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Modeling, Simulation and Verification of Contactless Power Transfer Systems

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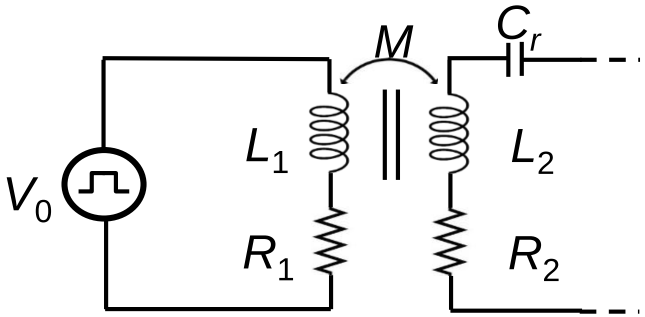
Components and operating principle

- Primary coil
- Secondary coil
- Flux concentrators
- Lenz-Faraday
- Inductive coupling

Basic schematic

- Inverter → AC voltage → AC current
- Loosely coupled transformer
- Receiver circuit (resonance capacitor, rectifier and load)

L: Coil inductance
R: Coil resistance
M: Mutual inductance
C_r : Resonant capacitor



Definitions

- Induction efficiency:

$$\eta = \frac{\text{Transmitted power}}{\text{Total power}}$$

- Quality factor:

$$Q_1 = \frac{\omega_0 L_1}{R_1},\ Q_2 = \frac{\omega_0 L_2}{R_2}, \qquad Q = \sqrt{Q_1 Q_2}$$

- Coupling factor:

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

- Maximum efficiency [1]:

$$\eta_{max} = \frac{1}{1 + \frac{2}{(kQ)^2}\left(1 + \sqrt{1 + (kQ)^2}\right)}$$

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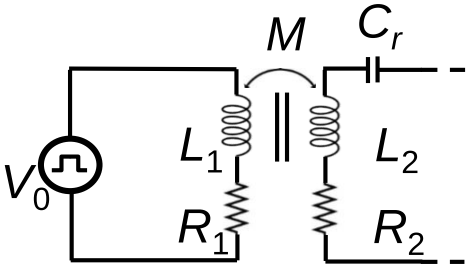
[1] G. Vandevoorde and R. Puers, “Wireless energy transfer for stand-alone systems: a comparison between low and high power applicability,” Sensors and Actuators.

Figures of Merit

- $kQ\uparrow \quad \Leftrightarrow \quad \eta_{max}\uparrow$



- $$kQ = \frac{M}{\sqrt{L_1 L_2}}\sqrt{\frac{(\omega_0 L_1)(\omega_0 L_2)}{R_1 R_2}}.$$

- <u>Objective:</u>

  Accurately predict the values of R_1 , R_2 , L_1 , L_2 and M.

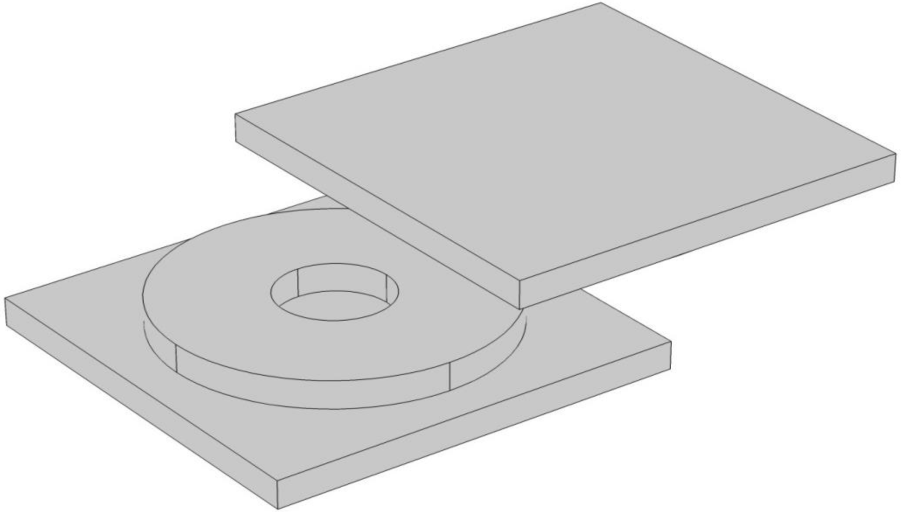
Simulation in COMSOL

- AC/DC module - Magnetic Fields
- Frequency domain
- 2D Axisymmetric simulation if coils are aligned (same revolution axis)
- 3D simulation if coils are misaligned

  (different revolution axes)

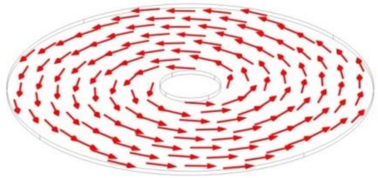
Geometry and materials

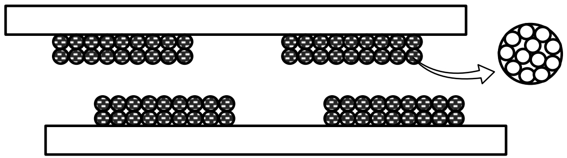
- Ring-type inductors.
  - Ideal non-lossy material ($\sigma \approx 0$ S/m, $\mu = 1$)
- Ferrite blocks
  - $\sigma \approx 0$ S/m, $\mu = 2000$

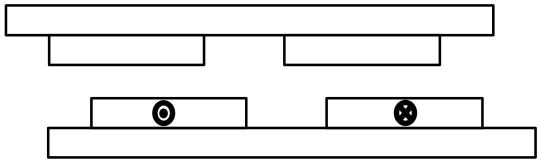


Physics – AC/DC Magnetic Fields

- Primary coil: External current density
  - Assuming multi-stranded Litz wire the current across the inductor's cross-section can be assumed constant.







Induced voltage calculation

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- $$V(\omega) = -\oint \vec{\mathbf{E}}(\omega)\cdot\vec{dl} = -\frac{1}{S_{\text{turn}}}\int_{V_{\text{coil}}} E_{\varphi}(\omega)\,dV$$

- Advisable to work in 2 physics:

- <u>mf1</u>
  - Set 1 A in coil 1
  - Obtain V in both coils

- <u>mf2</u>
  - Set 1 A in coil 2
  - Obtain V in both coils

Inductance calculation

- $Z(\omega) = \dfrac{V(\omega)}{I(\omega)}$
- $L(\omega) = \dfrac{\Im\left(Z(\omega)\right)}{\omega}$

- <u>mf1</u>

$$L_1(\omega) = \frac{\Im\left(V_1(\omega)/I_1(\omega)\right)}{\omega}$$

$$M(\omega) = \frac{\Im\left(V_2(\omega)/I_1(\omega)\right)}{\omega}$$

- <u>mf2</u>

$$L_2(\omega) = \frac{\Im\left(V_2(\omega)/I_2(\omega)\right)}{\omega}$$

$$M(\omega) = \frac{\Im\left(V_1(\omega)/I_2(\omega)\right)}{\omega}$$

Resistance calculation

- Resistance of Litz wire: $R_w = R_{cond} + R_{prox}$
  - Dc and skin effect losses: R_{cond}
    - Caused by the current driven when applying an external voltage
  - Proximity effect: R_{prox}
    - Caused by the current induced by neighboring conductors

Resistance calculation

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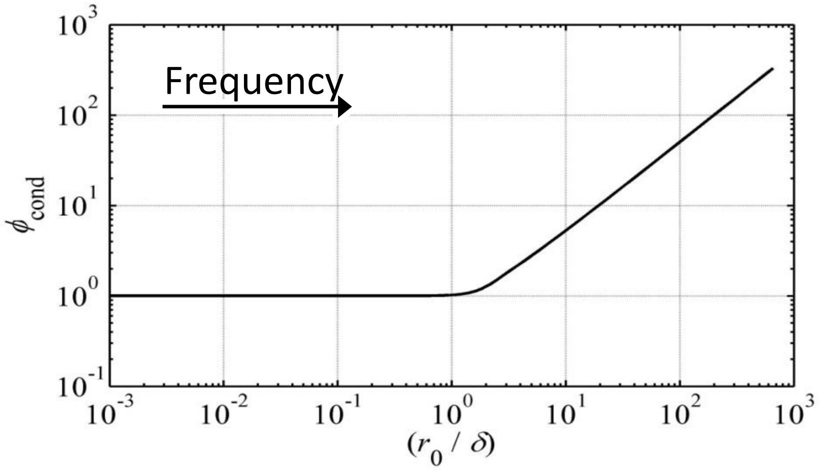
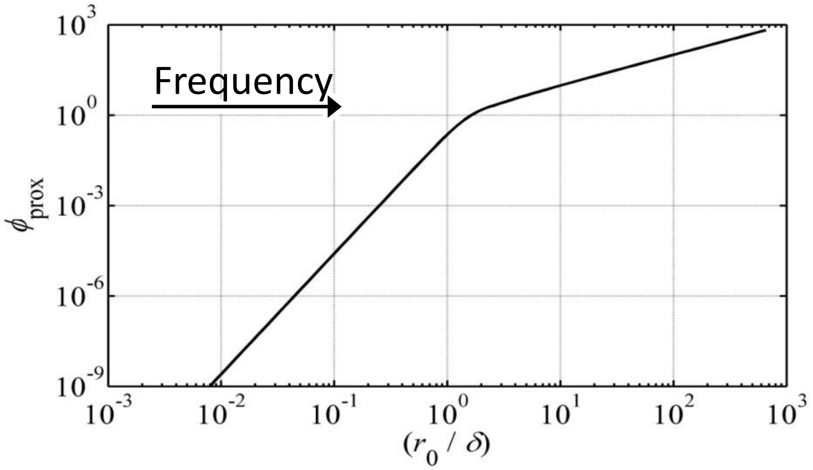
- $R_{cond} = \frac{n l_{avg}}{n_s \pi r_0^2 \sigma} \Phi_{cond}(r_0/\delta)$ [2]
- $R_{prox} = \frac{n^3 n_s 4\pi}{\sigma} \Phi_{prox}(r_0/\delta) \left\langle \left| \overline{H}_t \right|^2 \right\rangle_{coil}$ [2]





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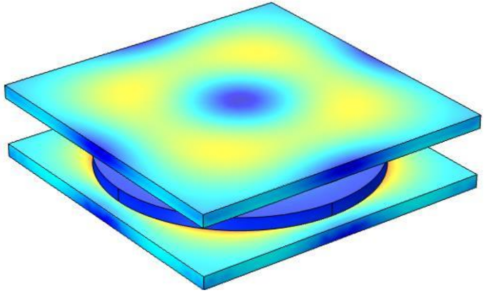
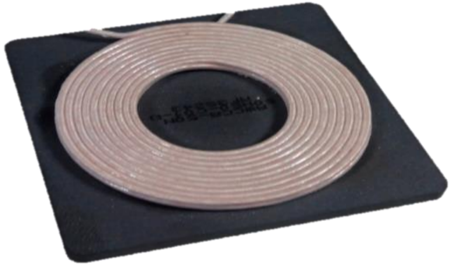
[2] C. Carretero et. Al. TM-TE decomposition of power losses in multistranded litz-wires used in electronic devices," Progress In Electromagnetics Research, December 2012.

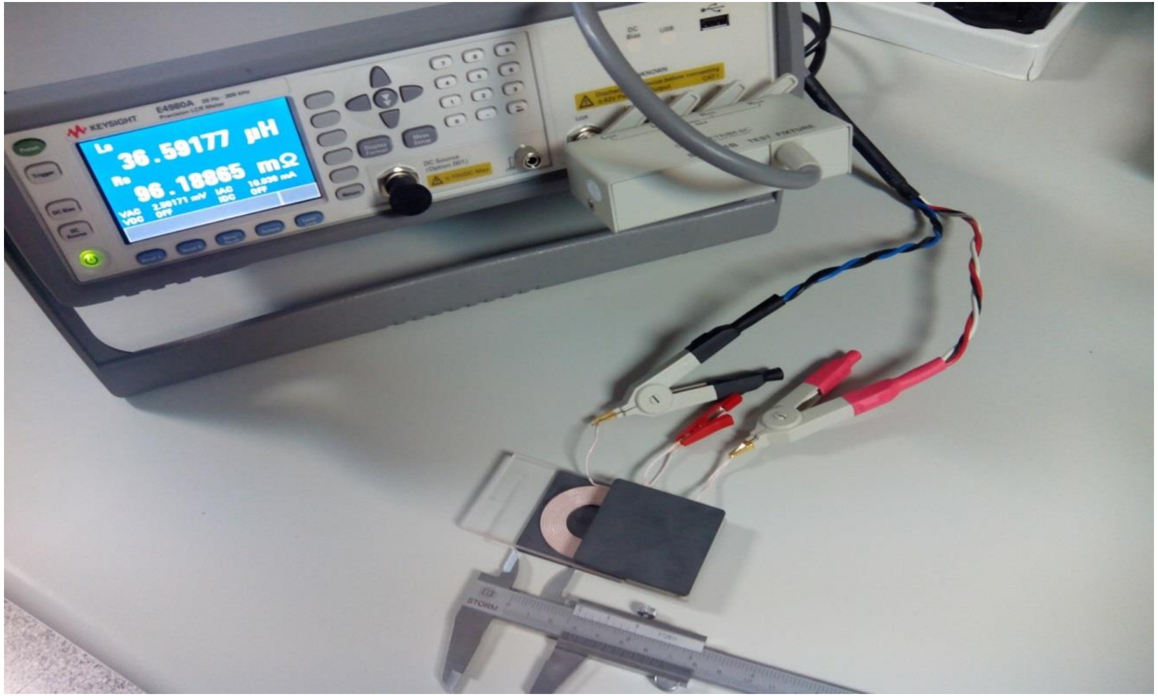
Experimental verification

- 2 identic coils: $R_1 = R_2$ and $L_1 = L_2$
- 20 turns of 105 strands (Ø 80um)
- Ext. radius: 22 mm - Int. radius: 10.12 mm.
- Coil separation: 4 mm.

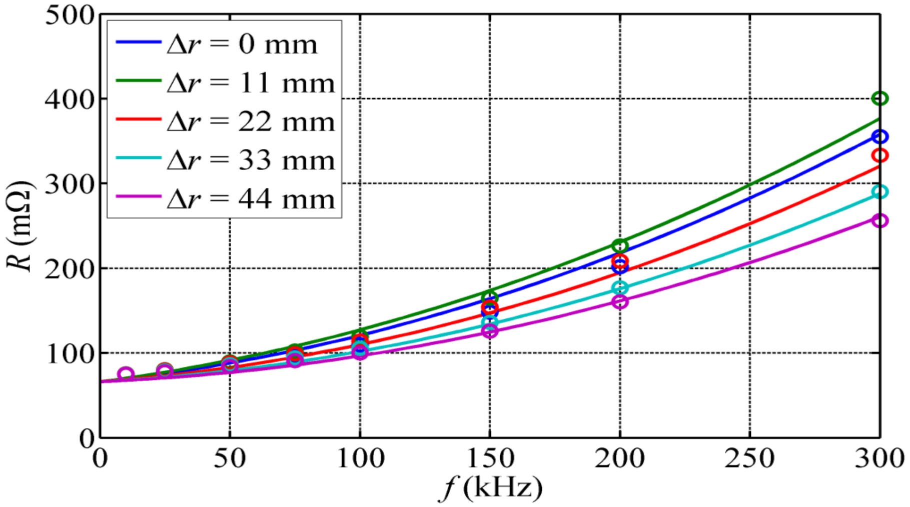


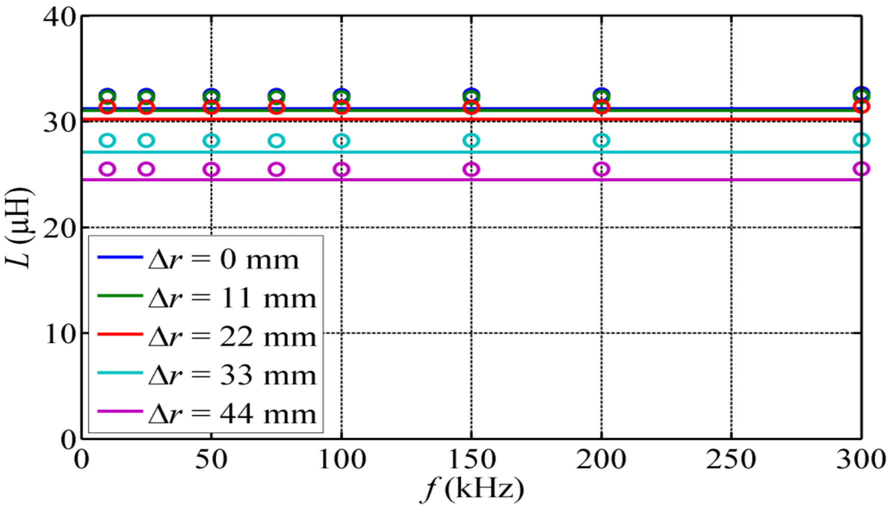


Experimental verification



Experimental verification





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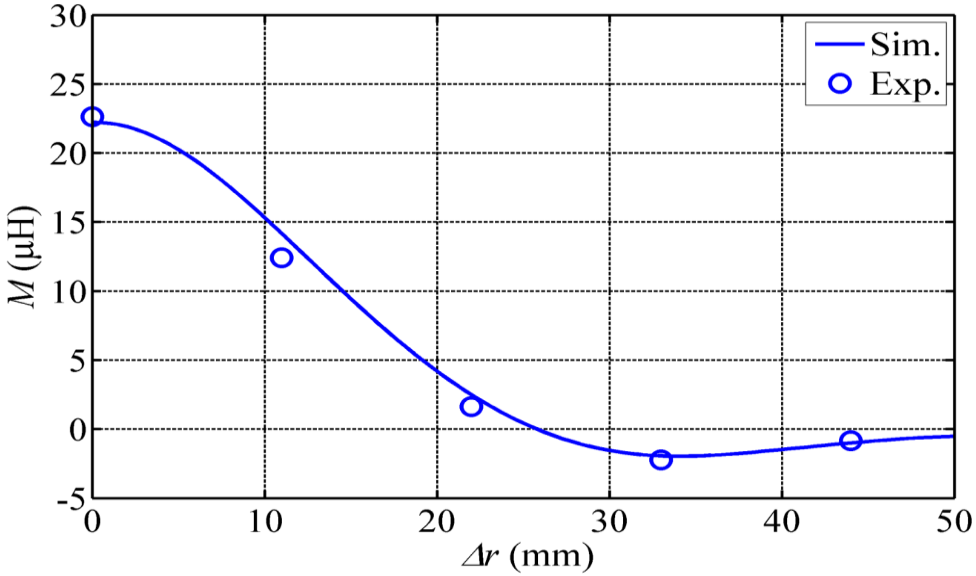

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Conclusions

- Accurate results with low computational cost (cabling structure is not simulated).
- Flexible and versatile:
  - Multi-coil WPT systems
  - Different cabling structures
    - solid wire, litz wire, PCB tracks…
  - Induction heating

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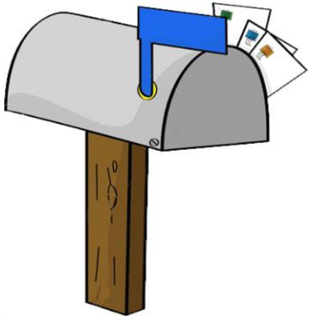
Thanks for your attention!



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