Combined Inductor and Transformer Design for Resonant Converters

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APEC 2020 Industry Session

Agenda

- Isolated resonant converter design
  - Types of resonant tank combinations
- Example designs for resonant LLC
  - Low turns ratio
  - High turns ratio
- Characterization of designs
  - Small signal measurements
  - Power testing
- Comparison of results
- Summary

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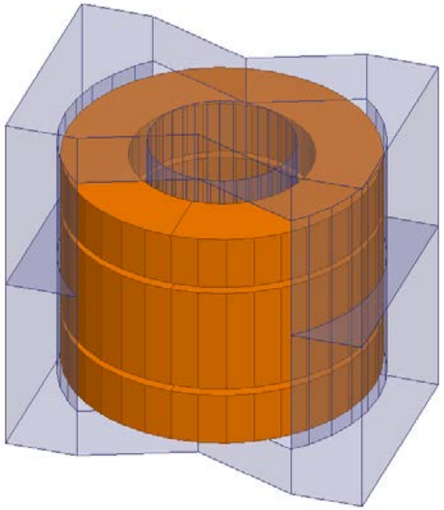
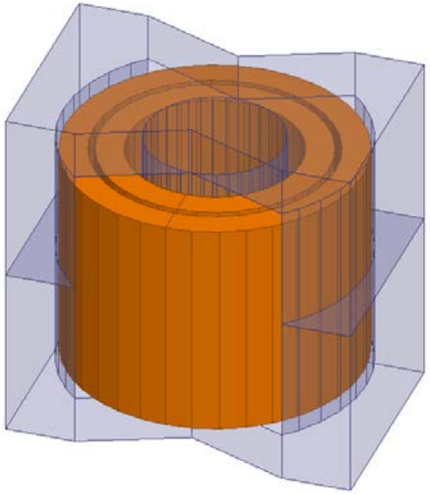
Motivation

- High-efficiency power converters
  - Isolation between energy storage systems
- Considerations for design optimization:
  - Application
  - Packaging constraints
  - Electrical specifications
  - Cost
  - Efficiency
- Challenge: Resonant transformer design
- Goal:

Optimize resonant tank design



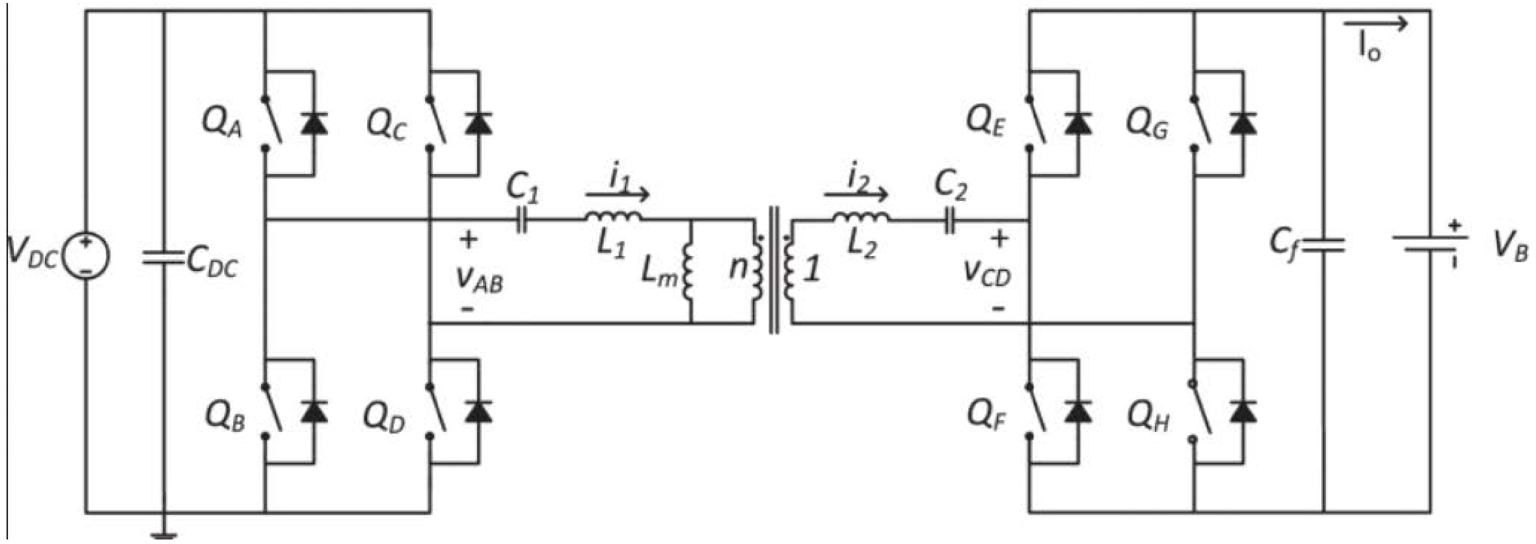


Resonant Converters

- International Electrotechnical Commission definition:
  - Resonant converter:
    - converter using (a) resonant circuit(s) to provide commutation or to reduce switching losses
- Today's design examples:
  - Full bridge LLC dc-dc converter
    - P = 3.3 kW
    - V_{in} = 400 V
    - V_{out} = 250-450 V
  - Half-bridge LLC dc-dc converter
    - P = 500 W
    - V_{in} = 400 V
    - V_{out} = 12 V

Design Example: Low turns ratio

- Bi-directional 3.3 kW resonant CLLLC



Parameter	Value	Units
Turns ratio P:S	2:1	-
Power level	3.3	kW
Primary peak current	16	A
Frequency	250	kHz
Skin depth at 250 kHz	0.14	mm
Packing factor	0.35	-
Maximum allowable flux density	125	mT

Image: Special Section on Battery Energy Storage and Management, “Modeling and Controller Design of a Bidirectional Resonant Converter Battery Charger”, Zakariya M. Dalala, Zaka Ullah Zahid, Osama S. Saadeh, Jih-Sheng Lai

Design Example: High turns ratio

- Uni-directional 500 W half bridge LLC

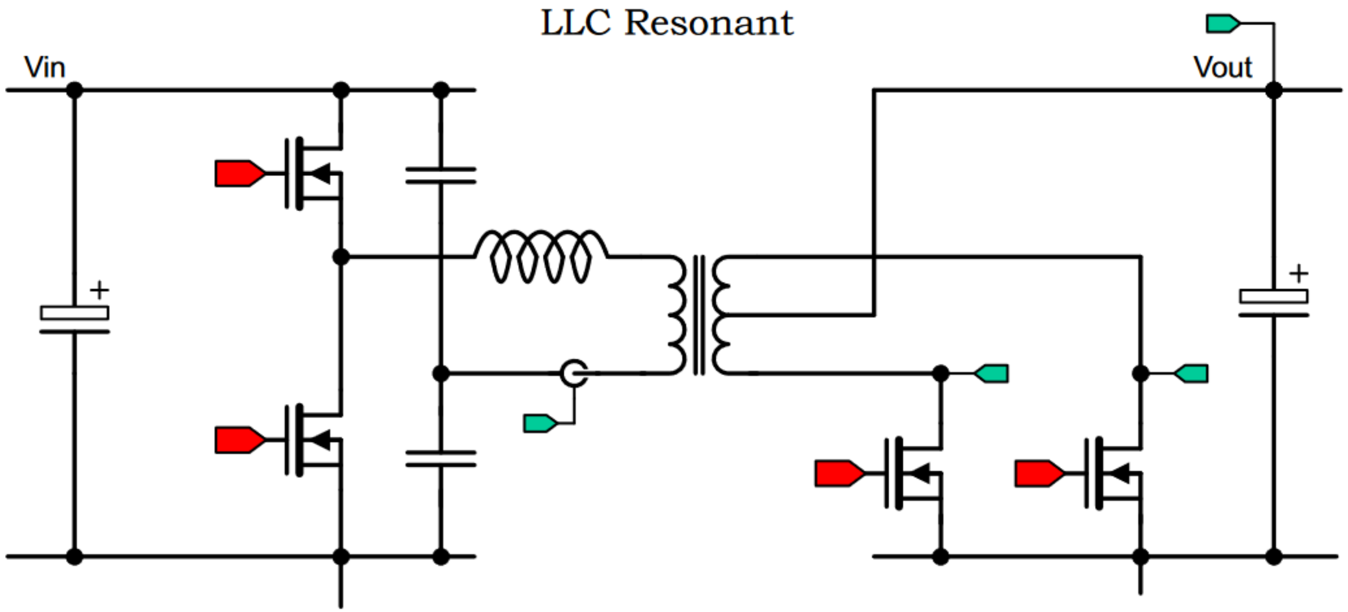


Figure 2. TMDSHVRESLLCKIT Circuit Diagram

Ref: http://www.ti.com/lit/ug/tidu256/tidu256.pdf

Parameter	Value	Units
Turns ratio P:S	16:1	-
Power level	500	W
Primary peak current		A
Frequency	250	kHz
Skin depth at 250 kHz	0.14	mm
Packing factor	0.35	-
Maximum allowable flux density	125	mT

Analytical: Transformer Quality Factor, Q

- Consider the Q of the leakage inductance:

$$Q = \frac{\omega L}{R}$$

- Inductive impedance
  - The energy stored in the space between the windings
  - Referred to the primary side
- Resistive impedance
  - Sum of DC resistance and proximity effect ESR
  - Secondary impedance reflected to primary side

$$Q = \frac{\omega L_{leak,p}}{R_{tot,p}}$$

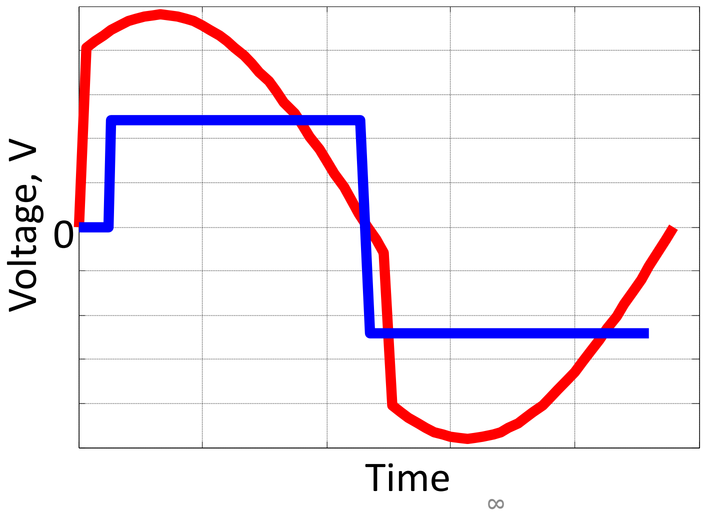
- Design parameters
  - Air leakage path
  - Frequency range: 100 – 500 kHz
  - Core: power ferrite
  - Winding: litz wire

Initial Transformer Core Sizing

- Find number of turns for a given core size
  - Primary voltage waveform
  - Given maximum peak flux density

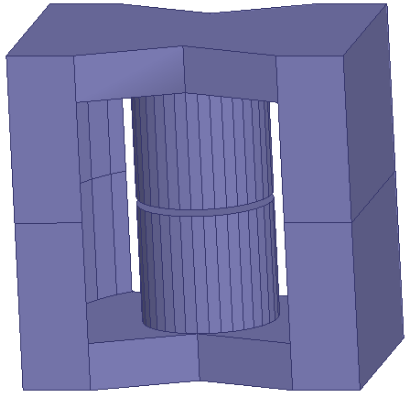
$$\lambda_{pp} = \int_0^{T/2} V_p(t)dt \qquad N_p = \frac{\lambda_{pp}}{\Delta B_{\max} \pi r_{core}^2}$$

$$P_{core,vol} = k_c f^{\alpha} \left(\frac{\Delta B}{2}\right)^{\beta}$$



- Winding loss
  - Primary and Secondary Current Waveforms
  - Assume Fr =2

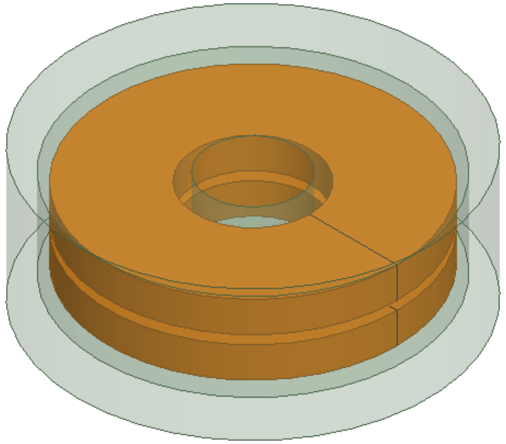
$$P_w = F_r R_{dc,p} I_{rms,p}^2 + F_r R_{dc,s} I_{rms,s}^2$$



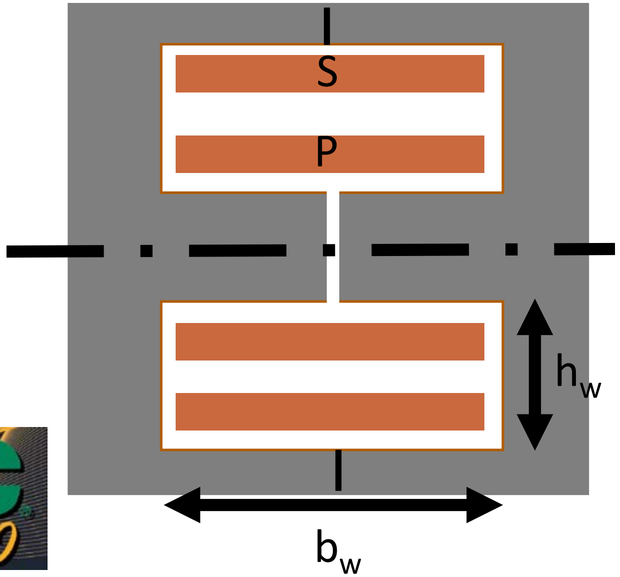
Analytical: Inductive Impedance

- Choose configuration to achieve the required leakage inductance

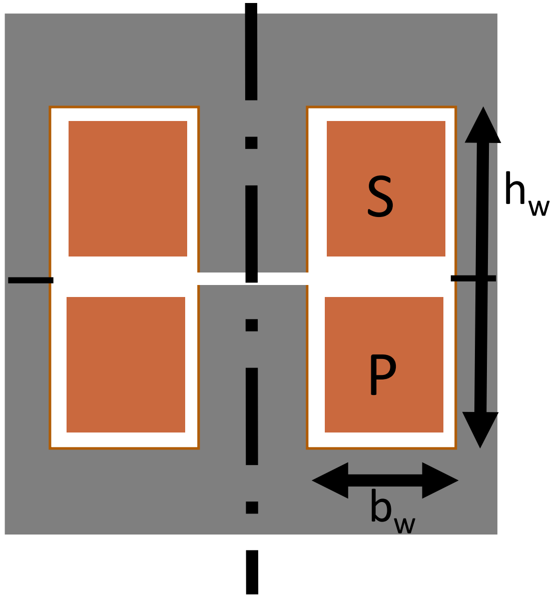
$$L_{leak,p} = \frac{k_L}{b_w}\left(\frac{h_p + h_s}{3} + h_{leak}\right)$$



Barrel wound P:S



Sectional wound P:S

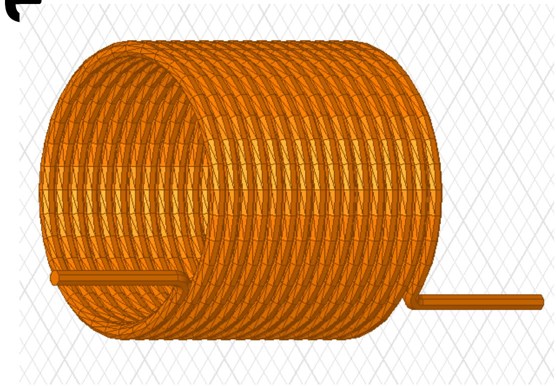


Constants:

$$k_L = \mu_0 N_p^2 l_{turn}$$

$$h_{ps} = h_p + h_s$$

Analytical: Resistive Impedance



- Assume: $N_p I_p = N_s I_s$
  - Space allocated to each winding is equal
  - Refer both windings' ESR to primary side
- DC resistance:

$$R_{dc,tot,p} = \frac{k_d}{h_{ps} b_w}$$

- Proximity ESR:

$$R_{prox,tot,p} = \frac{k_p h_{ps}}{b_w}$$

- Total winding Impedance

$$R_{total} = R_{prox,total} + R_{dc,total}$$

Constants:

$$k_d = 4\frac{\rho l_{turn} N_p^2}{F_p}$$

$$k_p = \frac{F_p d_s^2 \rho l_{turn} N_p^2}{12\delta^4}$$

Factors affecting Q

$$Q = Q_0 \frac{3\dfrac{h_w}{h_{ps}} - 2}{1 + \dfrac{k_d}{k_p h_{ps}^2}}$$

Include 2D and 3D effects:

- Core geometry
- Winding positions
- Termination locations

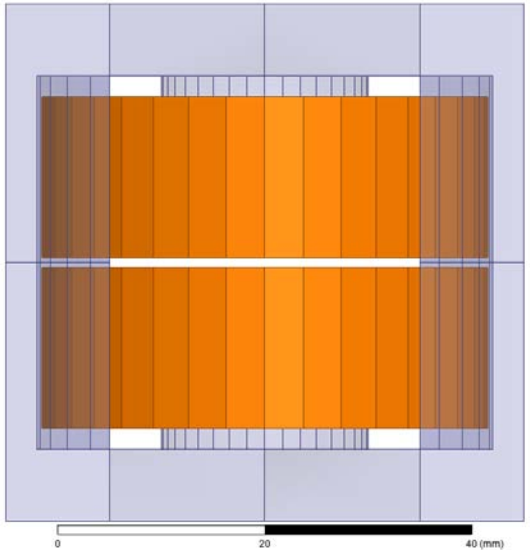
Cost for F_r =2

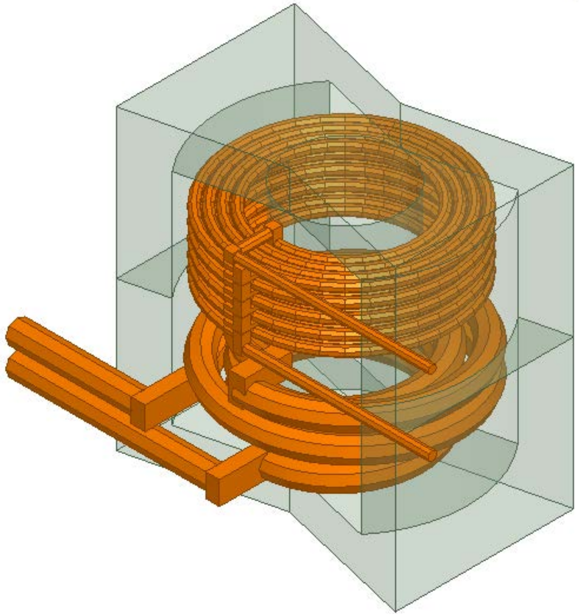
- Find winding height to maximize Q
  - Take derivative with respect to h_{ps} and set = 0

$$h_{ps,opt} = \frac{1}{\dfrac{2}{3h_w} + \sqrt{\dfrac{4}{9h_w^2} + \dfrac{k_p}{k_d}}}$$

FEA: Inductance Impedance

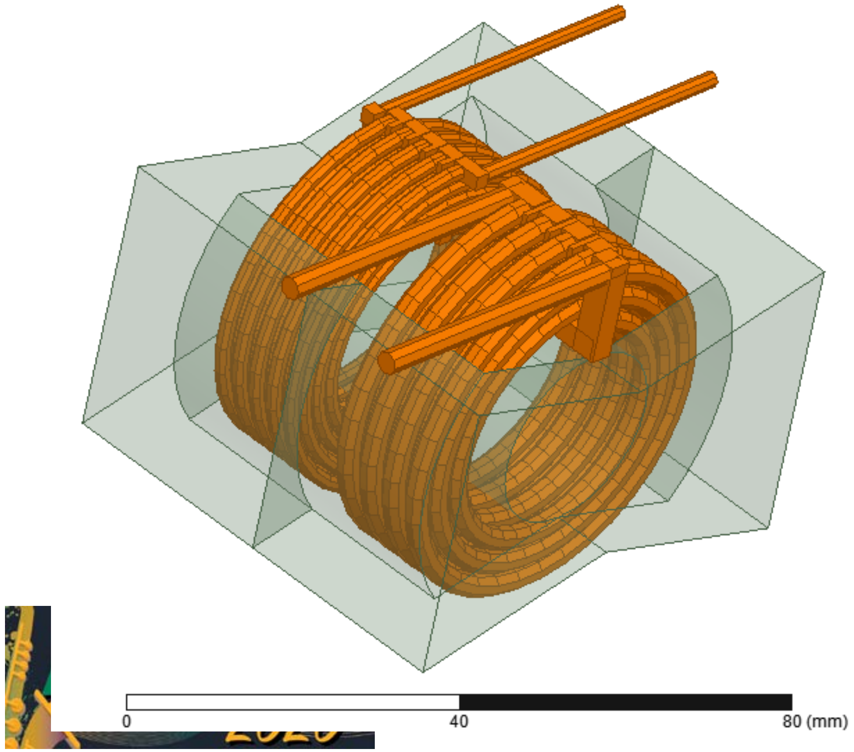
- Model: Rectangular winding areas
  - Find aspect ratio for winding window
- Model: Wire windings
  - Includes effect of lead layout
  - Consider different winding constructions
- Magnetostatic simulations
  - Leakage inductance
  - Magnetic field plots
  - Short simulation time

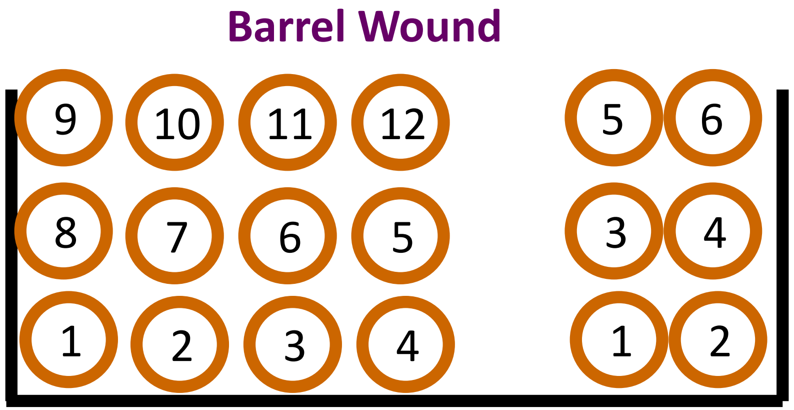


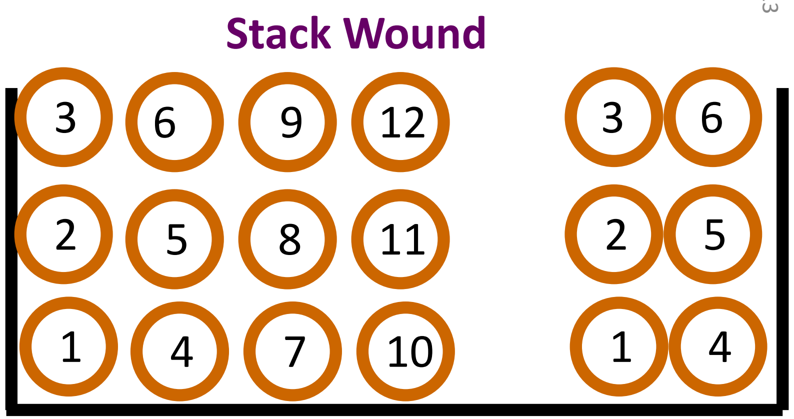


FEA: Wire Winding Models

- Investigate winding patterns
- Understand effect of terminations







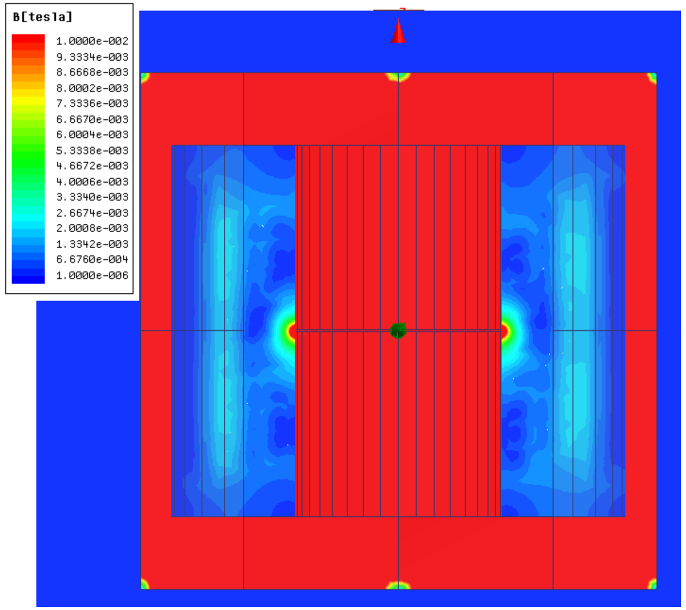
FEA: Leakage Inductance Calculation

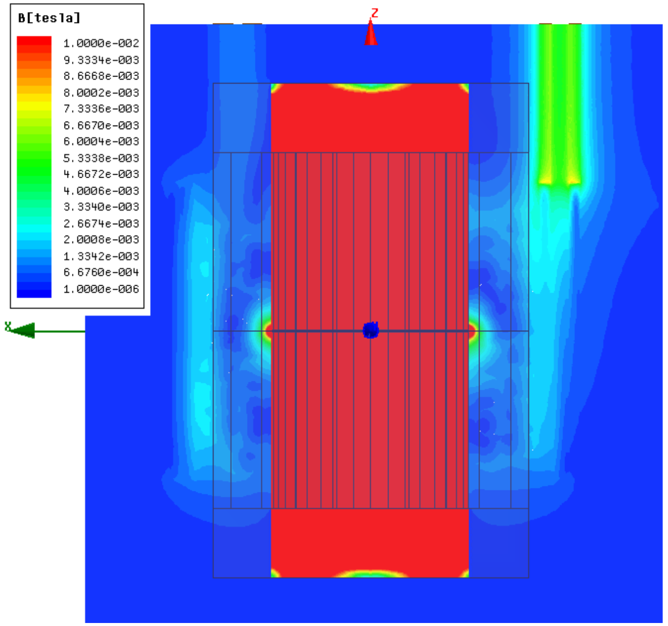
- Use total energy from convergence tab
- Find inductance from:

$$E = \frac{1}{2} L \left(\frac{I_p}{\sqrt{2}}\right)^2$$

Eddy current solver:

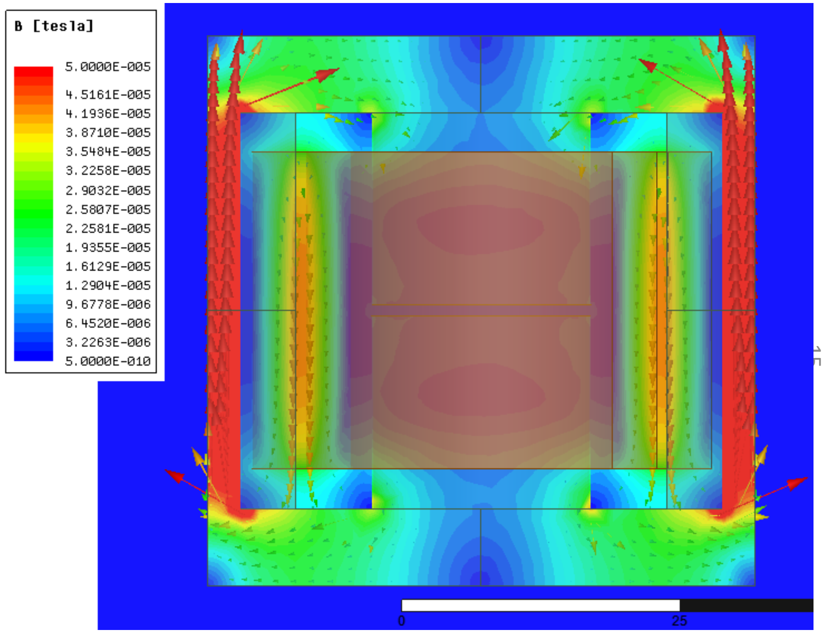
$$L_{leak} = \frac{2 * 2 * E}{I_p^2}$$





FEA: Resistive Impedance

- Layout of turns in winding window
  - Barrel
  - Stacked
- Litz-wire windings
  - Cost to meet Fr = 2?
- Solid wire windings
  - Exact solution for R_{ac} possible
  - Computationally expensive
  - Thermal simulations relatively easy



Designing Litz-wire Windings

- **Difficult to pick strand size and number of strands**

$$P = \frac{\pi \omega^2 l \, (2r)^4 B^2}{128 \rho_{cu}} + P_{dc}$$

  - Valid where wire diameter is small compared to skin depth

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} \qquad d << \delta$$

- Need the average value of magnitude of the flux density over a winding region:

Inductor: $\left\langle |B|^2 \right\rangle$

Transformer: $\begin{bmatrix} \left\langle |\vec{B}_1|^2 \right\rangle & \vec{B}_1 \cdot \vec{B}_2 \\ \vec{B}_2 \cdot \vec{B}_1 & \left\langle |\vec{B}_2|^2 \right\rangle \end{bmatrix}$

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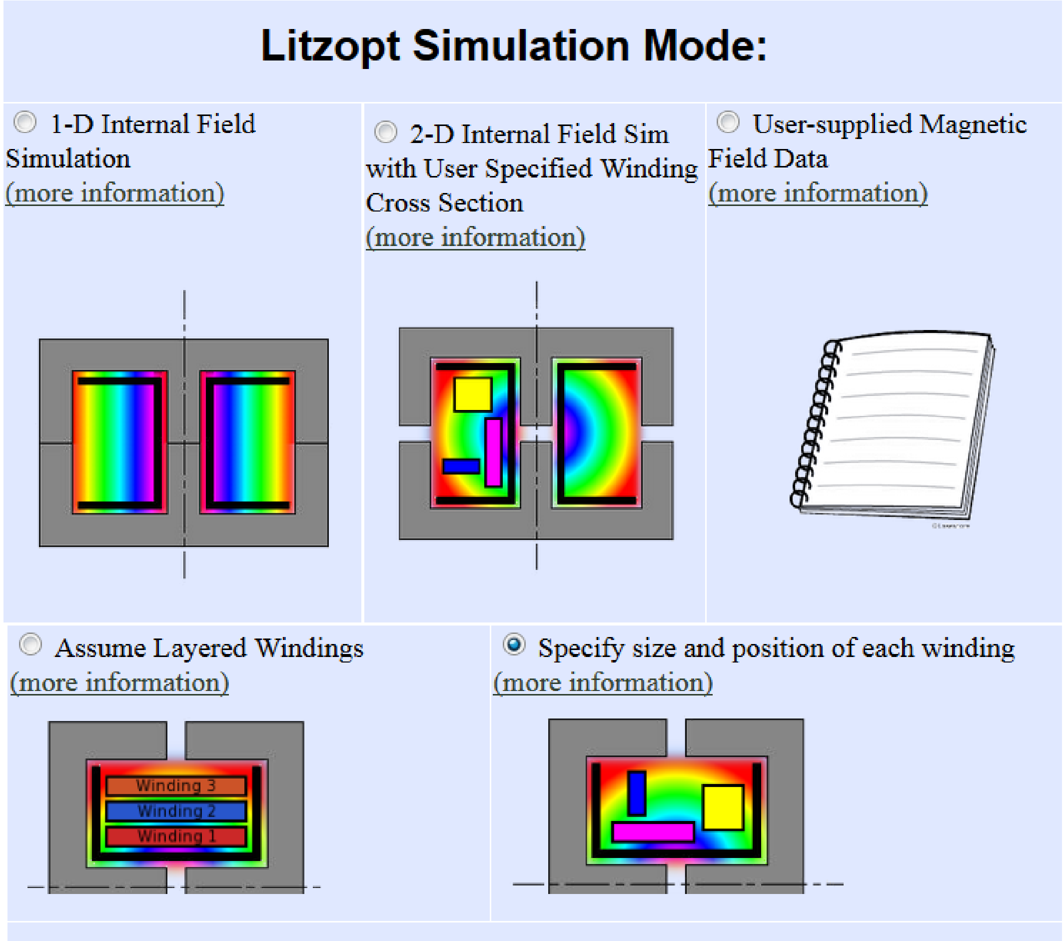
Free Litz-wire Design Software



http://engineering.dartmouth.edu/inductor/index.shtml

Prototypes: Small Signal Measurements

	Design 1:		Design 2:		Design 3:	
Parameter	Primary	Secondary	Primary	Secondary	Primary	Secondary
Frequency, kHz						
Rdc, milliohms						
Rac, milliohms						
Lm, uH						
Lleakage, uH						
C,interwinding, pF						
Weight, grams						

Prototypes: Power Measurements

Parameter	Design 1:	Design 2:	Design 3:	Design 4:	Design 5:	Design 6:
Input power, W						
Vin, V						
Vout, V						
Frequency, kHz						
Lr, uH						
Cr, uH						
Efficiency, %						

Comparison of Designs

Conclusions

- Many possible ways to create resonant tanks
- Best design depends on application requirements
  - Packaging constraints
  - Performance requirements
  - Cost targets
- Design examples show opportunities for different applications

Thank you for your attention!

Questions?

Thank you

- My Harley Davidson team
- PSMA Magnetic Committee
- Rubadue Wire
- Ferroxcube
- TDK

References

- J. D. Pollock and C.R. Sullivan, “Design Consideration for High-Efficiency Leakage Transformers,” IEEE APEC 2015
- G. Gamache, “Design and optimization of a low-porfile, low-loss resonant converter transformer,” in MS Thesis, Dartmouth College, 2011.
- G. E. Gamache and C. R. Sullivan, “Resonant converter transformer design and optimization,” in Energy Conversion Congress and Exposition (ECCE), 2011 IEEE, 2011, pp. 590–597.
- J. D. Pollock, T. Abdallah, and C. R. Sullivan, “Easy-to-use CAD tools for litz-wire winding optimization,” in 2003 IEEE Applied Power Electronics Conference, vol. 2, 2003, pp. 1157–1163.
- Dartmouth Magnetic Component Research Web Site, http://engineering.dartmouth.edu/inductor.
- C. R. Sullivan and R. Zhang;, “Simplified design method for litz wire,” in IEEE 29th Annual Applied Power Electronics Conference, 2014, pp. 2667–2674.
- E. C. Snelling, Soft Ferrites, Properties and Applications, 2nd ed. Butterworths, 1988.
- C. R. Sullivan, “Optimal choice for number of strands in a litz-wire transformer winding,” IEEE Transactions on Power Electronics, vol. 14, no. 2, pp. 283–291, 1999
- Special Section on Battery Energy Storage and Management, “Modeling and Controller Design of a Bidirectional Resonant Converter Battery Charger”, Zakariya M. Dalala, Zaka Ullah Zahid, Osama S. Saadeh, Jih-Sheng Lai