



Power Supply Design seminar

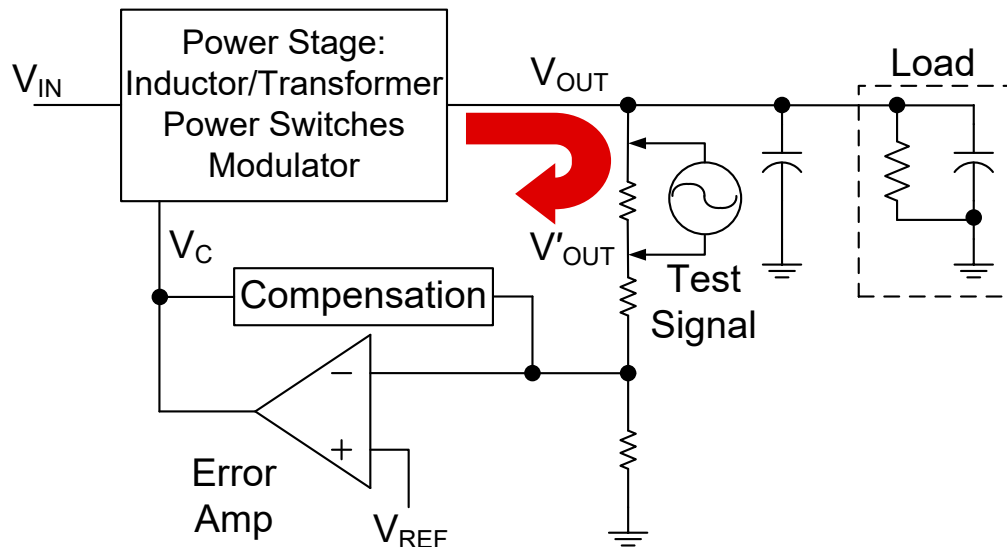
Switch-mode power converter compensation made
easy
Bosheng Sun

Agenda

- Compensation design and objective
- Explanation of poles and zeros
- Power stage characteristics
- Error amplifier and transconductance amplifier
- Isolated feedback with opto-coupler
- Compensation examples
- Circuit limitations and other issues

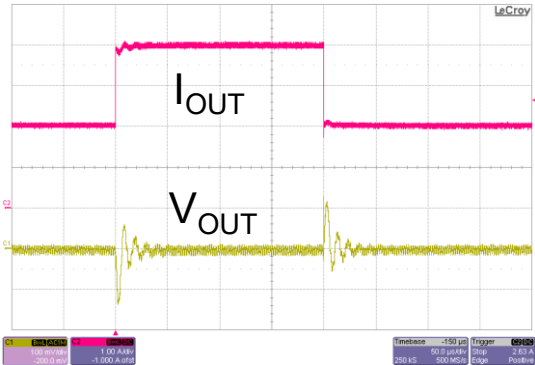
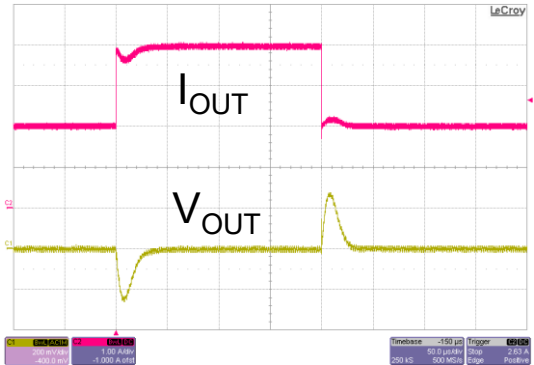
Compensation design and objectives

Why do we need feedback and why do we need compensation?

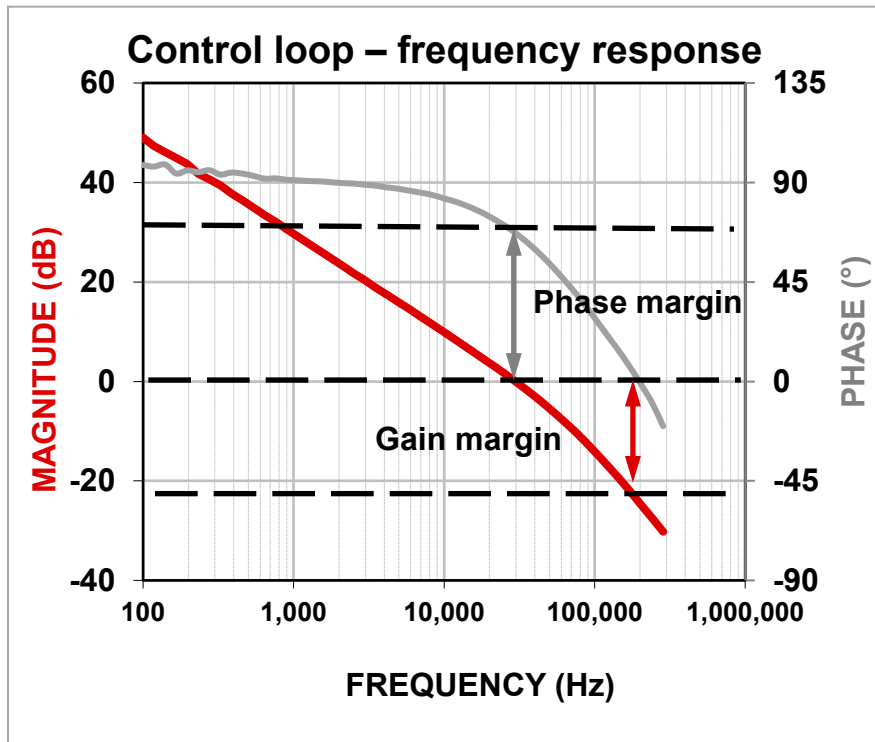


- Feedback is needed to regulate the output voltage
- The control loop bandwidth influences the response time

Control loop response

Poor transient response	Objective	Good transient response
 The plot shows a step change in output current I_{OUT} (magenta trace) from 0 A to 1.00 A. The output voltage V_{OUT} (yellow trace) exhibits significant undershoot and sustained oscillations before settling. The LeCroy oscilloscope interface shows a 200 ns timebase and 500 mV vertical scale for V_{OUT}.	• Maximize crossover frequency for fastest transient response • Adjust compensation for best settling behavior	 The plot shows a step change in output current I_{OUT} (magenta trace) from 0 A to 1.00 A. The output voltage V_{OUT} (yellow trace) shows a clean, well-damped recovery with minimal overshoot and no sustained oscillations. The LeCroy oscilloscope interface shows a 200 ns timebase and 500 mV vertical scale for V_{OUT}.
• Response is under-damped causing oscillatory behavior		• Response is well damped with good settling behavior

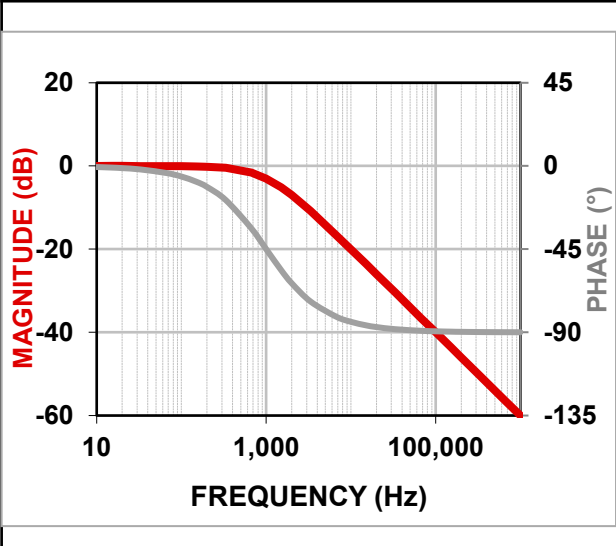
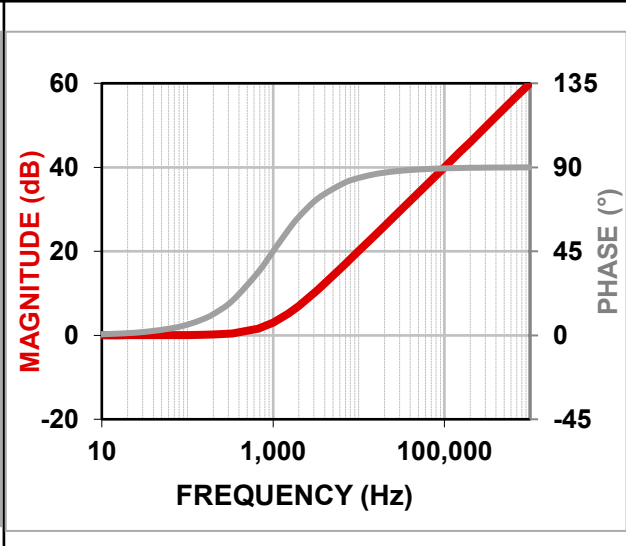
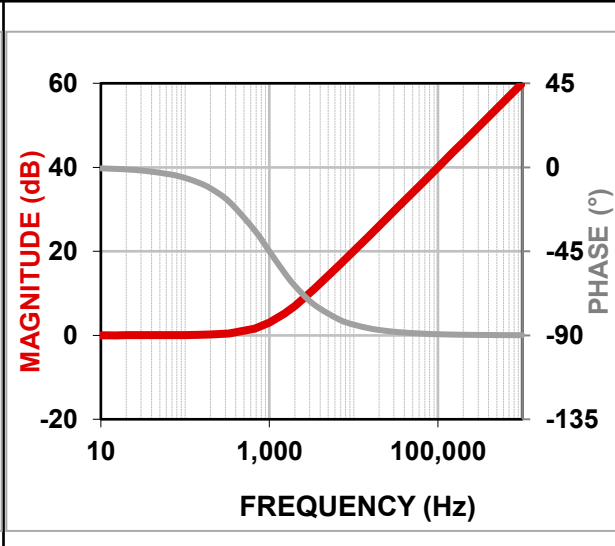
Phase margin and gain margin



Phase margin and stability

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

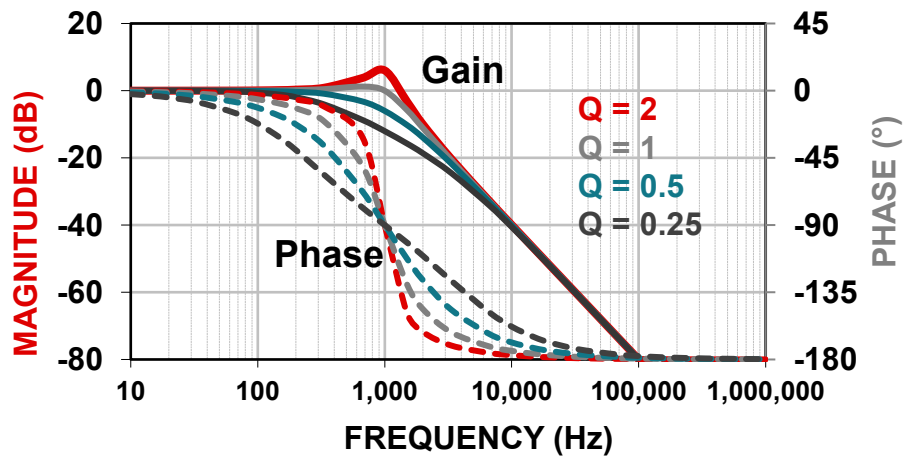
Poles, zeros and right-half-plane zeros

Pole	Zero	Right-half-plane zero
$H(s) = \frac{1}{1 + \frac{s}{\omega_P}}$	$H(s) = \frac{1 + \frac{s}{\omega_Z}}{1}$	$H(s) = \frac{1 - \frac{s}{\omega_Z}}{1}$
		

Complex conjugate pole and ESR zero

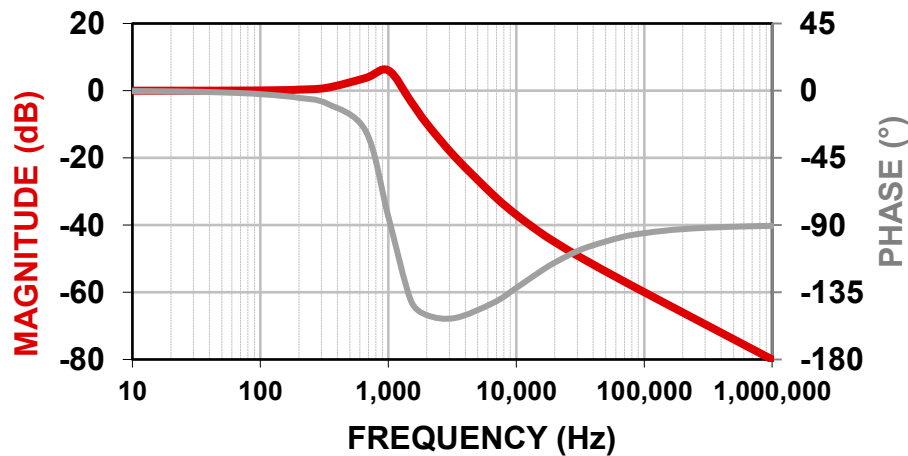
Complex conjugate pole

$$H(s) = \frac{1}{1 + \frac{s}{Q_0 \cdot \omega_0} + \frac{s^2}{\omega_0^2}}$$



With ESR zero

$$H(s) = \frac{1 + \frac{s}{\omega_Z}}{1 + \frac{s}{Q_0 \cdot \omega_0} + \frac{s^2}{\omega_0^2}}$$



Control methods and operating modes

Control methods

- Voltage-mode control
- Current-mode control

Operating modes

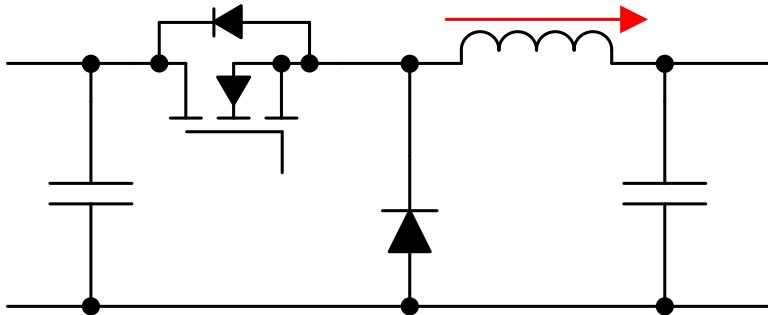
- Fixed frequency
- Continuous conduction-mode (CCM)

Switching frequency and period

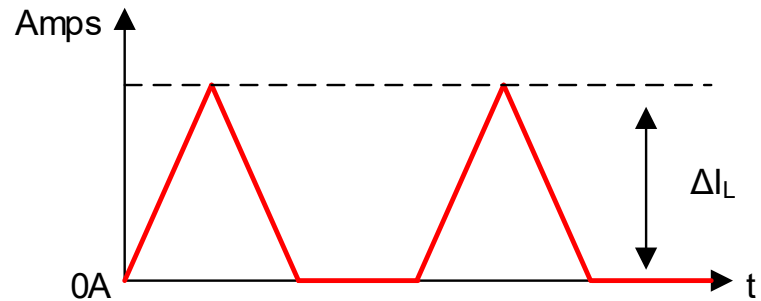
- Switching frequency – f_{sw}
- Switching period – T

$$T = \frac{1}{f_{sw}}$$

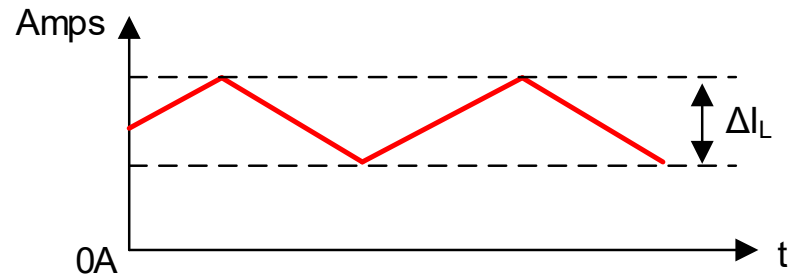
DCM vs CCM



Discontinuous Conduction Mode (DCM)

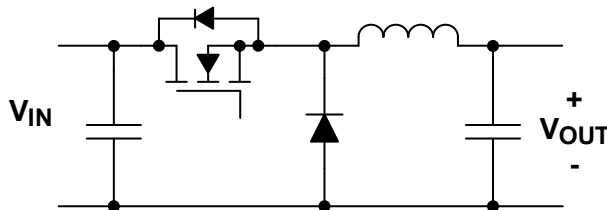


Continuous Conduction Mode (CCM)



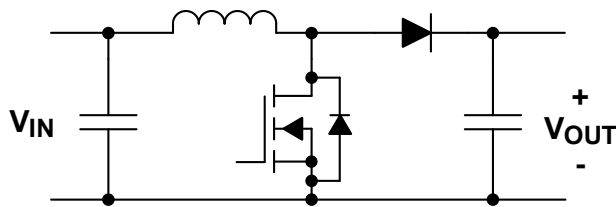
Buck, boost, and buck-boost derived topologies

Buck, forward, push-pull, bridge



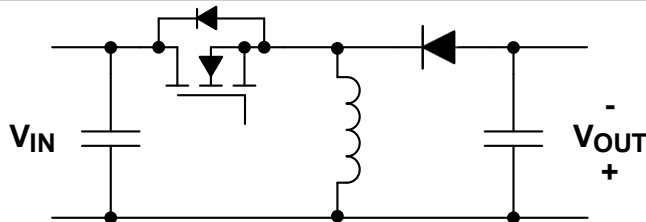
$$V_{OUT} = V_{IN} \times D$$

Boost



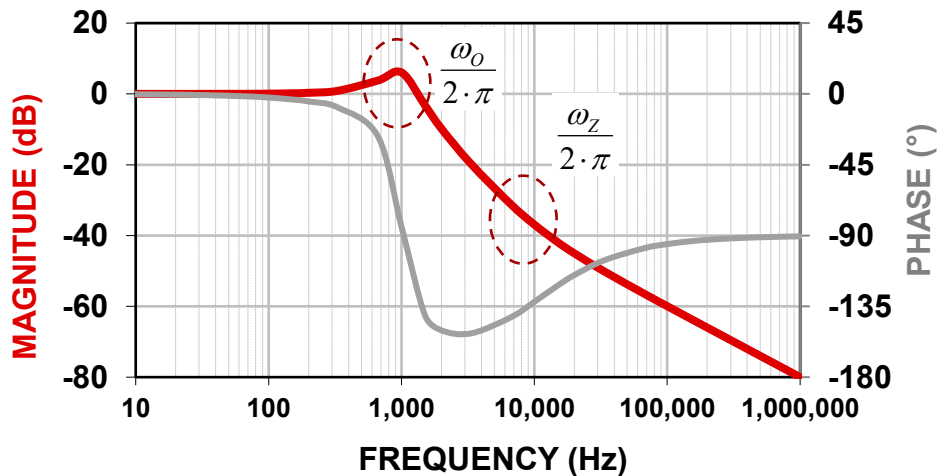
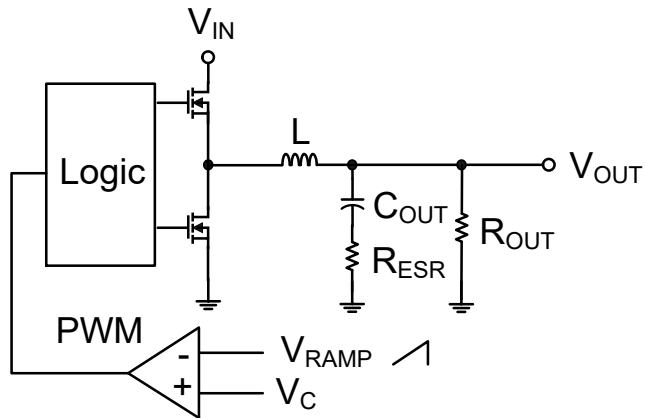
$$V_{OUT} = V_{IN} \times \frac{1}{1 - D}$$

Buck-boost, SEPIC, flyback



$$V_{OUT} = V_{IN} \times \frac{D}{1 - D}$$

Voltage-mode buck power stage



$$A_{VC} = \frac{V_{IN}}{V_{RAMP}}$$

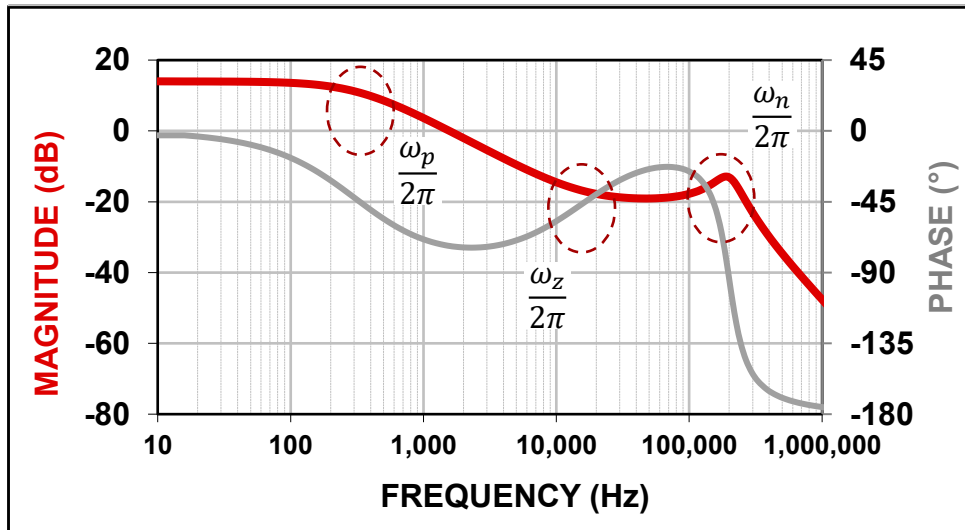
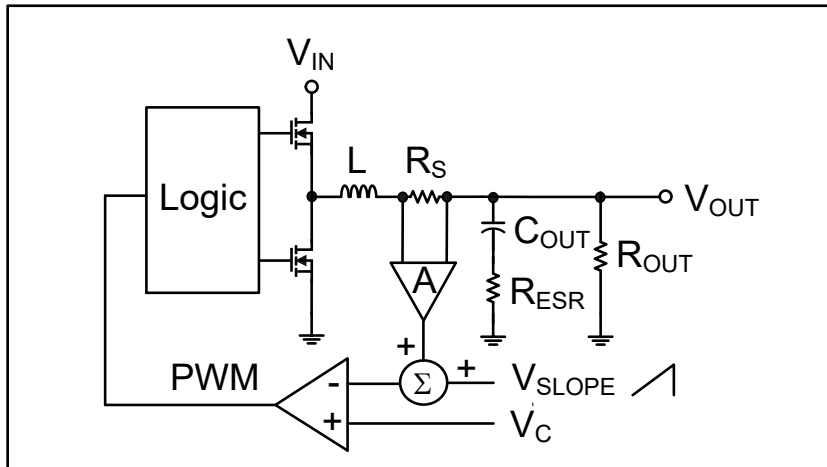
$$\omega_o = \frac{1}{\sqrt{L \cdot C_{OUT}}}$$

$$Q_o = \frac{R_{OUT}}{\sqrt{L/C_{OUT}}}$$

$$\omega_z = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} = A_{VC} \cdot \frac{1 + \frac{s}{\omega_z}}{1 + \frac{s}{Q_o \cdot \omega_o} + \frac{s^2}{\omega_o^2}}$$

Current-mode buck power stage



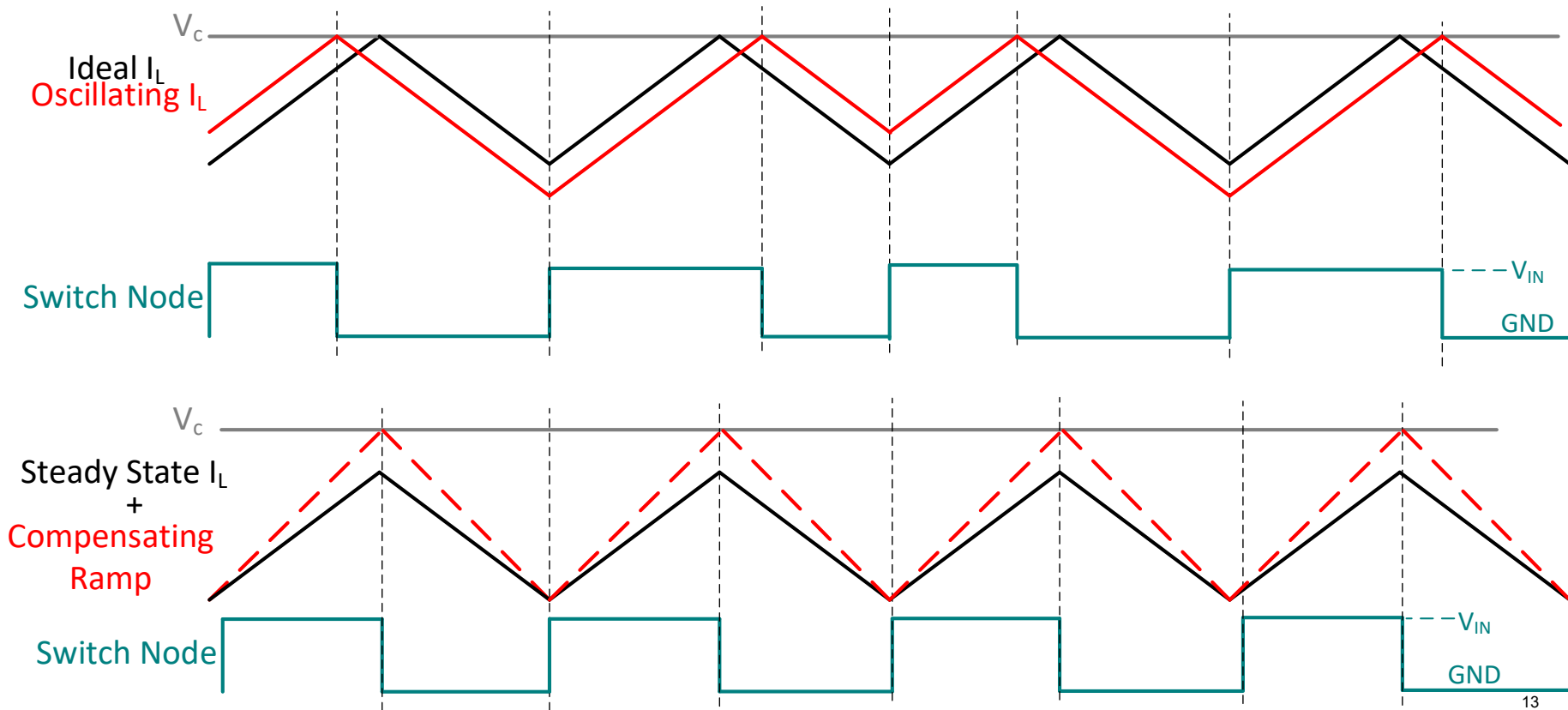
$$\omega_p \approx \frac{1}{C_{out} \cdot R_{out}} \quad \omega_z = \frac{1}{R_{ESR} \cdot C_{out}}$$

$$A_{VC} \approx \frac{R_{out}}{R_i} = \frac{R_{out}}{A \cdot R_S} \quad F_h(s) = \frac{1}{1 + \frac{s}{\omega_n \cdot Q_p} + \left(\frac{s}{\omega_n}\right)^2}$$

$$\omega_n = \frac{\omega_{fsw}}{2} \quad \text{at } D = 0.5$$

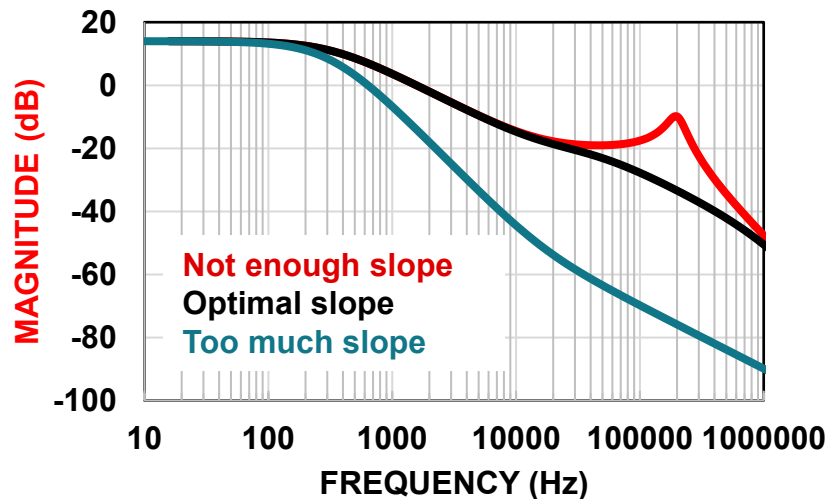
$$\frac{\hat{v}_{out}}{\hat{v}_c} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_z}}{1 + \frac{s}{\omega_p}} \cdot F_h(s)$$

Why is slope compensation needed?



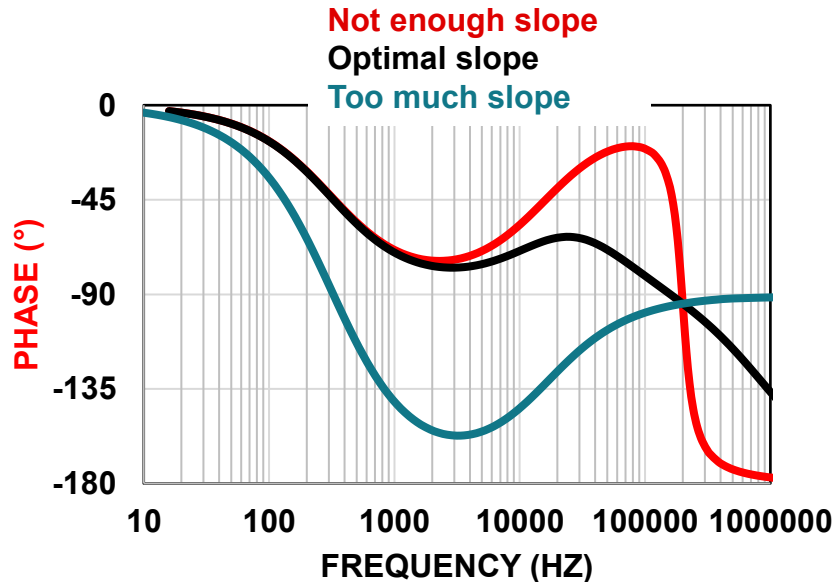
Impact of slope compensation

Gain

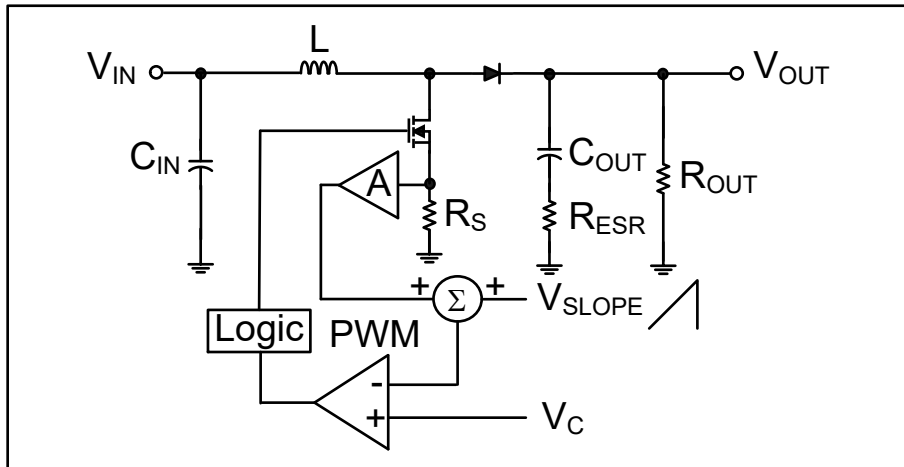


*gain curves normalized to 14 dB DC gain

Phase



Current-mode boost power stage

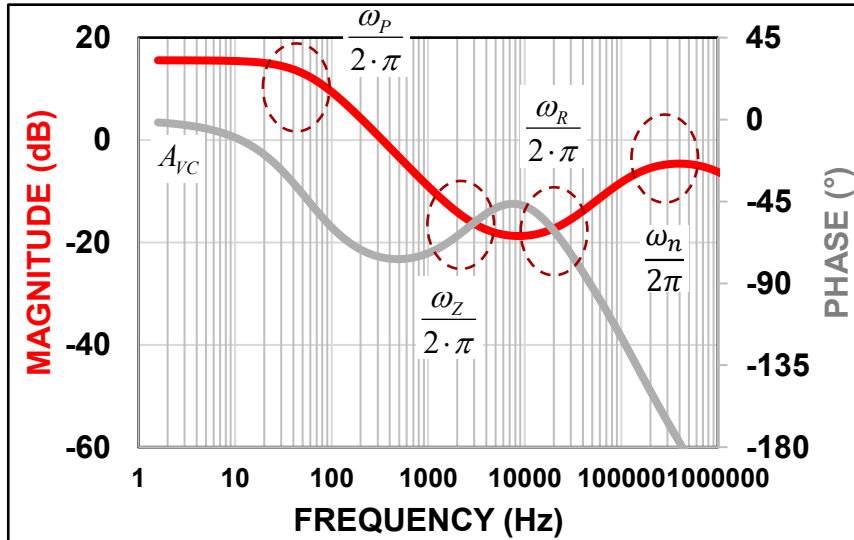


$$R_i = A \cdot R_S$$

$$\omega_r \approx \frac{R_{out} \cdot (1-D)^2}{L} \quad \omega_n = \frac{\omega_{fsw}}{2}$$

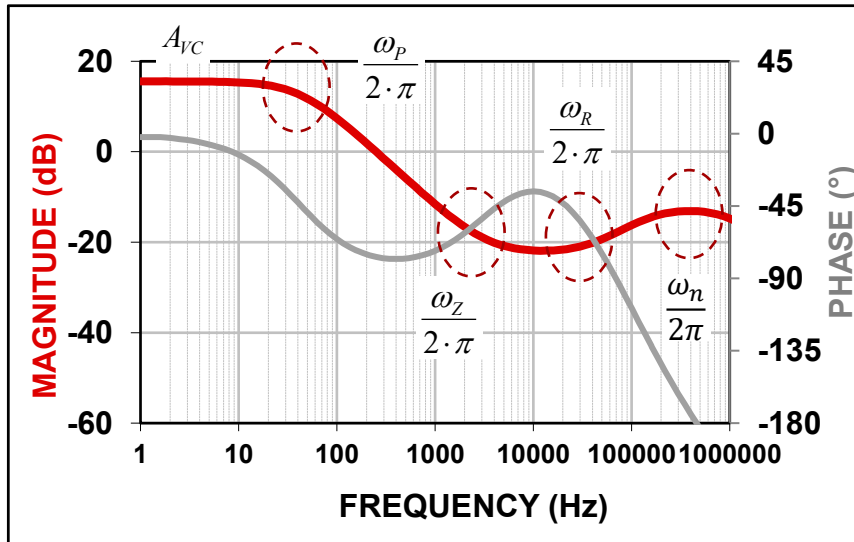
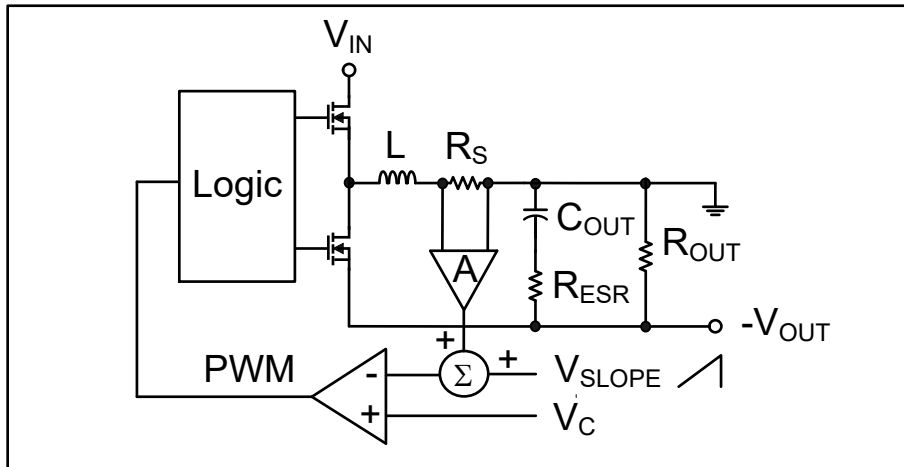
$$A_{VC} \approx \frac{R_{out} \cdot (1-D)}{2 \cdot R_i} \quad \omega_z = \frac{1}{R_{ESR} \cdot C_{OUT}} \quad \text{at } D = 0.5$$

$$\omega_p \approx \frac{2}{C_{OUT} \cdot R_{OUT}} \quad F_h(s) = \frac{1}{1 + \frac{s}{\omega_n \cdot Q_p} + \left(\frac{s}{\omega_n}\right)^2}$$



$$\frac{\hat{v}_{out}}{\hat{v}_c} \approx A_{VC} \cdot \frac{\left(1 + \frac{s}{\omega_z}\right) \left(1 - \frac{s}{\omega_r}\right)}{1 + \frac{s}{\omega_p}} \cdot F_h(s)$$

Current-mode buck-boost power stage



$$R_i = A \cdot R_s$$

$$\omega_r \approx \frac{R_{out} \cdot (1 - D)^2}{L \cdot D}$$

$$A_{VC} \approx \frac{R_{out} \cdot (1 - D)}{(1 + D) \cdot R_i}$$

$$\omega_z = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

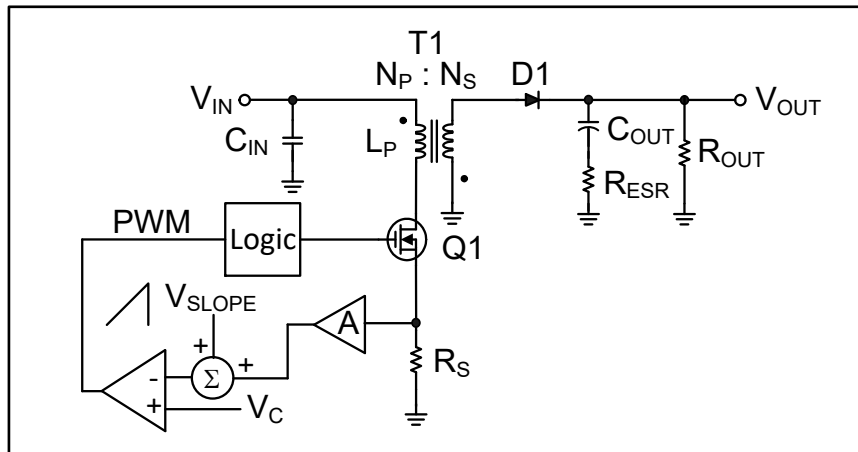
$$\omega_p \approx \frac{1 + D}{C_{OUT} \cdot R_{OUT}}$$

$$F_h(s) = \frac{1}{1 + \frac{s}{\omega_n \cdot Q_p} + \left(\frac{s}{\omega_n}\right)^2}$$

at D = 0.5

$$\frac{\hat{v}_{out}}{\hat{v}_c} \approx A_{VC} \cdot \frac{\left(1 + \frac{s}{\omega_z}\right) \left(1 - \frac{s}{\omega_r}\right)}{1 + \frac{s}{\omega_p}} \cdot F_h(s)$$

Current-mode flyback power stage



$$R_i = A \cdot R_S$$

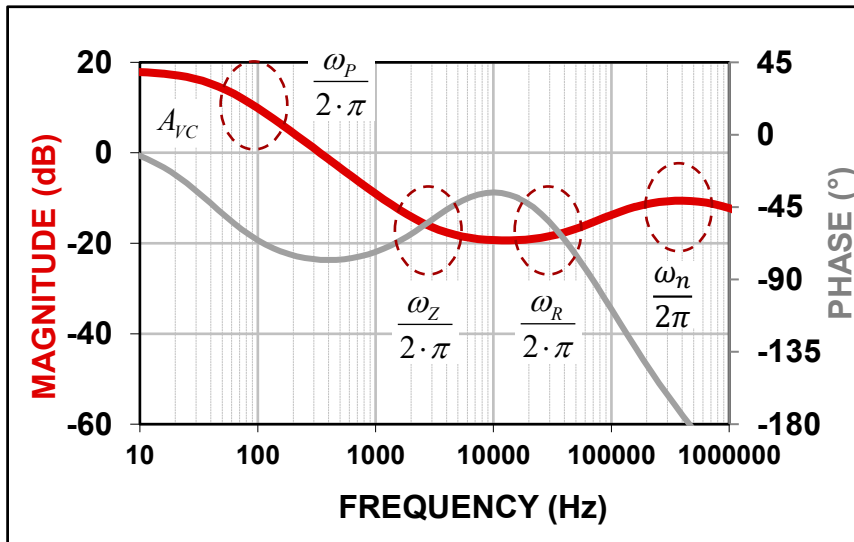
$$\omega_r \approx \frac{R_{out} \cdot (1-D)^2}{L \cdot D} \left(\frac{N_p}{N_s} \right)^2$$

$$A_{VC} \approx \frac{R_{out} \cdot (1-D)}{(1+D) \cdot R_i} \cdot \frac{N_p}{N_s}$$

$$\omega_z = \frac{1}{R_{ESR} \cdot C_{OUT}} \quad \text{at } D = 0.5$$

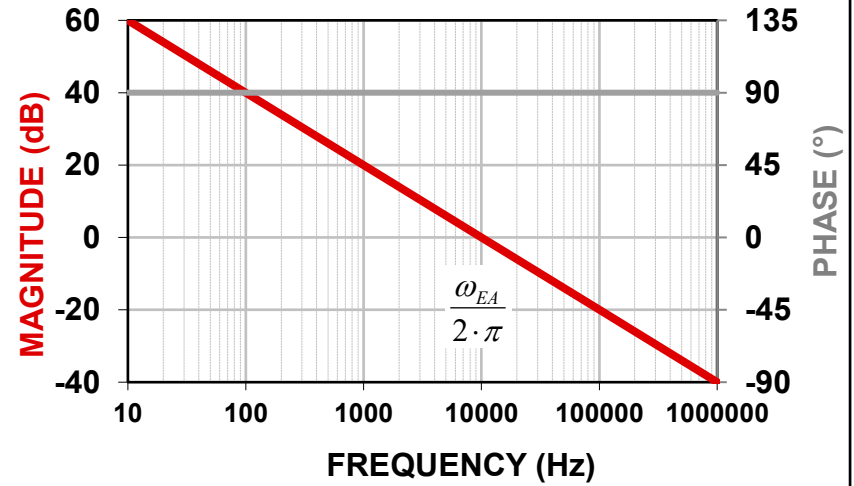
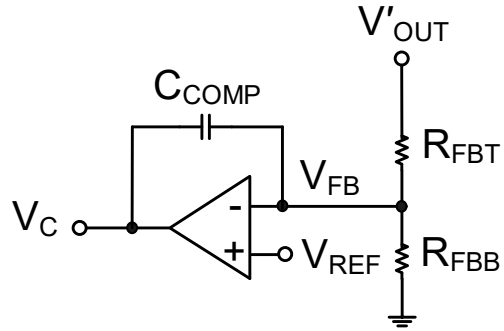
$$\omega_p \approx \frac{1+D}{C_{OUT} \cdot R_{OUT}}$$

$$F_h(s) = \frac{1}{1 + \frac{s}{\omega_n \cdot Q_p} + \left(\frac{s}{\omega_n} \right)^2}$$



$$\frac{\hat{v}_{out}}{\hat{v}_c} \approx A_{VC} \cdot \frac{\left(1 + \frac{s}{\omega_z} \right) \left(1 - \frac{s}{\omega_r} \right)}{1 + \frac{s}{\omega_p}} \cdot F_h(s)$$

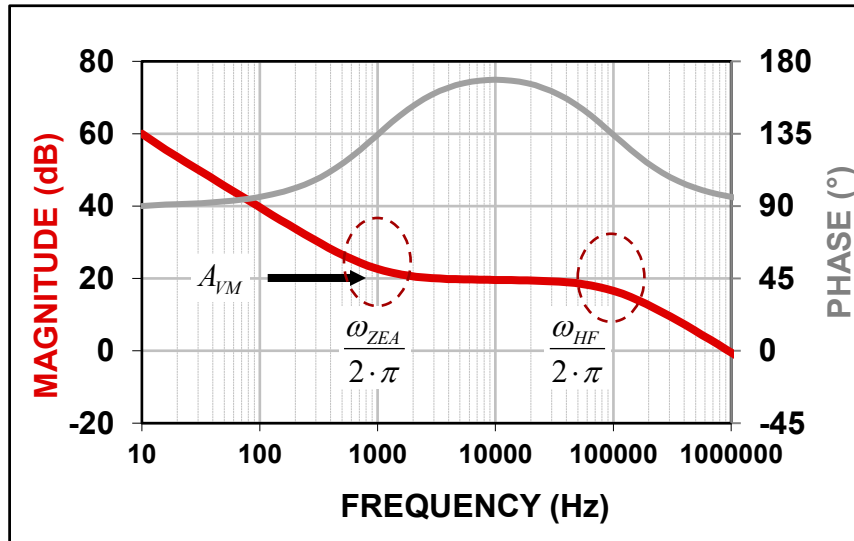
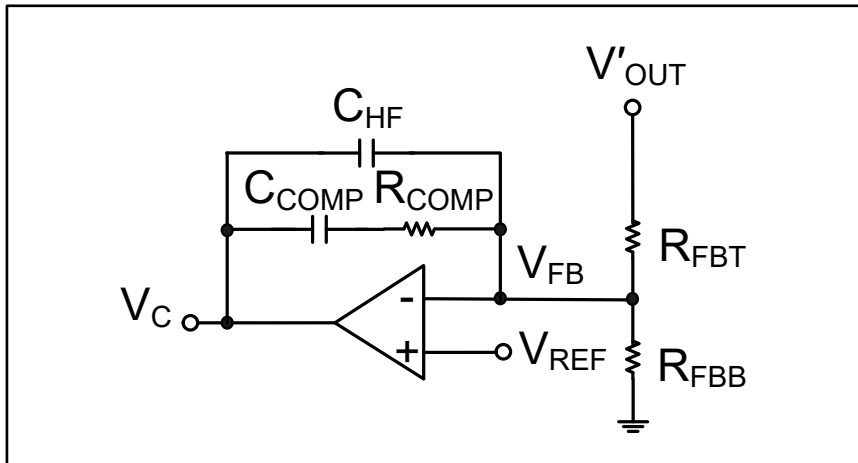
Type I error amplifier



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

$$\frac{\hat{v}_C}{\hat{v}'_{OUT}} \approx -\frac{\omega_{EA}}{s}$$

Type II error amplifier

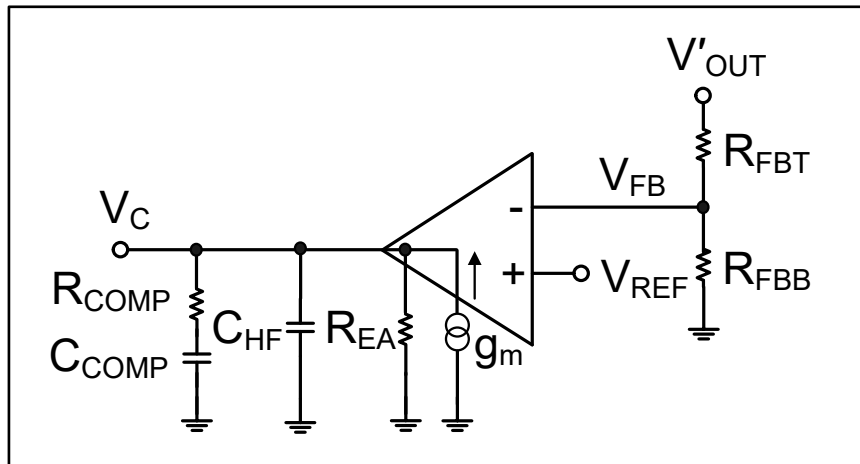


$$A_{VM} \approx \frac{R_{COMP}}{R_{FBT}} \quad \omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}}$$

$$\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}} \quad \text{Assumption: } C_{COMP} \gg C_{HF}$$

$$\frac{\hat{v}_c}{\hat{v}'_{out}} \approx - \frac{A_{VM} \cdot \omega_{ZEA}}{s} \cdot \frac{1 + \frac{s}{\omega_{ZEA}}}{1 + \frac{s}{\omega_{HF}}}$$

Type II transconductance amplifier



$$A_{VM} = K_{FB} \cdot g_m \cdot R_{COMP}$$

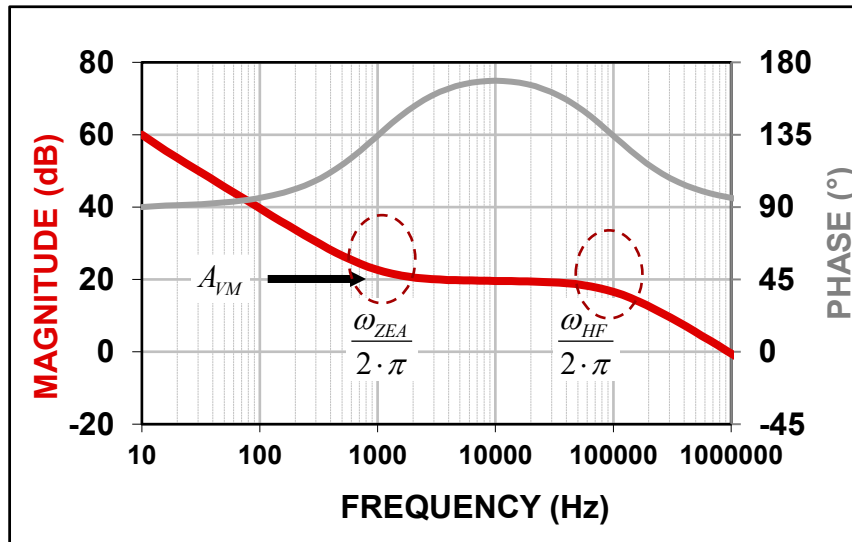
$$\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}}$$

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

$$K_{FB} = \frac{R_{FBB}}{R_{FBB} + R_{FBT}}$$

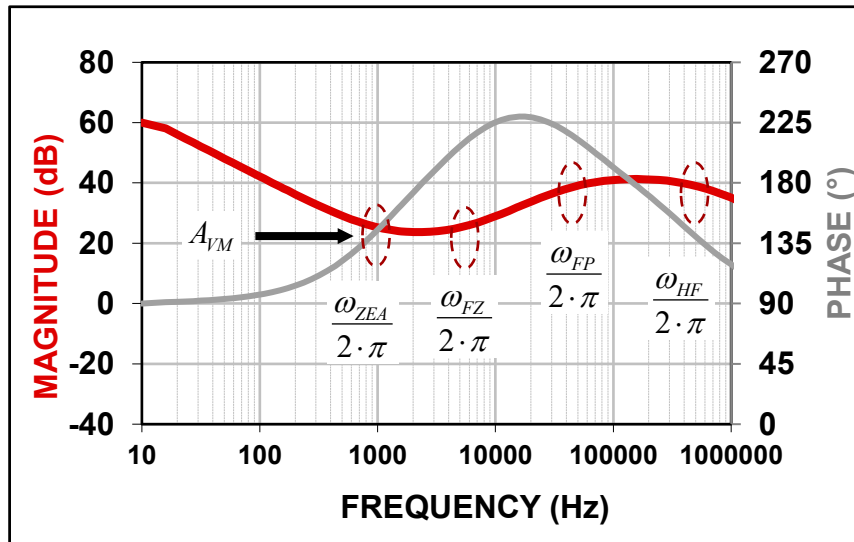
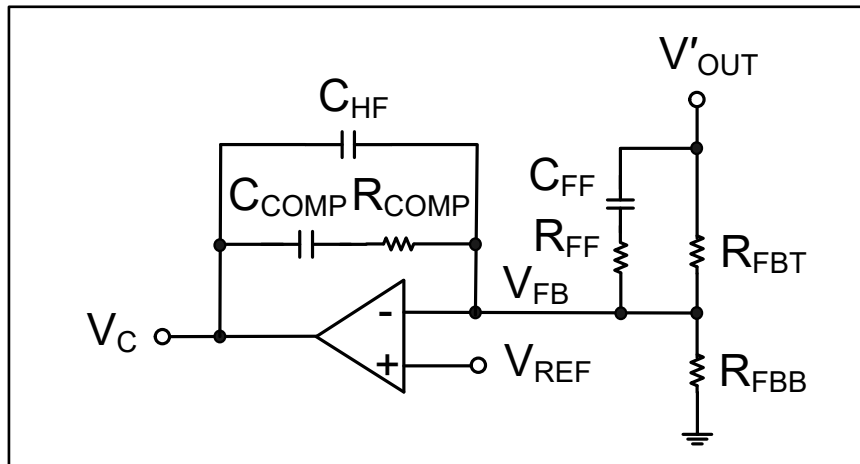
$$A_{OL} = g_m \cdot R_{EA}$$

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



$$\frac{\hat{v}_c}{\hat{v}'_{out}} \approx - \frac{A_{VM} \cdot \omega_{ZEA}}{s} \cdot \frac{1 + \frac{s}{\omega_{ZEA}}}{1 + \frac{s}{\omega_{HF}}}$$

Type III error amplifier



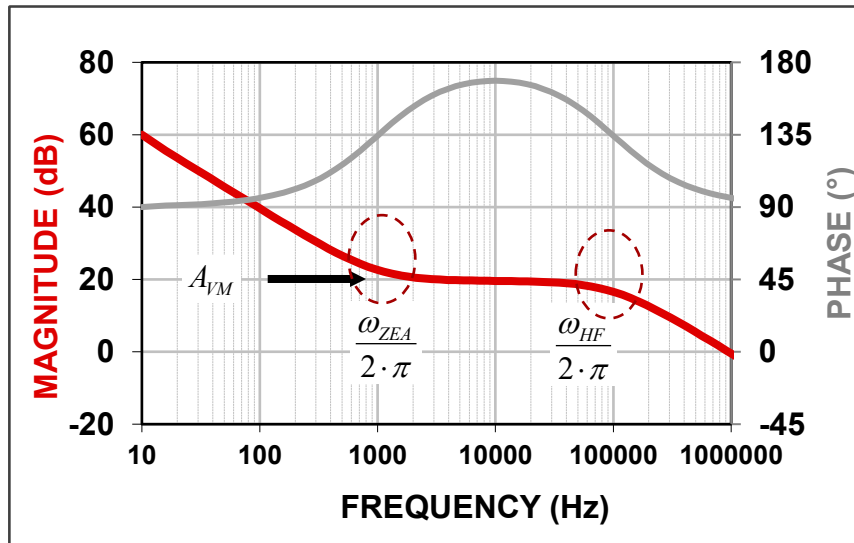
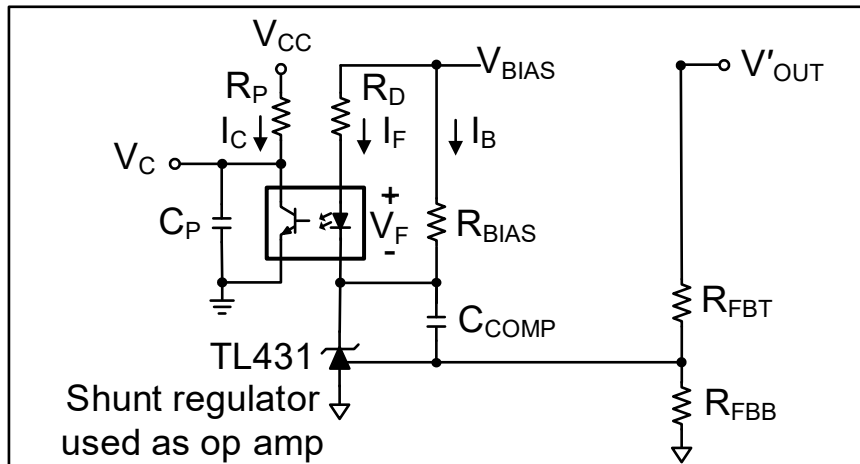
$$A_{VM} \approx \frac{R_{COMP}}{R_{FBT}} \quad \omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}} \quad \omega_{FP} = \frac{1}{R_{FF} \cdot C_{FF}}$$

$$\omega_{FZ} \approx \frac{1}{R_{FBT} \cdot C_{FF}} \quad \omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}}$$

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

$$\frac{\hat{v}_c}{\hat{v}'_{out}} \approx -\frac{A_{VM} \cdot \omega_{ZEA}}{s} \cdot \frac{\left(1 + \frac{s}{\omega_{ZEA}}\right) \cdot \left(1 + \frac{s}{\omega_{FZ}}\right)}{\left(1 + \frac{s}{\omega_{FP}}\right) \cdot \left(1 + \frac{s}{\omega_{HF}}\right)}$$

Type II isolated feedback with fixed bias

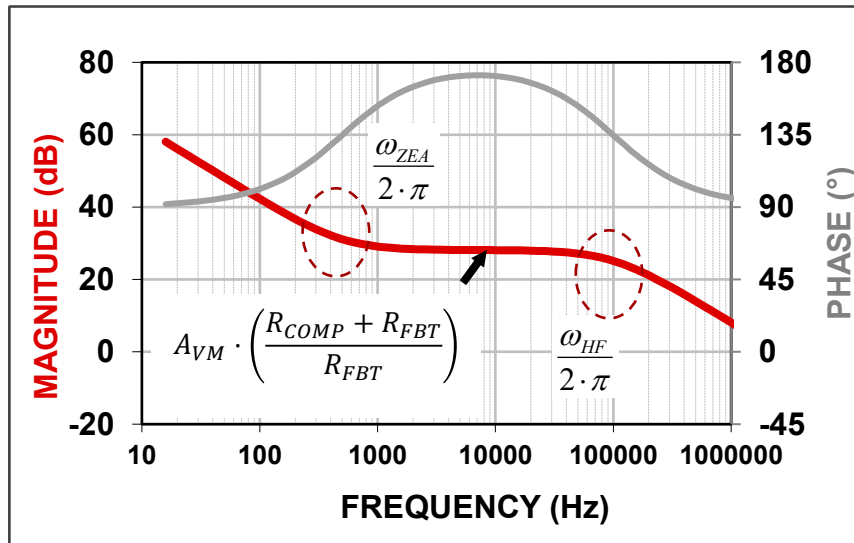
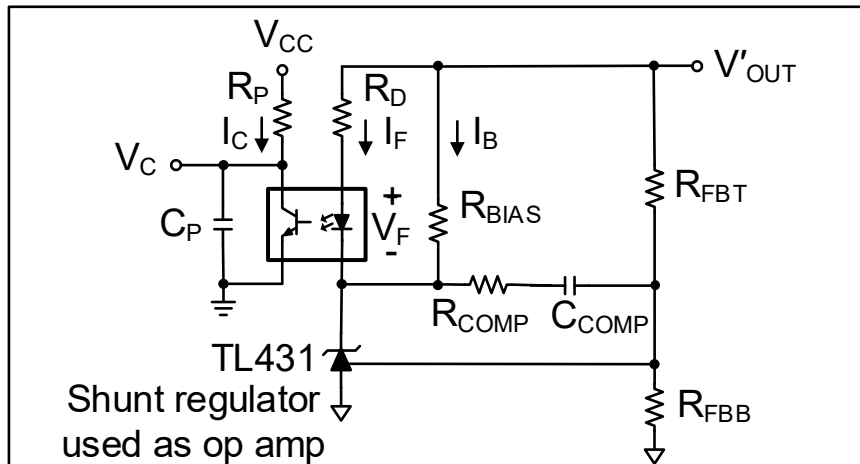


$$A_{VM} = CTR \cdot \frac{R_P}{R_D} \quad CTR = \frac{I_C}{I_F}$$

$$\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}} \quad \omega_{HF} = \frac{1}{R_P \cdot C_P}$$

$$\frac{\hat{v}_C}{\hat{v}'_{OUT}} \approx \frac{A_{VM} \cdot \omega_{EA}}{s} \cdot \frac{1 + \frac{s}{\omega_{EA}}}{1 + \frac{s}{\omega_{HF}}}$$

Type II isolated feedback with Vout bias



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

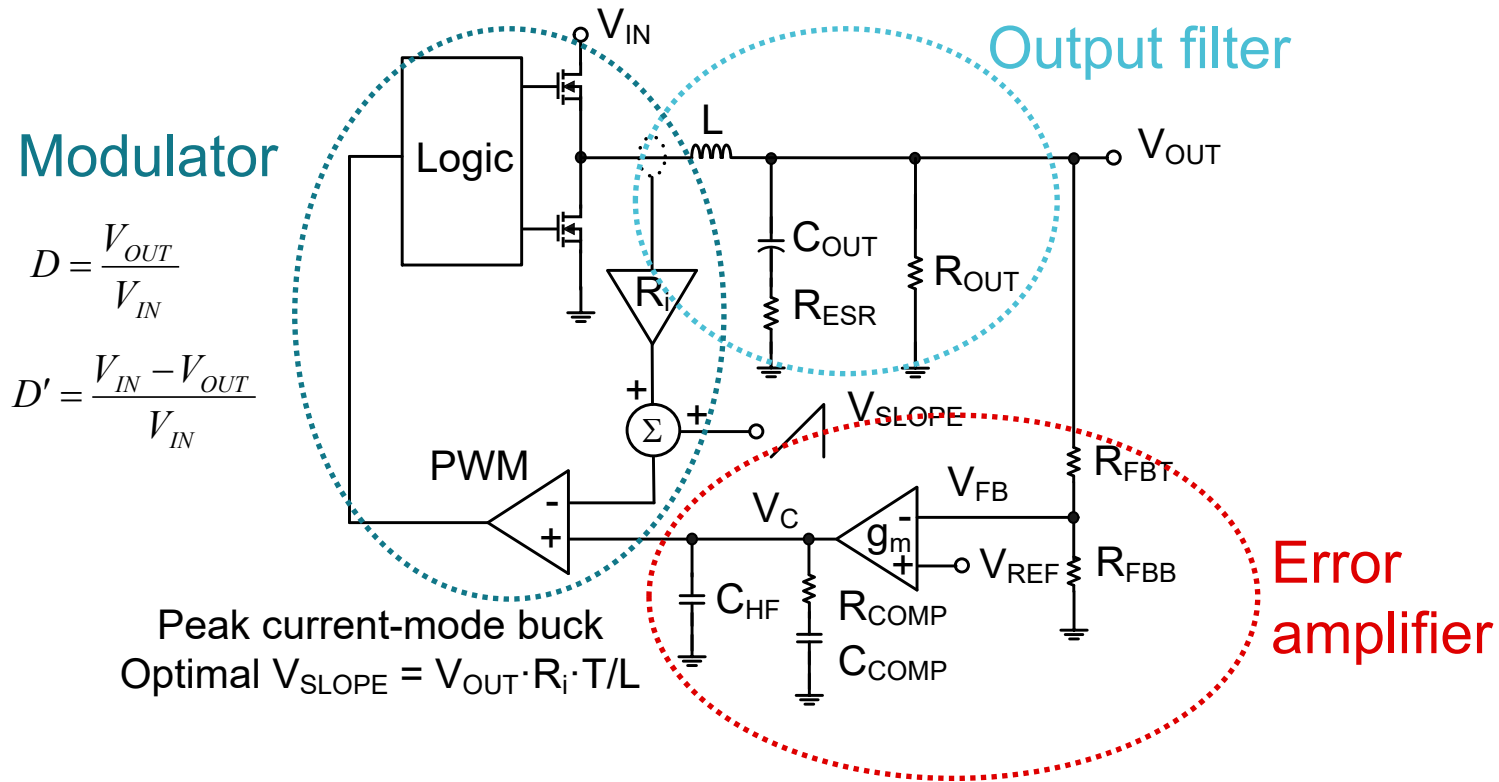
$$CTR = \frac{I_C}{I_F}$$

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

$$\omega_{HF} = \frac{1}{R_P \cdot C_P}$$

$$\frac{\hat{v}_C}{\hat{v}'_{OUT}} \approx \frac{A_{VM} \cdot \omega_{EA}}{s} \cdot \frac{1 + \frac{s}{\omega_{EA}}}{1 + \frac{s}{\omega_{HF}}}$$

Current-mode buck



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 ω_{ZEA} equal to 1/10 the target crossover frequency:
$$\omega_{ZEA} = \omega_C/10$$
- Set ω_{HF} equal to the ESR zero frequency:
$$\omega_{HF} = \omega_Z$$

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

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

$$R_{COMP} = A_{VM} \cdot R_{FBT} \text{ (op amp)}$$

$$R_{COMP} = \frac{A_{VM}}{g_m \cdot K_{FB}} \text{ (g}_m \text{ amp)}$$

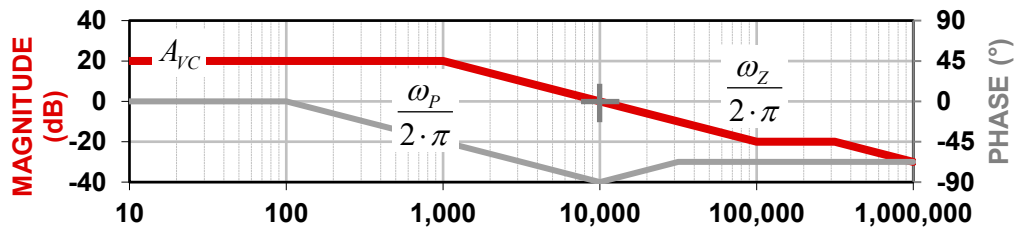
$$C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}$$

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

Current-mode buck compensation results

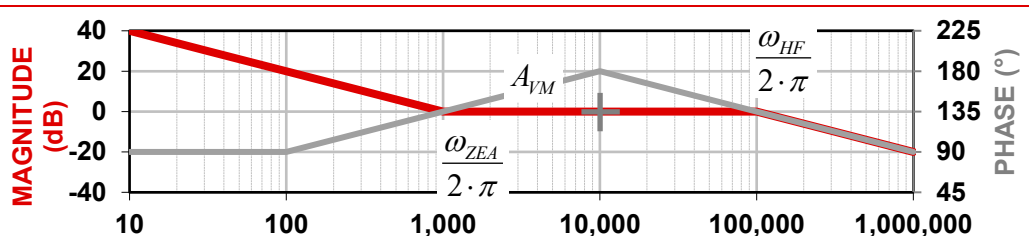
Power stage

$$\frac{\hat{v}_{out}}{\hat{v}_c} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_z}}{1 + \frac{s}{\omega_p}} \cdot F_h(s)$$



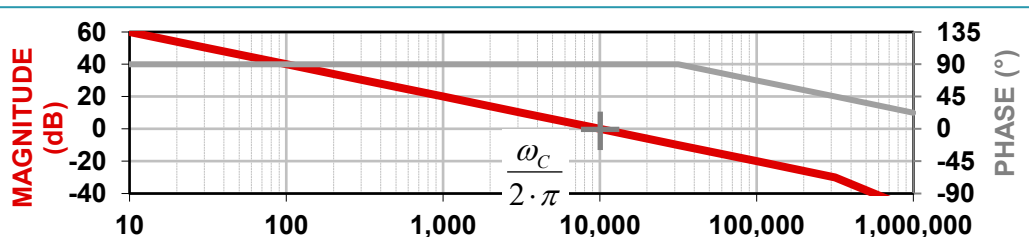
Error amplifier

$$\frac{\hat{v}_c}{\hat{v}'_{OUT}} \approx -A_{VM} \cdot \frac{1 + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}}$$



Control loop

$$\frac{\hat{v}_{OUT}}{\hat{v}'_{OUT}} = \frac{\hat{v}_{OUT}}{\hat{v}_c} \cdot \frac{\hat{v}_c}{\hat{v}'_{OUT}}$$

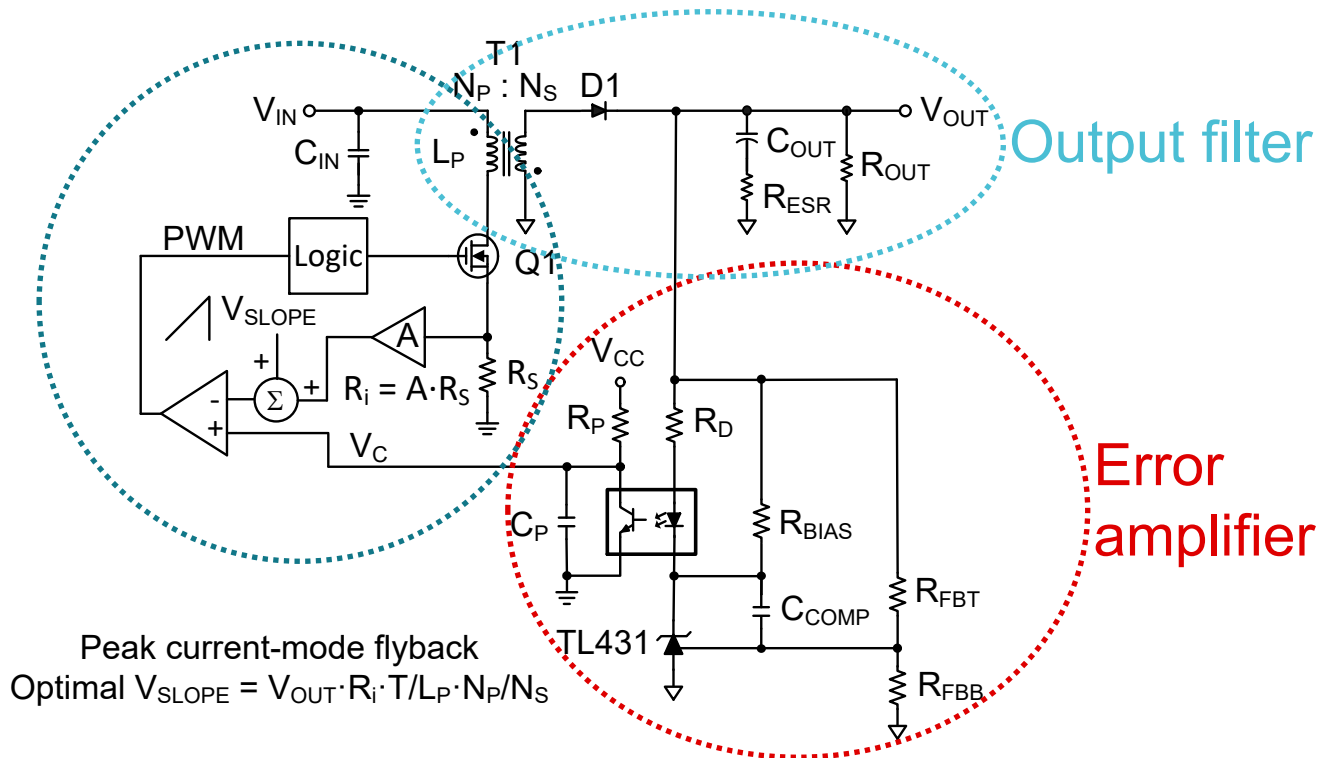


Isolated current-mode flyback

Modulator

$$D = \frac{V_{OUT}}{V_{IN} \cdot \frac{N_S}{N_P} + V_{OUT}}$$

$$D' = \frac{V_{IN}}{V_{IN} + V_{OUT} \cdot \frac{N_P}{N_S}}$$



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:
 $\omega_C = 2 \cdot \pi \cdot f_C = \omega_R/4$
- Find the mid-band gain A_{VM} to achieve target bandwidth
Adjust R_D , R_P and C_{OUT} as required
- Set ω_{ZEA} equal to 1/10 the target crossover frequency:
 $\omega_{ZEA} = \omega_C/10$
- Set ω_{HF} equal to the lower of the RHP or ESR zero frequency:
 $\omega_{HF} = \omega_R$ or ω_Z

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

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

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

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

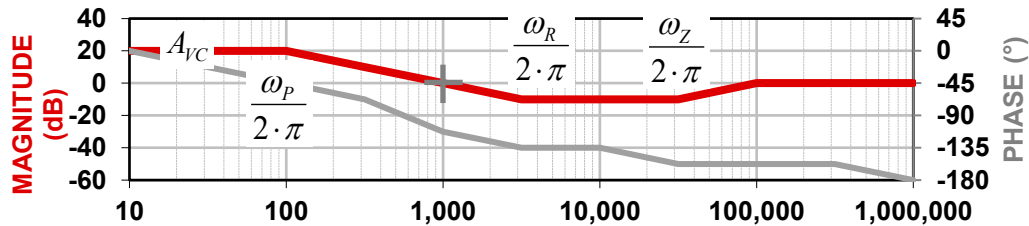
$$C_{COMP} = \frac{1}{R_{FBT} \cdot \omega_{ZEA}}$$

$$C_P = \frac{1}{R_P \cdot \omega_{HF}}$$

Current-mode flyback compensation results

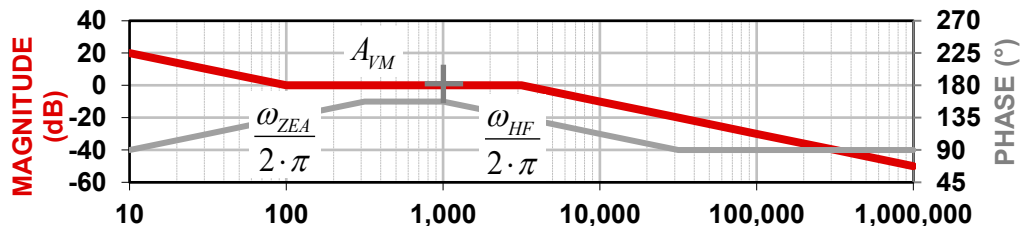
Power stage

$$\frac{\hat{v}_{out}}{\hat{v}_c} \approx A_{VC} \cdot \frac{\left(1 + \frac{s}{\omega_z}\right) \left(1 - \frac{s}{\omega_r}\right)}{1 + \frac{s}{\omega_p}} \cdot F_h(s)$$



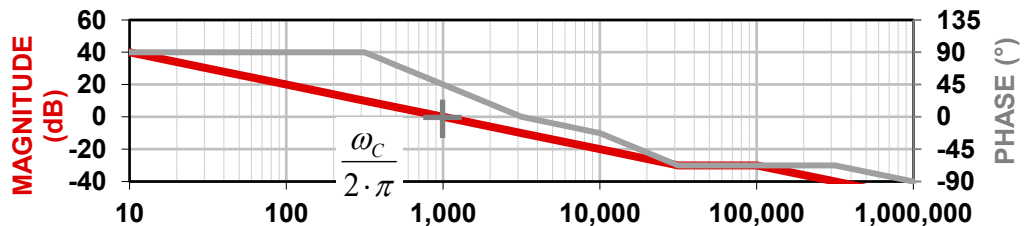
Error amplifier

$$\frac{\hat{v}_c}{\hat{v}'_{OUT}} \approx -A_{VM} \cdot \frac{1 + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}}$$



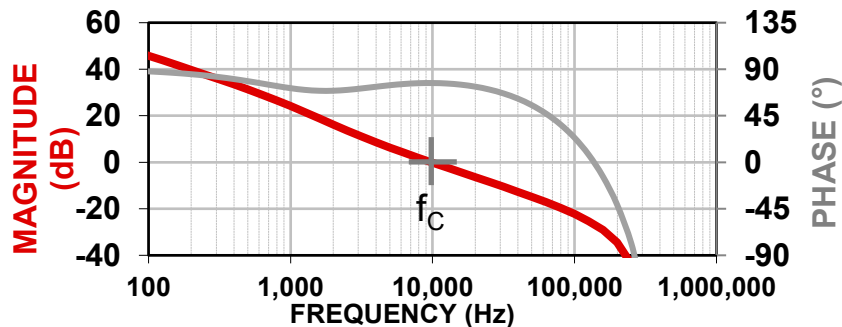
Control loop

$$\frac{\hat{v}_{OUT}}{\hat{v}'_{OUT}} = \frac{\hat{v}_{OUT}}{\hat{v}_c} \cdot \frac{\hat{v}_c}{\hat{v}'_{OUT}}$$

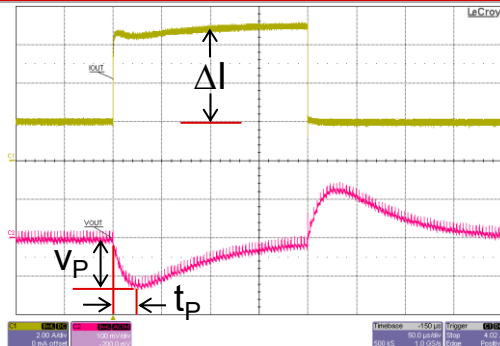


Bandwidth vs transient response

Current-mode bandwidth



Current-mode transient response



With no ESR, slew rate or duty cycle limiting:

$$t_p = \frac{1}{4 \cdot f_c}$$

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:

$$V_P = \frac{\Delta I}{8 \cdot f_c \cdot C_{OUT}}$$

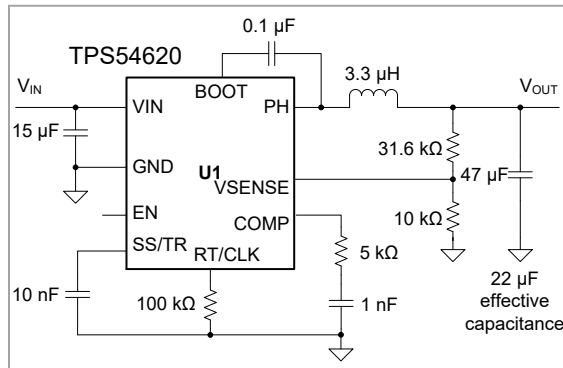
$$t_p = \frac{1}{4 \cdot 10\text{kHz}} = 25\mu\text{s}$$

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

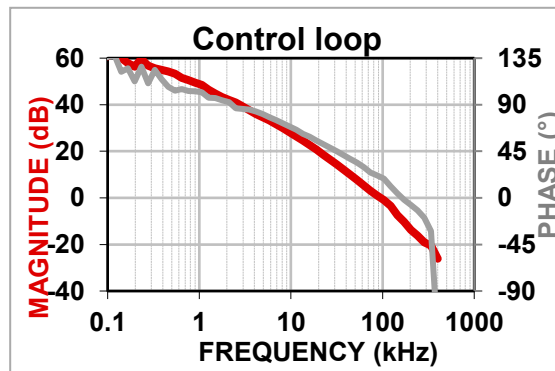
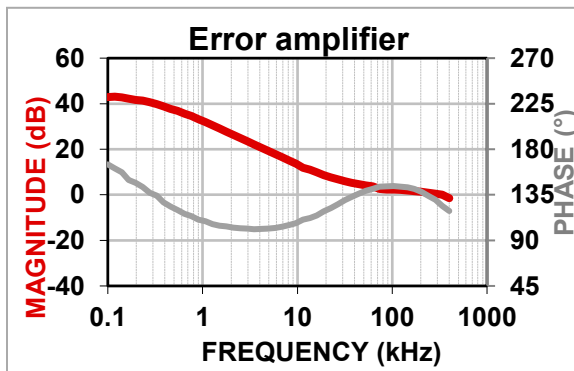
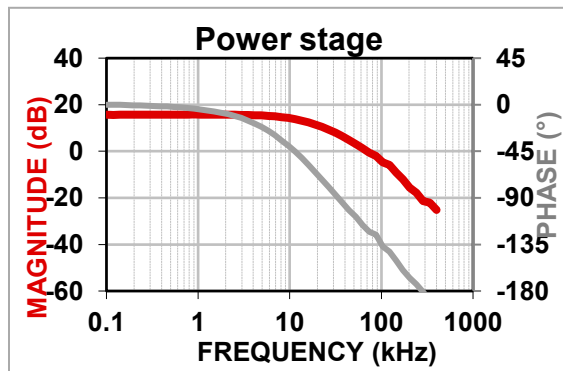
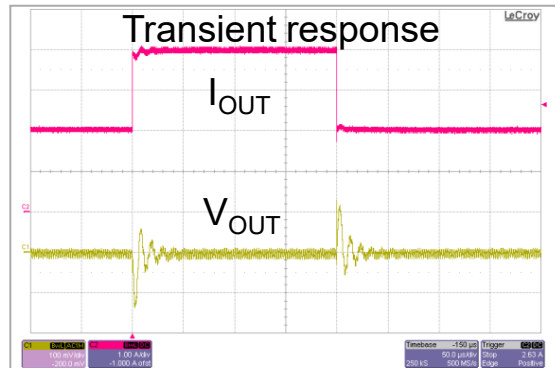
$$V_P = \frac{5\text{A}}{e \cdot \pi \cdot 10\text{kHz} \cdot 440\mu\text{F}} = 130\text{mV} \text{ shown above}$$

$$V_P = \frac{5\text{A}}{8 \cdot 10\text{kHz} \cdot 440\mu\text{F}} = 140\text{mV}$$

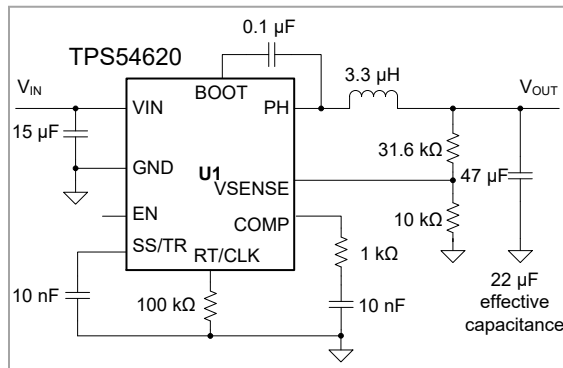
Switching regulator with poor compensation



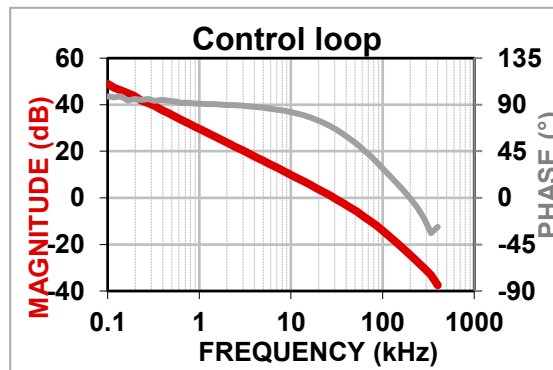
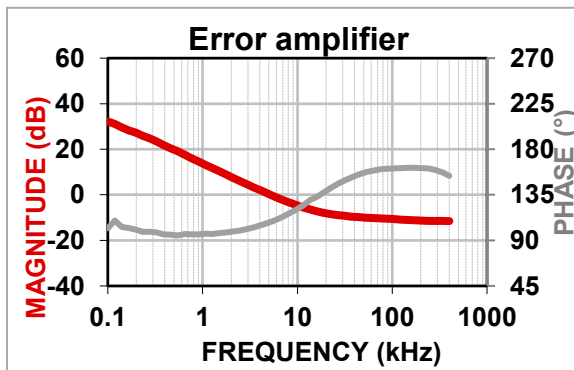
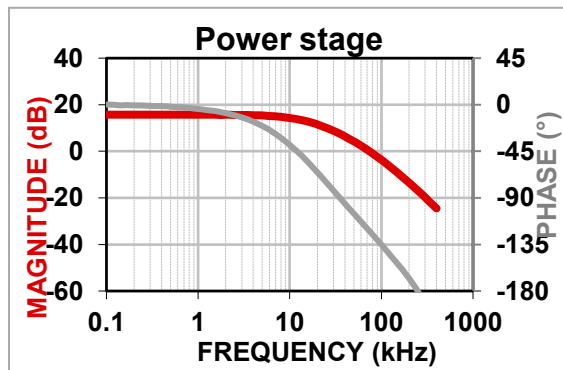
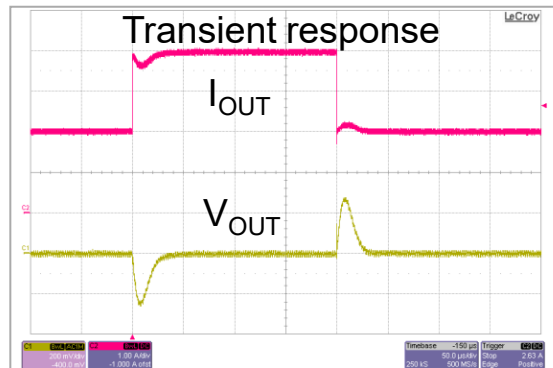
- Power stage: phase at -180° indicates high internal slope compensation
- Error amplifier: zero appears high and mid-band gain is 3 dB
- Control loop: f_C is 95 kHz with only 20° phase margin



Switching regulator with revised compensation

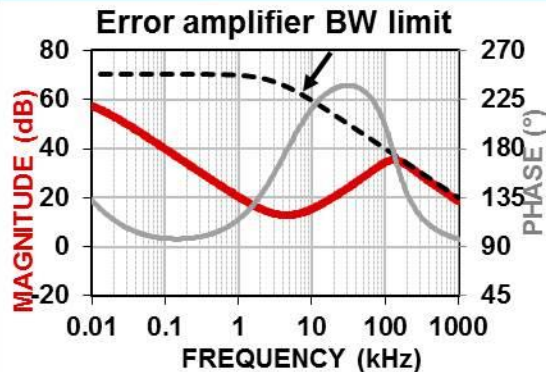


- Power stage: cannot change slope compensation
- Error amplifier: decrease R_{COMP} and rescale C_{COMP}
- Control loop: now f_c is 30 kHz with 67° phase margin



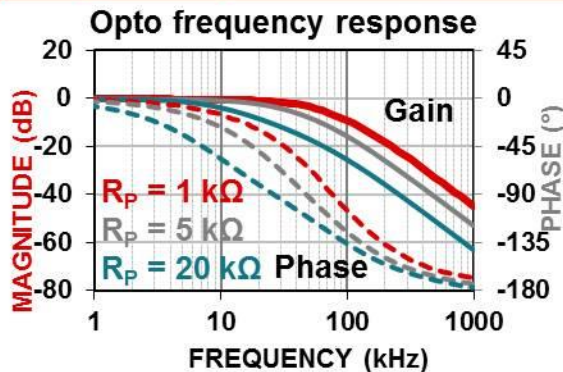
Practical limitations

Error amplifier bandwidth



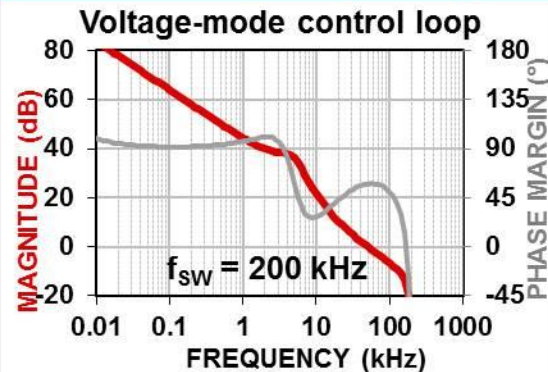
- Error amp BW can limit maximum f_c
- Wider BW op amp needed for voltage-mode due to Type III compensation

Optocoupler bandwidth



- Resistance seen by output transistor forms a pole in kHz range
- More of an issue for forward topologies at higher f_c

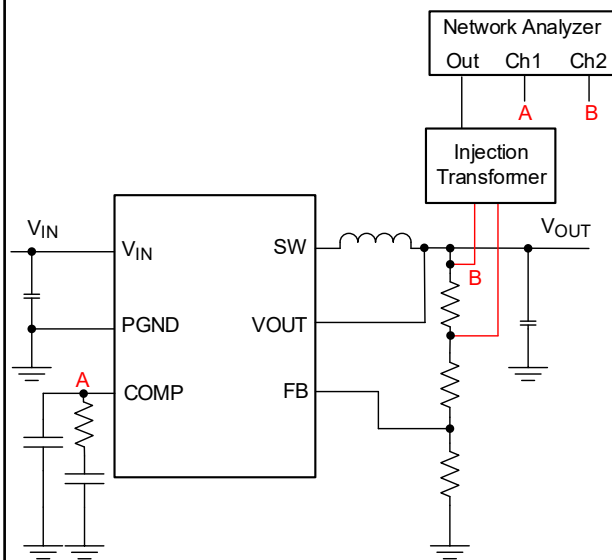
Switching frequency



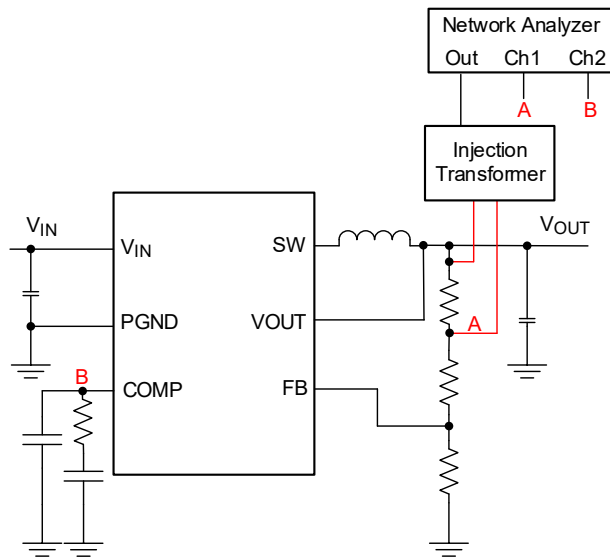
- Maximum f_c is a fraction of f_{sw}
- Rule of thumb is 1/5 to 1/10 of f_{sw}

Measuring transfer functions

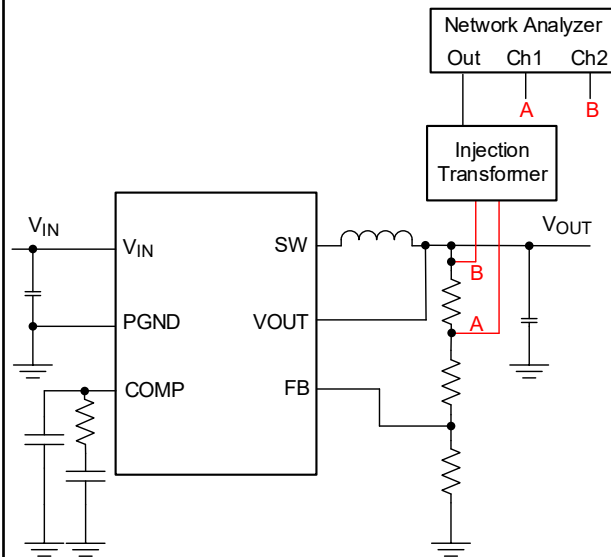
Power stage



Compensator

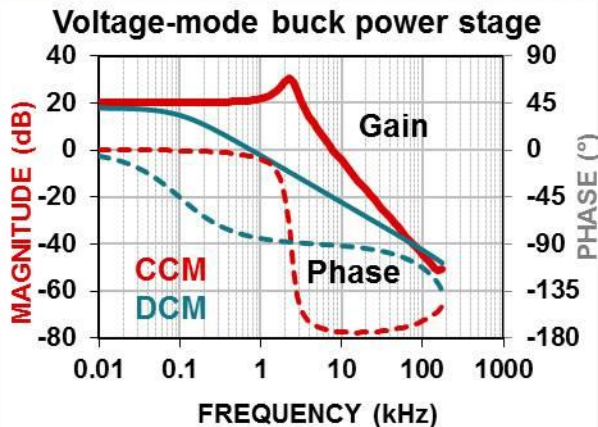
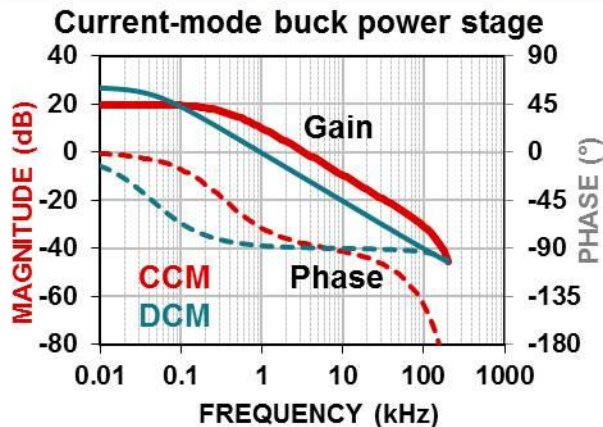


Total loop



DCM vs CCM characteristics

Discontinuous vs. continuous conduction-mode



- DCM causes a reduction in loop bandwidth compared to CCM
- Generally, if the loop is stable in CCM, it will be stable in DCM

DCM duty cycle

- Buck

$$D = \sqrt{\frac{2 \cdot L \cdot f_{SW} \cdot I_{OUT} \cdot V_{OUT}}{V_{IN} \cdot (V_{IN} - V_{OUT})}}$$

- Boost

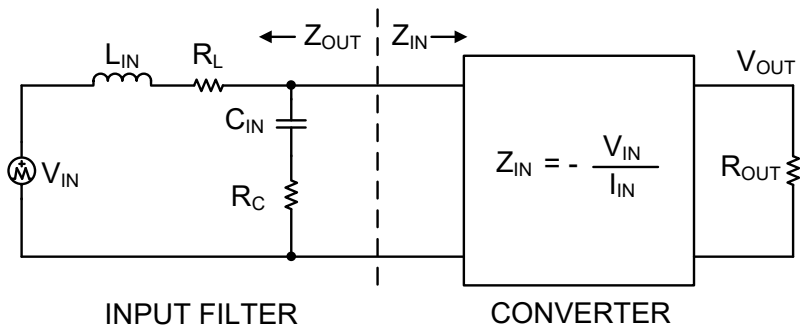
$$D = \frac{\sqrt{2 \cdot L \cdot f_{SW} \cdot I_{OUT} \cdot (V_{OUT} - V_{IN})}}{V_{IN}}$$

- Buck-boost

$$D = \frac{\sqrt{2 \cdot L \cdot f_{SW} \cdot I_{OUT} \cdot V_{OUT}}}{V_{IN}}$$

Filter considerations

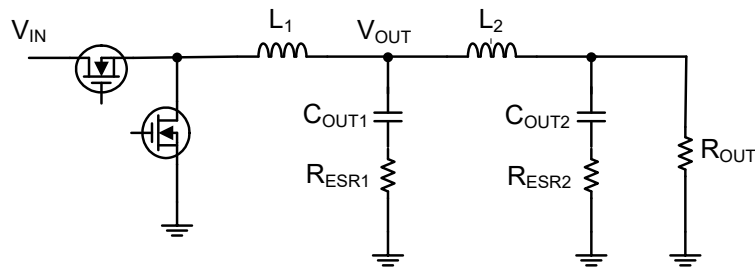
Input filter stability



For stability: Filter $Z_{OUT} \ll$ Converter Z_{IN}

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

Second stage filters



- 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
- Select appropriate compensation network based on control mode and topology
- Tune compensation and loop gain to achieve required loop bandwidth and transient response

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 New Small-Signal Model for Current-Mode Control"](#) by Ray Ridley
- ["Current-Mode Control Modeling"](#) by Lloyd Dixon
- ["Designing Stable Control Loops"](#) by Dan Mitchell and Bob Mammano, SEM1400
- ["Current-Mode Modeling – Reference Guide"](#) by Robert Sheehan, SNVA542
- ["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
- [Power Tips: Compensating Isolated Power Supplies](#) by Brian King
- [Practical Feedback Loop Analysis for Current-Mode Boost Converter](#) by SW Lee



© Copyright 2026 Texas Instruments Incorporated. All rights reserved.

This material is provided strictly “as-is,” for informational purposes only, and without any warranty.
Use of this material is subject to TI’s **Terms of Use**, viewable at [TI.com](https://www.ti.com)

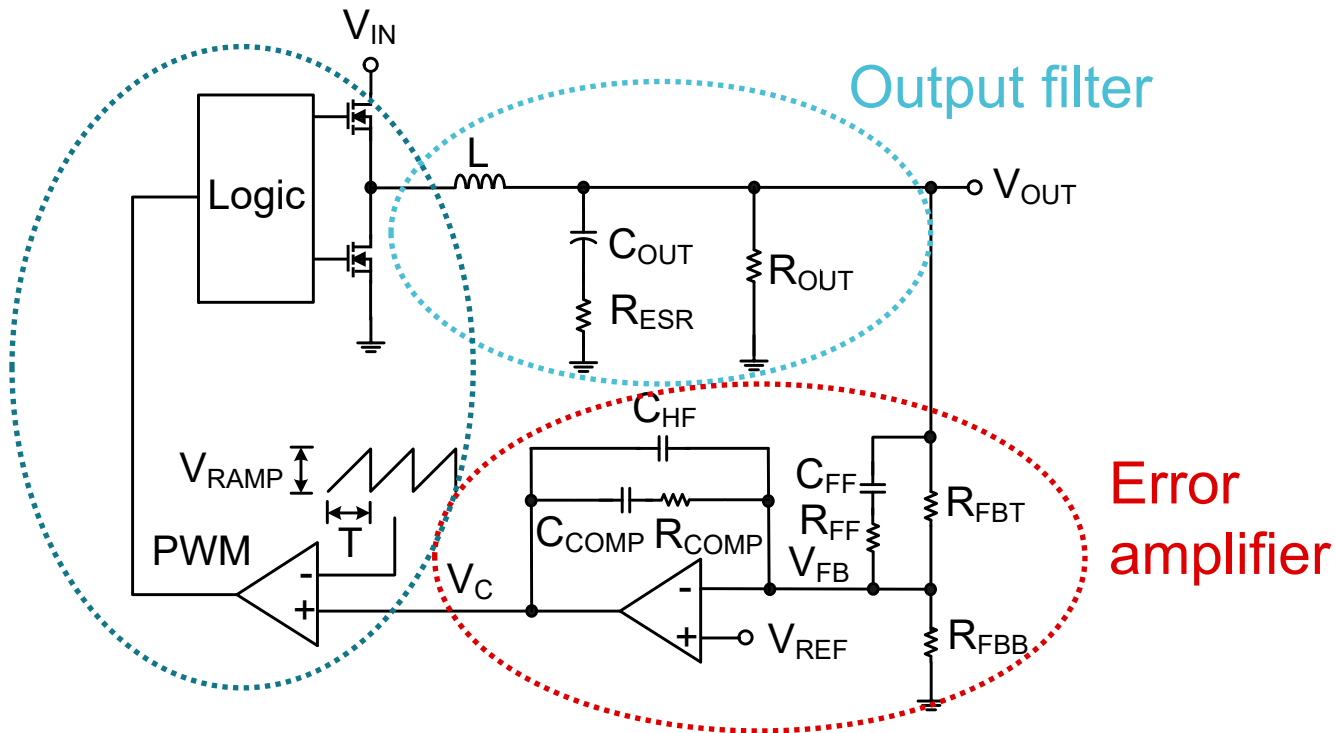
Appendix

Voltage-mode buck

Modulator

$$D = \frac{V_{OUT}}{V_{IN}}$$

$$D' = \frac{V_{IN} - V_{OUT}}{V_{IN}}$$



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 ω_{ZEA} and ω_{FZ} equal to the output filter complex conjugate pole ω_O :
 $\omega_{ZEA} = \omega_{FZ} = \omega_O$
- Set ω_{FP} equal to the output filter zero ω_Z :
 $\omega_{FP} = \omega_Z$
- Set ω_{HF} equal to half the switching frequency:
 $\omega_{HF} = 2 \cdot \pi \cdot f_{SW}/2$

$$A_{VM} = \frac{\omega_C}{A_{VC} \cdot \omega_O}$$

$$R_{COMP} = A_{VM} \cdot R_{FBT}$$

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

$$C_{FF} = \frac{1}{\omega_{FZ} \cdot R_{FBT}}$$

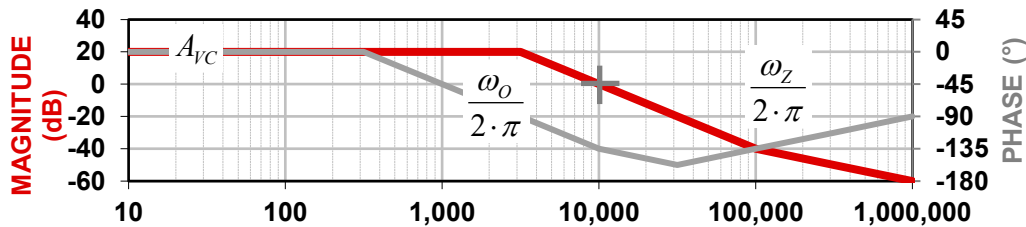
$$R_{FF} = \frac{1}{\omega_{FP} \cdot C_{FF}}$$

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

Voltage-mode buck compensation results

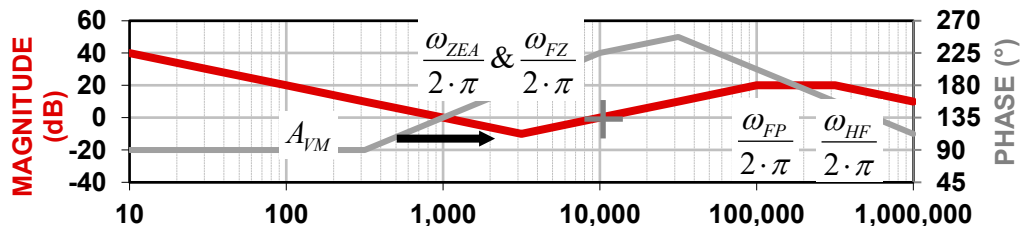
Power stage

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



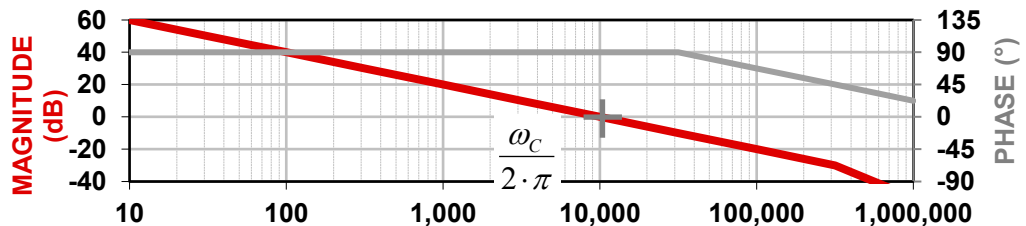
Error amplifier

$$\frac{\hat{v}_C}{\hat{v}'_{OUT}} \approx -A_{VM} \cdot \frac{\left(1 + \frac{\omega_{ZEA}}{s}\right) \cdot \left(1 + \frac{s}{\omega_{FZ}}\right)}{\left(1 + \frac{s}{\omega_{FP}}\right) \cdot \left(1 + \frac{s}{\omega_{HF}}\right)}$$



Control loop

$$\frac{\hat{v}_{OUT}}{\hat{v}'_{OUT}} = \frac{\hat{v}_{OUT}}{\hat{v}_C} \cdot \frac{\hat{v}_C}{\hat{v}'_{OUT}}$$



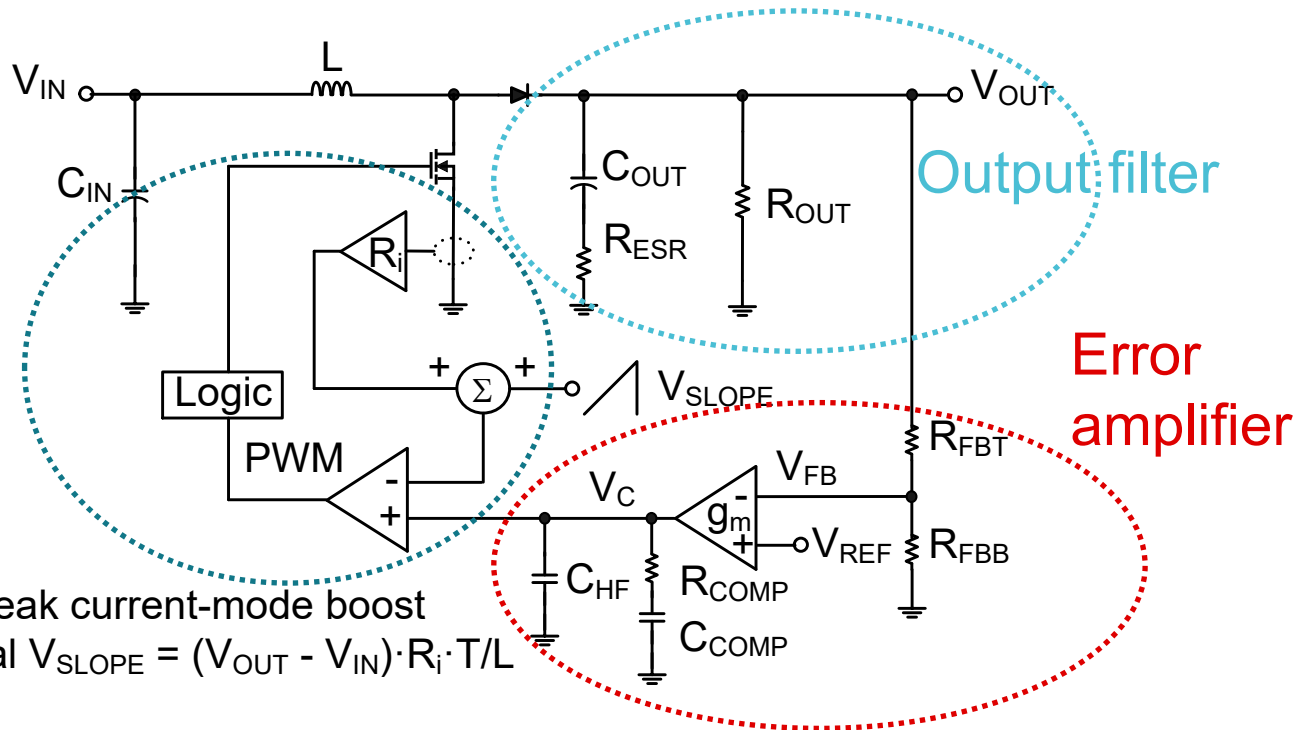
Current-mode boost

Modulator

$$D = \frac{V_{OUT} - V_{IN}}{V_{OUT}}$$

$$D' = \frac{V_{IN}}{V_{OUT}}$$

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



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 ω_{ZEA} equal to 1/10 the target crossover frequency:
 $\omega_{ZEA} = \omega_C / 10$
- Set ω_{HF} equal to the lower of the RHP or ESR zero frequency:
 $\omega_{HF} = \omega_R$ or ω_Z

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

$$\omega_R = \frac{R_{OUT} \cdot D'^2}{L}$$

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

$$R_{COMP} = A_{VM} \cdot R_{FBT} \text{ (op amp)}$$

$$R_{COMP} = \frac{A_{VM}}{g_m \cdot K_{FB}} \text{ (g}_m \text{ amp)}$$

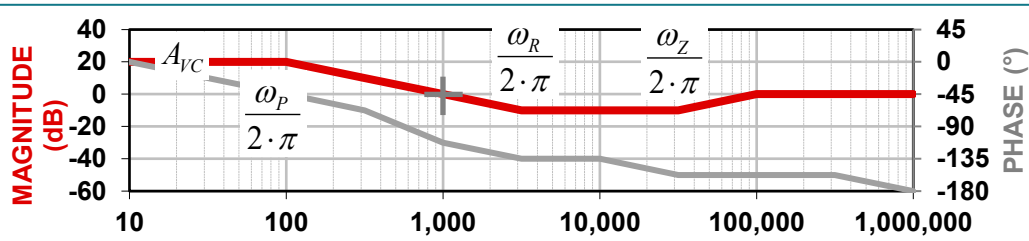
$$C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}$$

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

Current-mode boost compensation results

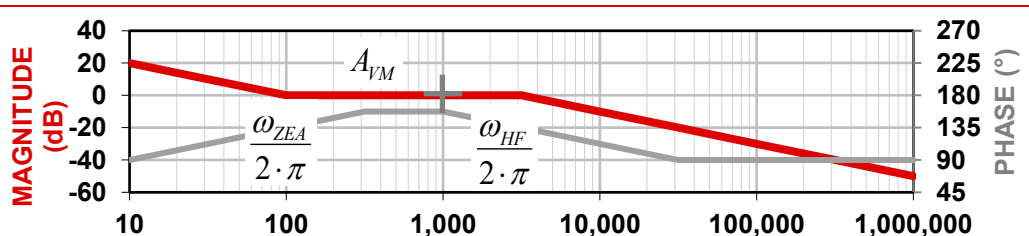
Power stage

$$\frac{\hat{v}_{out}}{\hat{v}_c} \approx A_{VC} \cdot \frac{\left(1 + \frac{s}{\omega_z}\right) \left(1 - \frac{s}{\omega_r}\right)}{1 + \frac{s}{\omega_p}} \cdot F_h(s)$$



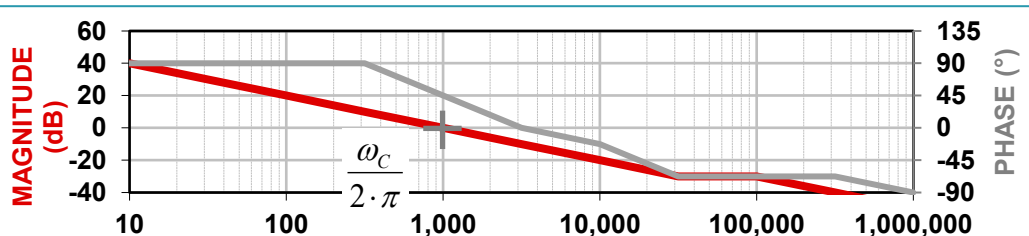
Error amplifier

$$\frac{\hat{v}_c}{\hat{v}'_{OUT}} \approx -A_{VM} \cdot \frac{1 + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}}$$

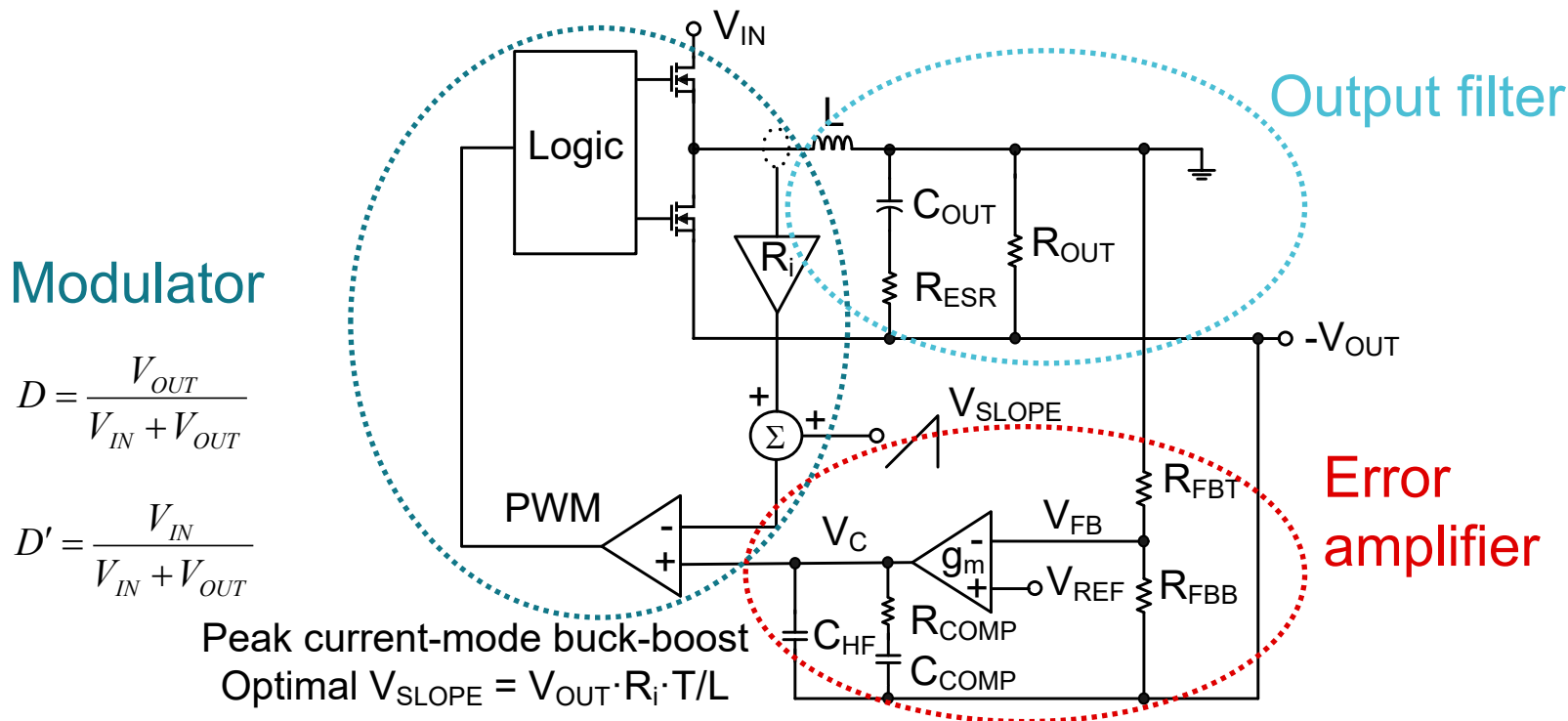


Control loop

$$\frac{\hat{v}_{OUT}}{\hat{v}'_{OUT}} = \frac{\hat{v}_{OUT}}{\hat{v}_c} \cdot \frac{\hat{v}_c}{\hat{v}'_{OUT}}$$



Current-mode buck-boost



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:
 $\omega_C = 2 \cdot \pi \cdot f_C = \omega_R / 4$
- Find the mid-band gain A_{VM} to achieve target bandwidth
- Set ω_{ZEA} equal to 1/10 the target crossover frequency:
 $\omega_{ZEA} = \omega_C / 10$
- Set ω_{HF} equal to the lower of the RHP or ESR zero frequency:
 $\omega_{HF} = \omega_R$ or ω_Z

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

$$\omega_R = \frac{R_{OUT} \cdot D'^2}{L \cdot D}$$

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

$$R_{COMP} = A_{VM} \cdot R_{FBT} \text{ (op amp)}$$

$$R_{COMP} = \frac{A_{VM}}{g_m \cdot K_{FB}} \text{ (g}_m \text{ amp)}$$

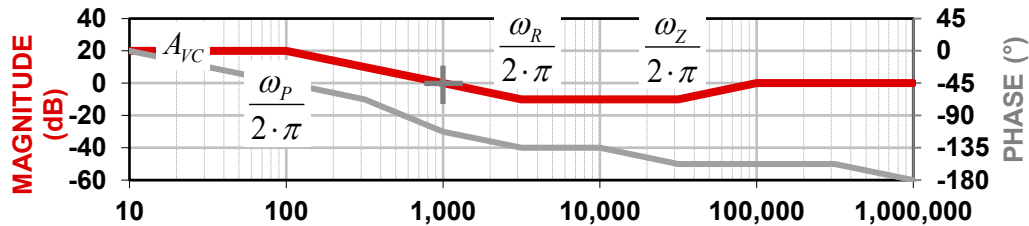
$$C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}$$

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

Current-mode buck-boost compensation results

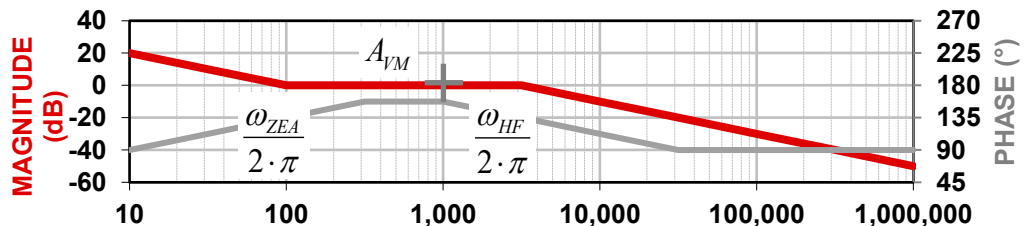
Power stage

$$\frac{\hat{v}_{out}}{\hat{v}_c} \approx A_{VC} \cdot \frac{\left(1 + \frac{s}{\omega_z}\right) \left(1 - \frac{s}{\omega_r}\right)}{1 + \frac{s}{\omega_p}} \cdot F_h(s)$$



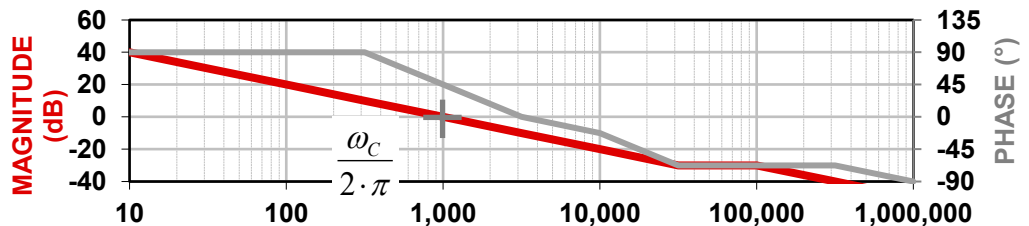
Error amplifier

$$\frac{\hat{v}_c}{\hat{v}'_{OUT}} \approx -A_{VM} \cdot \frac{1 + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}}$$



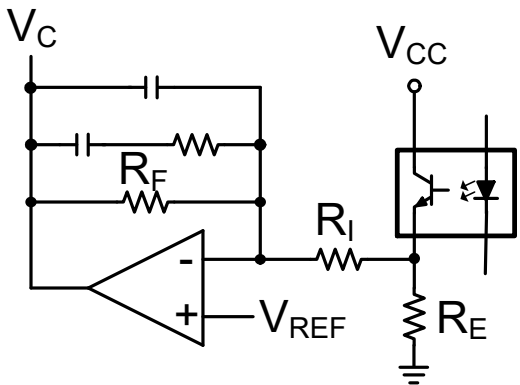
Control loop

$$\frac{\hat{v}_{OUT}}{\hat{v}'_{OUT}} = \frac{\hat{v}_{OUT}}{\hat{v}_c} \cdot \frac{\hat{v}_c}{\hat{v}'_{OUT}}$$



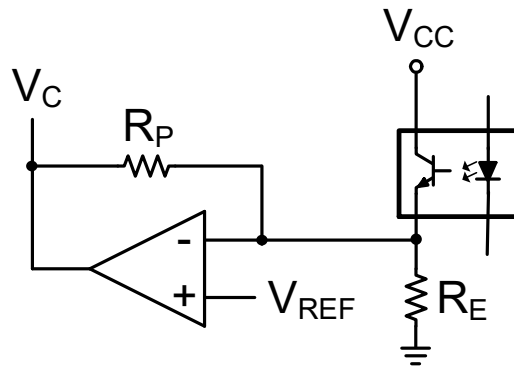
Primary side compensation

Primary side compensation



- Uses primary side inverting amplifier to implement frequency compensation

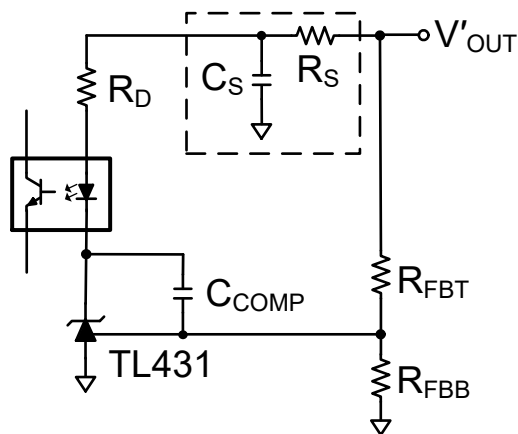
High bandwidth configuration



- Opto emitter is at virtual ground of V_{REF}
- This minimizes pole due to opto parasitic capacitance

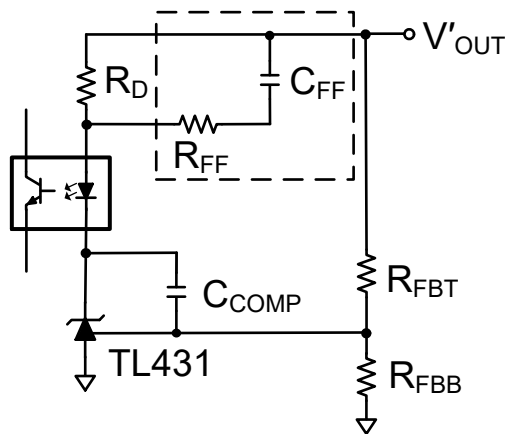
Secondary side compensation

ESR zero compensation



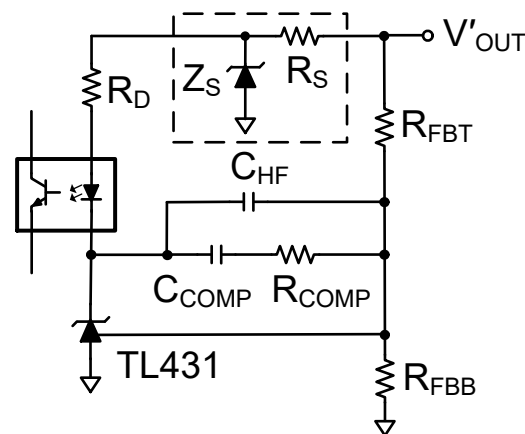
- An RC pole to the opto can be used to cancel the output capacitor ESR zero

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



© Copyright 2026 Texas Instruments Incorporated. All rights reserved.

This material is provided strictly “as-is,” for informational purposes only, and without any warranty.
Use of this material is subject to TI’s **Terms of Use**, viewable at [TI.com](https://www.ti.com)

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you fully indemnify TI and its representatives against any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to [TI's Terms of Sale](#), [TI's General Quality Guidelines](#), or other applicable terms available either on [ti.com](https://www.ti.com) or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products. Unless TI explicitly designates a product as custom or customer-specified, TI products are standard, catalog, general purpose devices.

TI objects to and rejects any additional or different terms you may propose.

Copyright © 2026, Texas Instruments Incorporated

Last updated 10/2025