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

<table>
<thead>
<tr>
<th>Conduction Losses</th>
<th>Frequency-Dependent Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFETS</td>
<td>IGBTs</td>
</tr>
<tr>
<td>• $R_{op}$</td>
<td>• $r_{cc}$</td>
</tr>
<tr>
<td>• $V_{op}$</td>
<td>• $V_{ce}$</td>
</tr>
<tr>
<td>Capacitors</td>
<td>MOSFETS</td>
</tr>
<tr>
<td>• $C_{loss}$</td>
<td></td>
</tr>
</tbody>
</table>
Inductor Core Loss

- Governed by Steinmetz Equation:

\[ P_v = K_{fe} f_s^\alpha (\Delta B)^\beta \text{ [mW/cm}^3\text{]} \]

- Parameters \( K_{fe}, \alpha, \) 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 by the following formula:

\[ P_{\text{core}} = C_m \cdot f^x \cdot B_{\text{peak}}^y \cdot (c_{t0} - c_{t1}T + c_{t2}T^2) \]  \[3\]

\[ = C_m \cdot C_T \cdot f^x \cdot B_{\text{peak}}^y \]  \[\text{[mW/cm}^3]\]

### Table 1: Fit parameters to calculate the power loss density

<table>
<thead>
<tr>
<th>Ferrite</th>
<th>f (kHz)</th>
<th>Cm</th>
<th>x</th>
<th>y</th>
<th>c_{t2}</th>
<th>c_{t1}</th>
<th>c_{t0}</th>
</tr>
</thead>
<tbody>
<tr>
<td>JIC30</td>
<td>20-100</td>
<td>7.13 \times 10^{-3}</td>
<td>1.42</td>
<td>3.02</td>
<td>5.65 \times 10^{-4}</td>
<td>6.65 \times 10^{-2}</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>100-200</td>
<td>7.13 \times 10^{-3}</td>
<td>1.42</td>
<td>5.02</td>
<td>4.10 \times 10^{-4}</td>
<td>6.8 \times 10^{-2}</td>
<td>3.8</td>
</tr>
<tr>
<td>JIC90</td>
<td>20-200</td>
<td>3.2 \times 10^{-3}</td>
<td>1.36</td>
<td>2.75</td>
<td>1.65 \times 10^{-4}</td>
<td>3.1 \times 10^{-2}</td>
<td>2.45</td>
</tr>
<tr>
<td>JIC94</td>
<td>20-200</td>
<td>2.37 \times 10^{-3}</td>
<td>1.36</td>
<td>2.75</td>
<td>1.65 \times 10^{-4}</td>
<td>3.1 \times 10^{-2}</td>
<td>2.45</td>
</tr>
<tr>
<td>280-400</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>
<td></td>
</tr>
<tr>
<td>JF3</td>
<td>100-200</td>
<td>0.25 \times 10^{-3}</td>
<td>1.63</td>
<td>2.45</td>
<td>0.72 \times 10^{-4}</td>
<td>1.65 \times 10^{-2}</td>
<td>1.26</td>
</tr>
<tr>
<td>300-500</td>
<td>2.1 \times 10^{-3}</td>
<td>1.8</td>
<td>2.5</td>
<td>0.72 \times 10^{-4}</td>
<td>1.65 \times 10^{-2}</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td>500-1000</td>
<td>5.6 \times 10^{-3}</td>
<td>2.4</td>
<td>2.75</td>
<td>0.67 \times 10^{-4}</td>
<td>0.81 \times 10^{-2}</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>JF4</td>
<td>500-1000</td>
<td>12.1 \times 10^{-3}</td>
<td>1.75</td>
<td>2.9</td>
<td>0.95 \times 10^{-4}</td>
<td>1.1 \times 10^{-2}</td>
<td>1.15</td>
</tr>
<tr>
<td>1000-3000</td>
<td>1.1 \times 10^{-11}</td>
<td>2.8</td>
<td>2.4</td>
<td>0.34 \times 10^{-4}</td>
<td>0.61 \times 10^{-2}</td>
<td>0.67</td>
<td></td>
</tr>
</tbody>
</table>

### NSE/iGSE

- More complex empirical loss models exist, and remain valid for non-sinusoidal waveforms
- NSE/iGSE:

\[ P_{\text{NSE}} = \left( \frac{\Delta B}{2} \right)^{\alpha} \cdot k \cdot \frac{T}{T_0} \int_0^T \left| \frac{dR}{dt} \right| \, dt \]

\[ P_{\text{NSE}} \text{ [kW/m}^3\text{]} \]

\[
\begin{array}{c}
D \\
0.5 \\
0.6 \\
0.7 \\
0.8 \\
0.9 \\
1
\end{array}
\]

\[
\begin{array}{c}
P_{\text{NSE}} \\
50 \\
100 \\
150 \\
200
\end{array}
\]
NSE/iGSE Shortcut for Squarewaves

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

\[ k_N = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos \theta|^\alpha d\theta} \]  (8)

\[ P_{NSE} = k_N f^\alpha (\Delta B)^\beta \left( \left( \frac{2}{D} \right) + \left( \frac{2}{1-D} \right) (1-D) \right) \]  (9)

• Full Paper included on materials page of website


Inductor Design
**Magnetics Losses**

- Magnetic Device Losses
  - Copper Loss
  - Core Loss
  - DC Copper Loss
  - AC Copper Loss
  - Eddy Current
  - Hysteresis

**High Frequency Losses**
- Skin Effect
- Proximity Effect
- Fringing Flux

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**$K_g$ and $K_{gfe}$ 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>Losses</th>
<th>$K_g$</th>
<th>$K_{gfe}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Copper</td>
<td>DC Copper</td>
<td>DC Copper, SE Core Loss</td>
</tr>
<tr>
<td>(specified)</td>
<td></td>
<td>(optimized)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Saturation</th>
<th>Specified</th>
<th>Checked After</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{max}$</td>
<td>Specified</td>
<td>Optimized</td>
</tr>
</tbody>
</table>

1/26/2014
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

```
.model myO D(Ron=1m Roff=1G Vtwd=0.5)
.model mySw SW(Ron=10m Roff=1G Vt=0 Von=1 Voff=.5)
```

![Custom Transistor Model Diagram](image)
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

\[ L \frac{d\langle i_L \rangle}{dt} = \langle v_{\text{bus}} \rangle - (1 - d)\langle v_{\text{bus}} \rangle \]
\[ C \frac{d\langle v_{\text{bus}} \rangle}{dt} = (1 - d)\langle i_L \rangle - \langle i_{\text{bus}} \rangle \]

Implementation in LTSpice

\[ \langle v_1(t) \rangle_{T_2} = d(t) \langle v_2(t) \rangle_{T_2} \]
\[ \langle i_2(t) \rangle_{T_3} = d(t) \langle i_1(t) \rangle_{T_3} \]
Circuit Averaging and Averaged Switch Modeling

- Historically, circuit averaging was the first method known for modeling the small-signal ac behavior of CCM PWM converters
- It was originally thought to be difficult to apply in some cases
- There has been renewed interest in circuit averaging and its corrolary, averaged switch modeling, in the last two decades
- Can be applied to a wide variety of converters
  - We will use it to model DCM, CPM, and resonant converters
  - Also useful for incorporating switching loss into ac model of CCM converters
  - Applicable to 3Ø PWM inverters and rectifiers
  - Can be applied to phase-controlled rectifiers
- Rather than averaging and linearizing the converter state equations, the averaging and linearization operations are performed directly on the converter circuit

Boost converter example

Ideal boost converter example

Two ways to define the switch network

(a) (b)
Circuit Averaging

Averaged time-invariant network containing converter reactive elements

\[ C \quad L \]
\[ + \quad \langle v_C(t) \rangle T_s \quad - \quad \langle i_L(t) \rangle T_s \]
\[ R \quad + \quad \langle v(t) \rangle T_s \quad - \quad \langle v_g(t) \rangle T_s \]

Control input \( d(t) \)

Power input Load

Compute average values of dependent sources

Average the waveforms of the dependent sources:

\[ \langle v_1(t) \rangle T_s = d'(t) \langle v_2(t) \rangle T_s \]
\[ \langle i_2(t) \rangle T_s = d'(t) \langle i_1(t) \rangle T_s \]
Summary: Circuit averaging method

Model the switch network with equivalent voltage and current sources, such that an equivalent time-invariant network is obtained.

Average converter waveforms over one switching period, to remove the switching harmonics.

Implementation in LTSpice
Averaged Switch Model

- Can perturb an linearize as normal for linear SSM
- Most general switch cell is included in library file, switch.lib
Switch.lib CCM1 Model

Generalized Equations:

\[ \langle v_1(t) \rangle_{t_s} = \frac{d}{dt} \langle v_2(t) \rangle_{t_s} \]
\[ \langle i_1(t) \rangle_{t_s} = \frac{d}{dt} \langle i_2(t) \rangle_{t_s} \]

- Subcircuit: CCM1
- Application: two-switch PWM converters
- Limitations: ideal switches, CCM only, no transformer
- Parameters: none
- Nodes:
  1: transistor positive (drain for an n-channel MOS)
  2: transistor negative (source for an n-channel MOS)
  3: diode cathode
  4: diode anode
- 5: duty cycle control input

```
.subckt CCM1 1 2 3 4 5
Et 1 2 value=[(1-v(5))*v(3,4)/v(5)]
Gd 4 3 value=[(1-v(5))/|Et|*v(5)]
.ends
```

Fig. B.1: Averaged switch model CCM1: (a) the general two-switch network; (b) symbol for the averaged switch subcircuit model; (c) PSpice netlist of the subcircuit.

Averaged Switch Modeling: Further Comments

- Model is slightly different but can be produced in same manner for
  - Inclusion of loss models
  - Transformer isolated converters
  - Converters in DCM
- See book appendix B.2 for further notes
Averaged Model With Losses

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