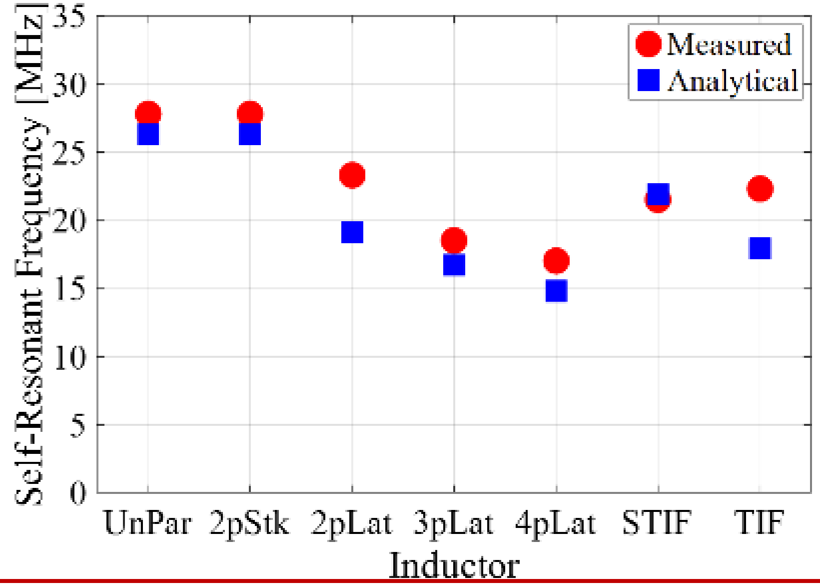


Wires
Air
Plastic
Tube
0
100
200 (mm
Cross Section
Jvol [A/m^2]
3.0000E+02
2.8000E+02
2.6000E+02
2.2000E+02
2.0000E+02
1.8000E+02
1.6000E+02
1.2000E+02
1.0000E+02
8.0000E+01
6.0000E+01
4.0000E+01
2.0000E+01
0.0000E+00
Wires
Air
Plastic Tube

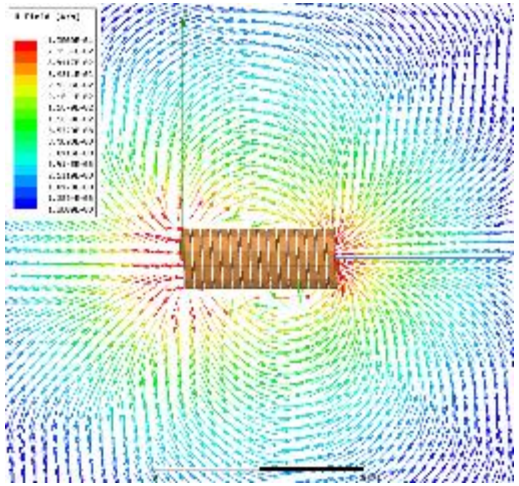
Coupled Inductor Performance Comparison



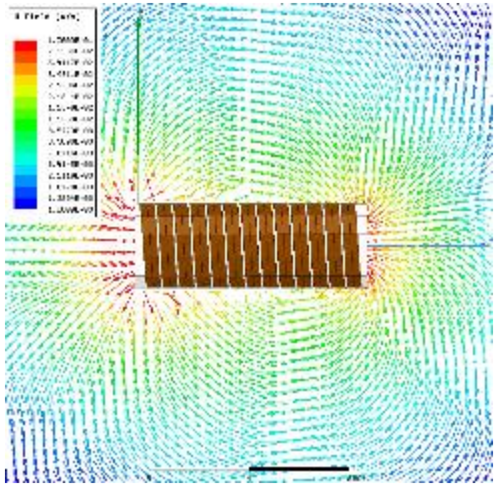




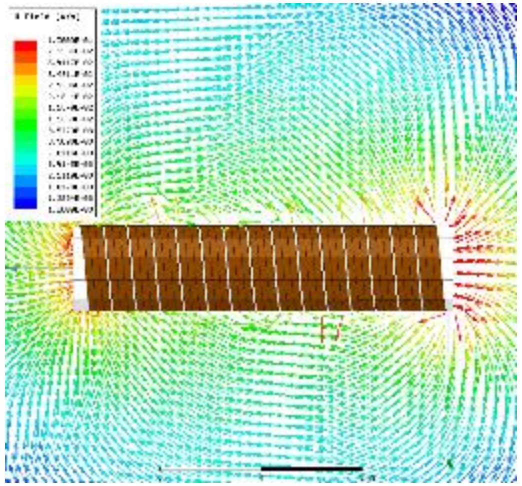
Magnetic Field Containment Comparison



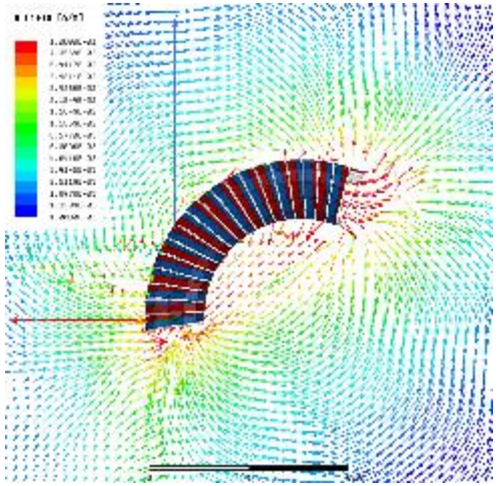
Single/
Double



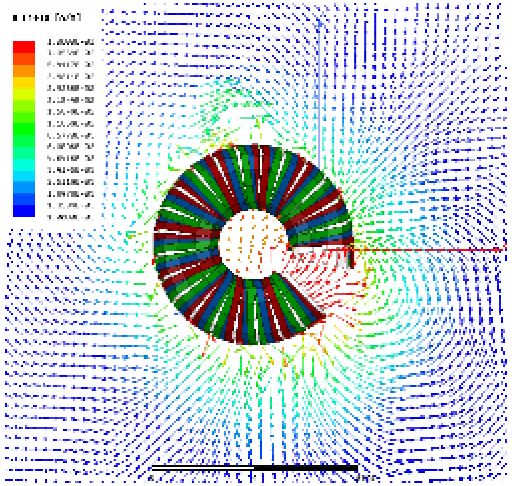
2x Wire
Parallel



3x Wire
Parallel

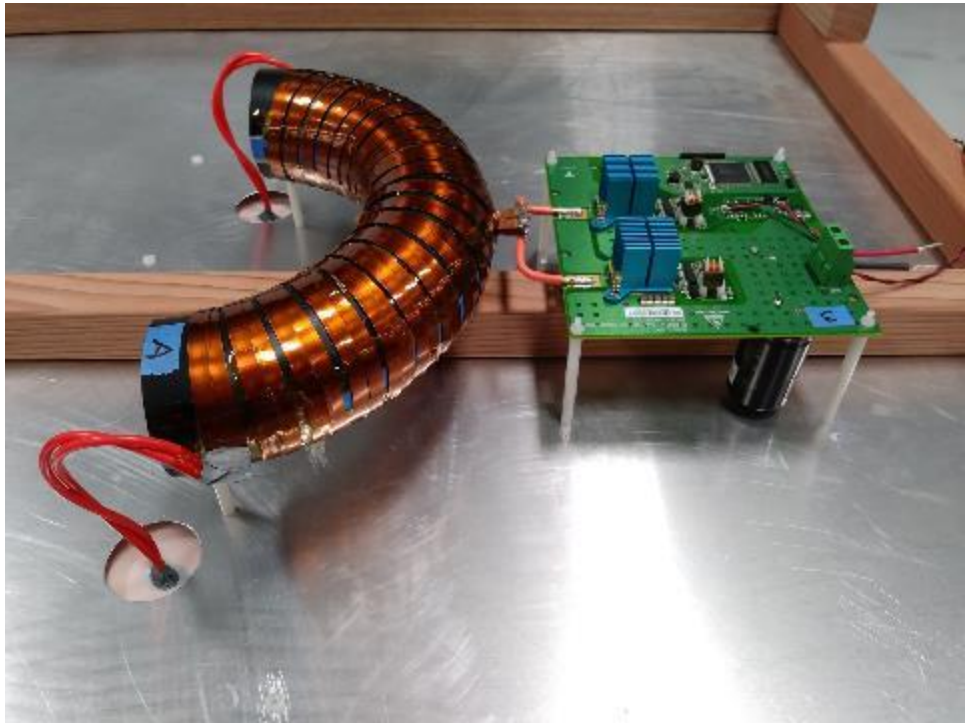


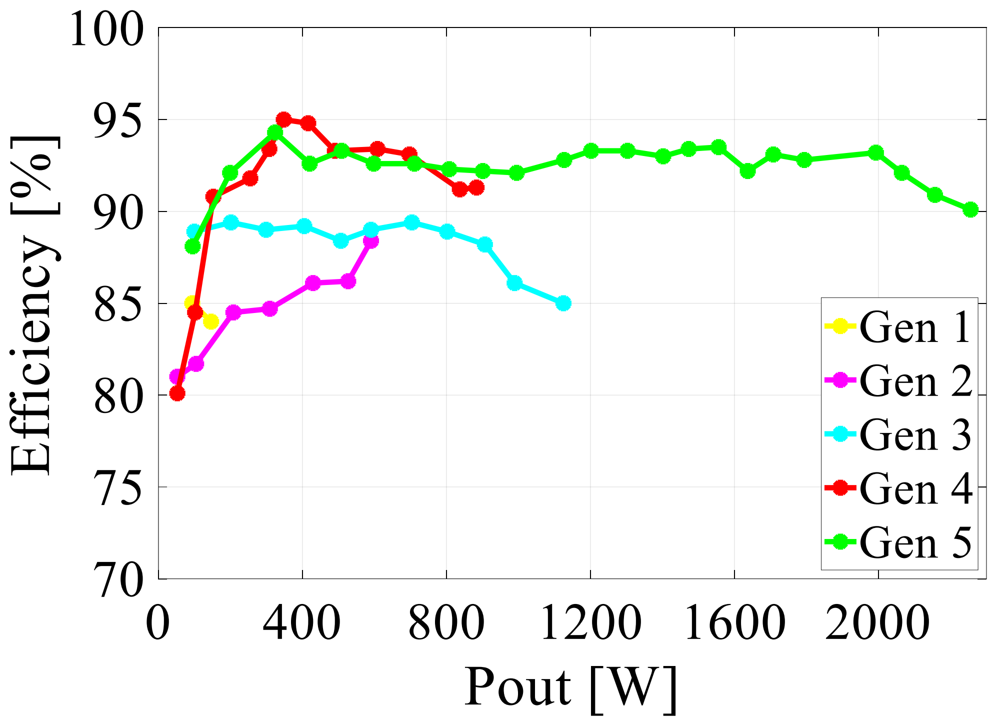
STIF



TIF

13.56-MHz STIF Inductor Based Capacitive WPT System





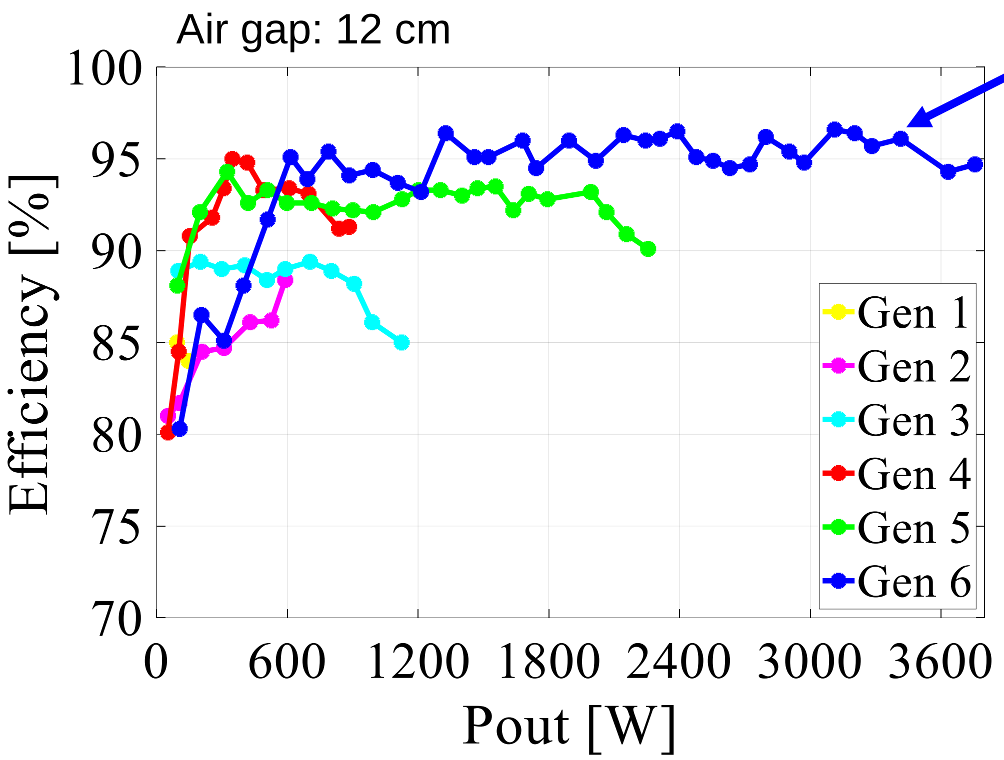
Output Power: 2256 W

Full-Power Efficiency: 91%

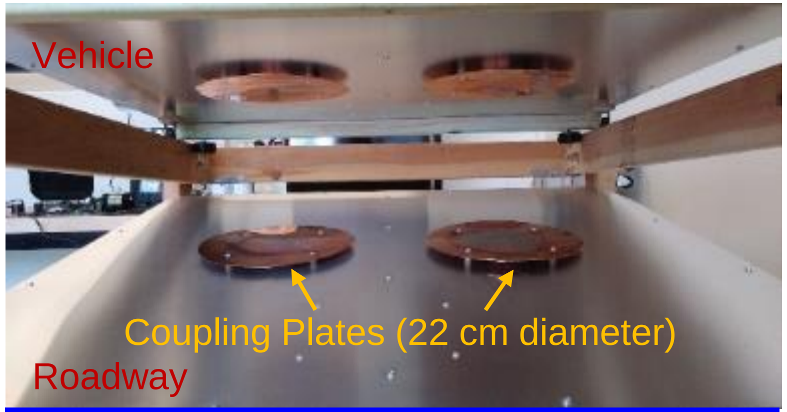
Peak Efficiency: 94%

Power Transfer Density: 29.7 kW/m^2

13.56-MHz TIF Inductor Based Capacitive WPT System



Operating frequency: 13.56 MHz

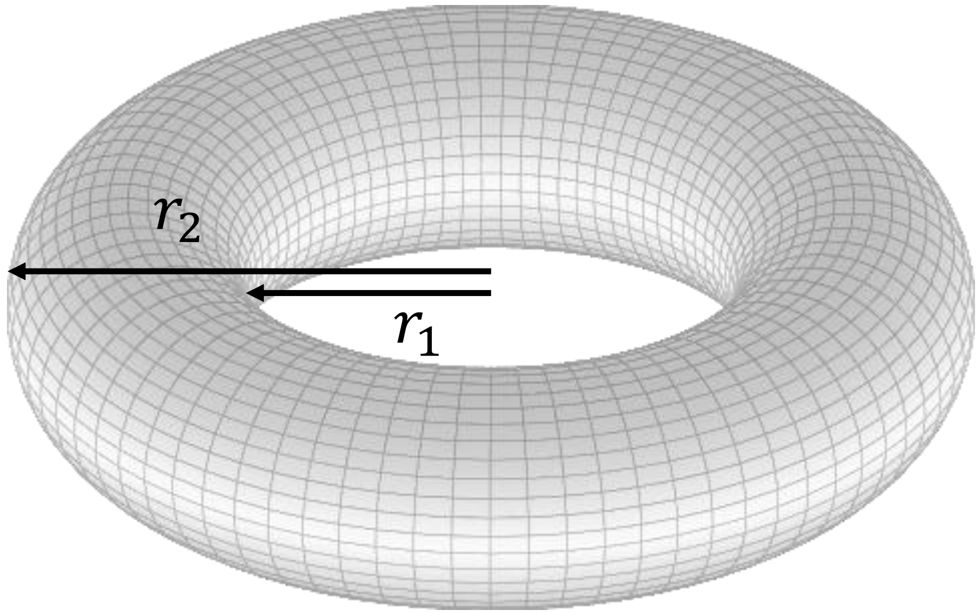


Gen-6 System

Output Power: 3756 W

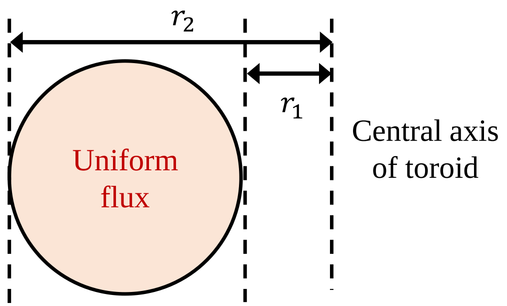
Power Transfer Density: 49.4 kW/m^2

Optimal Aspect Ratio of Air-Core Toroidal Inductor



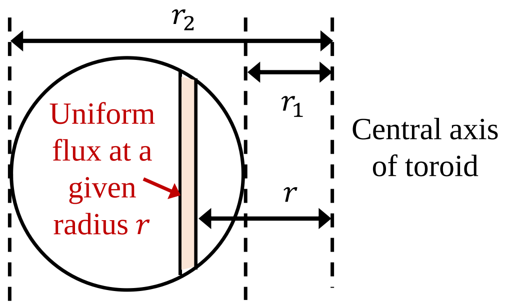
Toroidal Inductor Modeling

Analytical Method 1



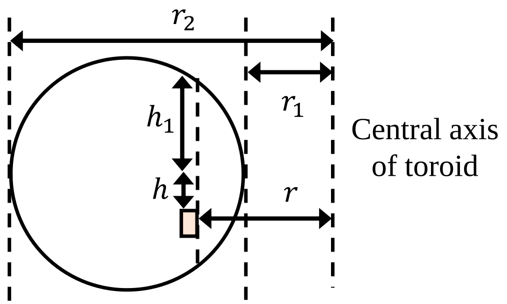
$$L = \frac{\mu_0 N^2}{4} \frac{(r_2 - r_1)^2}{(r_2 + r_1)}$$

Analytical Method 2



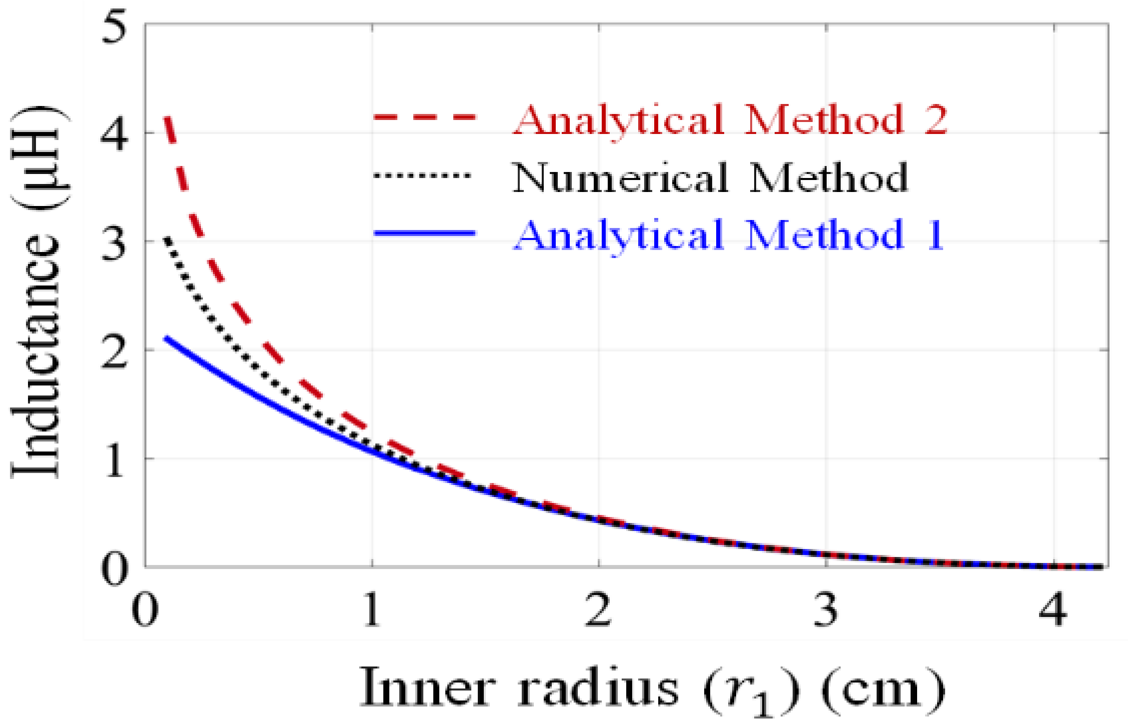
$$L = \frac{\mu_0 N^2}{8} (r_2 - r_1) \log\left(\frac{r_2}{r_1}\right)$$

Numerical Method



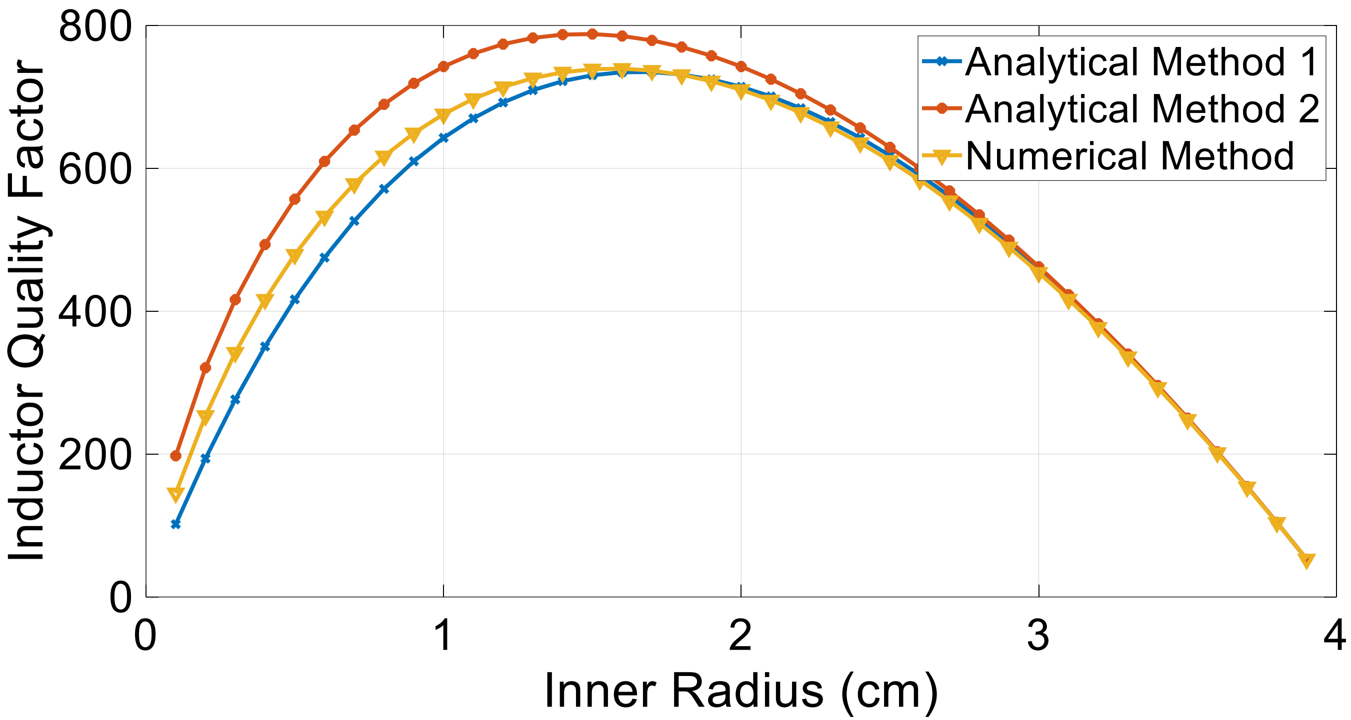
$$L = \int_{r_1}^{r_2} \int_{-h_1(r)}^{h_1(r)} \frac{\mu_0 N H(r, h)}{I} \, dh \, dr$$

Comparison of Inductance Models



- Numerical method value is bounded by analytical method values
- Inductance values from both analytical methods match well with numerical method value when inner radius is large

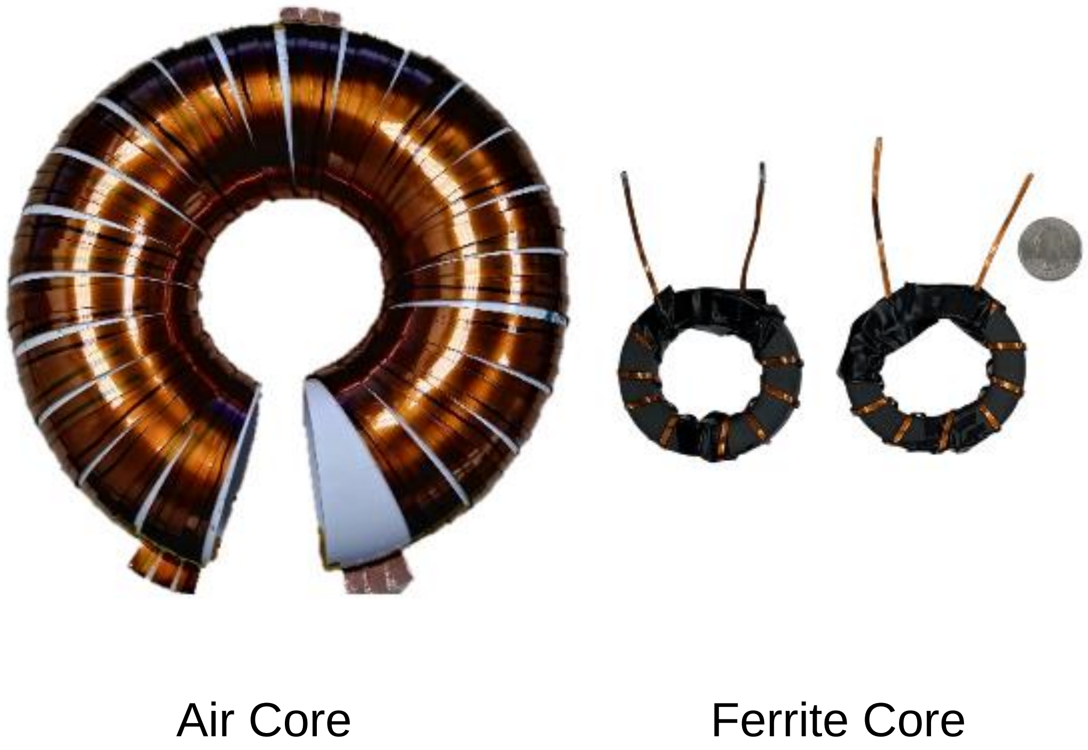
Optimal Ratio of Outer to Inner Radius

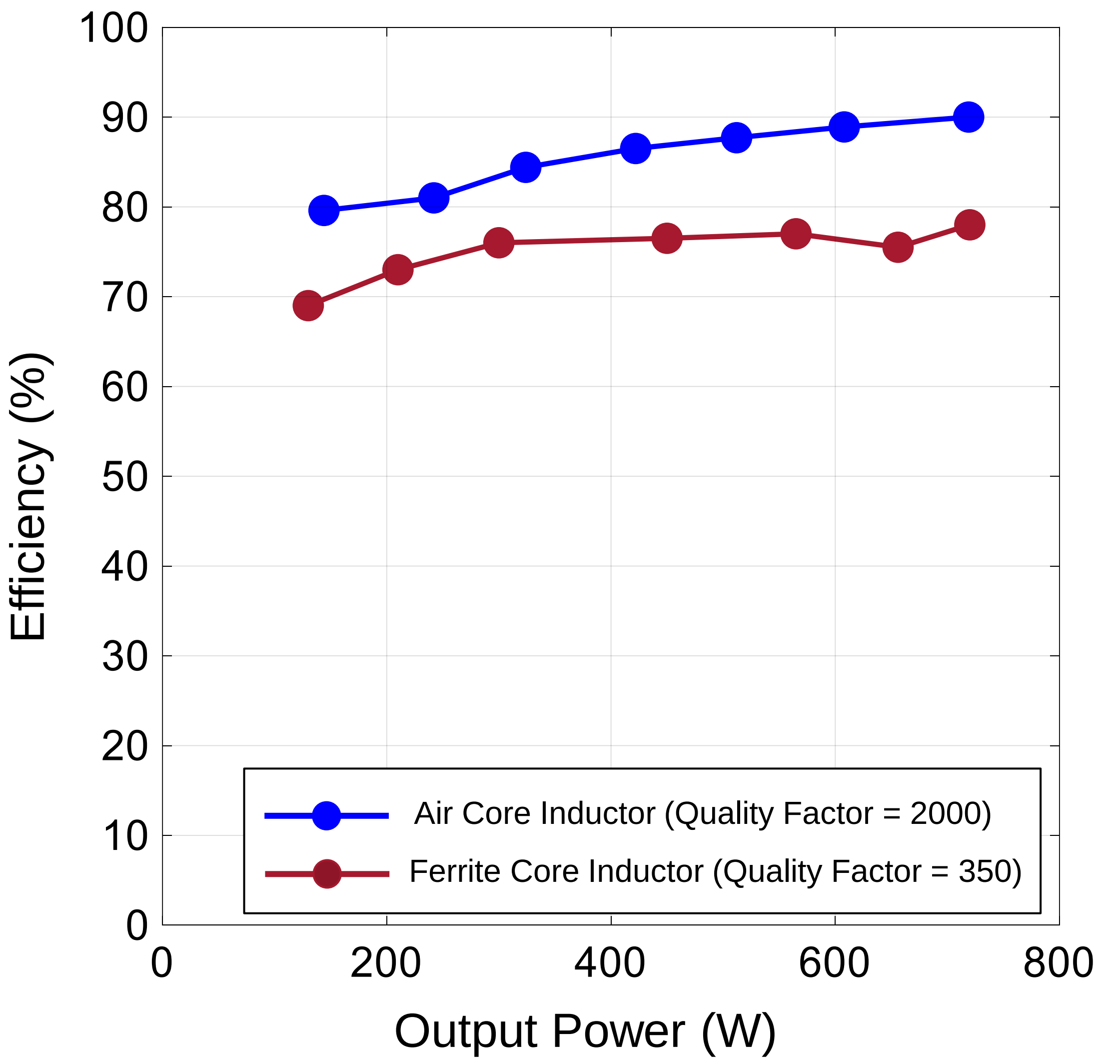


Optimal ratio of outer to inner radius maximizes quality factor is bounded by:

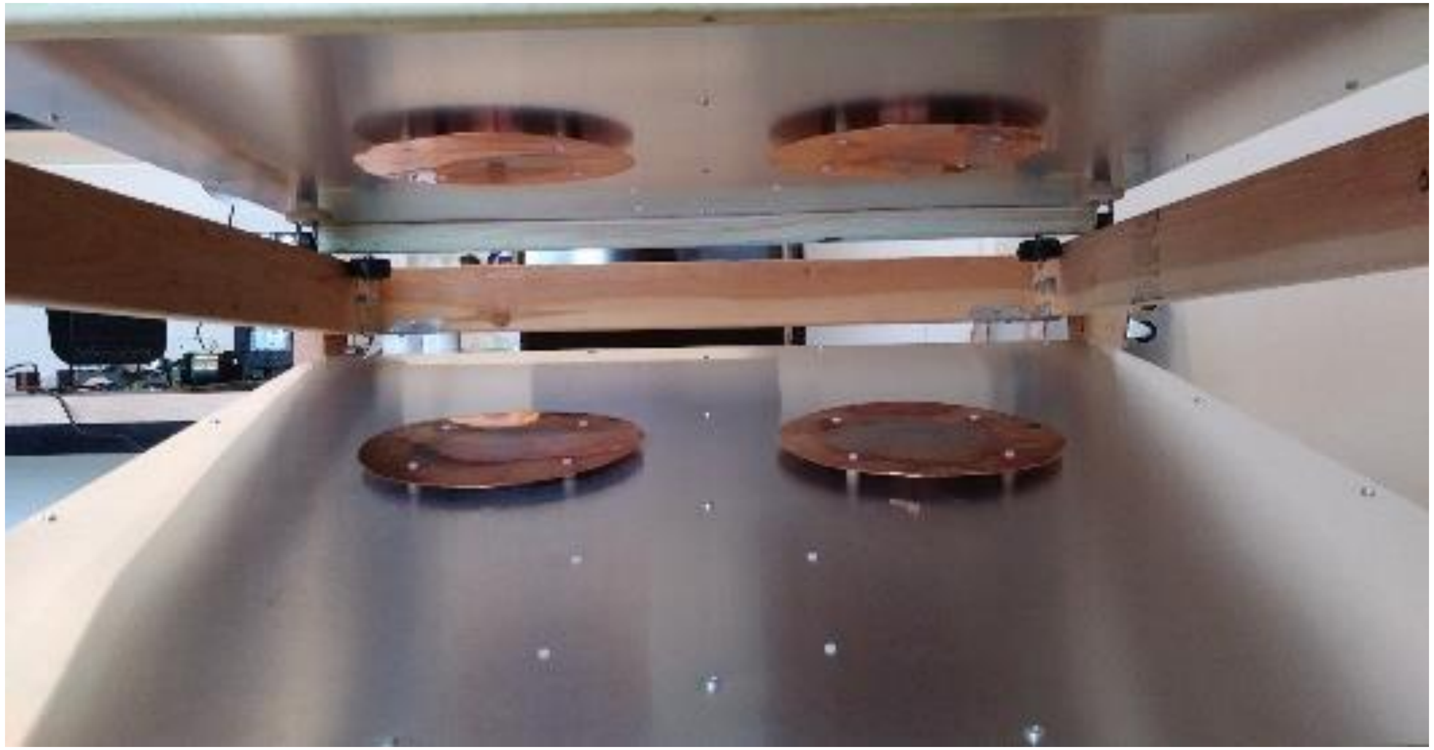
$$1+\sqrt{2} < \frac{r_2}{r_1} < e$$

Potential for Further Improvements





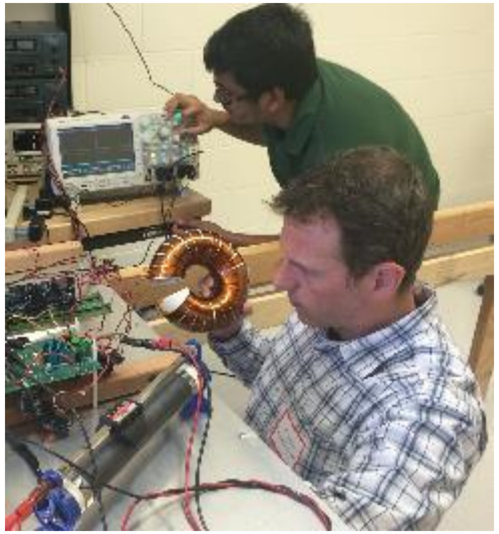
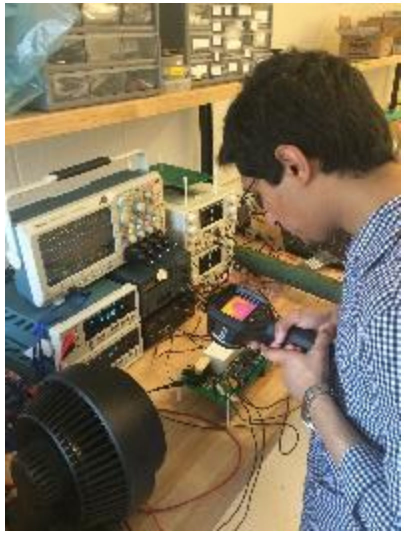
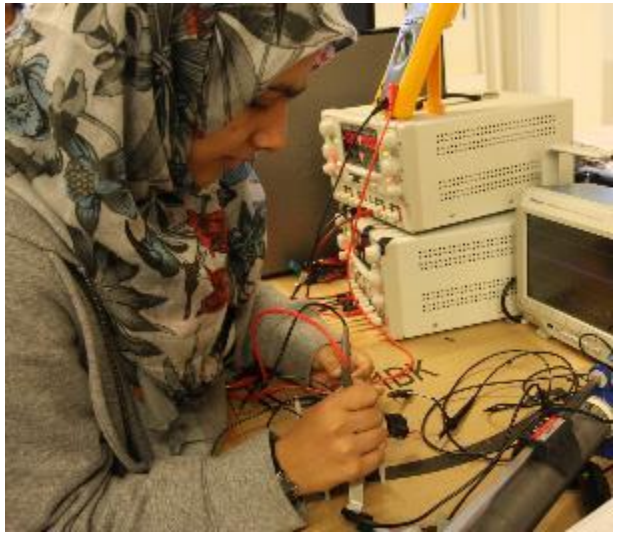
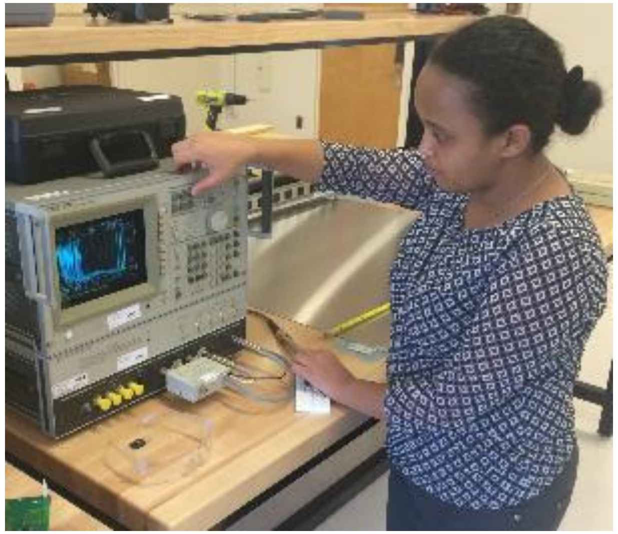
Summary and Conclusions



Plug-in Charging

Dynamic Wireless Charging

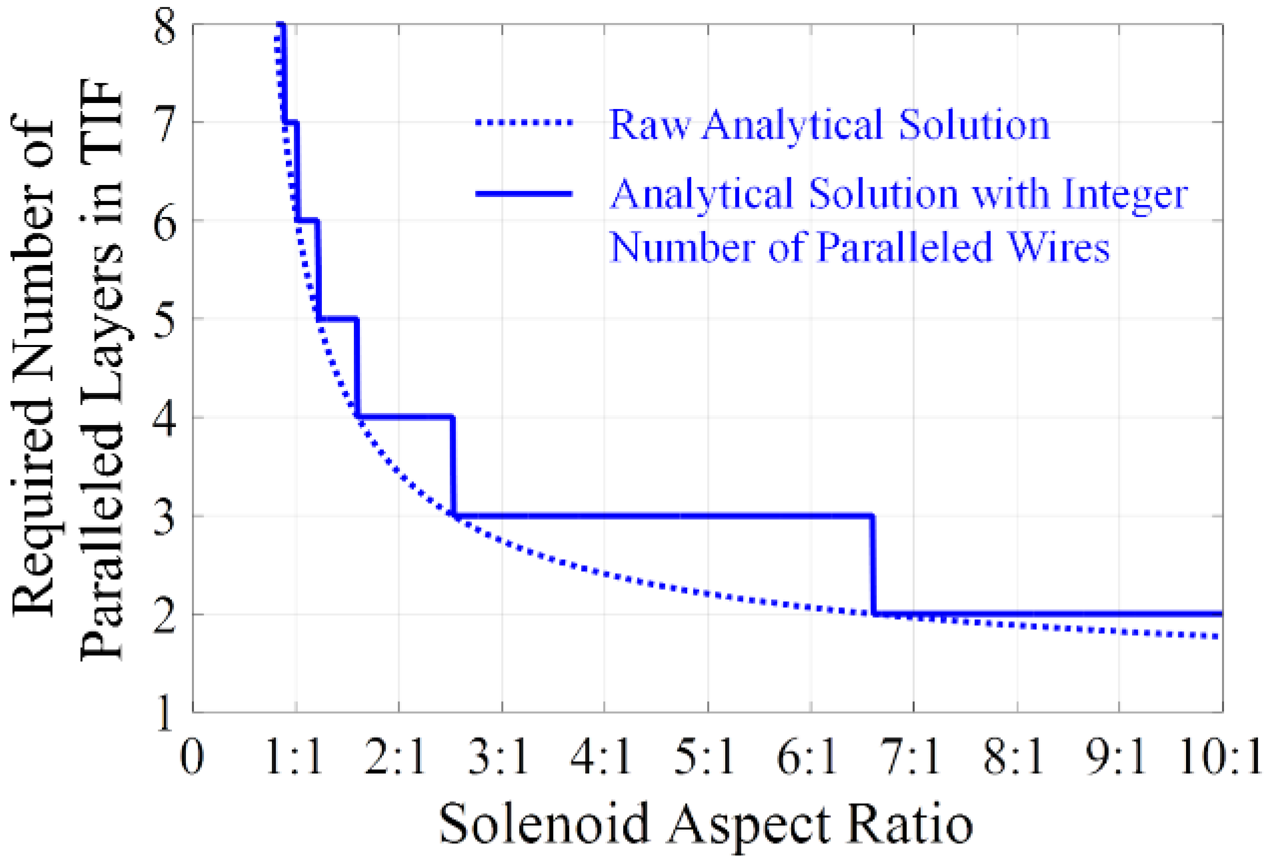
Cornell High Frequency Power Electronics Group

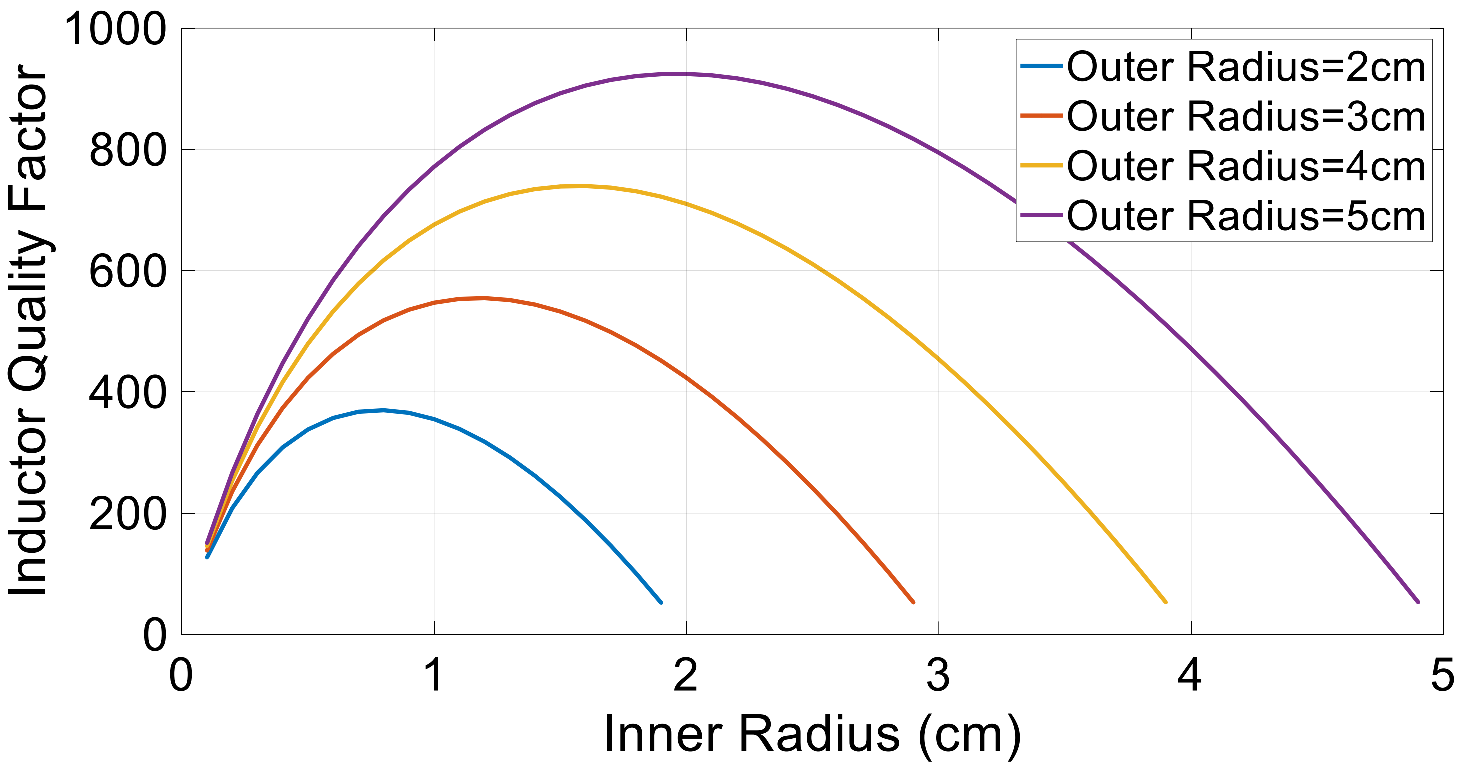

Q & A

Quality Factor Comparison Between TIF and Solenoid

Minimum Number of Paralleled Wires needed in TIF Inductor for its Quality Factor to Exceed that of a Solenoidal Inductor of Same Volume



Optimal Ratio of Outer to Inner Radius



- Computed using numerical method
- Sweet spot exits for any outer radius