Converter Loss Analysis

ECE 482 Lecture 4
January 17, 2014

Announcements

• Finish Experiment 1: report due Monday, 1/27
• This week: Experiment 2
  – Boost open-loop construction and modeling
  – Prelab: Inductor design and switch selection
• Component kits available in circuits store
  – $80 per group for components for Labs 2 and 3
  – Plan to spend additional <$5.00 on resistors
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

Boost Converter Loss Analysis

• Begin by solving important waveforms throughout converter assuming lossless operation
Power Stage Losses

**Conduction Losses**
- MOSFETS:
  - $R_{on}$
  - $r_{on}$
  - $V_f$
  - $R_d$
  - $C_{oss}$
  - $C_d$
- IGBTs:
  - $V_{ce}$
- Diodes:
  - $R_{di}$
- Inductor:
  - $R_{dt}$
- Capacitors:
  - ESR

**Frequency-Dependent Losses**
- Current tailing
- Reverse-Recovery
- Skin Effect
- Core Loss
- Fringing
- Proximity
- Dielectric Losses

**Conduction Loss Modeling**
MOSFET Equivalent Circuit

- Considering only power stage losses (gate drive neglected)
- MOSFET operated as power switch
- Intrinsic body diode behaviors considered using normal diode analysis

MOSFET On Resistance

- On resistance extracted from datasheet waveforms
- Significantly dependent on $V_{gs}$ amplitude, temperature
Boost Converter RMS Currents

- MOSFET conduction losses due to \((r_{ds})_{on}\) depend given as

\[
P_{\text{cond,FET}} = I_{d,rms}^2 (r_{ds})_{on}
\]

MOSFET Conduction Losses

- RMS values of commonly observed waveforms
appendix from Power Book
Diode Loss Model

- Example loss model includes resistance and forward voltage drop extracted from datasheet

IGBT Loss Model

\[ P_{\text{cond}} = I_{V_{\text{rms}}}^2 r_{\text{ce}} + V_{ce} I_{V_{\text{avg}}} \]
Semiconductor Switch Conduction Loss

- Equivalent circuit of MOSFET with external antiparallel diode has two, non-ideal diodes
- Diodes, even when matched, will not share current equally, but \( v_d = v_{ds} \) must remain true
- Silicon rectifier diodes are minority carrier devices
  - Concentration of minority carriers depends heavily on temperature

Diode Paralleling

12 Forward characteristics of reverse diode

\[ I_d = f(V_{bd}) \]

Parameter: \( T_j \)
DC Inductor Resistance

- DC Resistance given by
  \[ R_{DC} = \rho \frac{l_b}{A_w} \]
- At room temp, \( \rho = 1.724 \cdot 10^{-6} \text{ } \Omega \text{-cm} \)
- At 100°C, \( \rho = 2.3 \cdot 10^{-6} \text{ } \Omega \text{-cm} \)
- Losses due to DC current:
  \[ P_{cu,DC} = I_{L,rms}^2 R_{DC} \]

Inductor Conduction Losses

- Conduction losses dependent on RMS current through inductor
Skin Effect in Copper Wire

- Current profile at high frequency is exponential function of distance from center with characteristic length $\delta$

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Skin Depth

*Fig. 13.23 Penetration depth $\delta$, as a function of frequency $f$, for copper wire.*
AC Resistance

\[ A_{w,\text{eff}} = \pi r_w^2 - \pi (r_w - \delta)^2 \]

\[ R_{ac} = \rho \frac{l_b}{A_{w,\text{eff}}} \]

Proximity Effect

- In foil conductor closely spaced with \( h \gg \delta \), flux between layers generates additional current according to Lentz’s law.

\[ P_1 = I_{L,rms}^2 R_{ac} \]

- Power loss in layer 2:

\[ P_2 = I_{L,rms}^2 R_{ac} + (2I_{L,rms})^2 R_{ac} \]

\[ P_2 = 5P_1 \]

- Needs modification for non-foil conductors
Capacitor Loss Model

- Operation well below resonance
- All loss mechanisms in a capacitor are generally lumped into an empirical loss model
- Equivalent Series Resistance (ESR) is *highly* frequency dependent
- Datasheets may give effective impedance at a frequency, or loss factor:

\[
\delta = \frac{\pi}{2} - \theta
\]

\[
D = \tan(\delta)
\]

Capacitor ESR Extraction

<table>
<thead>
<tr>
<th>WV</th>
<th>Cap (µF)</th>
<th>Case size (mmXmmXmm)</th>
<th>Impedance (Ωmax/100kHz)</th>
<th>Rated ripple current (mA/100kHz)</th>
<th>Part No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>5 x 11</td>
<td>1.4</td>
<td>4.6</td>
<td>125</td>
<td>ECZ10H E-06R5M11C</td>
</tr>
<tr>
<td>13</td>
<td>6.3 x 11</td>
<td>0.82</td>
<td>2.3</td>
<td>265</td>
<td>ECZ10H E-15R1M11C</td>
</tr>
<tr>
<td>27</td>
<td>4 x 11.5</td>
<td>0.36</td>
<td>1.4</td>
<td>355</td>
<td>ECZ10H E-04R4M11C</td>
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<tr>
<td>39</td>
<td>3 x 15</td>
<td>0.25</td>
<td>1.0</td>
<td>460</td>
<td>ECZ10H E-04R4M15D</td>
</tr>
<tr>
<td>47</td>
<td>10 x 12.5</td>
<td>0.17</td>
<td>0.86</td>
<td>480</td>
<td>ECZ10H E-04R4M12D</td>
</tr>
<tr>
<td>56</td>
<td>8 x 20</td>
<td>0.19</td>
<td>0.75</td>
<td>560</td>
<td>ECZ10H E-04R4M20D</td>
</tr>
<tr>
<td>68</td>
<td>10 x 16</td>
<td>0.11</td>
<td>0.47</td>
<td>660</td>
<td>ECZ10H E-06R4M16D</td>
</tr>
<tr>
<td>82</td>
<td>10 x 20</td>
<td>0.084</td>
<td>0.34</td>
<td>800</td>
<td>ECZ10H E-06R4M20D</td>
</tr>
<tr>
<td>100</td>
<td>12 x 18</td>
<td>0.11</td>
<td>0.34</td>
<td>750</td>
<td>ECZ10H E-06R4M18D</td>
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<tr>
<td>120</td>
<td>15 x 25</td>
<td>0.069</td>
<td>0.28</td>
<td>900</td>
<td>ECZ10H E-06R4M25D</td>
</tr>
<tr>
<td>150</td>
<td>12 x 20</td>
<td>0.067</td>
<td>0.18</td>
<td>1.300</td>
<td>ECZ10H E-06R4M20D</td>
</tr>
<tr>
<td>180</td>
<td>12 x 25</td>
<td>0.047</td>
<td>0.14</td>
<td>1.250</td>
<td>ECZ10H E-06R4M25D</td>
</tr>
<tr>
<td>220</td>
<td>14 x 20</td>
<td>0.044</td>
<td>0.16</td>
<td>1.560</td>
<td>ECZ10H E-06R4M20D</td>
</tr>
<tr>
<td>270</td>
<td>12 x 30</td>
<td>0.057</td>
<td>0.33</td>
<td>1.560</td>
<td>ECZ10H E-06R4M30D</td>
</tr>
</tbody>
</table>

**Dissipation Factor:** 1% Max. (25 °C, 1kHz)

<table>
<thead>
<tr>
<th>Dissipation Factor (%)</th>
<th>Rated voltage (Volts)</th>
<th>0.3V</th>
<th>1.5V</th>
<th>15V</th>
<th>30V</th>
<th>60V</th>
<th>85V</th>
<th>100V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.18</td>
<td>0.14</td>
<td>0.17</td>
<td>0.10</td>
<td>0.09</td>
<td>0.09</td>
</tr>
</tbody>
</table>

When nominal capacitance exceeds 1,000µF, add 0.02 to the values above for each 1,000µF increase.

(at 20°C, 120kHz)
Switching Loss Modeling

MOSFET Parasitic Capacitances

- p-n junction is reverse-biased
- off-state voltage appears across n region

$V_{ds} > V$
Lump Switched Node Capacitance

- Consider a single equivalent capacitor at switched node which combines energy storage due to all four semiconductor devices.
$Q_1$ Turn off

$E_{loss} = \phi$

$Q_1$ Turn on

$E_{Q_1, on} = \frac{1}{2} C_s V_{bus}^2$

$P_{sw} = E_{Q_1, on} f_S$
Device Output Capacitances

**Measurements** are small-signal

**At any voltage:**

\[ \hat{i}_{ds} = C_{oss} \left| V_{gs} \right| \frac{d\hat{v}_{ds}}{dt} \]

**Total energy** is then:

\[ E_{ds}(V) = \int_{0}^{t} \hat{i}_{ds}(\tau) \hat{v}_{ds}(\tau) d\tau \]

\[ E_{ds}(V) = \int_{0}^{t} C_{oss} \left| v_{gs}(\tau) \right| \frac{d\hat{v}_{ds}(\tau)}{d\tau} \hat{v}_{ds}(\tau) d\tau \]

\[ E_{ds}(V) = \int_{0}^{t} v_{ds} C_{ds} \left( v_{gs} \right) dv_{ds} \]

\[ C_{eq,ds}(V) = \frac{2E_{ds}(V)}{V^2} \]
Energy Storage Example

- Different device (FDMC2610)
- Charged to 100 V, capacitance stores same energy as 67pF linear capacitor

\[ E = \text{trapz}(v_x(x), C_x(x) \times \text{abs}(v_x(x))); \]
\[ C_{\text{per}} = 2 \times (E)/V_g^2; \]

Diode Reverse Recovery

- Diodes will turn on during dead time intervals
- Significant reverse recovery possible on both body diode and external diode

\[ E_{\text{on,rr}} = \left( I_L - \Delta I_L \right) I_{\text{rr}} + Q_{\text{rr}} V_{\text{bus}} \]
IGBT Switching

IGBT Switching Waveforms
Datasheet Reporting of IGBT Switching Loss

### Switching Characteristics

<table>
<thead>
<tr>
<th>Condition</th>
<th>Turn-On Delay Time</th>
<th>Rise Time</th>
<th>Turn-Off Delay Time</th>
<th>Fall Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>V(<em>{CC}) = 200 V, I(</em>{C}) = 20 A, R(<em>{G}) = 5 (\Omega), V(</em>{G}) = 15 V, Resistive Load, T(_{C}) = 25°C</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Condition</td>
<td>V(<em>{CC}) = 200 V, I(</em>{C}) = 20 A, R(<em>{G}) = 5 (\Omega), V(</em>{G}) = 15 V, Resistive Load, T(_{C}) = 125°C</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Figure 15. Switching Loss vs. Gate Resistance

- Common Emitter
- V\(_{CC}\) = 200V, V\(_{G}\) = 15V
- I\(_{C}\) = 50A
- T\(_{C}\) = 20°C
- T\(_{C}\) = 120°C...

#### Figure 16. Switching Loss vs. Collector Current

- Common Emitter
- V\(_{CC}\) = 15V, R\(_{G}\) = 50Ω
- T\(_{C}\) = 20°C
- T\(_{C}\) = 120°C...