High Step-Up Conversion Ratios

Boost Converter

Flyback, $n=100$

Flyback Leakage Inductance
Switch Ratings

Active Switch Stress / Switch Utilization
Semiconductor Proportional Cost

\[
\left( \frac{\text{semiconductor cost}}{\text{per kW output power}} \right) = \frac{\left( \frac{\text{semiconductor device cost}}{\text{per rated kVA}} \right)}{\left( \frac{\text{voltage derating factor}}{\text{current derating factor}} \right) \left( \frac{\text{converter switch utilization}}{\text{}} \right)}
\]

(\text{semiconductor device cost per rated kVA}) = \text{cost of device, divided by product of rated blocking voltage and rms current, in $/kVA. Typical values are less than $1/kVA.}

(\text{voltage derating factor}) \text{ and (current derating factor) are required to obtain reliable operation. Typical derating factors are 0.5 - 0.75.}

\text{Typical cost of active semiconductor devices in an isolated dc-dc converter: $1 - $10 per kW of output power.}

Switch Utilization Table

<table>
<thead>
<tr>
<th>Converter</th>
<th>( U(D) )</th>
<th>max ( U(D) )</th>
<th>max ( U(D) ) occurs at ( D = )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>( \frac{D}{1} )</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Boost</td>
<td>( \frac{D'}{1} )</td>
<td>( \infty )</td>
<td>0</td>
</tr>
<tr>
<td>Buck-boost, flyback, nonisolated SEPIC, isolated SEPIC, nonisolated Cuk, isolated Cuk</td>
<td>( \frac{D}{\sqrt{3}} )</td>
<td>( \frac{2}{\sqrt{3}} ) = 0.385</td>
<td>( \frac{1}{3} )</td>
</tr>
<tr>
<td>Forward, ( n_1 = n_2 )</td>
<td>( \frac{D}{1} )</td>
<td>( \frac{1}{\sqrt{2}} ) = 0.353</td>
<td>( \frac{1}{2} )</td>
</tr>
<tr>
<td>Other isolated buck-derived converters (full-bridge, half-bridge, push-pull)</td>
<td>( \frac{D}{2} )</td>
<td>( \frac{1}{\sqrt{2}} ) = 0.353</td>
<td>1</td>
</tr>
<tr>
<td>Isolated boost-derived converters (full bridge, push-pull)</td>
<td>( \frac{D}{2\sqrt{1+D}} )</td>
<td>( \frac{1}{2} )</td>
<td>0</td>
</tr>
</tbody>
</table>
Converter Design

• No definitive way to determine best converter topology for a given application
• Performance in power electronics depends heavily on details of implementation
  – Circuit layout
  – Gate driver design
  – Cooling system
  – Materials
• Switch stress/utilization give some direction on candidate topologies
  – Active switches often dominate loss and cost of converter

Parameterized Design

• To design converter independent of device implementation, consider voltage and current stresses of all elements
• In transformer isolated converters, the turns ratio is a degree of freedom for the design
• Use design equations in e.g. Excel or Matlab to examine effects of design on resulting stresses
Spreadsheet Design Example

**Specifications**
- Maximum input voltage $V_g$ 390 V
- Minimum input voltage $V_g$ 260 V
- Output voltage $V$ 15 V
- Maximum load power $P_{load}$ 200 W
- Minimum load power $P_{load}$ 20 W
- Switching frequency $f_s$ 100 kHz
- Maximum output ripple $\Delta v$ 0.1 V
- Input voltage: rectified 230 Vrms ±20%
- Regulated output of 15 V
- Rated load power 200 W
- Must operate at 10% load
- Select switching frequency of 100 kHz
- Output voltage ripple ≤ 0.1V

Compare single-transistor forward and flyback converters in this application.
Specifications are entered at top of spreadsheet.

---

**Forward Converter in CCM**

![Forward Converter Circuit Diagram]

**Design variables**
- Reset winding turns ratio $n_2/n_1$ 1
- Turns ratio $n_3/n_1$ 0.125
- Inductor current ripple $\Delta i$ 2A ref to sec
- Design for CCM at full load; may operate in DCM at light load

---
Flyback Converter in CCM

**Design variables**
- Turns ratio $n_2/n_1$: 0.125
- Inductor current ripple $\Delta i$: 3 A ref to sec

- Design for CCM at full load; may operate in DCM at light load

---

**Forward Converter Analysis**

Maximum duty cycle occurs at minimum $V_g$ and maximum $P_{load}$.

Converter then operates in CCM, with

$$D = \frac{n_1}{n_3} \frac{V}{V_g}$$

Inductor current ripple is

$$\Delta i = \frac{DVT_s}{2L}$$

Solve for $L$:

$$L = \frac{DVT_s}{2\Delta i}$$

$\Delta i$ is a design variable. For a given $\Delta i$, the equation above can be used to determine $L$. To ensure CCM operation at full load, $\Delta i$ should be less than the full-load output current. $C$ can be found in a similar manner.
Forward Converter DCM Bound

Check for DCM at light load. The solution of the buck converter operating in DCM is

$$V = \frac{n_3}{n_1} \frac{V_g}{\sqrt{1 + \frac{4K}{D^2}}}$$

with \( K = 2L/R_{T_s} \) and \( R = V^2/P_{load} \)

These equations apply equally well to the forward converter, provided that all quantities are referred to the transformer secondary side.

Solve for \( D \):

$$D = \frac{2\sqrt{K}}{\sqrt{\left(\frac{2n_3V_g}{n_1V} - 1\right)^2 - 1}} \text{ in DCM}$$

$$D = \frac{n_1V}{n_3V_g} \text{ in CCM}$$

at a given operating point, the actual duty cycle is the small of the values calculated by the CCM and DCM equations above. Minimum \( D \) occurs at minimum \( P_{load} \) and maximum \( V_g \).

Fundamentals of Power Electronics 93 Chapter 6: Converter circuits

Forward Converter Stress

Worst-case component stresses can now be evaluated.

Peak transistor voltage is

$$\max\left(v_{Q1}\right) = V_g \left(1 + \frac{n_1}{n_2}\right)$$

RMS transistor current is

$$I_{Q1,rms} = \frac{n_3}{n_1} \sqrt{D} \sqrt{I^2 + \frac{(\Delta i)^2}{3}} \approx \frac{n_3}{n_1} \sqrt{D} I$$

(this neglects transformer magnetizing current)

Other component stresses can be found in a similar manner. Magnetics design is left for a later chapter.
## Spreadsheet Design Results

<table>
<thead>
<tr>
<th>Forward converter design, CCM</th>
<th>Flyback converter design, CCM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design variables</strong></td>
<td><strong>Design variables</strong></td>
</tr>
<tr>
<td>Reset winding turns ratio $n_2/n_1$</td>
<td>1</td>
</tr>
<tr>
<td>Turns ratio $n_2/n_1$</td>
<td>0.125</td>
</tr>
<tr>
<td>Inductor current ripple $\Delta i$</td>
<td>2 A ref to sec</td>
</tr>
<tr>
<td><strong>Results</strong></td>
<td><strong>Results</strong></td>
</tr>
<tr>
<td>Maximum duty cycle $D$</td>
<td>0.462</td>
</tr>
<tr>
<td>Minimum $D$, at full load</td>
<td>0.308</td>
</tr>
<tr>
<td>Minimum $D$, at minimum load</td>
<td>0.251</td>
</tr>
<tr>
<td><strong>Worst-case stresses</strong></td>
<td><strong>Worst-case stresses</strong></td>
</tr>
<tr>
<td>Peak transistor voltage $v_{Q1}$</td>
<td>780 V</td>
</tr>
<tr>
<td>Rms transistor current $I_{Q1}$</td>
<td>1.13 A</td>
</tr>
<tr>
<td>Transistor utilization $U$</td>
<td>0.226</td>
</tr>
<tr>
<td>Peak diode voltage $v_{D2}$</td>
<td>49 V</td>
</tr>
<tr>
<td>Rms diode current $I_{D2}$</td>
<td>9.1 A</td>
</tr>
<tr>
<td>Peak diode voltage $v_{D3}$</td>
<td>49 V</td>
</tr>
<tr>
<td>Rms diode current $I_{D3}$</td>
<td>11.1 A</td>
</tr>
<tr>
<td>Rms output capacitor current $i_c$</td>
<td>1.15 A</td>
</tr>
</tbody>
</table>

### Design Comparison

**Flyback converter**

- Ideal peak transistor voltage: 510V
- Actual peak voltage will be higher, due to ringing causes by transformer leakage inductance
- An 800V or 1000V MOSFET would have an adequate design margin

**Forward converter**

- Ideal peak transistor voltage: 780V, 53% greater than flyback
- Few MOSFETs having voltage rating of over 1000 V are available—when ringing due to transformer leakage inductance is accounted for, this design will have an inadequate design margin
- Fix: use two-transistor forward converter, or change reset winding turns ratio

A conclusion: reset mechanism of flyback is superior to forward
Converter Current Stresses

*Forward*
- 1.13A worst-case
- transistor utilization 0.226

*Flyback*
- 1.38A worst case, 22% higher than forward
- transistor utilization 0.284

CCM flyback exhibits higher peak and rms currents. Currents in DCM flyback are even higher

Secondary Device Stresses

*Forward*
- peak diode voltage 49V
- rms diode current 9.1A / 11.1A
- rms capacitor current 1.15A

*Flyback*
- peak diode voltage 64V
- rms diode current 16.3A
- peak diode current 22.2A
- rms capacitor current 9.1A

Secondary-side currents, especially capacitor currents, limit the practical application of the flyback converter to situations where the load current is not too great.
Chapter 6: Summary

- Transformer-based converters often useful when extreme conversion ratios or galvanic isolation are required
- Isolated converters can be analyzed using conventional approaches, first replacing transformer by ideal transformer with magnetizing inductance
- Must ensure transformer volt-second balance, even in converters where $L_m$ is not used as an energy storage element
- Selecting the best topology for a given application is often a multivariate optimization problem, but active switch stress and utilization are figures-of-merit that give some insight
- Full comparison requires detailed analysis of candidate topologies

Part II: Converter Dynamics and Control

7. AC equivalent circuit modeling
8. Converter transfer functions
9. Controller design
10. Input filter design
11. AC and DC equivalent circuit modeling of the discontinuous conduction mode
12. Current programmed control