EXXELIA
A HEICO COMPANY

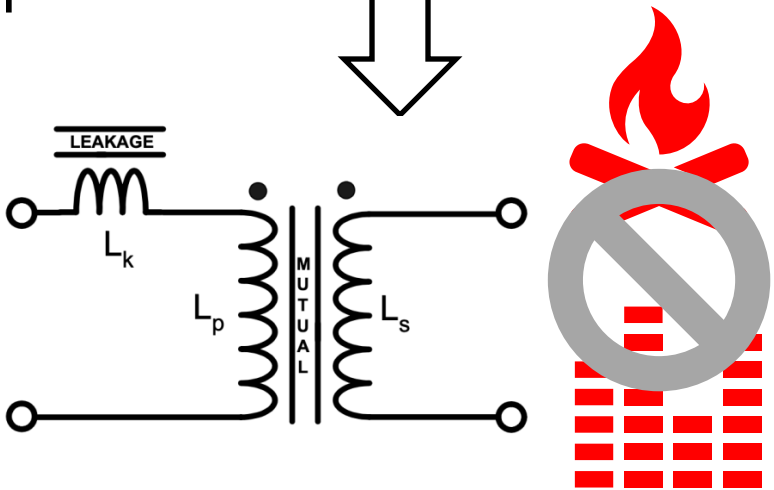
# Compact and Reliable Transformer with Integrated Inductor

Victor W. Quinn
Exxelia US Magnetics Design Center
vquinn@exxelia.com
585-230-4368

# Inductor Integration

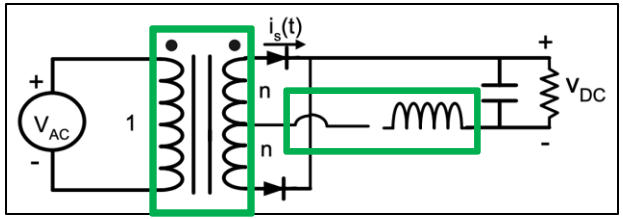
- Why integrate?
- History of integration
- Increase leakage flux in insulation
- Risks of loss and field emission
- Increase leakage flux using core material
- Design and test considerations
- Preferred configurations
- Suggestions

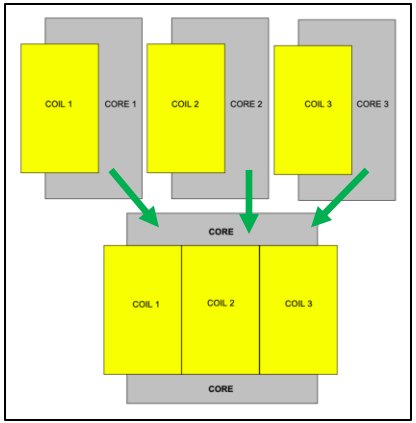
$$\iiint (B_{mutual} + B_{leakage})dV$$

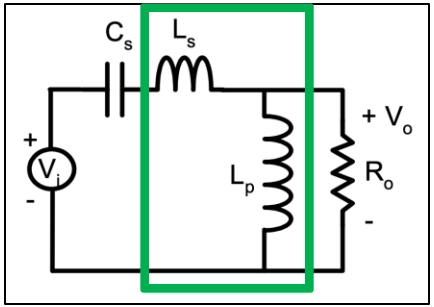


# Potential Benefits of Integrated Inductor

- Reduces dead space between discrete components.
- Reduces volume otherwise by consolidating:
  - mountings
  - terminations
  - coil turns
  - flux paths
- Improves efficiency and density of power convertors. (resonant & bidirectional examples)

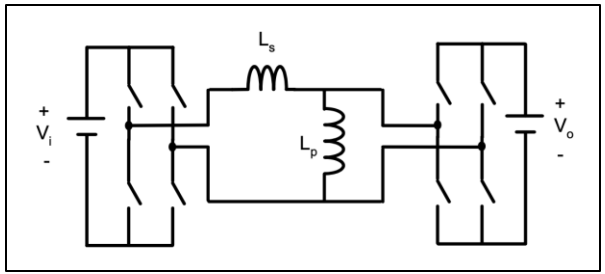


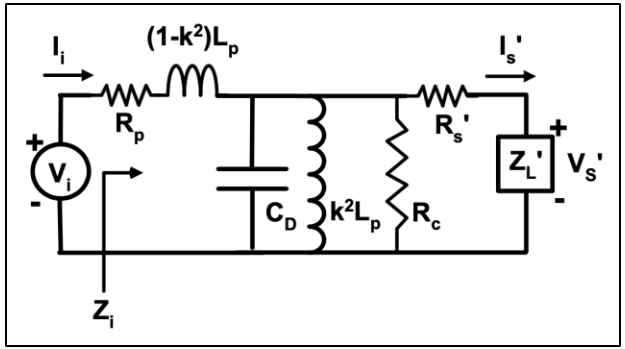



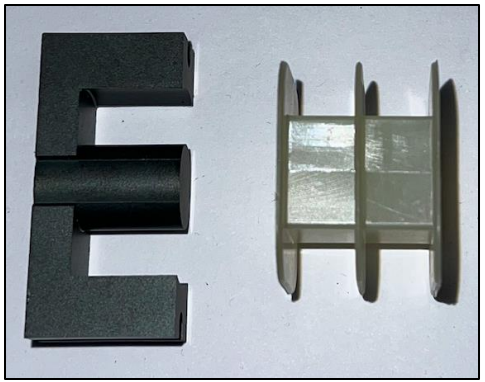



# Integration Enablers & Inhibitors

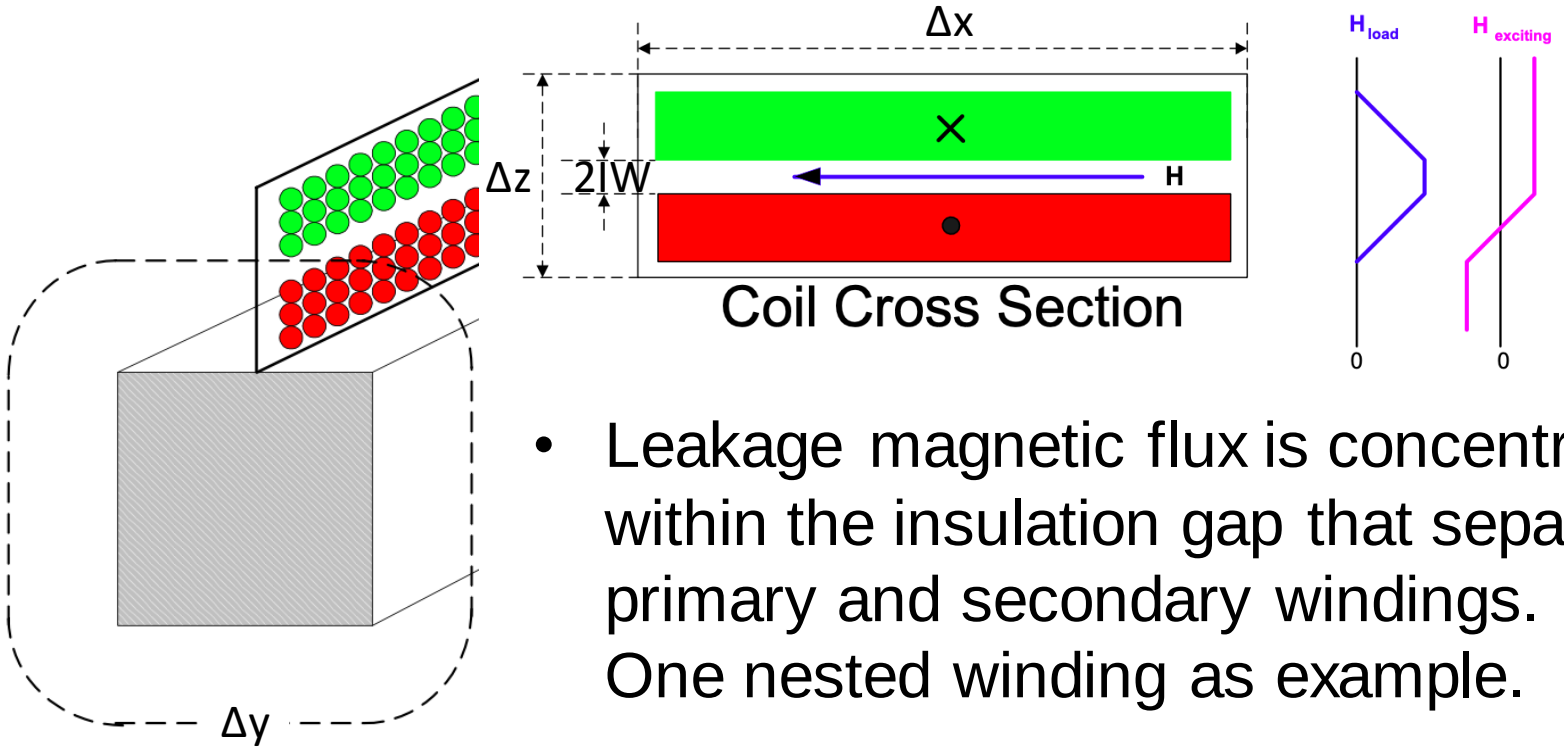
- Enablers
  - Power electronics needs
  - Inherent reactive parasitics
  - Freedoms of customization
- Inhibitors
  - Limitations of COTS components
  - Delay & cost penalties from customizing COTS components
  - Still maturing applications



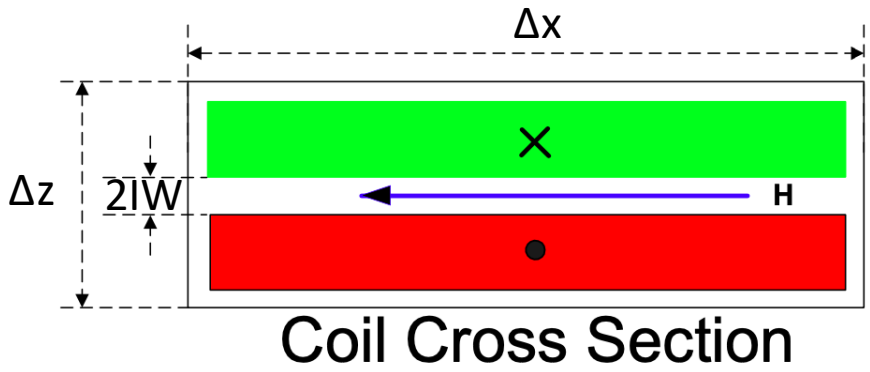



# Leakage Flux In Coil Insulation




- Leakage magnetic flux is concentrated within the insulation gap that separates primary and secondary windings. One nested winding as example.

# Enhance Leakage Flux In Coil Insulation



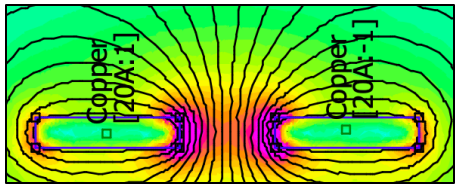
Coil Cross Section

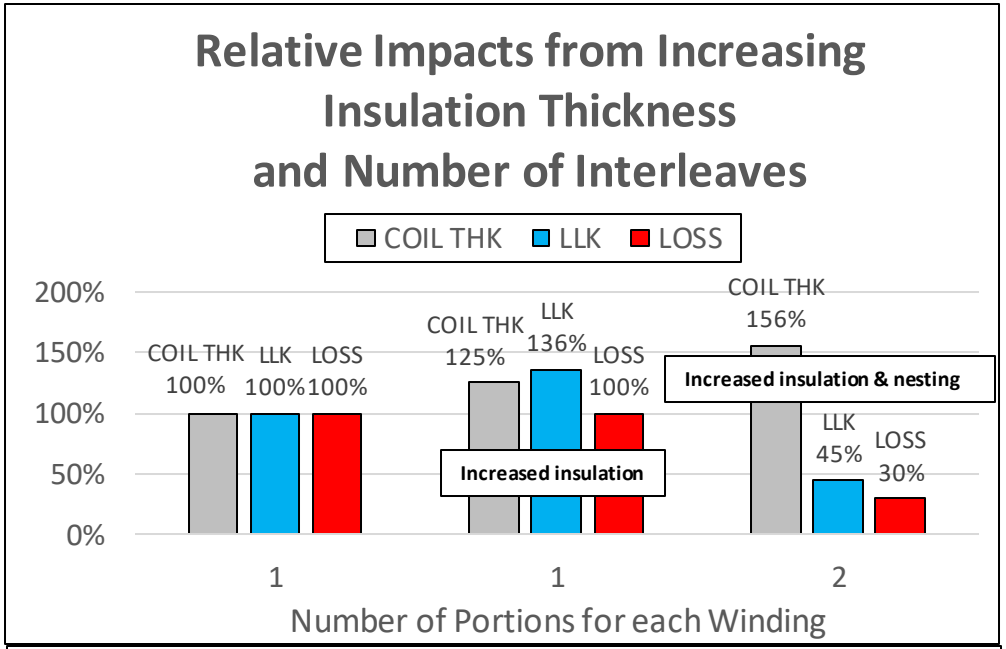
$$L_{eq\ primary} \approx \frac{\mu_0 \Delta y}{3\Delta x}\left[\frac{\Delta z}{n_m^2} + \frac{2IW}{n_m}\right] N_p^2$$

- Reduce number of nested windings ($n_m$)
- Increase turns ($N_p$)
- Increase clearance between nested windings (2IW)
- Separate windings

# Beware Excessive Loss or Field Emissions

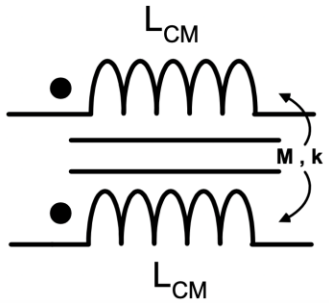
- But loss and H field emissions increase from:
  - Reduced nesting
  - Increased turns
  - Increased clearance
  - Separated windings



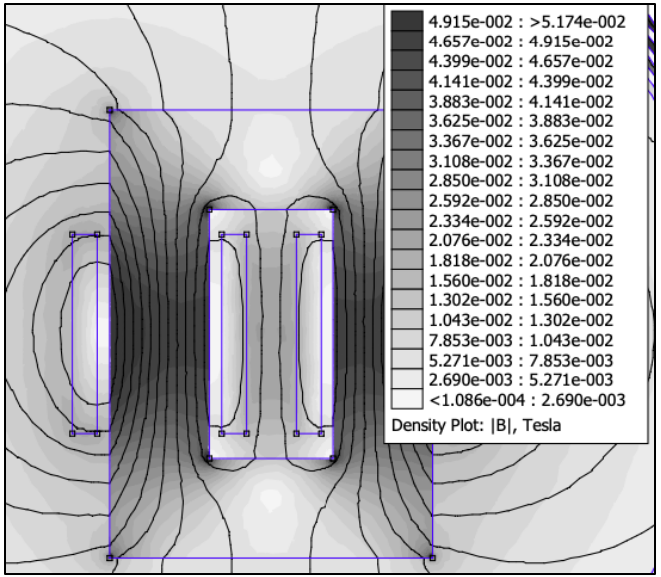

**Increasing insulation thickness between windings is not volume efficient means to enhance leakage flux when increased nesting is required for reduced coil loss.**

# DM Problems with CM Inductor




$$L_{DM} = (1-k)2L_{CM}$$

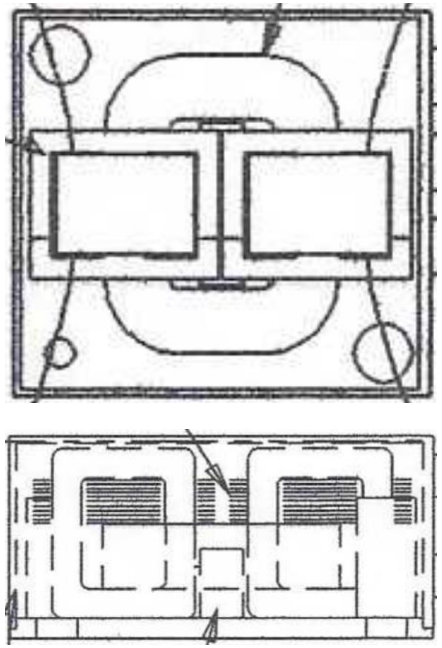
$$k \sim 96.8\%$$

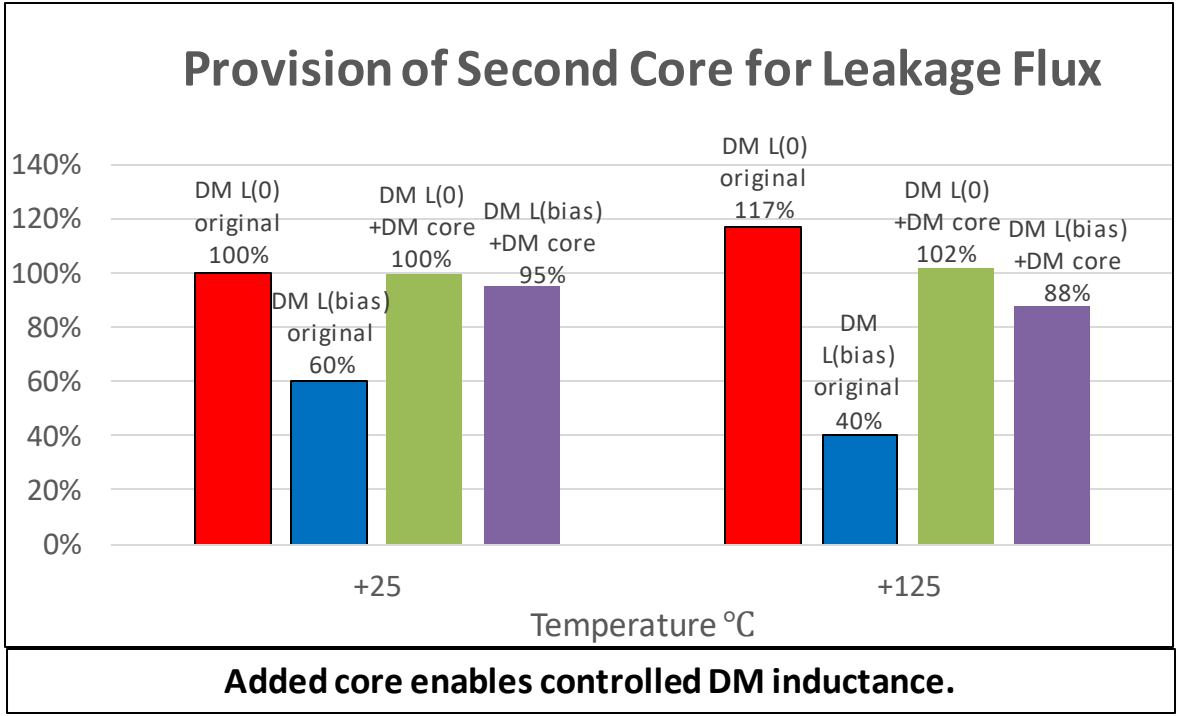



- DC Leakage Flux
  - Intercepts ferrite CM core
  - Polarizing CM core and reducing effective permeability for DM flux especially at high temperature

Add laminated core to enhance leakage flux with improved control.

# Consistent DM Inductance



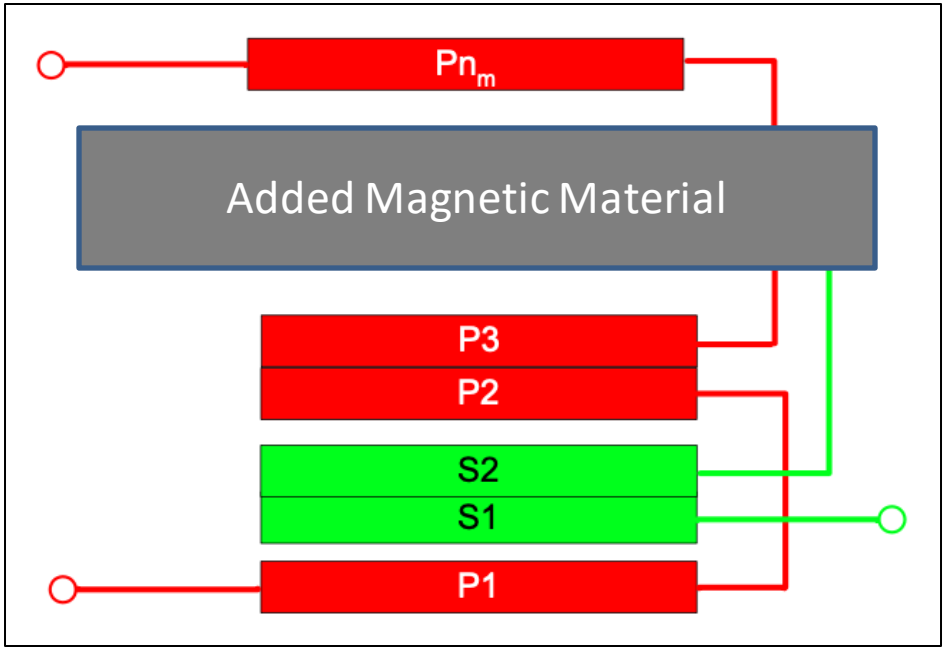



**Added core enables controlled DM inductance.**

Improved design achieves DM inductance at bias current over temperature.

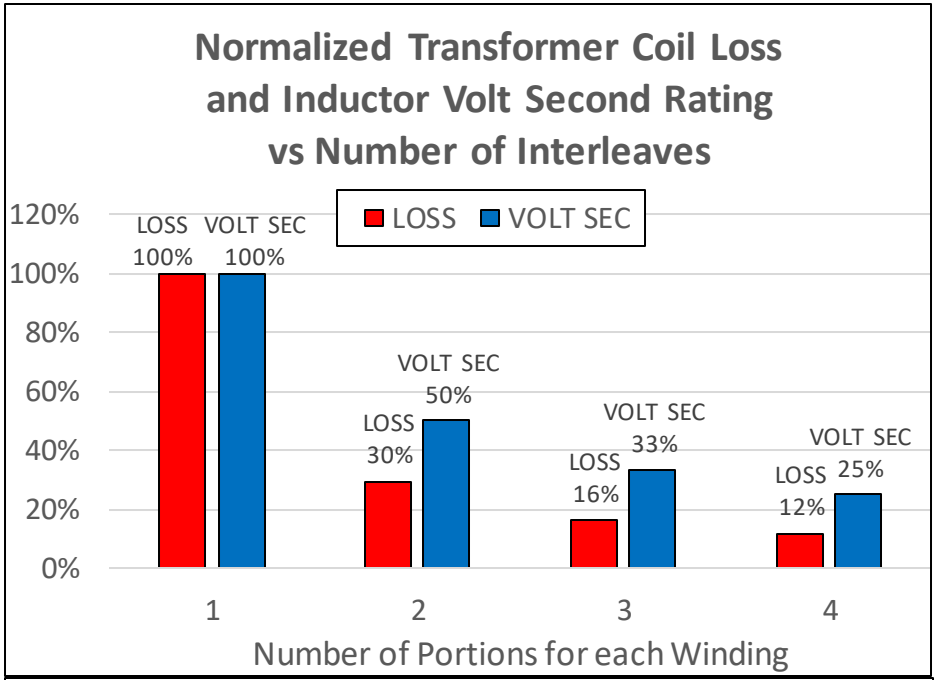
# Enhance Leakage Flux Using Core Material

- Added magnetic material between coil portions increases leakage flux.
  - Preferred nesting of primary and secondary reduces eddy current loss.



# Mitigate Loss Or Density Penalty

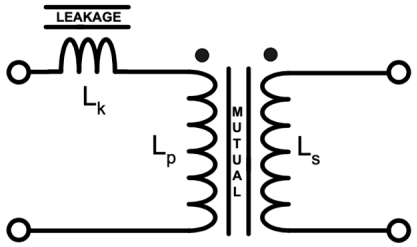
- Coil Loss
  - ACR driven by AC leakage flux.
- Core Loss
  - Core loss driven by flux time derivative.
- Beware complex leakage field losses.
- Beware Volt Second capacity of added inductor is reduced from nesting.
- Compare integrated result to best case discrete components.




**Reduction of transformer eddy current loss reduces Volt Second capacity of added inductor.**

# Checklist For Integrated Inductor Design

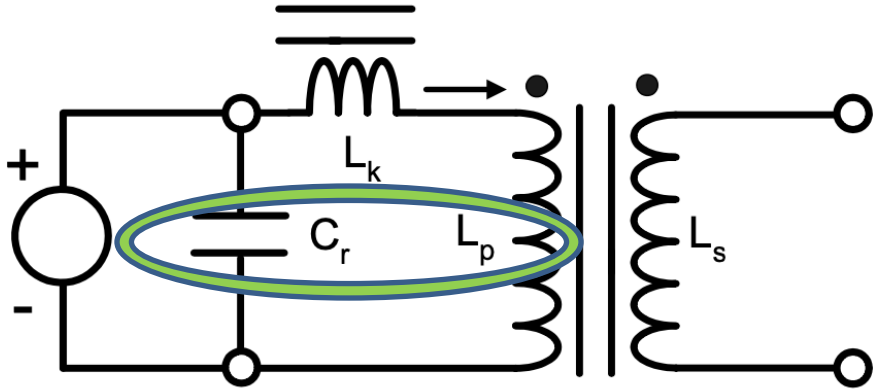
- Operating waveforms
  - steady state & transient
  - potentials for net bias current
- Maximum Volt-Time ratings
  - transformer
  - inductor
- Total transformer + inductor VA
- Worst case flux time derivative and current harmonics
- Environmental extremes
- Empirical test verification
- Compare integrated design to best case discrete



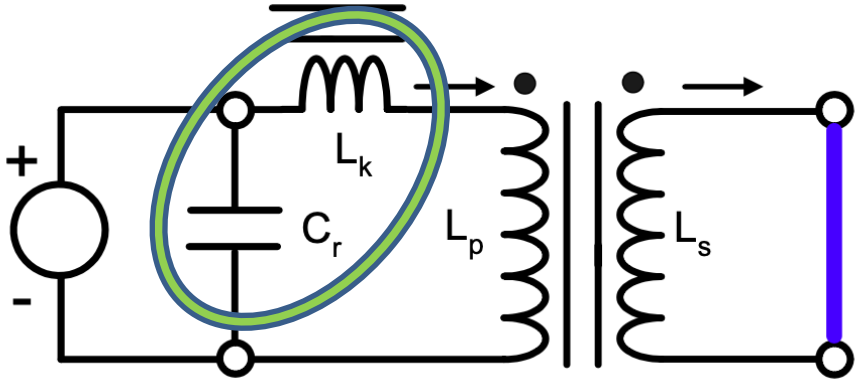

$$\sum_{Mutual\ \&\ Leakage\ Inductors} (Area_{core} \times Area_{coil}) \propto \frac{\text{Total VA}}{\text{Frequency} \times \text{Flux Density} \times \text{Current Density}}$$

# Test Loss Under Operating Conditions

- Rated Volt-Sec (zero output current)

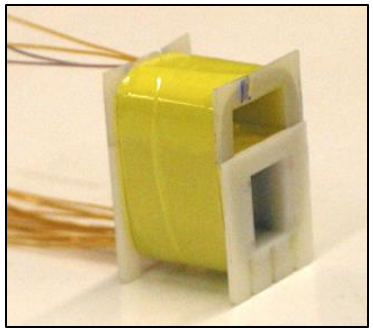



- Rated Load Current (zero output voltage)



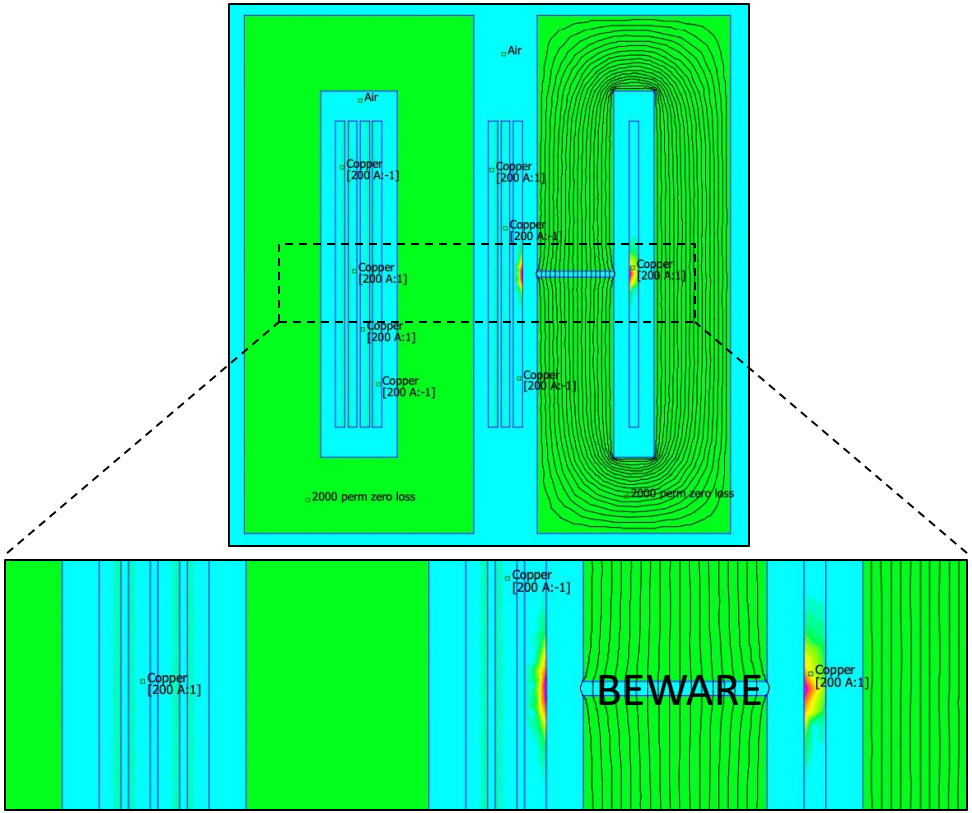
# Modify COTS Bobbins & Cores

- Vast majority of COTS components are tooled for purpose of discrete transformer and inductor.
- Integration of inductor in transformer may require extensive modification of COTS components with low volume utilization.
- Availability of optimal COTS components for integrated magnetics will be driven by market demand.
  (CCFL tooled frame & bar core example)



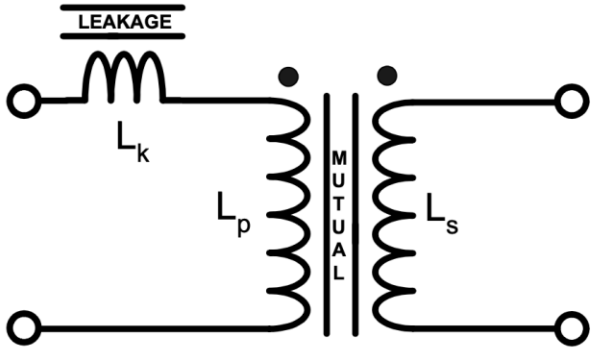
# Preferred Configurations

- Maximize volume utilization
  - Current and magnetic field densities approach results for best case discrete components.
  - Conductor loss induced by leakage flux is minimal contributor.
- Mitigate field emission



# Suggestions

- Beware loss (temperature rise) and emitted field impacts from inductor integration.
- Check field intensity in all magnetic material for each operating condition.
- Perform empirical testing to verify calculated results and reduce failure risk.
- Validate integration benefits by rigorous comparison to best case custom discrete inductor and transformer.




# References


- P. R. K. Chetty, "Resonant power supplies: their history and status," in IEEE Aerospace and Electronic Systems Magazine, vol. 7, no. 4, pp. 23-29, April 1992, doi: 10.1109/62.143195.
- John C Schuder. “Powering an Artificial Heart: Birth of the Inductively Coupled-Radio Frequency System in 1960”. In: Artificial organs 26.11 (2002), pp. 909–915
- P. Vinciarelli, "Forward Converter Switching At Zero Current," U.S. Patent # 4,415,959 (1983)
- Rudolf P.Severns and Gordon E.Bloom, Modern DC-to-DC switch-mode power converter circuits, 1985.
- Z. Ouyang et al. “Analysis and Design of Fully Integrated Planar Magnetics for Primary–Parallel Isolated Boost Converter”, IEEE Transactions on Industrial Electronics 60.2 (2013), pp. 494–508.
- M. Abu Bakar, Stefan Haller & Kent Bertilsson (2021) Contribution of leakage flux to the total losses in transformers with magnetic shunt, International Journal of Electronics, 108:4, 558-573, DOI: 10.1080/00207217.2020.1793404