Overlooked Loss Mechanisms In Flyback Transformers

Isaac Cohen
Agenda

• Flyback transformer basics
• Review of Flyback transformer losses:
  – Core loss
    • Dependence on DC bias
    • Effect of waveform and duty cycle
  – Effect of snubber clamp voltage on leakage losses
• Effect of input voltage range on the FB transformer power density
Core Loss – Effect of Waveform & DC Flux Bias

- **Traditional assumptions:**
  - DC Bias has no effect
  - Square-wave close to sine

- **Traditional method:**
  - Calculate $\Delta B_{ac}$ at $F_{sw}$, neglect $B_{dc}$
  - Core material manufacturer data sheet:
    - Read core loss at $\Delta B_{ac}$ and $F_{sw}$
    - Loss data provided for sine excitation

- **The reality:**
  - Waveform and duty cycle have significant impact on core loss
  - DC bias has significant impact on core loss
  - Several papers published on the subject
    - *Reference [1] and [2] provide most useful information*

Effect of Waveform on Core Loss [1]

- Proposed curve fit equation for square-wave excitation, based on measured data:
  \[
  \frac{P_{v\_rect}}{P_{v\_sine}} = F_{wave\_form} = \frac{8}{\pi^2 \cdot [4D \cdot (1-D)]^{\gamma+1}}
  \]  
  (Eq. 1)

- \(P_{v\_sine}\) – conventionally-calculated core loss
  - For sinewave excitation of equal flux swing (available from the material data sheet)

- \(D\) – duty cycle of square-wave

- \(\gamma\) – correction factor
  - Depends on material, frequency & temperature
  - Could be measured and provided by the magnetic material manufacturers
  - Values for several ferrites at 25°C empirically determined in [1]

<table>
<thead>
<tr>
<th></th>
<th>200kHz</th>
<th>500kHz</th>
<th>1MHz</th>
<th>1.5MHz</th>
<th>3MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C90</td>
<td>-0.37</td>
<td>-0.12</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3F3</td>
<td>-0.37</td>
<td>-0.12</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3F35</td>
<td>-</td>
<td>-0.12</td>
<td>0.15</td>
<td>0.18</td>
<td>-</td>
</tr>
<tr>
<td>3F5</td>
<td>-</td>
<td>-</td>
<td>-0.5</td>
<td>-0.05</td>
<td>-</td>
</tr>
<tr>
<td>N49</td>
<td>-0.35</td>
<td>0.16</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DMR50B</td>
<td>-0.4</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4C65</td>
<td>-</td>
<td>-</td>
<td>-0.7</td>
<td>-</td>
<td>-0.7</td>
</tr>
</tbody>
</table>

---

$F_{\text{waveform}}$ for Square-wave vs. $D$ at $F_{\text{sw}}$ 1 MHz \cite{1}

- 50% duty-cycle
  -> lower loss than sine
- Significant loss increase as duty cycle approaches 100% or 0%
- Some new HF materials perform noticeably better at duty cycle extremes:
  - 3F5
  - 4C65

- **Recommendation**
  - make your own in-circuit measurements
  - ask TI for help

\[ \frac{P_{v_{\text{rect}}}}{P_{v_{\text{sin}}}} \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\end{figure}

\begin{itemize}
    \item \cite{1} “A New Core Loss Model for Rectangular AC Voltages”, Mingkai Mu, Fred C. Lee, CPES, Virginia Tech, ECCE 2014
Effect of DC Bias \[2\]

• DC Bias shown to have significant impact on core loss
  – Many different papers published

• The effect is measured and quantified for two ferrite core materials:
  – 3F35
  – PC90

• A function \( F(H_{dc}) \) is developed (by curve fit to measured data)

• Enables calculation of core loss under DC bias

Loss vs. DC Bias Normalized to zero DC Bias [2]

3F35 @ 500 kHz, vary $B_{pk}$, $D$

Curve fit: $F(H_{dc}) = 2.1875 \times 10^{-4} H_{dc}^2 + 1$

PC90 @ 1 MHz, vary $B_{pk}$, $D$

Curve fit: $F(H_{dc}) = \sqrt{0.04 \times H_{dc} + 1}$

Core Loss Discussion Points

• DC bias, wave-shape & Duty-cycle cannot be neglected!
  – *May help to explain excess core loss in some situations*

• Practical method to account for effects:
  \[ P_{v_{\text{total}}} = P_{v_{\text{sine}}} \cdot F_{\text{waveform}}(\gamma, D) \cdot F_{\text{DC}}(H_{\text{DC}}) \]  
  *(Eq. 2)*

• Effect of extreme duty cycles on loss
  – Often-neglected penalty for wide input and/or output voltage range
  – *Advantage of Flyback over Forward: Lower D range for same input voltage variation*

• Effect of DC bias on core loss
  • Effect on materials other than ferrite not known.
    – May significantly reduce the benefit of deep CCM operation
    – Illustrates advantage of double-ended topologies over single-ended

• **Users need to insist that ferrite manufacturers provide** \( \gamma \) **and** \( F_{\text{DC}} \) **data!**
• **Recommend making your own in-circuit measurements**
Impact of Snubber Clamp Voltage

• Switch Q turn-off:
  – Energy -> clamp until $L_{leak}$ current -> zero
  – Time depends on ($V_{clamp} - V_{reflected}$) difference & on $L_{leak}$ value
  – Also magnetising energy -> clamp
  – Smaller difference ($V_{clamp} - V_{reflected}$)
    => more magnetising energy absorbed by the clamp

• Lower clamp voltage
  – Lower voltage FET, lower $R_{dson}$
  – But extra clamp loss
    • Clamp loss can out-weigh FET loss saving

• Higher clamp voltage
  – Higher voltage FET => higher $R_{dson}$
Comparison of Clamp Level Effect

Vclamp/Vo*1.1 (Np/Ns=1)

Vclamp/Vo*1.5 (Np/Ns=1)
Effect of Clamp Voltage on Energy Loss

- Lower clamp voltage attracts more magnetizing energy to the clamp!
- Can defeat, or even out-weight, benefit of lower $R_{dson}$

\[ \frac{V_{clamp}}{N \cdot V_{out}} \]

\[ \gamma(\alpha, \%) \]

\[ \frac{L_{\text{leak}}}{L_{\text{mag}}} = 5\% \]

\[ \frac{L_{\text{leak}}}{L_{\text{mag}}} = 2.5\% \]

\[ \frac{L_{\text{leak}}}{L_{\text{mag}}} = 1\% \]
Effect of the input voltage range on power density of Flyback TM converters

- How does the input voltage range affect the power density and/or the efficiency of a FB transformer?
- Investigate the effect of input voltage range on loss of Flyback transformers
- To verify, design a TM Flyback converter optimized to deliver a power $P$ at a frequency $F$ and an input voltage $V_{\text{in}}$.
- Examine the effect of reducing the input voltage $V_{\text{in}}$ by a factor $K_v$
Mag Current at $V_{in}=375V$ and $70V$ input

- Frequency decreases, peak current must increase to maintain same output power
- Energy storage in the transformer ($=\text{size}$) must increase
- Output cap must increase
**Analysis result**

- The volume of a TM transformer designed to deliver a power P at 375V has to be increased by a factor of 2.361 to deliver the same power at 70V!!!
  - CCM is only slightly better: Starting in TM at high line, the volume of a TM transformer will increase by a factor 2.044

- The output cap will increase by a factor of between 2 and 3 (depending if selection dominated by capacitance or ESR)
  - Much smaller increase for CCM (frequency is fixed)

- The effect on other topologies will also be significant

- Reducing the dynamic range of the input voltage is very beneficial for density and/or efficiency improvement
  - That’s a justification for two stage conversion and the phenomenal power density of “DC transformers”!
Verification: High $L_{\text{mag}}$ vs. Low $L_{\text{mag}}$

- Valley Switched Flyback Transformer designed to work at $70V < \text{Vin} < 375V$ has been re-gapped for operation over $200V < \text{Vin} < 375V$ range
- Significant efficiency improvement: 2% - that is 35% reduction in total loss!
Appendix

Ferroxcube Power Ferrites Core Loss Calculator
Recommended literature & further reading