Considerations for Integrating Inductor Within Transformer

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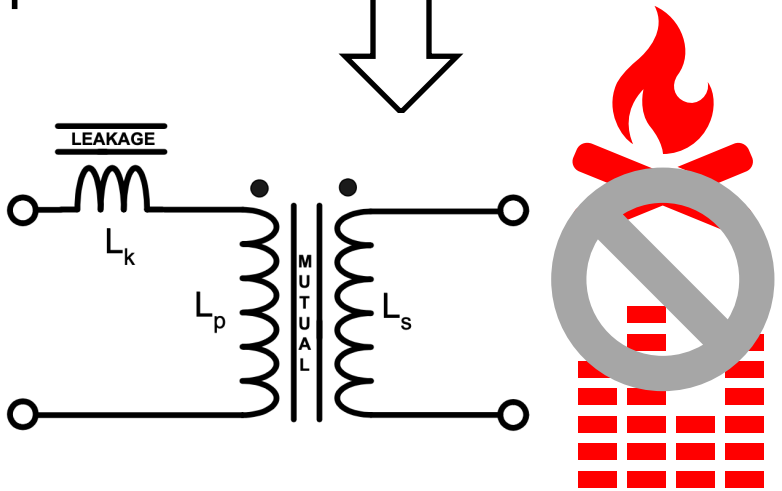
Inductor Integration

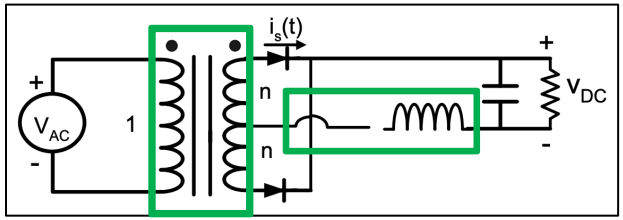
- Why integrate?
- History of integration
- Increase leakage flux in insulation
- Risks of loss and field emission
- Increase leakage flux using core material
- Design and test considerations
- Preferred configurations
- Suggestions

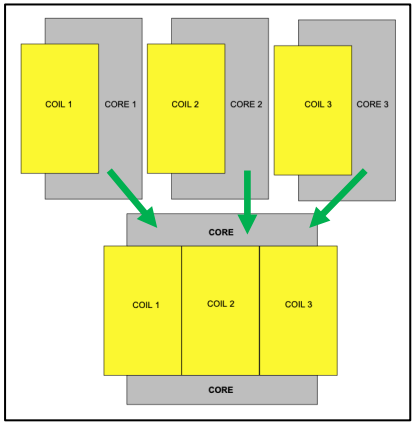
$$\iiint (B_{mutual} + B_{leakage})dV$$

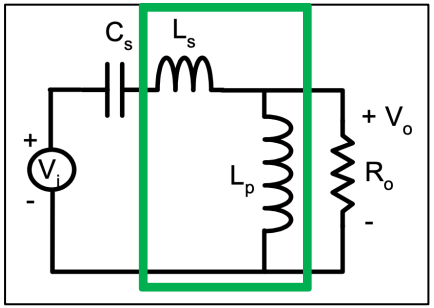


Potential Benefits of Integrated Inductor

- 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)

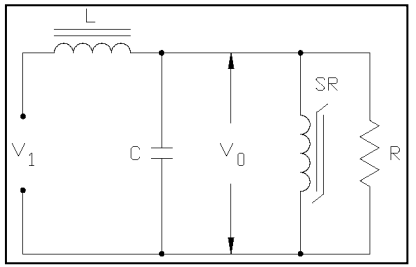


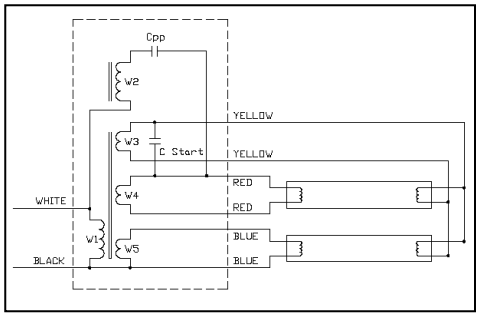


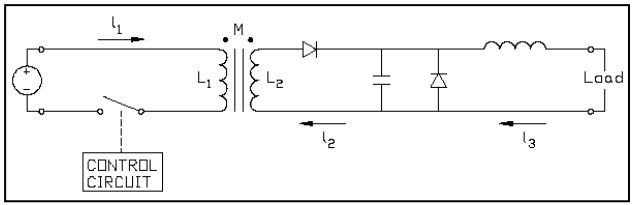


Legacy Magnetics Integration

- Selected Advancements
  - Henry & Faraday - induction (1830s)
  - Coupled inductors (1870s)
  - Multiple phase transformer (1890s)
  - Ferroresonant regulator (1920s)
  - Ballast transformers (1940s)
  - Royer oscillator (1950s)
  - Subcutaneous secondary (1960s)
  - Reduced switching loss (1980s)

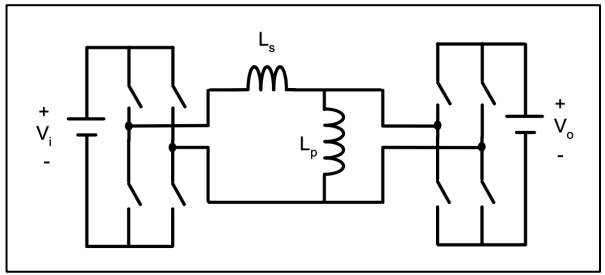


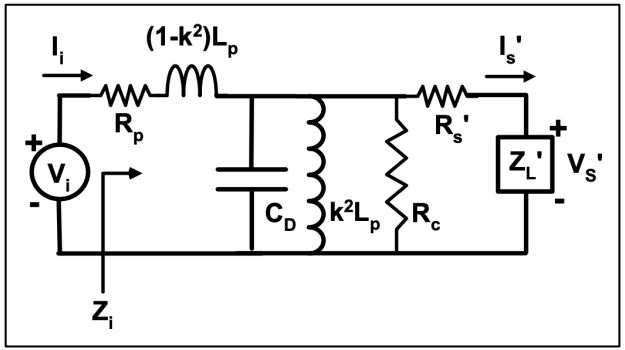


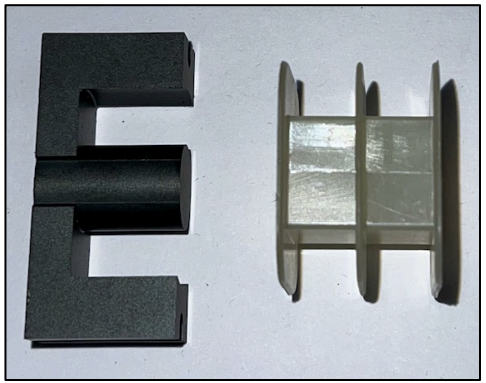


Integration Enablers & Inhibitors

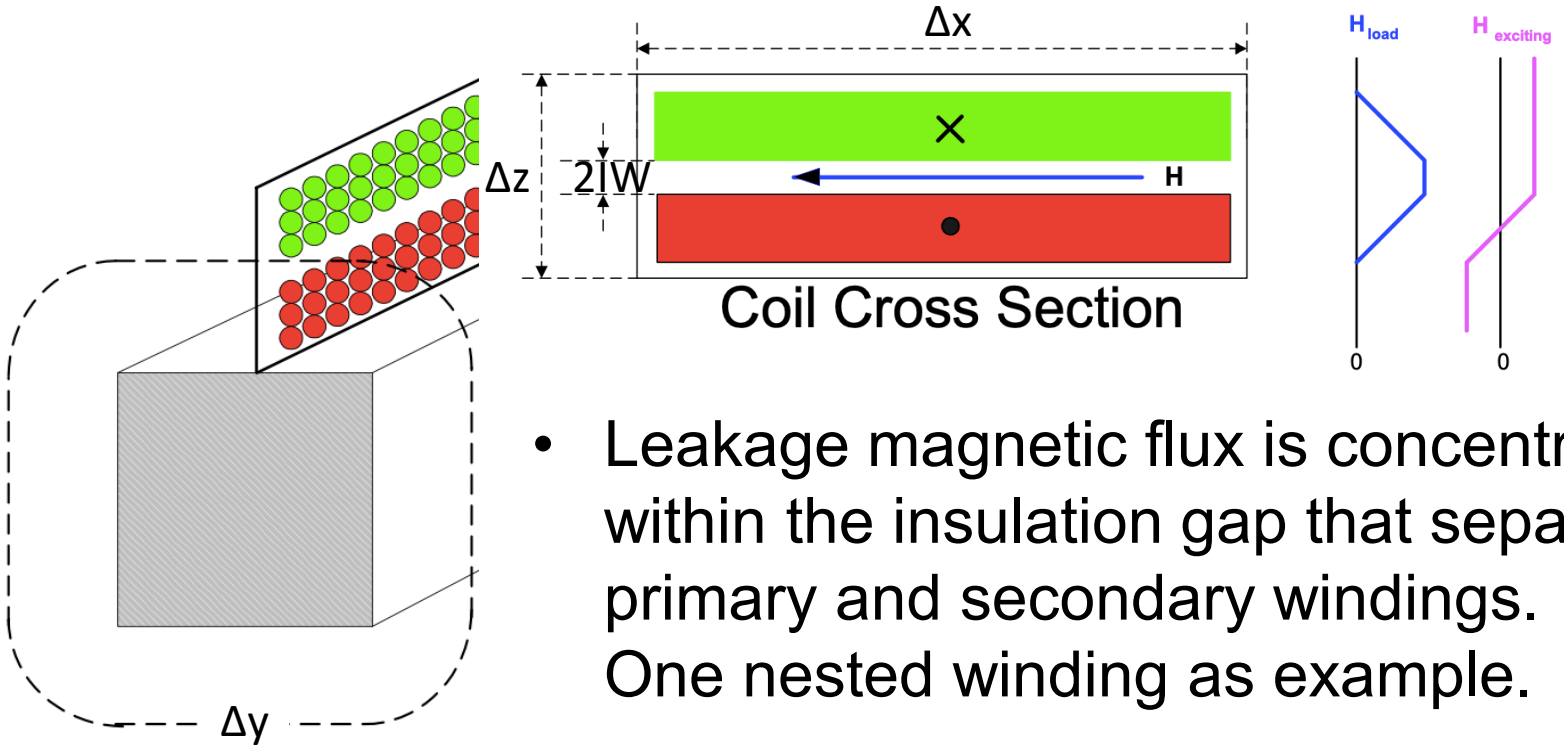
- Enablers
  - Power electronics needs
  - Inherent reactive parasitics
  - Freedoms of customization
- Inhibitors
  - Limitations of COTS components
  - Delay & cost penalties from customizing COTS components
  - Still maturing applications





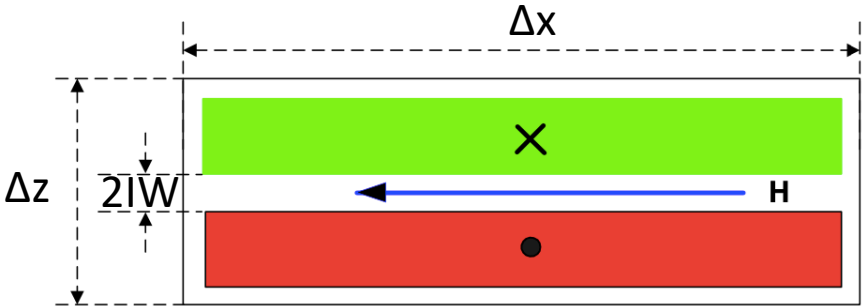


Leakage Flux In Coil Insulation



- 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



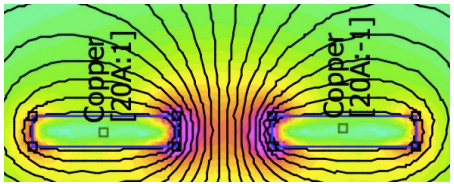
Coil Cross Section

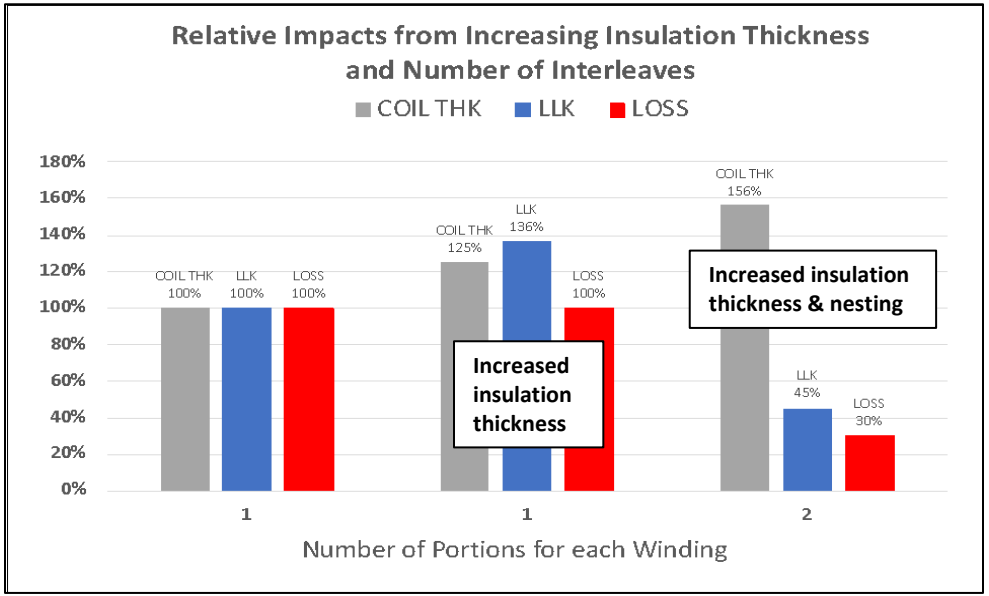
$$L_{eq\ primary} \approx \frac{\mu_0 \Delta y}{3\Delta x}\left[\frac{\Delta z}{n_m^{\ 2}} + \frac{2IW}{n_m}\right] N_p^{\ 2}$$

- 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

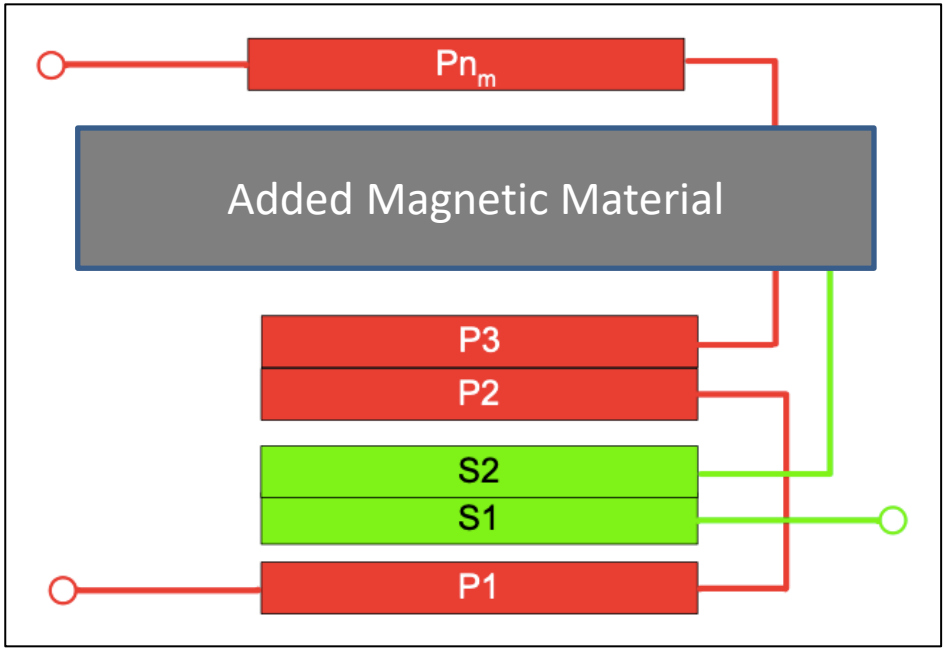




Increasing insulation thickness between windings is not volume efficient means to enhance leakage flux when increased nesting is required for reduced coil loss.

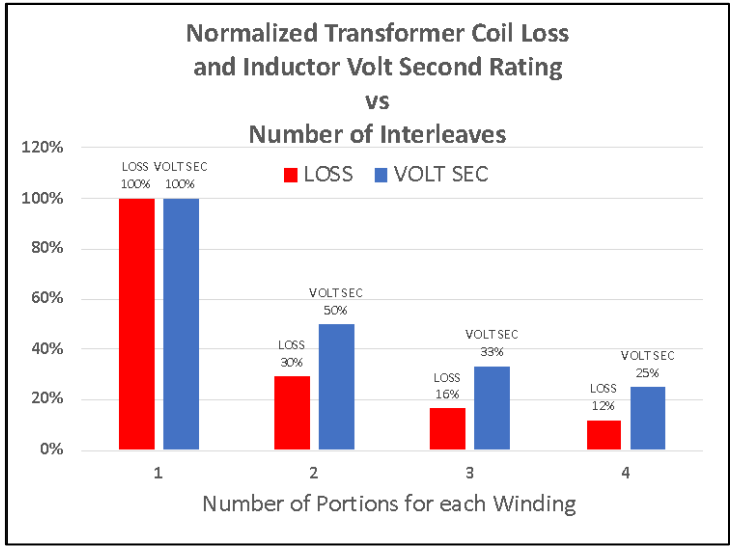
Enhance Leakage Flux Using Core Material

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



Mitigate Loss Or Density Penalty

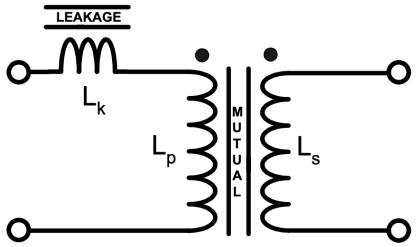
- Coil Loss
  - ACR driven by AC leakage flux.
- Core Loss
  - Core loss driven by flux time derivative.
- Beware complex leakage field losses.
- Beware Volt Second capacity of added inductor is reduced from nesting.
- Compare integrated result to best case discrete components.



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

Checklist For Integrated Inductor Design

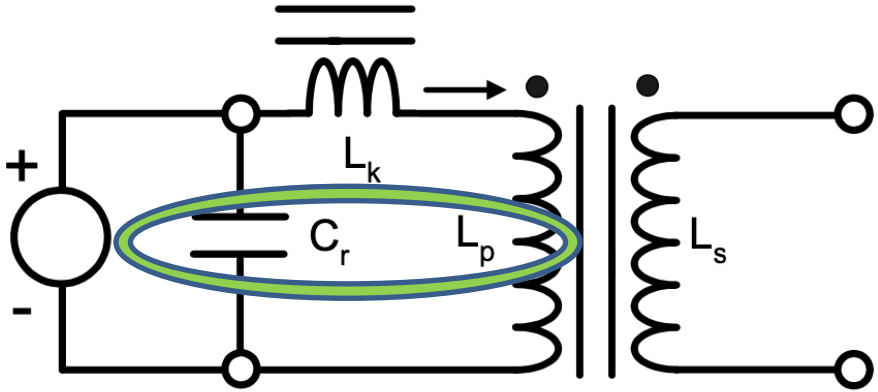
- Operating waveforms
  - steady state & transient
  - potentials for net bias current
- Maximum Volt-Time ratings
  - transformer
  - inductor
- Total transformer + inductor VA
- Worst case flux time derivative and current harmonics
- Environmental extremes
- Empirical test verification
- Compare integrated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



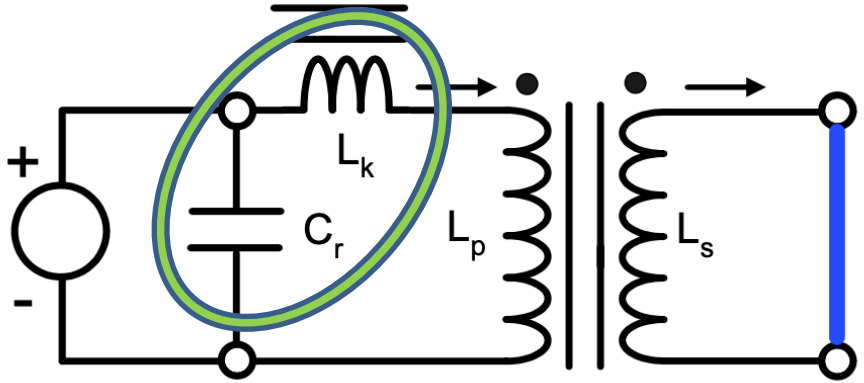
$$\sum_{Mutual\ \&\ Leakage\ Inductors} (Area_{core} \times Area_{coil}) \propto \frac{\text{Total VA}}{\text{Frequency} \times \text{Flux Density} \times \text{Current Density}}$$

Test Loss Under Operating Conditions

- Rated Volt-Sec (zero output current)

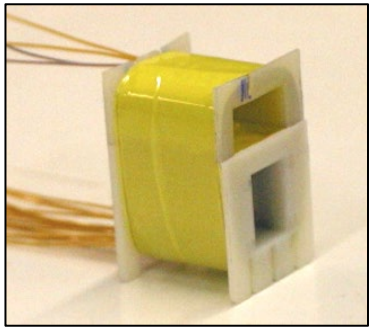


- Rated Load Current (zero output voltage)



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)

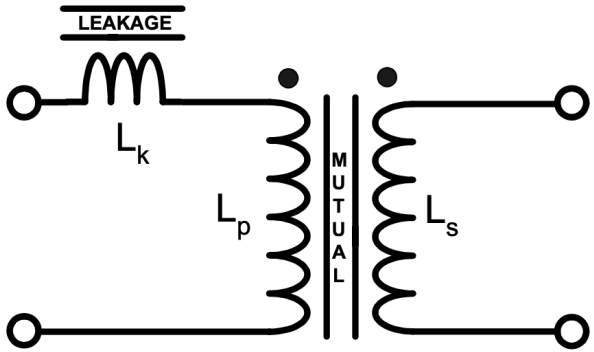


Preferred Configurations

- 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.



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