Switch-mode power converter compensation made easy

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Switch-mode power converter compensation made easy

Louis Diana
Robert Sheehan
 Agenda

• Compensation design and objectives
• Explanation of poles and zeros
• Power stage characteristics
• Error amplifier and transconductance amplifier
• Isolated feedback with optocoupler
• Compensation examples
• Circuit limitations and other issues
**Compensation design and objectives**

<table>
<thead>
<tr>
<th>Why do we need feedback and why do we need compensation?</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Feedback is needed to regulate the output voltage</td>
</tr>
<tr>
<td>- The bandwidth of the control loop determines the response time</td>
</tr>
</tbody>
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**Diagram:**

- **Power Stage:** Inductor/Transformer, Power Switches, Modulator
- **Compensation**
- **Error Amp**
- **V<sub>IN</sub>**
- **V<sub>C</sub>**
- **V<sub>OUT</sub>**
- **V<sub>REF</sub>**
- **Load**
- **Test Signal**
Control loop response

Objective

- Maximize crossover frequency for fastest transient response
- Adjust compensation for best settling behavior

Poor transient response

- Response is under-damped causing oscillatory behavior

Good transient response

- Response is well damped with good settling behavior
Phase margin and gain margin

- Sufficient phase margin is needed to prevent oscillation (45º min.)
- Gain margin goal 10 dB min.
- Slope of −20 dB/decade when passing through 0 dB
- Bandwidth rule of thumb is 1/5 to 1/10 of switching frequency
Poles and zeros

\[ H(s) = \frac{1}{1 + \frac{s}{\omega_p}} \]

\[ H(s) = \frac{1 + \frac{s}{\omega_z}}{1} \]
Inverted and right-half-plane zeros

<table>
<thead>
<tr>
<th>Inverted zero</th>
<th>Right-half-plane zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H(s) = \frac{1+\frac{\omega_z}{s}}{1}$</td>
<td>$H(s) = \frac{1-\frac{s}{\omega_z}}{1}$</td>
</tr>
</tbody>
</table>

![Graph showing phase and magnitude vs frequency for inverted and right-half-plane zeros](image-url)
## Complex conjugate pole and ESR zero

**Complex conjugate pole**

\[ H(s) = \frac{1}{1 + \frac{s}{Q_o \cdot \omega_o} + \frac{s^2}{\omega_o^2}} \]

**With ESR zero**

\[ H(s) = \frac{1 + \frac{s}{\omega_z}}{1 + \frac{s}{Q_o \cdot \omega_o} + \frac{s^2}{\omega_o^2}} \]

### Graphs

- **Gain** and **Phase** vs. **Frequency (Hz)**

- **MAGNITUDE (dB)** and **PHASE (°)**

- **Q = 2**, **Q = 1**, **Q = 0.5**, **Q = 0.25**

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Control methods and operating modes

| Control methods   | • Voltage-mode control  
|                   | • Current-mode control |
| Operating modes   | • Fixed frequency       
|                   | • Continuous conduction-mode (CCM) |
| Switching frequency and period | • Switching frequency – $f_{SW}$  
|                   | • Switching period – $T$  
|                   | $T = \frac{1}{f_{SW}}$ |
# Buck, boost and buck-boost derived topologies

<table>
<thead>
<tr>
<th>Topologies</th>
<th>Circuit Diagram</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Buck, forward, push-pull, bridge</strong></td>
<td><img src="image" alt="Buck Converter Circuit" /></td>
<td>( V_{OUT} = V_{IN} \cdot D )</td>
</tr>
<tr>
<td><strong>Boost</strong></td>
<td><img src="image" alt="Boost Converter Circuit" /></td>
<td>( V_{OUT} = V_{IN} \cdot \frac{1}{D'} )</td>
</tr>
<tr>
<td><strong>Buck-boost, SEPIC, flyback</strong></td>
<td><img src="image" alt="Buck-Boost Converter Circuit" /></td>
<td>( V_{OUT} = V_{IN} \cdot \frac{D}{D'} )</td>
</tr>
</tbody>
</table>

- **Forward**
- **Two switch forward**
- **Active clamp forward**
- **Half bridge**
  \[ V_{OUT} = V_{IN} \cdot D \cdot \frac{N_s}{N_p} \]
- **Push-pull**
- **Full bridge**
- **Phase-shifted full bridge**
  \[ V_{OUT} = V_{IN} \cdot 2 \cdot D \cdot \frac{N_s}{N_p} \]

- **Boost topology**

On-time duty cycle: \( D \)
Off-time duty cycle: \( D' = 1 - D \)

- **Buck-boost derived topologies**
- **SEPIC**
- **Cuk**

- **Flyback**

\[ V_{OUT} = V_{IN} \cdot \frac{D}{D'} \cdot \frac{N_s}{N_p} \]
Voltage-mode buck power stage

\[ A_{\text{VC}} = \frac{V_{\text{IN}}}{V_{\text{RAMP}}} \]

\[ \omega_o = \frac{1}{\sqrt{L \cdot C_{\text{OUT}}}} \]

\[ Q_O = \frac{R_{\text{OUT}}}{\sqrt{L/C_{\text{OUT}}}} \]

\[ \omega_Z = \frac{1}{R_{\text{ESR}} \cdot C_{\text{OUT}}} \]

\[ \frac{\hat{v}_{\text{OUT}}}{\hat{v}_C} = A_{\text{VC}} \cdot \frac{1 + \frac{s}{\omega_o}}{1 + \frac{s}{Q_O \cdot \omega_o} + \frac{s^2}{\omega_o^2}} \]
Current-mode buck power stage

\[ R_i = A \cdot R_S \]

\[ \omega_Z = \frac{1}{R_{ESR} \cdot C_{OUT}} \]

\[ A_{VC} \approx \frac{R_{OUT}}{R_i} \]

\[ K_m \approx \frac{V_{IN}}{V_{SLOPE}} \]

\[ \omega_p \approx \frac{1}{C_{OUT} \cdot R_{OUT}} \]

\[ \omega_L = \frac{K_m \cdot R_i}{L} \]

\[ \hat{V}_{OUT} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_p}}{1 + \frac{s}{\omega_L}} \]

\[ \hat{V}_C \approx \frac{\omega_p}{2 \cdot \pi} \]

\[ \frac{\omega_z}{2 \cdot \pi} \]

\[ \frac{\omega_L}{2 \cdot \pi} \]

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Current-mode boost power stage

\[ R_i = A \cdot R_S \]
\[ \omega_r = \frac{R_{OUT} \cdot D'^2}{L} \]
\[ \omega_l = \frac{K_m \cdot R_i}{L} \]
\[ A_{VC} \approx \frac{R_{OUT} \cdot D'}{2 \cdot R_i} \]
\[ \omega_p \approx \frac{2}{C_{OUT} \cdot R_{OUT}} \]
\[ K_m \approx \frac{V_{OUT}}{V_{SLOPE}} \quad \text{at } D = 0.5 \]

\[ \hat{v}_{OUT} \approx A_{VC} \cdot \left\{ \frac{1}{\omega_p} + \frac{1}{\omega_l} \right\} \cdot \left\{ \frac{1}{\omega_p} - \frac{1}{\omega_l} \right\} \]
Current-mode buck-boost power stage

\[ R_i = A \cdot R_s \]
\[ \omega_R = \frac{R_{OUT} \cdot D^2}{L \cdot D} \]
\[ \omega_L = \frac{K_m \cdot R_i}{L} \]
\[ A_{VC} \approx \frac{R_{OUT} \cdot D'}{(1 + D) \cdot R_i} \]
\[ \omega_Z = \frac{1}{R_{ESR} \cdot C_{OUT}} \]
\[ \omega_p \approx \frac{1 + D}{C_{OUT} \cdot R_{OUT}} \]
\[ K_m \approx \frac{V_{IN} + V_{OUT}}{V_{SLOPE}} \quad \text{at } D = 0.5 \]

\[ \hat{v}_{OUT} \approx A_{VC} \cdot \left( \frac{1 - s}{\omega_p} \right) \cdot \left( \frac{1 + s}{\omega_L} \right) \]

\[ \hat{v}_C \approx \left( \frac{1 - s}{\omega_p} \right) \cdot \left( \frac{1 + s}{\omega_L} \right) \]
Current-mode forward power stage

\[ R_i = A \cdot R_s \]
\[ \omega_z = \frac{1}{R_{ESR} \cdot C_{OUT}} \]
\[ A_{VC} \approx \frac{R_{OUT} \cdot N_p}{R_i \cdot N_S} \]
\[ K_m \approx \frac{V_{IN}}{V_{SLOPE}} \]
\[ \omega_p \approx \frac{1}{C_{OUT} \cdot R_{OUT}} \]
\[ \omega_L = \frac{K_m \cdot R_i \cdot (N_S/N_P)^2}{L} \]

\[ \frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_z}}{\left(1 + \frac{s}{\omega_p}\right) \left(1 + \frac{s}{\omega_L}\right)} \]
Current-mode flyback power stage

\[ R_i = A \cdot R_s \]
\[ A_{VC} \approx \frac{R_{OUT} \cdot D'}{1 + D} \cdot \frac{N_p}{N_S} \]
\[ \omega_p = \frac{1 + D}{C_{OUT} \cdot R_{OUT}} \]
\[ \omega_z = \frac{1}{R_{ESR} \cdot C_{OUT}} \]
\[ \omega_R = \frac{R_{OUT} \cdot D'^2 \cdot \left( \frac{N_p}{N_S} \right)^2}{L_p \cdot \frac{N_p}{N_S}} \]
\[ K_m \approx \frac{V_{IN} + V_{OUT} \cdot \frac{N_p}{N_S}}{V_{SLOPE}} \]
\[ \omega_L = K_m \cdot R_i \frac{1}{L_p} \]

at \( D = 0.5 \)

\[ \hat{v}_{OUT} \approx A_{VC} \cdot \frac{1 - \frac{s}{\omega_R}}{1 + \frac{s}{\omega_p}} \cdot \frac{1 + \frac{s}{\omega_L}}{1 + \frac{s}{\omega_z}} \]
Type I error amplifier

\[ \omega_{EA} = \frac{1}{R_{FBT} \cdot C_{COMP}} \]

\[ \hat{v}_C \approx \frac{\omega_{EA}}{s} \hat{v}_{OUT} \]
Type II error amplifier

\[ A_{VM} \approx \frac{R_{COMP}}{R_{FBT}} \]
\[ \omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}} \]
\[ \omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}} \]

Assumption: \( C_{COMP} \gg C_{HF} \)

\[ \hat{V}_C \approx -A_{VM} \cdot \frac{1 + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}} \approx -\frac{A_{VM} \cdot \omega_{ZEA}}{s} \cdot \frac{1 + \frac{s}{\omega_{ZEA}}}{1 + \frac{s}{\omega_{HF}}} \]

Diagram showing frequency response with magnitude and phase plots.
Type II transconductance amplifier

\[
A_{VM} = K_F \cdot g_m \cdot R_{COMP}
\]

\[
\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}}
\]

\[
K_F = \frac{R_{FB}}{R_{FB} + R_{FB}}
\]

\[
\omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}}
\]

\[
A_{OK} = g_m \cdot R_{EA}
\]

Assumptions: \( C_{COMP} \gg C_{HF} \) & \( R_{EA} \gg R_{COMP} \)

\[
\frac{\hat{V}_C}{V_{OUT}} = -A_{VM} \cdot \frac{1 + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}}
\]

\[
\approx A_{VM} \cdot \omega_{ZEA} \cdot \frac{1 + \frac{s}{\omega_{ZEA}}}{s} \cdot \frac{1 + \frac{s}{\omega_{HF}}}{1 + \frac{s}{\omega_{HF}}}
\]
Type III error amplifier

\[ A_{VM} \approx \frac{R_{COMP}}{R_{FBT}} \]

\[ \omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}} \]

\[ \omega_{FZ} \approx \frac{1}{R_{FBT} \cdot C_{FF}} \]

\[ \omega_{FP} = \frac{1}{R_{FF} \cdot C_{FF}} \]

\[ \omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}} \]

Assumptions: \( C_{COMP} \gg C_{HF} \) & \( R_{FBT} \gg R_{FF} \)

\[
\frac{\dot{v}_c}{\dot{v}_{OUT}} = -A_{VM} \left( \frac{1 + \frac{s}{\omega_{ZEA}}}{1 + \frac{s}{\omega_{FP}}} \right) \left( \frac{1 + \frac{s}{\omega_{FZ}}}{1 + \frac{s}{\omega_{HF}}} \right)
\]

\[
= -A_{VM} \cdot \omega_{ZEA} \left( \frac{1 + \frac{s}{\omega_{ZEA}}}{1 + \frac{s}{\omega_{FP}}} \right) \left( \frac{1 + \frac{s}{\omega_{FZ}}}{1 + \frac{s}{\omega_{HF}}} \right)
\]
Isolated feedback with optocoupler

\[ A_{VM} = CTR \cdot \frac{R_p}{R_d} \]

\[ CTR = \frac{I_C}{I_f} \]

\[ \omega_{ZEA} = \frac{1}{R_{FBT} \cdot C_{COMP}} \]

\[ \omega_{HF} = \frac{1}{R_p \cdot C_p} \]

\[ \frac{\dot{v}_c}{v'_{OUT}} \approx -A_{VM} \cdot \frac{s + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}} \approx -A_{VM} \cdot \omega_{ZEA} \cdot \frac{s}{1 + \frac{s}{\omega_{HF}}} \]
Voltage-mode buck

Modulator

\[ D = \frac{V_{OUT}}{V_{IN}} \]

\[ D' = \frac{V_{IN} - V_{OUT}}{V_{IN}} \]

Output filter

Error amplifier

\[ V_{IN} \]

\[ V_{RAMP} \]

PWM

\[ V_C \]

\[ V_{REF} \]

\[ V_{FB} \]

\[ V_{VD} \]

\[ V_{OUT} \]

\[ R_{ESR} \]

\[ L \]

\[ C_{OUT} \]

\[ R_{OUT} \]

\[ C_{HF} \]

\[ C_{COMP} \]

\[ R_{COMP} \]

\[ C_{FF} \]

\[ R_{FF} \]

\[ R_{FBT} \]

\[ R_{FBB} \]
### Voltage-mode buck compensation strategy

- Choose a value for $R_{FBT}$ based on bias current and power dissipation
- Pick target bandwidth, typically $f_{SW}/10$:
  \[ \omega_C = 2 \cdot \pi \cdot f_C \]
- Find the mid-band gain $A_{VM}$ to achieve target bandwidth
- Set $\omega_{ZEA}$ and $\omega_{FZ}$ equal to the output filter complex conjugate pole $\omega_O$:
  \[ \omega_{ZEA} = \omega_{FZ} = \omega_O \]
- Set $\omega_{FP}$ equal to the output filter zero $\omega_Z$:
  \[ \omega_{FP} = \omega_Z \]
- Set $\omega_{HF}$ equal to half the switching frequency:
  \[ \omega_{HF} = 2 \cdot \pi \cdot f_{SW}/2 \]

<table>
<thead>
<tr>
<th>$A_{VM}$</th>
<th>$\frac{\omega_C}{A_{VC} \cdot \omega_O}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{COMP}$</td>
<td>$A_{VM} \cdot R_{FBT}$</td>
</tr>
<tr>
<td>$C_{COMP}$</td>
<td>$\frac{1}{\omega_{ZEA} \cdot R_{COMP}}$</td>
</tr>
<tr>
<td>$C_{FF}$</td>
<td>$\frac{1}{\omega_{FZ} \cdot R_{FBT}}$</td>
</tr>
<tr>
<td>$R_{FF}$</td>
<td>$\frac{1}{\omega_{FP} \cdot C_{FF}}$</td>
</tr>
<tr>
<td>$C_{HF}$</td>
<td>$\frac{1}{\omega_{HF} \cdot R_{COMP}}$</td>
</tr>
</tbody>
</table>
Voltage-mode buck compensation results

**Power stage**

\[
\frac{\hat{v}_{\text{OUT}}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_Z}}{1 + \frac{s}{Q_o \cdot \omega_o} + \frac{s^2}{\omega_o^2}}
\]

**Error amplifier**

\[
\frac{\hat{v}_C}{\hat{v}_{\text{OUT}}^\prime} = -A_{VM} \cdot \left(1 + \frac{\omega_{ZEA}}{s}\right) \cdot \left(1 + \frac{s}{\omega_{FZ}}\right) \cdot \left(1 + \frac{s}{\omega_{HP}}\right) \cdot \left(1 + \frac{s}{\omega_{HF}}\right)
\]

**Control loop**

\[
\frac{\hat{v}_{\text{OUT}}^\prime}{\hat{v}_{\text{OUT}}} = \frac{\hat{v}_{\text{OUT}}}{\hat{v}_C} \cdot \frac{\hat{v}_C}{\hat{v}_{\text{OUT}}}
\]
Isolated current-mode flyback

Modulator

\[ D = \frac{V_{\text{OUT}}}{V_{\text{IN}}} \cdot \frac{N_S}{N_P} + V_{\text{OUT}} \]

\[ D' = \frac{V_{\text{IN}}}{V_{\text{IN}} + V_{\text{OUT}}} \cdot \frac{N_P}{N_S} \]

Peak current-mode flyback

Optimal \( V_{\text{SLOPE}} = V_{\text{OUT}} \cdot R_i \cdot T/L_P \cdot N_P/N_S \)

Output filter

Error amplifier

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Current-mode flyback compensation strategy

- Choose a value for $R_{FBT}$ based on bias current and power dissipation
- Find the modulator transconductance in A/V
- Find the RHPZ frequency at minimum input voltage and maximum load current
- Set the target bandwidth to 1/4 of the RHPZ frequency:
  \[ \omega_C = 2\pi f_C = \omega_R/4 \]
- Find the mid-band gain $A_{VM}$ to achieve target bandwidth
  - Adjust $R_D$, $R_P$ and $C_{OUT}$ as required
- Set $\omega_{ZEA}$ equal to 1/10 the target crossover frequency:
  \[ \omega_{ZEA} = \omega_C/10 \]
- Set $\omega_{HF}$ equal to the lower of the RHP or ESR zero frequency:
  \[ \omega_{HF} = \omega_R \text{ or } \omega_Z \]

$$G_m \text{ (mod)} = \frac{D'}{R_i} \cdot \frac{N_P}{N_S}$$

$$\omega_R = \frac{R_{OUT} \cdot D^2}{L_p \cdot D} \left( \frac{N_P}{N_S} \right)^2$$

$$A_{VM} = \frac{\omega_C \cdot C_{OUT}}{G_m \text{ (mod)}}$$

$$R_D = CTR \cdot \frac{R_P}{A_{VM}}$$

$$C_{COMP} = \frac{1}{R_{FBT} \cdot \omega_{ZEA}}$$

$$C_P = \frac{1}{R_P \cdot \omega_{HF}}$$
Current-mode flyback compensation results

Power stage
\[
\hat{v}_{\text{OUT}} \approx A_{\text{VC}} \cdot \left(1 - \frac{s}{\omega_R} + \frac{s}{\omega_L}\right) \cdot \left(1 + \frac{s}{\omega_p} + \frac{s}{\omega_m}\right)
\]

Error amplifier
\[
\frac{\hat{v}_c}{\hat{v}_{\text{OUT}}} \approx -A_{\text{VM}} \cdot \frac{1 + \omega_{ZEA}}{s} \cdot \frac{s}{1 + \frac{s}{\omega_{HF}}}
\]

Control loop
\[
\frac{\hat{v}_{\text{OUT}}'}{\hat{v}_{\text{OUT}}} = \frac{\hat{v}_{\text{OUT}}}{\hat{v}_c} \cdot \frac{\hat{v}_c}{\hat{v}_{\text{OUT}}}
\]
Bandwidth vs. transient response

With no ESR, slew rate or duty cycle limiting:

Current-mode single pole approximation:

\[ V_P = \frac{\Delta I}{2 \cdot \pi \cdot f_C \cdot C_{OUT}} \]

Current-mode critically damped:

\[ V_P = \frac{\Delta I}{e \cdot \pi \cdot f_C \cdot C_{OUT}} \]

Voltage-mode:

\[ V_P = \frac{\Delta I}{8 \cdot f_C \cdot C_{OUT}} \]

\[ t_P = \frac{1}{4 \cdot f_C} \]

\[ t_P = \frac{1}{4 \cdot 10kHz} = 25\mu s \]

\[ V_P = \frac{5A}{2 \cdot \pi \cdot 10kHz \cdot 440\mu F} = 180mV \]

\[ V_P = \frac{5A}{e \cdot \pi \cdot 10kHz \cdot 440\mu F} = 130mV \text{ shown above} \]

\[ V_P = \frac{5A}{8 \cdot 10kHz \cdot 440\mu F} = 140mV \]
Switching regulator with poor compensation

- Power stage: phase at −180° indicates high internal slope compensation
- Error amplifier: zero appears high and mid-band gain is 3 dB
- Control loop: $f_c$ is 95 kHz with only 20° phase margin
Switching regulator with revised compensation

- Power stage: cannot change slope compensation
- Error amplifier: decrease $R_{COMP}$ and rescale $C_{COMP}$
- Control loop: now $f_C$ is 30 kHz with 67° phase margin

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Practical limitations

- Error amp BW can limit maximum $f_C$
- Wider BW op amp needed for voltage-mode due to Type III compensation
- Resistance seen by output transistor forms a pole in kHz range
- More of an issue for forward topologies at higher $f_C$
- Maximum $f_C$ is a fraction of $f_{SW}$
- Rule of thumb is 1/5 to 1/10 of $f_{SW}$
DCM vs. CCM characteristics

- Discontinuous conduction-mode (DCM) occurs when the inductor current dwells at zero before the end of the switching cycle.
- This causes a reduction in the bandwidth.
- Generally, if the loop is stable in CCM, it will be stable in DCM.

DCM duty cycle

- Buck
\[ D = \sqrt{2 \cdot L \cdot f_{SW} \cdot I_{OUT} \cdot V_{OUT}} \]
\[ V_{IN} \cdot (V_{IN} - V_{OUT}) \]

- Boost
\[ D = \sqrt{2 \cdot L \cdot f_{SW} \cdot I_{OUT} \cdot (V_{OUT} - V_{IN})} \]
\[ V_{IN} \]

- Buck-boost
\[ D = \sqrt{2 \cdot L \cdot f_{SW} \cdot I_{OUT} \cdot V_{OUT}} \]
\[ V_{IN} \]
Filter considerations

For stability: Filter $Z_{OUT} << $ Converter $Z_{IN}$

- Characteristic impedance $Z_s = \sqrt{\frac{L_{IN}}{C_{IN}}}$
- Damping factor $\zeta = \frac{1}{2} \left( \frac{R_L + R_C}{Z_s} + \frac{Z_s}{Z_{IN}} \right)$

- Capacitors: make $C_{OUT1}$ smaller than $C_{OUT2}$
- Inductors: make $L_2$ smaller than $L_1$
- Resonance: make second stage filter resonance 3 times $f_C$
- Damping: make second stage filter damped to a $Q$ of 1
Summary

• Identify poles and zeros of the power stage
• Cancel with zeros and poles in the error amp
• Adjust the gain for best performance
Resources and references

- “Closing the Feedback Loop” by Lloyd Dixon, SEM300
- “Current-Mode Control of Switching Power Supplies” by Lloyd Dixon, SEM400
- “The Right-Half-Plane Zero -- A Simplified Explanation” by Lloyd Dixon, SEM500
- “Isolating the Control Loop” by Robert Mammano, SEM700
- “Control Loop Design” by Lloyd Dixon, SEM800
- “Control Loop Cookbook” by Lloyd Dixon, SEM1100
- “A More Accurate Current-Mode Control Model” by Ray Ridley, SEM1300
- “Designing Stable Control Loops” by Dan Mitchell and Bob Mammano, SEM1400
- “Understanding and Applying Current-Mode Control Theory” by Robert Sheehan, SNVA555
- “Frequency Compensation and Power Stage Design for Buck Converters to Meet Load Transient Specifications” by S. Bag, R. Sheehan, et al., APEC 2014
Appendix

• Current-mode buck compensation
• Current-mode boost compensation
• Current-mode buck-boost compensation
• Isolated compensation techniques
• Isolated forward converter compensation
Current-mode buck

Modulator

\[ D = \frac{V_{OUT}}{V_{IN}} \]

\[ D' = \frac{V_{IN} - V_{OUT}}{V_{IN}} \]

Peak current-mode buck
Optimal \( V_{SLOPE} = V_{OUT} \cdot R_i \cdot T/L \)

Output filter

Error amplifier

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Current-mode buck compensation strategy

- Choose a value for $R_{FBT}$ based on bias current and power dissipation
- Find the modulator transconductance in A/V
- Pick target bandwidth, typically $f_{SW}/10$:
  \[ \omega_c = 2 \cdot \pi \cdot f_c \]
- Find the mid-band gain $A_{VM}$ to achieve target bandwidth
- Set $\omega_{ZEA}$ equal to 1/10 the target crossover frequency:
  \[ \omega_{ZEA} = \omega_c / 10 \]
- Set $\omega_{HF}$ equal to the ESR zero frequency:
  \[ \omega_{HF} = \omega_Z \]

\[
G_m (\text{mod}) = \frac{1}{R_i}
\]

\[
A_{VM} = \frac{\omega_c \cdot C_{OUT}}{G_m (\text{mod})}
\]

\[
R_{COMP} = A_{VM} \cdot R_{FBT} \quad \text{(op amp)}
\]

\[
R_{COMP} = \frac{A_{VM}}{g_m \cdot K_{FB}} \quad \text{(g_m amp)}
\]

\[
C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}
\]

\[
C_{HF} = \frac{1}{\omega_{HF} \cdot R_{COMP}}
\]
Current-mode buck compensation results

Power stage
\[ \frac{\hat{v}_{\text{OUT}}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_p}}{1 + \frac{s}{\omega_Z}} \cdot \frac{1 + \frac{s}{\omega_p}}{1 + \frac{s}{\omega_L}} \]

Error amplifier
\[ \frac{\hat{v}_C}{\hat{v}_{\text{OUT}}'} \approx -A_{VM} \cdot \frac{1 + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}} \]

Control loop
\[ \frac{\hat{v}_{\text{OUT}}'}{\hat{v}_{\text{OUT}}} = \frac{\hat{v}_{\text{OUT}}}{\hat{v}_C} \cdot \frac{\hat{v}_C}{\hat{v}_{\text{OUT}}'} \]
Current-mode boost

Modulator

\[ D = \frac{V_{OUT} - V_{IN}}{V_{OUT}} \]
\[ D' = \frac{V_{IN}}{V_{OUT}} \]

Peak current-mode boost
Optimal \( V_{SLOPE} = (V_{OUT} - V_{IN}) \cdot R_i \cdot T/L \)

Output filter

Error amplifier

\[ V_{IN} \]
\[ L \]
\[ C_{IN} \]
\[ \text{Logic} \]
\[ \Sigma \]
\[ \text{PWM} \]
\[ V_{SLOPE} \]
\[ V_{C} \]
\[ C_{HF} \]
\[ R_{COMP} \]
\[ C_{COMP} \]
\[ V_{FB} \]
\[ R_{FBT} \]
\[ R_{FBB} \]
\[ V_{OUT} \]
\[ C_{OUT} \]
\[ R_{ESR} \]
\[ R_{OUT} \]
Current-mode boost compensation strategy

- Choose a value for $R_{FBT}$ based on bias current and power dissipation
- Find the modulator transconductance in A/V
- Find the RHPZ frequency at minimum input voltage and maximum load current
- Set the target bandwidth to 1/4 of the RHPZ frequency:
  \[ \omega_C = 2 \cdot \pi \cdot f_C = \omega_R / 4 \]
- Find the mid-band gain $A_{VM}$ to achieve target bandwidth
- Set $\omega_{ZEA}$ equal to 1/10 the target crossover frequency:
  \[ \omega_{ZEA} = \omega_C / 10 \]
- Set $\omega_{HF}$ equal to the lower of the RHP or ESR zero frequency:
  \[ \omega_{HF} = \omega_R \text{ or } \omega_Z \]

\[
G_m (\text{mod}) = \frac{D'}{R_i} \\
\omega_R = \frac{R_{OUT} \cdot D'^2}{L} \\
A_{VM} = \frac{\omega_C \cdot C_{OUT}}{G_m (\text{mod})} \\
R_{COMP} = A_{VM} \cdot R_{FBT} \quad \text{(op amp)} \\
R_{COMP} = \frac{A_{VM}}{g_m \cdot K_{FB}} \quad \text{(g}_m \text{ amp)} \\
C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}} \\
C_{HF} = \frac{1}{\omega_{HF} \cdot R_{COMP}}
\]
Current-mode boost compensation results

**Power stage**
\[
\frac{\hat{v}_{\text{OUT}}}{\hat{v}_C} \approx A_{V_C} \left(\frac{1}{2\pi} \frac{s}{\omega_2} \right) \left(1 + \frac{s}{\omega_3}ight) \left(1 + \frac{s}{\omega_p} \right) \left(1 + \frac{s}{\omega_L}\right)
\]

**Error amplifier**
\[
\frac{\hat{v}_C}{\hat{v}_{\text{OUT}}} \approx -A_{V_M} \cdot \frac{1}{s} \left(1 + \frac{s}{2\pi \omega_{\text{ZEA}}} \right)
\]

**Control loop**
\[
\frac{\hat{v}_{\text{OUT}}}{\hat{v}'_{\text{OUT}}} = \frac{\hat{v}_{\text{OUT}}}{\hat{v}_C} \frac{\hat{v}_C}{\hat{v}'_{\text{OUT}}}
\]
Current-mode buck-boost

\[
D = \frac{V_{OUT}}{V_{IN} + V_{OUT}}
\]

\[
D' = \frac{V_{IN}}{V_{IN} + V_{OUT}}
\]

Peak current-mode buck-boost

Optimal \( V_{SLOPE} = V_{OUT} \cdot Ri \cdot T/L \)

Output filter

Error amplifier
Current-mode buck-boost compensation strategy

- Choose a value for $R_{FBT}$ based on bias current and power dissipation
- Find the modulator transconductance in $A/V$
- Find the RHPZ frequency at minimum input voltage and maximum load current
- Set the target bandwidth to $1/4$ of the RHPZ frequency:
  \[ \omega_C = 2\pi f_C = \frac{\omega_R}{4} \]
- Find the mid-band gain $A_{VM}$ to achieve target bandwidth
- Set $\omega_{ZEA}$ equal to $1/10$ the target crossover frequency:
  \[ \omega_{ZEA} = \frac{\omega_C}{10} \]
- Set $\omega_{HF}$ equal to the lower of the RHP or ESR zero frequency:
  \[ \omega_{HF} = \omega_R \text{ or } \omega_Z \]

\[
G_m (\text{mod}) = \frac{D'}{R_i}
\]
\[
\omega_R = \frac{R_{OUT} \cdot D'^2}{L \cdot D}
\]
\[
A_{VM} = \frac{\omega_c \cdot C_{OUT}}{G_m (\text{mod})}
\]
\[
R_{COMP} = A_{VM} \cdot R_{FBT} \quad \text{(op amp)}
\]
\[
R_{COMP} = \frac{A_{VM}}{g_m \cdot K_{FB}} \quad \text{(gm amp)}
\]
\[
C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}
\]
\[
C_{HF} = \frac{1}{\omega_{HF} \cdot R_{COMP}}
\]
Current-mode buck-boost compensation results

**Power stage**

\[
\frac{\hat{v}_{\text{OUT}}}{\hat{v}_C} \approx A_{\text{VC}} \left( \frac{1 - s}{\omega_R} \right) \left( \frac{1 + s}{\omega_L} \right) \left( \frac{1}{1 + \frac{s}{\omega_p}} \right) \]

**Error amplifier**

\[
\frac{\hat{v}_C'}{\hat{v}_{\text{OUT}}} \approx -A_{\text{VM}} \cdot \frac{1 + \frac{s}{\omega_{\text{ZEA}}}}{\frac{s}{\omega_{\text{HF}}}}
\]

**Control loop**

\[
\frac{\hat{v}_{\text{OUT}}'}{\hat{v}_{\text{OUT}}} = \frac{\hat{v}_{\text{OUT}}}{\hat{v}_C} \cdot \frac{\hat{v}_C'}{\hat{v}_{\text{OUT}}}
\]
Isolated compensation techniques

Simplest method: Optocoupler with shunt regulator

- **CTR** – Current transfer ratio
  \[ CTR = \frac{I_C}{I_F} \]
- **C_P** – Includes opto parasitic capacitance. This creates a pole with gain setting resistor \( R_P \)

- **R_D** – Connected to \( V_{OUT} \) creates a feedback path even when \( C_{COMP} \) rolls off the gain

- **TL431** – Cathode cannot pull lower than the reference voltage

\[
\frac{\dot{v}_C}{\dot{v}_{OUT}} \approx -CTR \cdot \frac{R_P}{R_D} \cdot \frac{1}{1 + s \cdot \frac{C_{COMP} \cdot R_{FBT}}{1 + s \cdot C_P \cdot R_P}}
\]
Primary side compensation

- Uses primary side inverting amplifier to implement frequency compensation
- Opto emitter is at virtual ground of $V_{REF}$
  - This minimizes pole due to opto parasitic capacitance

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Secondary side compensation

**ESR zero compensation**
- An RC pole to the opto can be used to cancel the output capacitor ESR zero

**Phase boost**
- Feed-forward across $R_D$ adds phase boost for increased bandwidth

**Zener bias**
- Zener bias for $R_D$ eliminates the high frequency feedback path for secondary-side compensation
Isolated current-mode forward

Modulator

\[ D = \frac{V_{OUT}}{V_{IN}} \cdot \frac{N_P}{N_S} \]

\[ D' = \frac{V_{IN} - V_{OUT} \cdot \frac{N_P}{N_S}}{V_{IN}} \]

Peak current-mode forward

Optimal \( V_{SLOPE} = V_{OUT} \cdot R_i \cdot T/L \cdot N_S/N_P \)
Current-mode forward compensation strategy

- Choose a value for $R_{FBT}$ based on bias current and power dissipation
- Find the modulator transconductance in A/V
- Pick target bandwidth, typically $f_{SW}/10$:
  $$\omega_C = 2\pi f_C$$
- Find the mid-band gain $A_{VM}$ to achieve target bandwidth
  Adjust $R_D$, $R_P$ and $C_{OUT}$ as required
- Set $\omega_{ZEA}$ equal to 1/10 the target crossover frequency:
  $$\omega_{ZEA} = \omega_C / 10$$
- Set $\omega_{HF}$ equal to the ESR zero frequency:
  $$\omega_{HF} = \omega_Z$$

\[
G_m (\text{mod}) = \frac{1}{R_i} \cdot \frac{N_P}{N_S}
\]

\[
A_{VM} = \frac{\omega_C \cdot C_{OUT}}{G_m (\text{mod})}
\]

\[
R_D = CTR \cdot \frac{R_P}{A_{VM}}
\]

\[
C_{COMP} = \frac{1}{R_{FBT} \cdot \omega_{ZEA}}
\]

\[
C_S = \frac{1}{R_S \cdot \omega_{HF}}
\]
Current-mode forward compensation results

Power stage
\[ \frac{\hat{v}_{\text{OUT}}}{\hat{v}_{\text{C}}} \approx A_{\text{VC}} \cdot \frac{1 + \frac{s}{\omega_{p}}}{\left(1 + \frac{s}{\omega_{p}}\right)\left(1 + \frac{s}{\omega_{s}}\right)} \]

Error amplifier
\[ \frac{\hat{v}_{\text{C}}}{\hat{v}_{\text{OUT}}}' \approx -A_{\text{VM}} \cdot \frac{1 + \frac{\omega_{\text{ZE}}}{s}}{1 + \frac{s}{\omega_{\text{HF}}}} \]

Control loop
\[ \frac{\hat{v}_{\text{OUT}}'}{\hat{v}_{\text{OUT}}} = \frac{\hat{v}_{\text{OUT}}}{\hat{v}_{\text{C}}} \cdot \frac{\hat{v}_{\text{C}}}{\hat{v}_{\text{OUT}}}' \]
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Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
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