Combined Inductor and Transformer Design for Resonant Converters
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
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</tr>
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<tbody>
<tr>
<td>Turns ratio P:S</td>
<td>2:1</td>
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<tr>
<td>Power level</td>
<td>3.3</td>
<td>kW</td>
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<tr>
<td>Primary peak current</td>
<td>16</td>
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<tr>
<td>Frequency</td>
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<tr>
<td>Skin depth at 250 kHz</td>
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<td>mm</td>
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<tr>
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</tr>
<tr>
<td>Maximum allowable flux density</td>
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Design Example: High turns ratio

- Uni-directional 500 W half bridge LLC

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

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

\[ Q = \frac{\omega L_{\text{leak},p}}{R_{\text{tot},p}} \]
**Initial Transformer Core Sizing**

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

\[
\lambda_{pp} = \int_0^{T/2} V_p(t) dt
\]

\[
N_p = \frac{\lambda_{pp}}{\Delta B_{\text{max}} \pi r^2_{\text{core}}}
\]

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

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

\[
P_w = F_r R_{dc, p} I_{\text{rms}, p}^2 + F_r R_{dc, s} I_{\text{rms}, s}^2
\]
**Analytical: Inductive Impedance**

- Choose configuration to achieve the required leakage inductance

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

Barrel wound P:S

Sectional wound P:S

**Constants:**

\[ k_L = \mu_0 N_p^2 I_{\text{turn}} \]

\[ h_{ps} = h_p + h_s \]
**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:**
  \[ R_{dc,\text{tot},p} = \frac{k_d}{h_{ps} b_w} \]

- **Proximity ESR:**
  \[ R_{prox,\text{tot},p} = \frac{k_p h_{ps}}{b_w} \]

- **Total winding Impedance**
  \[ R_{total} = R_{prox,\text{total}} + R_{dc,\text{total}} \]

**Constants:**

\[
\begin{align*}
k_d &= 4 \frac{\rho_{\text{turn}} N_p^2}{F_p} \\
k_p &= \frac{F_p d_s^2 \rho_{\text{turn}} N_p^2}{12 \delta^4}
\end{align*}
\]
Factors affecting $Q$

\[ Q = Q_0 + \frac{h_w}{h_{ps}} - 2 \]

\[ Q = Q_0 + \frac{k_d}{k_p h_{ps}^2} \]

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 $= 0$

\[ h_{ps, opt} = \frac{1}{\frac{2}{3h_w} + \sqrt{\frac{4}{9h_w^2} + \frac{k_p}{k_d}}} \]
**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:**

\[ L_{\text{leak}} = \frac{2 \times 2 \times E}{I_p^2} \]
**FEA: Resistive Impedance**

- Layout of turns in winding window
  - Barrel
  - Stacked
- Litz-wire windings
  - Cost to meet $F_r = 2$?
- 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

\[ \delta = \sqrt{\frac{\rho}{\pi \mu f}} \quad \quad \quad d << \delta \]

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

Inductor: \[ \langle |B|^2 \rangle \]  
Transformer: \[ \begin{bmatrix} r \\ \langle |B_1|^2 \rangle & B_1 \cdot B_2 \\ r \\ B_2 \cdot B_1 & \langle |B_2|^2 \rangle \end{bmatrix} \]
Free Litz-wire Design Software

http://engineering.dartmouth.edu/inductor/index.shtml
## Prototypes: Small Signal Measurements

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<th>Design 1:</th>
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<th>Design 2:</th>
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Prototypes: Power Measurements

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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

• 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