DC-DC Converters Feedback and Control
Agenda

- Feedback generalities
- Conditions for stability
- Poles and zeros
- Phase margin and quality coefficient
- Undershoot and crossover frequency
- Compensating the converter
- Compensating with a TL431
- Watch the optocoupler!
- Compensating a DCM flyback
- Compensating a CCM flyback
- Simulation and bench results
- Conclusion
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What is Feedback?

- A target is assigned to one or several state-variables, e.g. $V_{out} = 12 \text{ V}$.
- A circuit monitors $V_{out}$ deviations related to $V_{in}$, $I_{out}$, $T^\circ$ etc.
- If $V_{out}$ deviates from its target, an error is created and fed-back to the power stage for action.
- The action is a change in the control variable: duty-cycle (VM), peak current (CM) or the switching frequency.

Compensating for the converter shortcomings!
The Feedback Implementation

- $V_{out}$ is permanently compared to a reference voltage $V_{ref}$.
- The reference voltage $V_{ref}$ is precise and stable over temperature.
- The error $\varepsilon = V_{ref} - \alpha V_{out}$ is amplified and sent to the control input.
- The power stage reacts to reduce $\varepsilon$ as much as it can.
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Positive or Negative Feedback?

- Do we want to build an oscillator?

\[ V_{in}(s) + H(s) \frac{E}{G(s)} - \]

\[ V_{out}(s) \]

\[ \frac{V_{out}(s)}{V_{in}(s)} = \frac{H(s)}{1 + H(s)G(s)} \]

Open-loop gain \( T(s) \)

\[ V_{out}(s) = \lim_{V_{in}(s) \to 0} \left[ \frac{H(s)}{G(s)H(s)} \right] V_{in}(s) \]

To sustain self-oscillations, as \( V_{in}(s) \) goes to zero, quotient must go infinite

Sign is neg for:
\[ \phi = -180^\circ \]
Conditions for Oscillations

- when the open-loop gain equals 1 (0 dB) – cross over point
- total rotation is $-360^\circ$: $-180^\circ$ for $H(s)$ and $-180^\circ$ for $G(s)$
- we have self-sustaining oscillating conditions

Total phase delay at $f_c$:
- $-180^\circ$ $H(s)$ power stage
- $-180^\circ$ $G(s)$ opamp
- total = $-360^\circ$
The Need for Phase Margin

- we need **phase** margin when \( T(s) = 0 \text{ dB} \)
- we need **gain** margin when \( \arg T(s) = -360^\circ \)

**Phase margin:**
The margin before the loop phase rotation \( \arg T(s) \) reaches \(-360^\circ\) at \( T(s) = 0 \text{ dB} \)

**Gain margin:**
The margin before the loop gain \( T(s) \) reaches 0 dB at a freq. where \( \arg T(s) = -360^\circ \)
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Poles and Zeros

- A plant (power stage) loop gain is defined by:
  \[ H(s) = \frac{N(s)}{D(s)} \]
  - Where \( H(s) \) is the numerator and \( D(s) \) is the denominator.

- Solving for \( N(s) = 0 \), the roots are called the **zeros**

- Solving for \( D(s) = 0 \), the roots are called the **poles**

\[
H(s) = \frac{(s + 5k)(s + 30k)}{s + 1k}
\]

- **Two zeros**:
  - \( s_{z_1} = -5k \)
  - \( s_{z_2} = -30k \)
- **One pole**:
  - \( s_{p_1} = -1k \)

- **Frequencies**:
  - \( f_{z_1} = \frac{5k}{2\pi} = 796 \text{ Hz} \)
  - \( f_{z_2} = \frac{30k}{2\pi} = 4.77 \text{ kHz} \)
  - \( f_{p_1} = \frac{1k}{2\pi} = 159 \text{ Hz} \)
Poles and Zeros

A pole lags the phase by -45° at its cutoff frequency.

\[
\frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{1 + sRC} = \frac{1}{1 + s/\omega_0}
\]

\[
\omega_0 = \frac{1}{RC}
\]
A zero boosts the phase by +45° at its cutoff frequency.

The general form of a zero:

$$G(s) = 1 + \frac{s}{\omega_0}$$
The Right Half-Plane Zero

- In a CCM boost, $I_{out}$ is delivered during the off time: $I_{out} = I_d = I_L (1 - D)$

If $D$ brutally increases, $D'$ reduces and $I_{out}$ drops!
- What matters is the inductor current slew-rate
- Occurs in flybacks, buck-boost, Cuk etc.
The Right-Half-Plane-Zero

- With a RHPZ we have a boost in gain but a lag in phase!

![Graph showing gain and phase response with RHPZ and LHPZ]

For LHPZ:

\[ G(s) = 1 + \frac{s}{\omega_0} \]

For RHPZ:

\[ G(s) = 1 - \frac{s}{\omega_0} \]
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How much Margin? The *RLC* Filter

- Let us study an *RLC* low-pass filter, a 2\textsuperscript{nd} order system

$$T(s) = \frac{1}{LCs^2 + RCS + 1}$$

- Parameters
  - \(f_0 = 235k\)
  - \(L = 10u\)
  - \(C = \frac{1}{(4 \times 3.14159^2 \times f_0^2 \times L)}\)
  - \(w_0 = (\{L\} \times \{C\})^{-0.5}\)
  - \(Q = 10\)
  - \(R = \frac{1}{(((\{C\}/(4 \times \{L\}))^{0.5} \times 2 \times \{Q\})}}\)

- Resonant freq. \(\omega_r\), damping factor \(\zeta\), and quality coeff. \(Q\):
  - \(\omega_r = \frac{1}{\sqrt{LC}}\)
  - \(\zeta = R \sqrt{\frac{C}{4L}}\)
  - \(Q = \frac{1}{2 \zeta}\)
The RLC Response to an Input Step

- changing $Q$ affects the transient response

- $Q = 0.1$: over damping
- $Q = 0.5$: critical damping
- $Q > 0.5$: under damping

- Fast response and no overshoot!

- Overshoot = 65%

- Asymptotically stable
Where is the Analogy with $T(s)$?

- in the vicinity of the crossover point, $T(s)$ combines:
  - one pole at the origin, $\omega_0$ and one high frequency pole, $\omega_2$
  - Link the closed-loop response to the open-loop phase margin:

\[
T(s) = \frac{1}{\left(\frac{s}{\omega_0}\right) \left(1 + \frac{s}{\omega_2}\right)} \quad \text{(OL)}
\]

Close the loop

\[
\frac{T(s)}{1 + T(s)} = \frac{1}{\frac{s^2}{\omega_0 \omega_2} + \frac{s}{\omega_0} + 1} \quad \text{(CL)}
\]

Link open-loop with closed-loop

\[
\varphi_m = Q
\]
Closed-Loop Q Versus Open-Loop $\phi_m$

- A $Q$ factor of 0.5 (critical response) implies a $\phi_m$ of 76°.
- A 45° $\phi_m$ corresponds to a $Q$ of 1.2: oscillatory response!
Summary on the Design Criteria

- compensate the open-loop gain for a phase margin of 70°
- make sure the open-loop gain margin is better than 15 dB
- never accept a phase margin lower than 45° in worst case
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A DC-DC conversion combines an inductor and a capacitor. As frequency \( f \) is swept, different elements dominate the output impedance \( Z_{out,OL} \). A buck equivalent circuit shows the components involved:

\[
Z_{out} = \left( sL_{out} + R_{Lf} \right) \| \left( R_{esr} + \frac{1}{sC_{out}} \right)
\]

Open-loop model and crossover region:

To avoid stability issues, \( f_c >> f_0 \).
Closing the Loop…

At the crossover frequency $Z_{out,CL} \approx Z_{out,OL}$
the closed-loop output impedance is dominated by $C_{out}$

$$\left| Z_{out, CL} \right| \approx \frac{1}{2\pi f_c C_{out}} \frac{1}{1+T(s)} \approx \frac{1}{2\pi f_c C_{out}} \frac{1}{\sqrt{2 - 2\cos(\phi_m)}}$$

Open-loop phase margin affects the closed-loop output impedance
An Example with a Buck

- Let’s assume an output capacitor of 1 mF
- The spec states a 80 mV undershoot for a 2 A step
- How to select the crossover frequency?

\[
\Delta V_{\text{out}} \approx \frac{\Delta I_{\text{out}}}{2\pi f_c C_{\text{out}}} \quad \Rightarrow \quad f_c \approx \frac{\Delta I_{\text{out}}}{\Delta V_{\text{out}} C_{\text{out}} 2\pi}
\]

\[
f_c \approx \frac{2}{80 \times 1 \times 2\pi} = 4 \text{ kHz}
\]

Select a 1000-µF capacitor featuring less than a 40-mΩ ESR.
Setting the Right Crossover Frequency

- Compensate the converter for a 4 kHz $f_c$

Compensated open-loop gain
Buck operated in voltage-mode

$\varphi_m = 70^\circ$

$\omega_c$

$4$ kHz

Frequency in hertz

10 100 1k 10k 100k

$-180$ $-90.0$ 0 $90.0$ $180$

$-180$ $-80.0$ $-40.0$ $0$ $40.0$ $80.0$ $180$

Gain

Phase

Gain

Phase

Plot1
Step Load the Output

- the load varies from 100 mA to 2.1 A

H(s)

PWM gain

G(s)
Measure the Obtained Undershoot

\[ \Delta V \approx 40m \times \frac{\Delta I}{\sqrt{2 - 2 \cos (\varphi_m)}} \]

\[ \Delta V \approx 40m \times \frac{2}{1.14} = 70 \text{ mV} \]
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How do we Stabilize the Converter?

1. Select the crossover frequency $f_c$ (assume 4 kHz)
2. Provide a high dc gain for a low static error and good input rejection
3. Shoot for a 70° phase margin at $f_c$
4. Evaluate the needed phase boost at $f_c$ to meet (3)
5. Shape the $G(s)$ path to comply with 1, 2 and 3

Open-loop Bode plot of the power stage, $H(s)$

\[ A_{sc,CL}(s) = \frac{A_{sc,OL}(s)}{1 + T(s)} \]
First, Provide Mid-Band Gain at Crossover

1. Adjust $G(s)$ to boost the gain by +21 dB at crossover
   ➢ Create the so-called mid-band gain

![Graph showing gain and phase]

- Push the gain up.
- $|H(s)| = -21$ dB
- $\text{Arg } H(s) = -175^\circ$
- $0$ dB at $f_c$

Tailor $G(s)$ to exhibit a gain of +21 dB at $f_c$. 
Second, Provide High Gain in DC

2. An integrator provides a high dc gain but rotates by -270°
   ➢ This is the origin pole
Third, Evaluate the Phase Boost at $f_c$

$$\arg H(s)$$

**arg $H(s)$ at 4 kHz**

-175°

**arg $G(s)$**

-113°

**Phase boost at $f_c$**

+155°

**arg $H(s)G(s)$**

$\varphi_m = 70°$

$$\arg H\left(f_c\right) - 270° + \text{BOOST} - \varphi_m = -360°$$

$$\text{BOOST} = \varphi_m - \arg H\left(f_c\right) - 90° = 70° + 175° - 90 = 155°$$
How do We Boost the Phase at $f_c$?

- The phase boost is created by combining zeros and poles

$$G(j\omega) = \frac{1 + j\frac{\omega}{\omega_{z1}}}{1 + j\frac{\omega}{\omega_{p1}}}, \quad \arg G(j\omega) = \text{boost} = \arg \frac{1 + j\frac{\omega}{\omega_{z1}}}{1 + j\frac{\omega}{\omega_{p1}}}$$

$$\arg G(f_c) = \arctan\left(\frac{f_c}{f_{z1}}\right) - \arctan\left(\frac{f_c}{f_{p1}}\right)$$

Assume 1 zero placed at 705 Hz, 1 pole at 22 kHz and a 4-kHz crossover frequency:

$$\arg G(4\text{ kHz}) = \arctan\left(\frac{4k}{705}\right) - \arctan\left(\frac{4k}{22k}\right) = 80 - 10.3 \approx 70^\circ$$

- If poles and zeros are coincident, no phase boost!
How do We Boost the Phase at $f_c$?

Gain $|G(s)|$

$G_{100 \text{ Hz}} = 38 \text{ dB}$

Gain at $f_c = 21 \text{ dB}$

$f_z = 705 \text{ Hz}$

Phase boost at $f_c = 71^\circ$

$f_p = 22 \text{ kHz}$
How do We Boost the Phase at $f_c$?

- The type 1 configuration
- No phase boost, pure integral term
- Permanent phase lag of $-270^\circ$
- Ok if $\arg H(f_c) < -45^\circ$ for a $\phi_m$ of $45^\circ$

$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{sR_1C_1} = \frac{1}{\omega_0}$$

$$\omega_{p1} = \frac{1}{R_1C_1}$$

1 pole at the origin
How do We Boost the Phase at $f_c$?

- The type 2 configuration
- Phase boost up to 90°
- Ok if $\text{arg} H(f_c) < -90°$

$$G(s) = -\frac{1 + sR_2C_1}{sR_1(C_1 + C_2) \left(1 + sR_2 \left[\frac{C_1C_2}{C_1 + C_2}\right]\right)}$$

If $C_2 \ll C_1$

$$\omega_{po} = \frac{1}{R_1C_1} \quad \omega_{p1} = \frac{1}{R_2C_2} \quad \omega_{z1} = \frac{1}{R_2C_1}$$

1 pole at the origin
1 zero
1 pole

Type 2
How do We Boost the Phase at $f_c$?

- The type 3 configuration
- Phase boost up to $180^\circ$
- Ok if $\arg H(f_c) < -180^\circ$

$$G(s) = -\frac{sR_2C_1 + 1}{sR_1(C_1 + C_2)\left(1 + sR_2\frac{C_1C_2}{C_1 + C_2}\right)}\frac{sC_3\left(R_1 + R_3\right) + 1}{(sR_3C_3 + 1)}$$

If $C_2 \ll C_1$ and $R_3 \ll R_1$

$$\omega_{z1} = \frac{1}{R_2C_1} \quad \omega_{z2} = \frac{1}{R_1C_3} \quad \omega_{po} = \frac{1}{R_1C_1}$$

$$\omega_{p1} = \frac{1}{R_3C_3} \quad \omega_{p2} = \frac{1}{R_2C_2}$$

1 pole at the origin
2 zeros
2 poles

Type 3
Finally, We Test the Open-Loop Gain

5. Given the necessary boost of $155^\circ$, we select a type-3 amplifier.
6. A SPICE simulation can give us the whole picture!

Buck stage

1 pole at the origin
2 zeros at 500 Hz
2 poles at 50 kHz
Finally, We Test the Open-Loop Gain

An ac simulation gives us the open-loop Bode plot

Gain $T(s)$

Phase $\text{Arg } T(s)$

$f_c = 4$ kHz

$\phi_m = 70^\circ$
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Type 2 with a TL431

- Literature examples use op amps to close the loop.
- Reality differs as the TL431 is widely implemented.
- How to convert a type 2 to a TL431 circuit?

A shunt regulator!
Type 2 with a TL431

A TL431 implements a two-loop configuration
Adding a Pole for a Type 2 Circuit

- The pole is a simple capacitor on the collector

![Circuit Diagram]

$$G(s) = \frac{V_{FB}(s)}{V_{out}(s)} = -\left(\frac{sR_{upper}C_{zero} + 1}{sR_{upper}C_{zero}}\right)\left(\frac{1}{1 + sR_{pullup}C_{pole}}\right)\frac{R_{pullup}}{R_{LED}} R_{CTR}$$

$$f_{po} = \frac{1}{2\pi R_{upper}C_{zero}} \quad f_z = \frac{1}{2\pi R_{upper}C_{zero}} \quad G = \frac{R_{pullup}}{R_{LED}} R_{CTR} \quad f_p = \frac{1}{2\pi R_{pullup}C_{pole}}$$

- Pole at the origin
- Low frequency zero
- Mid-band gain
- High frequency pole

Or on the emitter

The pole is a simple capacitor on the collector.
The Type 2 Final Implementation

- The LED resistor fixes the mid-band gain
What TL431?

- The TL431 is available under several grades
  - TL431AI, 2.495 V, ± 2.2% $T_A = -25 \, ^\circ C$ to $+85 \, ^\circ C$
  - TL431AC, 2.495 V, ± 1.6% $T_A = -25 \, ^\circ C$ to $+85 \, ^\circ C$
  - TL431BI, 2.495 V, ± 0.8% $T_A = -25 \, ^\circ C$ to $+85 \, ^\circ C$
  - $BV = 37 \, V$, $I_{K,\text{max}} = 100 \, mA$ and $I_{K,\text{min}} = 1 \, mA$

- The TLV431 can regulate to a lower output
  - TLV431A, 1.24 V, ± 2% $T_A = -25 \, ^\circ C$ to $+85 \, ^\circ C$
  - TLV431B, 1.24 V, ± 1% $T_A = -25 \, ^\circ C$ to $+85 \, ^\circ C$
  - $BV = 18 \, V$, $I_{K,\text{max}} = 20 \, mA$ and $I_{K,\text{min}} = 100 \, \mu A$

NCP100 down to 0.9 V
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The Optocoupler is the Treator Here!

- You need galvanic isolation between the prim. and the sec.
- An optocoupler transmits light only, no electrical link

CTR = \( \frac{I_c}{I_F} \times 100 \)

Current Transfer Ratio

Luigi Galvani, 1737-1798
Italian physician and physicist
The Internal Pole should be Known

- The photons are collected by a collector-base area.
- This area offers a large parasitic capacitance: opto pole!

\[
\frac{V_{FB}(s)}{V_{out}(s)} = -\frac{R_{\text{pullup}} \cdot \text{CTR}}{R_{LED}} \cdot \frac{1}{1 + sR_{\text{pullup}}C}
\]

If \( f_p \) is above 5 times \( f_c \), its effect is negligible.
If \( f_p \) is close to \( f_c \), phase margin degradation.
Assess the CTR Variations

- CTR changes with the operating current!
- Try to select collector bias currents around 2-5 mA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
<th>-4</th>
<th>-12</th>
<th>-23</th>
<th>-34</th>
<th>-13</th>
<th>-24</th>
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<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>$I_{C}/I_F$ ($I_F$=10 mA)</td>
<td>40–80</td>
<td>63–125</td>
<td>100–200</td>
<td>160–320</td>
<td>40–125</td>
<td>63–200</td>
<td>100–320</td>
<td>40–200</td>
<td>63–320</td>
<td>40–320</td>
<td>%</td>
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<tr>
<td>$I_{C}/I_F$ ($I_F$=1.0 mA)</td>
<td>30(&gt;13)</td>
<td>45(&gt;22)</td>
<td>70(&gt;34)</td>
<td>90(&gt;56)</td>
<td>30(&gt;13)</td>
<td>45(&gt;22)</td>
<td>70(&gt;34)</td>
<td>30(&gt;13)</td>
<td>45(&gt;22)</td>
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<tr>
<td>Collector-Emitter Leakage Current, $I_{CEO}, V_{CE}$=10 V</td>
<td>2.0(≤50)</td>
<td>2.0(≤50)</td>
<td>5.0(≤100)</td>
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<td>5.0(≤100)</td>
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<td>5.0(≤100)</td>
<td>5.0(≤100)</td>
<td>nA</td>
</tr>
</tbody>
</table>

CTR between 0.63 and 1.25
Normalized to 1 (0 dB)
0.63 gives -4 dB
1.25 gives +2 dB

Watch out for crossover frequency changes and phase margin at CTR extremes!
Changing the Pullup Affects the Pole Position

- A low pullup resistor offers better bandwidth!

- Changing the bias point affects the CTR
  \[ \frac{V_{FB}(s)}{V_{out}(s)} = -\frac{R_{pullup}}{R_{LED}} \text{CTR} \]

- If \( R_{pullup} = R_{LED} \), then \(|G_0| = 0 \text{ dB} \ldots ? \)
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Stabilizing a DCM Flyback Converter

- We want to stabilize a 20 W DCM adapter
- $V_{in} = 85$ to $265$ Vrms
- $V_{out} = 12$ V/1.7 A
- $F_{sw} = 60$ kHz
- Selected controller: NCP1216

1. Obtain a power stage open-loop Bode plot, $H(s)$
2. Look for gain and phase values at cross over
3. Compensate gain and build phase at cross over, $G(s)$
4. Run a loop gain analysis to check for margins, $T(s)$
5. Test transient responses in various conditions
Stabilizing a DCM Flyback Converter

- Capture a SPICE schematic with an averaged model

- Look for the bias points values: $V_{out} = 12$ V, ok
Stabilizing a DCM Flyback Converter

The feedback portion includes the optocoupler pole

```
parameters
Vout=12
Ibridge=250u
Rlower=2.5/Ibridge
Rupper=(Vout-2.5)/Ibridge
Lp=450u
Se=100m
fc=1k
pm=60
Gfc=-24
pfc=-77
G=10^(-Gfc/20)
boost=pm-(pfc)-90
p=3.14159
K=tan((boost/2+45)*pi/180)
Fzero=fc/k
Fpole=k*fc
Rpullup=20k
RLED=CTR*Rpullup/G
Czero=1/(2*pi*Fzero*Rupper)
Cpole=1/(2*pi*Fpole*Rpullup)
CTR=1.5
Pole=6k

Automated compensation
```
Stabilizing a DCM Flyback Converter

- Get the open-loop power stage transfer function, $H(s)$

![Graph showing Bode plot with gain and phase at 1 kHz]

- Gain at 1 kHz: -22.7 dB
- Phase at 1 kHz: -79°
Stabilizing a DCM Flyback Converter

- Boost the gain by +22 dB, boost the phase at $f_c$

| $|T(s)|$ | Cross over 1 kHz |
|-------|-----------------|
|       | GM 35 dB        |

<table>
<thead>
<tr>
<th>$\arg T(s)$</th>
<th>Margin at 1 kHz</th>
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<tbody>
<tr>
<td></td>
<td>60°</td>
</tr>
</tbody>
</table>
Stabilizing a DCM Flyback Converter

- Test the response at both input levels, 90 and 265 Vrms
- Sweep ESR values and check margins again

![Graph showing $V_{out}(t)$ over time with Hi and Low lines marked.]

- 100 mV
- 200 mA to 2 A in 1 A/µs
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- Conclusion
Stabilizing a CCM Flyback Converter

- We want to stabilize a 90 W CCM adapter
- \( V_{in} = 85 \text{ to } 265 \text{ Vrms} \)
- \( V_{out} = 19 \text{ V/4.8 A} \)
- \( F_{sw} = 60 \text{ kHz} \)
- Selected controller: NCP1230

1. Obtain a power stage open-loop Bode plot, \( H(s) \)
2. Look for gain and phase values at cross over
3. Compensate gain and build phase at cross over, \( G(s) \)
4. Run a loop gain analysis to check for margins, \( T(s) \)
5. Test transient responses in various conditions
Stabilizing a CCM Flyback Converter

- Capture a SPICE schematic with an averaged model

- Look for the bias points values: $V_{out} = 19$ V, ok
- $V_{setpoint} < 1$ V, enough margin on current sense
Stabilizing a CCM Flyback Converter

Capture a SPICE schematic with an averaged model

Parameters

- Vout=19
- Ibridge=250u
- Rlower=2.5/Ibridge
- Rupper=(Vout-2.5)/Ibridge
- Lp=350u
- Se=20k
- fc=1k
- pm=60
- Gfc=-22
- pfc=-71
- G=10^(-Gfc/20)
- boost=pm-(pfc)-90
- pi=3.14159
- K=tan((boost/2+45)*pi/180)
- Fzero=fc/k
- Fpole=k*fc
- Rpullup=20k
- RLED=CTR*Rpullup/G
- Czero=1/(2*pi*Fzero*Rupper)
- Cpole=1/(2*pi*Fpole*Rpullup)
- CTR=1.5
- Pole=6k

from Bode
Stabilizing a CCM Flyback Converter

- Capture a SPICE schematic with an averaged model

<table>
<thead>
<tr>
<th></th>
<th>H(s)</th>
<th></th>
<th>Gain at 1 kHz -22 dB</th>
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<tbody>
<tr>
<td></td>
<td>argH(s)</td>
<td>Phase at 1 kHz -71°</td>
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Inject ramp compensation

Sub harmonic poles
Stabilizing a CCM Flyback Converter

- The easiest way to damp the poles:
  - Calculate the equivalent quality coefficient at $F_{sw}/2$
  - Calculate the external ramp to make $Q$ less than 1

$$Q = \frac{1}{\pi \left( D \cdot \frac{S_e}{S_n} + \frac{1}{2} - D \right)} = \frac{1}{3.14 \times (0.5 - 0.46)} = 8$$

$$S_e = \frac{S_n}{D'} \left( \frac{1}{\pi} - 0.5 + D \right) = \frac{V_{in} R_i}{L_p D'} \left( \frac{1}{\pi} - 0.5 + D \right) = \frac{90 \times 0.25}{320 n \times (1 - 0.46)} \left( \frac{1}{3.14} - 0.5 + 0.46 \right) = 36 \text{ kV/s}$$

$$M_r = \frac{S_e}{S_n} = \frac{36k}{70k} = 51\%$$

$$S_{ramp} = \frac{2.3}{15 u} = 153 \text{ kV/s}$$

$$R_{current} = \frac{M_r S_n R_{ramp}}{S_{ramp}} = \frac{0.51 \times 70k \times 18k}{153k} = 4.1 k\Omega$$
Stabilizing a CCM Flyback Converter

- Boost the gain by +22 dB, boost the phase at $f_c$

![Graph showing |T(s)| and arg T(s) with crossover at 1 kHz and margin at 1 kHz being 60°. GM at 20 dB.]
Stabilizing a CCM Flyback Converter

- Test the response at both input levels, 90 and 265 Vrms
- Sweep ESR values and check margins again

![Graph showing V_{out}(t) with High and Low line levels and a 112 mV difference]
Agenda

- Feedback generalities
- Conditions for stability
- Poles and zeros
- Phase margin and quality coefficient
- Undershoot and crossover frequency
- Compensating the converter
- Compensating with a TL431
- Watch the optocoupler!
- Compensating a DCM flyback
- Compensating a CCM flyback
- **Simulation and bench results**
- Conclusion
Testing a UC3843 Converter

- A 19 V/3 A converter is built around an UC3843
- The converter operates in CCM or DCM
Full Load Leads to CCM Operation

CCM operation, $R_{load} = 6.3 \, \Omega$
Reduce the Load to Enter in DCM

DCM operation, $R_{load} = 20 \, \Omega$
From the Open-Loop Bode Plot, Compensate

- The TL431 is tailored to pass a 1 kHz bandwidth

- Calculate mid-band gain: +18 dB

  \[ R_{LED} = \frac{R_{\text{pullup}} \times CTR}{10^{20}} = \frac{4.7 \times 0.45}{7.94} = 266 \, \Omega \]

  We place a zero at 300 Hz:

  \[ C_{zero} = \frac{1}{2\pi f_{zero} R_{\text{upper}}} = \frac{1}{6.28 \times 300 \times 66 \times 10^6} = 8 \, nF \]

  We place a pole at 3.3 kHz:

  \[ C_{pole} = \frac{1}{2\pi f_{pole} R_{\text{pulldown}}} = \frac{1}{6.28 \times 3.3 \times 4.7 \times 10^6} = 10 \, nF \]

Verify in the Lab. the Open-Loop Gain

- Sweep extreme voltages and loads as well!

**Simulated**

CCM operation, \( R_{load} = 6.3 \, \Omega \), \( V_{in} = 150 \, V_{dc} \)
Verify in the Lab. the Open-Loop Gain

CCM operation, $R_{\text{load}} = 6.3\ \Omega$, $V_{\text{in}} = 330\ \text{Vdc}$
Verify in the Lab. the Open-Loop Gain

DCM operation, $R_{load} = 20 \, \Omega$, $V_{in} = 330 \, V_{dc}$
As a Final Test, Step Load the Output

- Good agreement between curves!

Vin = 150 V
CCM
2 to 3 A
1 A/µs
As a final test, Step Load the Output

- DCM operation at high line is also stable

\[ V_{in} = 330 \, V \]
DCM
0.5 to 1 A
1 A/\mu s
Conclusion

- DC-DC loop compensation cannot be overlooked
- It is important to understand the impact of phase margin
- The crossover frequency affects the output impedance
- Current mode CCM or DCM is ok with a TL431-based type 2
- Make sure the optocoupler is characterized, watch the pole!
- Use SPICE before going to the bench: NO trial and error!
- Once the simulation is stable, build the prototype
- Simulations and laboratory debug: the success recipe!
For More Information

- View the extensive portfolio of power management products from ON Semiconductor at www.onsemi.com

- View reference designs, design notes, and other material supporting the design of highly efficient power supplies at www.onsemi.com/powersupplies