Power Converter Simulation

ECE 482 Lecture 6
January 27, 2014

Announcements

• Lab report 1 due today
• This week: Continue Experiment 2
  – Boost open-loop construction and modeling
Analytical Loss Modeling

- High efficiency approximation is acceptable for hand calculations, as long as it is justified
  - Solve waveforms of lossless converter, then calculate losses
- Alternate approach: average circuit
  - Uses average, rather than RMS currents
  - Difficult to include losses other than conduction
- Argue which losses need to be included, and which may be neglected

Power Stage Losses

- Conduction Losses
  - MOSFETS: \( R_{on} \), \( r_{co} \), \( V_f \), \( R_d \)
  - IGBTs: \( r_{ce} \), \( V_{ce} \)
  - Diodes: \( R_{dc} \)
  - Capacitors: ESR
  - Inductor: \( R_{dc} \)
- Frequency-Dependent Losses
  - MOSFETS: \( C_{oss} \)
  - IGBTs: Reverse-Recovery
  - Diodes: Current Tailing
  - Inductor: Skin Effect, Core Loss, Fringing, Proximity
  - Capacitors: Dielectric Losses
Magnetics Losses

- Magnetic Device Losses
  - Copper Loss
  - Core Loss
- DC Copper Loss
- AC Copper Loss
- Eddy Current
- Skin Effect
- Proximity Effect
- Fringing Flux
- High Frequency Losses

Inductor Core Loss

- Governed by Steinmetz Equation:
  \[ P_v = K_{fe} s^{\alpha} (\Delta B)^{\beta} \text{ [mW/cm}^3\text{]} \]
- Parameters \( K_{fe}, \alpha, \text{ and } \beta \) extracted from manufacturer data
- \( \Delta B \propto \Delta i_L \rightarrow \) small losses with small ripple
  \[ P_{fe} = P_v A_c l_m \text{ [mW]} \]
Steinmetz Parameter Extraction

Fig. 6: Specific power loss as a function of peak flux density with frequency as a parameter.

Fig. 7: Specific power loss for several frequency/flux density combinations as a function of temperature.

Ferroxcube Curve Fit Parameters

Power losses in our ferrites have been measured as a function of frequency (f in Hz), peak flux density (B in T) and temperature (T in °C). Core loss density can be approximated (2) by the following formula:

\[ P_{\text{core}} = C_m \cdot f^x \cdot B_{\text{peak}}^y \cdot (c_{t_0} - c_{t_1} T + c_{t_2} T^2) \]  

\[ = C_m \cdot C_T \cdot f^x \cdot B_{\text{peak}}^y \]  

[mW/cm²]

<table>
<thead>
<tr>
<th>Ferrite</th>
<th>f (kHz)</th>
<th>Cm</th>
<th>x</th>
<th>y</th>
<th>c_{t_2}</th>
<th>c_{t_1}</th>
<th>c_{t_0}</th>
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<tr>
<td>2G30</td>
<td>20-100</td>
<td>7.13 \times 10^{-3}</td>
<td>1.42</td>
<td>3.02</td>
<td>3.65 \times 10^{-4}</td>
<td>6.65 \times 10^{-2}</td>
<td>4</td>
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<tr>
<td>100-200</td>
<td>7.13 \times 10^{-3}</td>
<td>1.42</td>
<td>3.02</td>
<td>4.1 \times 10^{-4}</td>
<td>6.8 \times 10^{-2}</td>
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<td>20-200</td>
<td>3.2 \times 10^{-3}</td>
<td>1.46</td>
<td>2.75</td>
<td>1.65 \times 10^{-4}</td>
<td>3.1 \times 10^{-2}</td>
<td>2.45</td>
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<td>3.1 \times 10^{-2}</td>
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<td>JF2</td>
<td>200-400</td>
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<td>2.6</td>
<td>2.75</td>
<td>1.65 \times 10^{-4}</td>
<td>3.1 \times 10^{-2}</td>
<td>2.45</td>
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<tr>
<td>100-300</td>
<td>2.1 \times 10^{-3}</td>
<td>2.6</td>
<td>2.75</td>
<td>1.65 \times 10^{-4}</td>
<td>3.1 \times 10^{-2}</td>
<td>2.45</td>
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<tr>
<td>JF3</td>
<td>300-500</td>
<td>0.25 \times 10^{-3}</td>
<td>1.63</td>
<td>2.45</td>
<td>0.79 \times 10^{-4}</td>
<td>1.65 \times 10^{-2}</td>
<td>1.26</td>
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<tr>
<td>500-1000</td>
<td>0.25 \times 10^{-3}</td>
<td>1.63</td>
<td>2.45</td>
<td>0.79 \times 10^{-4}</td>
<td>1.65 \times 10^{-2}</td>
<td>1.26</td>
<td></td>
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<tr>
<td>JF4</td>
<td>500-1000</td>
<td>1.2 \times 10^{-2}</td>
<td>1.25</td>
<td>2.9</td>
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<td>1000-3000</td>
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<td>0.81 \times 10^{-2}</td>
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Table 1: Fit parameters to calculate the power loss density.
• More complex empirical loss models exist, and remain valid for non-sinusoidal waveforms

• NSE/iGSE:

\[ P_{NSE} = \left( \frac{\Delta B}{2} \right)^{\frac{\alpha}{\beta}} \frac{k_N}{T} \int_0^T \left| \frac{dB}{dt} \right|^\alpha dt \]

NSE/iGSE Shortcut for Squarewaves

• For square wave excitation, the improved loss model can be reduced to:

\[ k_N = \frac{k_{NE}}{2\pi} \int_0^{2\pi} \left| \cos \theta \right|^\alpha d\theta \]

\[ P_{NSE} = k_N \int (\Delta B)^\beta \left( \frac{2}{D} \right)^\alpha + \left( \frac{2}{1-D} \right)^\alpha (1-D) \]

• Full Paper included on materials page of website

Inductor Design

Magnetetics Losses

- Magnetic Device Losses
  - Copper Loss
    - DC Copper Loss
    - Skin Effect
    - Proximity Effect
  - AC Copper Loss
  - Eddy Current
  - Fringing Flux
- Core Loss
- Hysteresis

High Frequency Losses
**Kg and Kgfe Methods**

- Two closed-form methods to solve for the optimal inductor design *under certain constraints/assumptions*
- Neither method considers losses other than DC copper and (possibly) Steinmetz core loss
- Both methods particularly well suited to spreadsheet/iterative design procedures

<table>
<thead>
<tr>
<th></th>
<th>Kg</th>
<th>Kgfe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Losses</td>
<td>DC Copper (specified)</td>
<td>DC Copper, SE Core Loss (optimized)</td>
</tr>
<tr>
<td>Saturation</td>
<td>Specified</td>
<td>Checked After</td>
</tr>
<tr>
<td>B_{max}</td>
<td>Specified</td>
<td>Optimized</td>
</tr>
</tbody>
</table>

**Kg Method Derivation**

The four constraints:

\[ nI_{\text{max}} = B_{\text{max}} A_c \frac{\ell_x}{A_0} = B_{\text{max}} \frac{\ell_x}{A_0} \]

\[ L = \frac{n^2}{R_g} = \frac{\mu_0 A_c n^2}{\ell_g} \]

\[ K_g W_A = nA_w \]

\[ R = \rho \frac{n(MLT)}{A_w} \]

These equations involve the quantities

- \( A_c, W_A, \) and \( MLT, \) which are functions of the core geometry,
- \( I_{\text{max}}, B_{\text{max}}, \mu_0, L, K_w, R, \) and \( \rho, \) which are given specifications or other known quantities, and
- \( n, \ell_g, \) and \( A_w, \) which are unknowns.

Elimination of \( n, \ell_g, \) and \( A_w, \) leads to

\[ A_c^2 W_A (MLT) \geq \frac{\rho L^2 I_{\text{max}}^2}{B_{\text{max}}^2 R K_g} \]
Simulation Modeling

Circuit Simulation

- Matlab, Simulink, LTSpice
  - Other tools accepted, but not supported
- Choose model type (switching, averaged, dynamic)
- Supplement analytical work rather than repeating it
- Show results which clearly demonstrate what matches and what does not with respect to experiments (i.e. ringing, slopes, etc.)
LTSpice Modeling Examples

- Example files added to course materials page

Custom Transistor Model

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Manufacturer Device Model

• Text-only netlist model of device including additional parasitics and temperature effects
• May slow or stop simulation if timestep and accuracy are not adjusted appropriately

Full Switching Simulation
Switching Model Simulation Results

• Simulation Time ≈ 15 minutes

Full Switching Model

• Gives valuable insight into circuit operation
  – Understand expected waveforms
  – Identify discrepancies between predicted and experimental operation
• Slow to simulate; significant high frequency content
• Cannot perform AC analysis
Averaged Switch Modeling: Motivation

- A large-signal, nonlinear model of converter is difficult for hand analysis, but well suited to simulation across a wide range of operating points
- Want an averaged model to speed up simulation speed
- Also allows linearization (AC analysis) for control design

Nonlinear, Large-Signal Equations
Nonlinear, Averaged Circuit

\[
\begin{align*}
L \frac{d\langle i_L \rangle}{dt} &= \langle v_{bat} \rangle - (1 - d)\langle v_{bus} \rangle \\
C \frac{d\langle v_{bus} \rangle}{dt} &= (1 - d)\langle i_L \rangle - \langle i_{bus} \rangle
\end{align*}
\]

Implementation in LTSpice

\[
\begin{align*}
\langle v_1(t) \rangle_{T_s} &= d^n(t) \langle v_2(t) \rangle_{T_s} \\
\langle i_2(t) \rangle_{T_s} &= d^l(t) \langle i_1(t) \rangle_{T_s}
\end{align*}
\]
Averaged Switch Model

Averaged Model With Losses

What known error will be present in loss predictions with this model?

\[ P_{loss} = V_{out} \cdot f_s \left[ I_{loss,1} + Q_r \right] \]

\[ F_{sw} = \frac{1}{f_s} Q_r \]