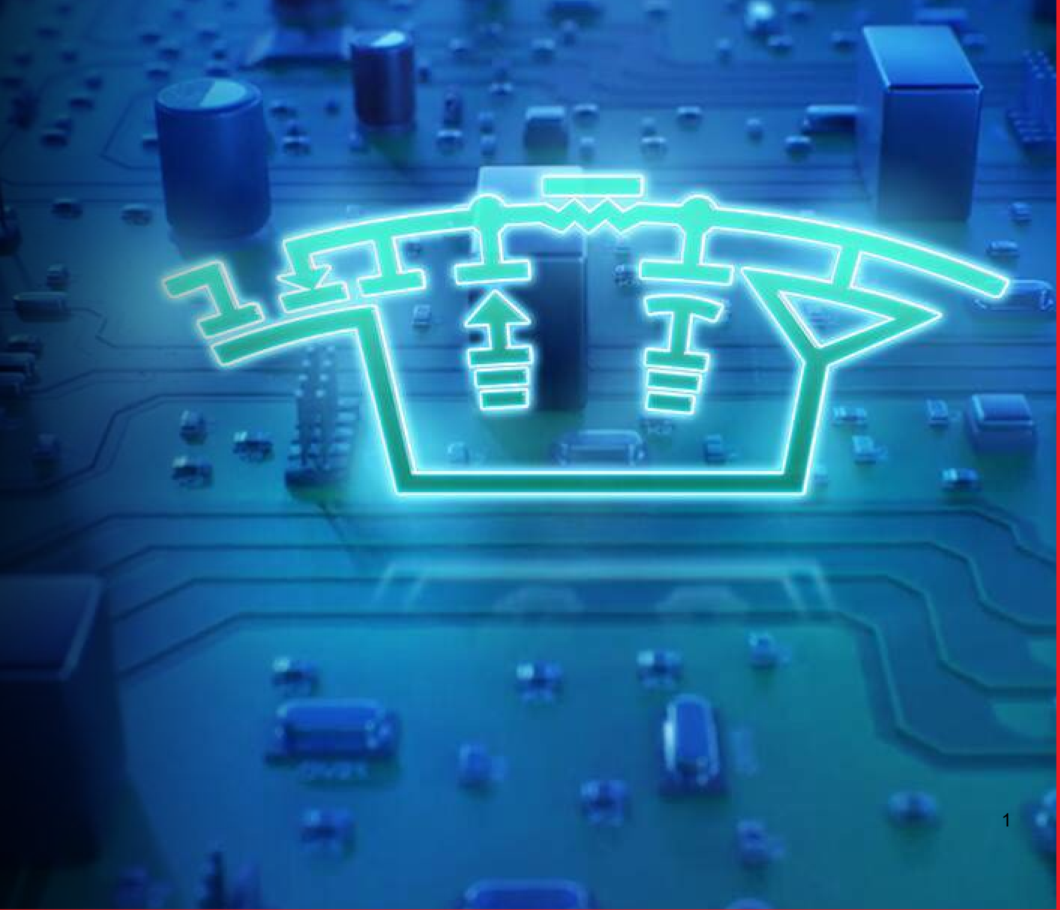
IEEE 2025

Switch-mode power converter compensation made easy



Authors
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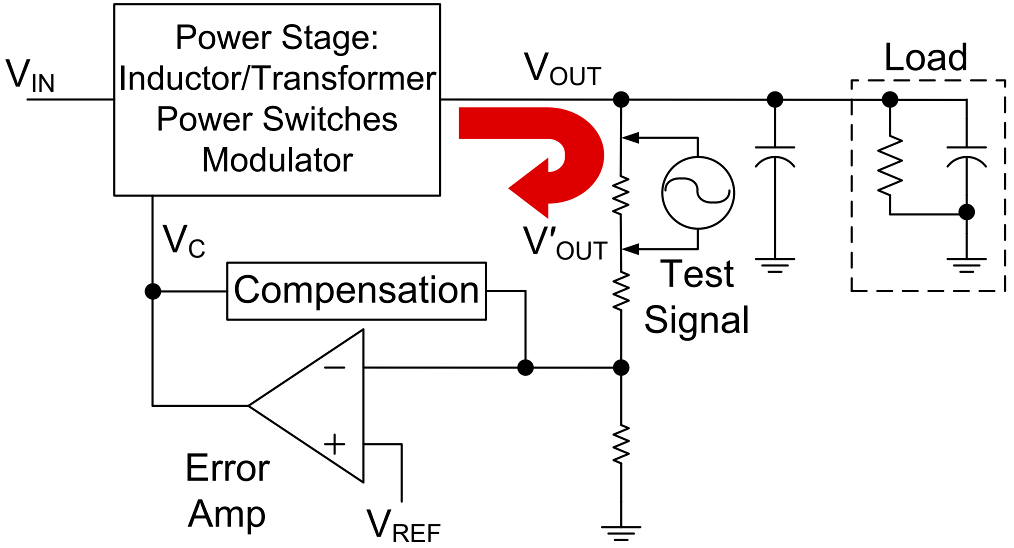
Agenda

- 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

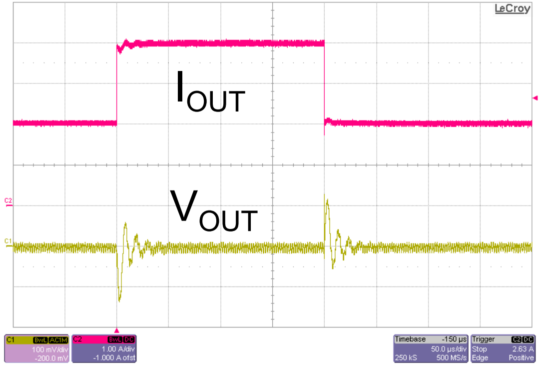
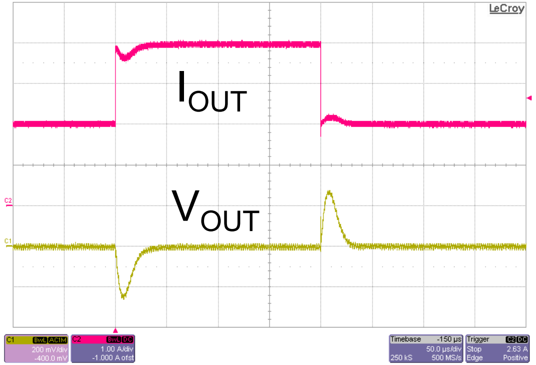
Compensation design and objectives

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

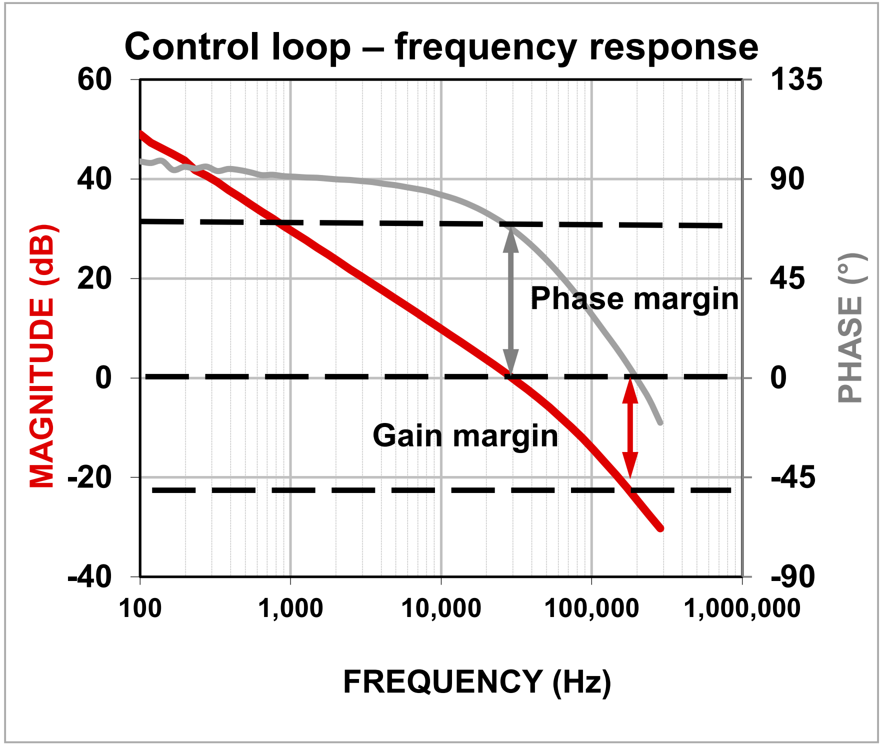


- Feedback is needed to regulate the output voltage
- The control loop bandwidth influences the response time

Control loop response

Poor transient response	Objective	Good transient response
 • Response is under-damped causing oscillatory behavior	• Maximize crossover frequency for fastest transient response • Adjust compensation for best setting behavior	 • Response is well damped with good setting behavior

Phase margin and gain margin

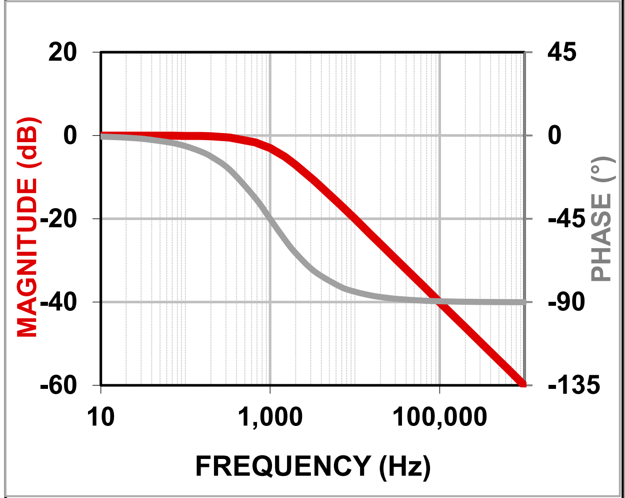


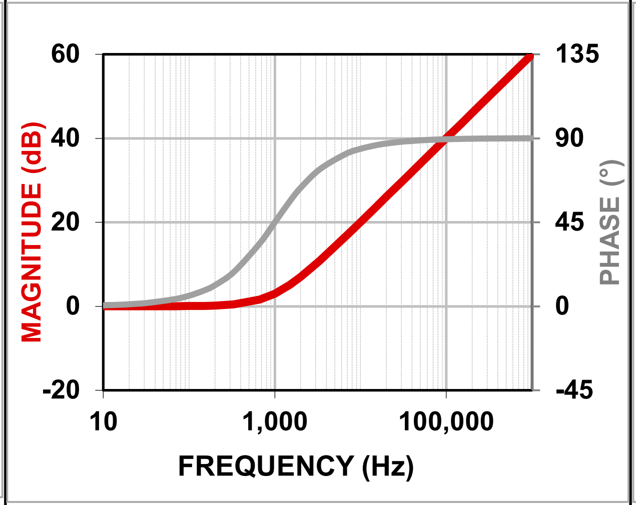
Phase margin and stability

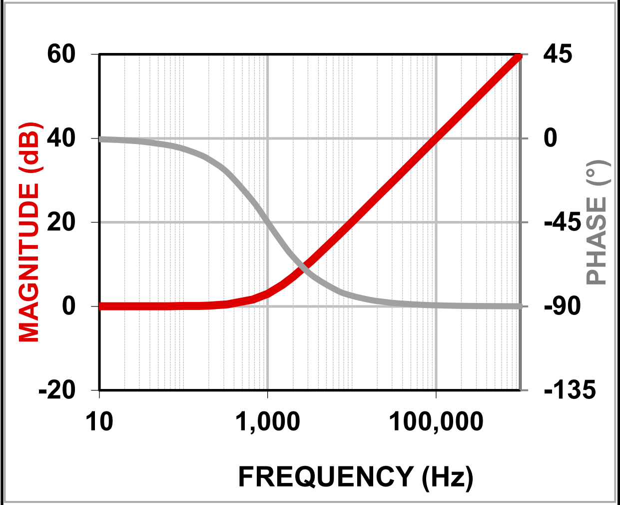
- Sufficient phase margin needed to prevent oscillation (45° min.)
- Gain margin goal of 10 dB min.
- Slope of -20dB/decade when passing through 0 dB
- Bandwidth rule of thumb is 1/5 to 1/10 of switching frequency

Poles, zeros and right-half-plane zeros

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

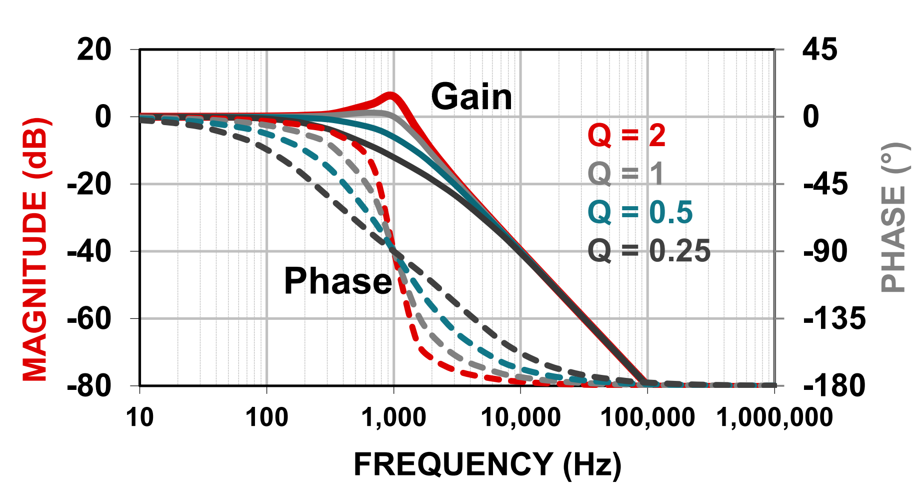


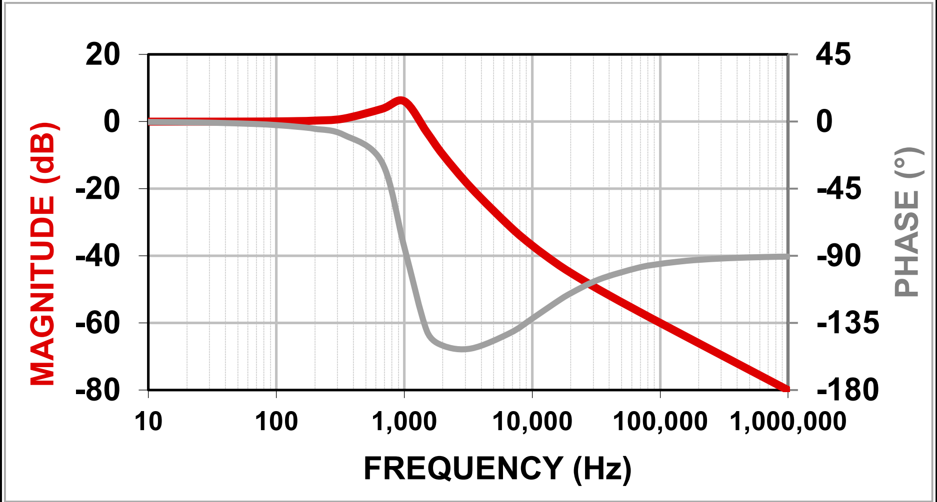




Complex conjugate pole and ESR zero

Complex conjugate pole	With ESR zero
$H(s) = \dfrac{1}{1 + \dfrac{s}{Q_0 \cdot \omega_0} + \dfrac{s^2}{\omega_0^2}}$	$H(s) = \dfrac{1 + \dfrac{s}{\omega_Z}}{1 + \dfrac{s}{Q_0 \cdot \omega_0} + \dfrac{s^2}{\omega_0^2}}$

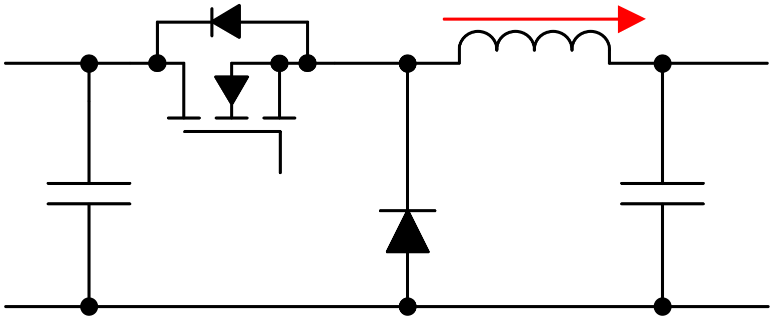


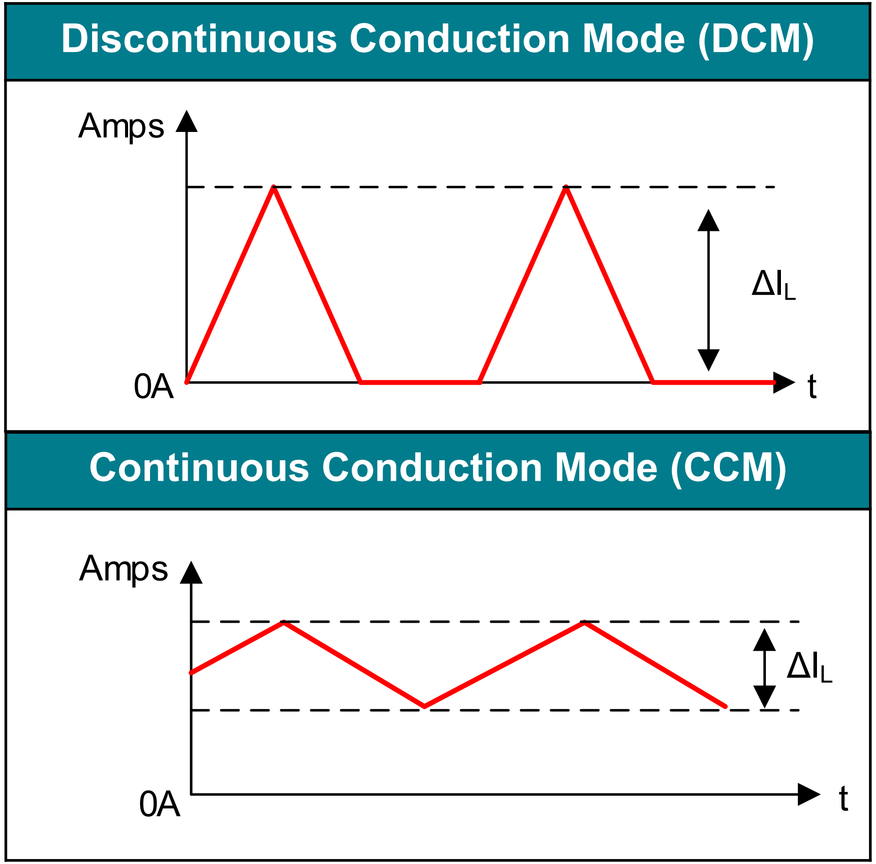


Control methods and operating modes

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

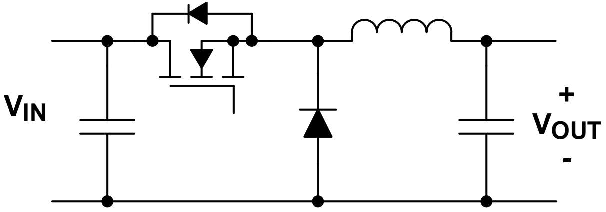




Discontinuous Conduction Mode (DCM)
Amps
ΔIL
0A
t
Continuous Conduction Mode (CCM)
Amps
ΔIL
0A
t

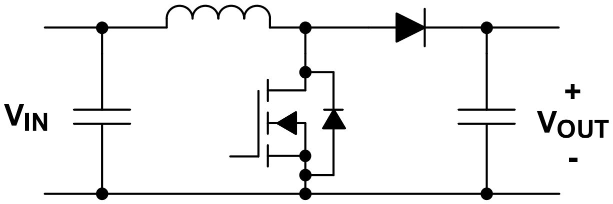
Buck, boost, and buck-boost derived topologies

Buck, forward, push-pull, bridge



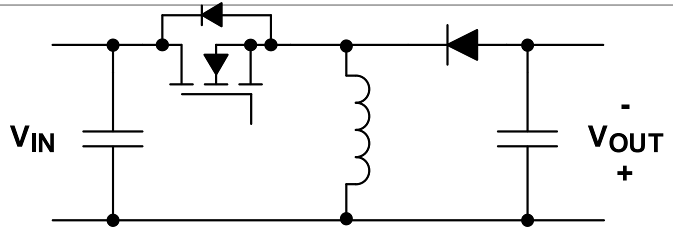
$$V_{OUT} = V_{IN} \times D$$

Boost



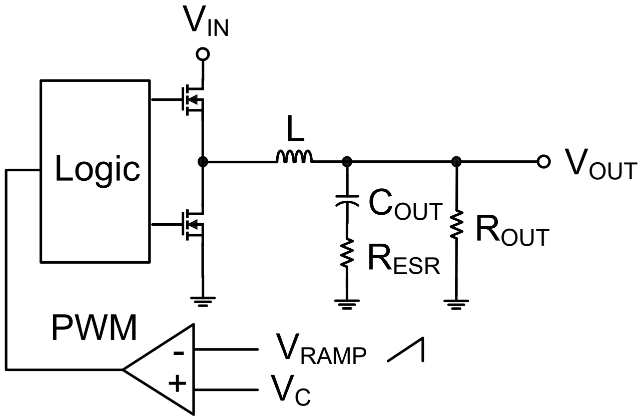
$$V_{OUT} = V_{IN} \times \frac{1}{1 - D}$$

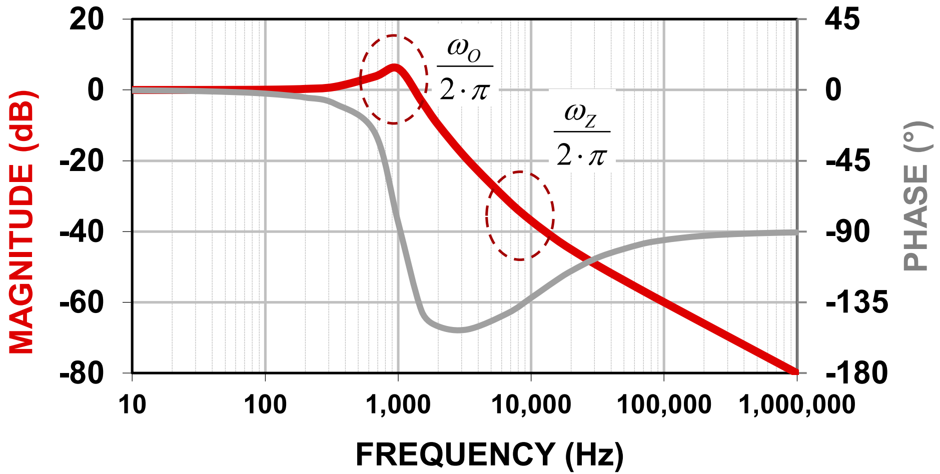
Buck-boost, SEPIC, flyback



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

Voltage-mode buck power stage





$$\frac{\omega_O}{2\cdot\pi}$$

$$\frac{\omega_Z}{2\cdot\pi}$$

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

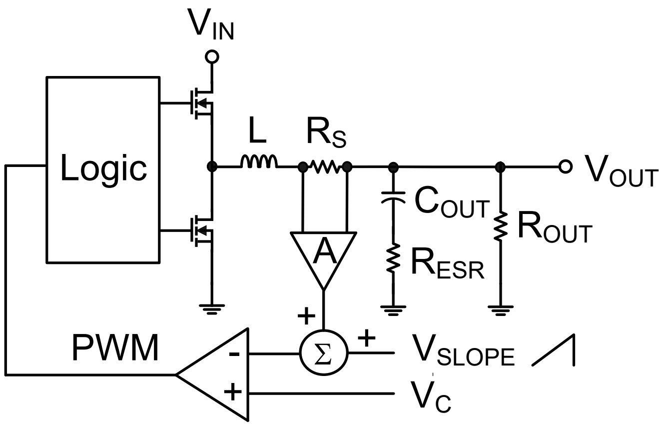
$$\omega_O=\frac{1}{\sqrt{L\cdot C_{OUT}}}$$

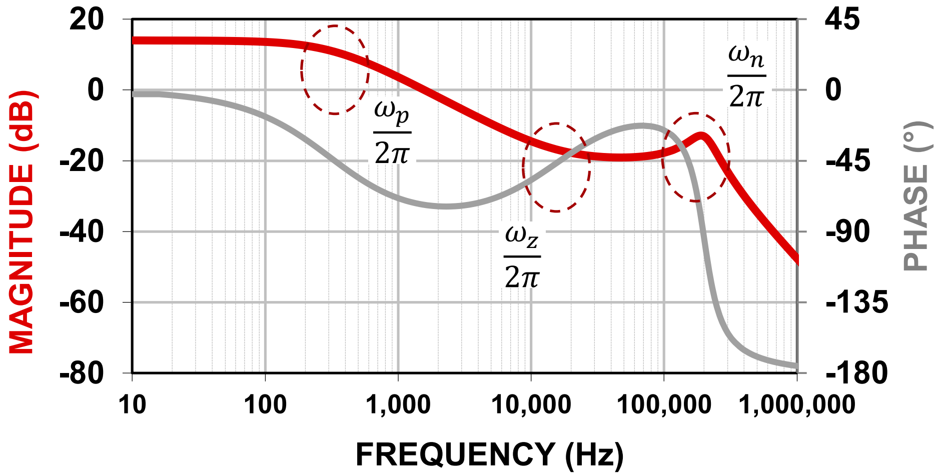
$$Q_O=\frac{R_{OUT}}{\sqrt{L/C_{OUT}}}$$

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

$$\frac{\hat{v}_{OUT}}{\hat{v}_C}=A_{VC}\cdot\frac{1+\frac{s}{\omega_Z}}{1+\frac{s}{Q_O\cdot\omega_O}+\frac{s^2}{\omega_O{}^2}}$$

Current-mode buck power stage





$$\omega_p \approx \frac{1}{C_{out} \cdot R_{out}}$$

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

$$A_{VC} \approx \frac{R_{out}}{R_i} = \frac{R_{out}}{A \cdot R_S}$$

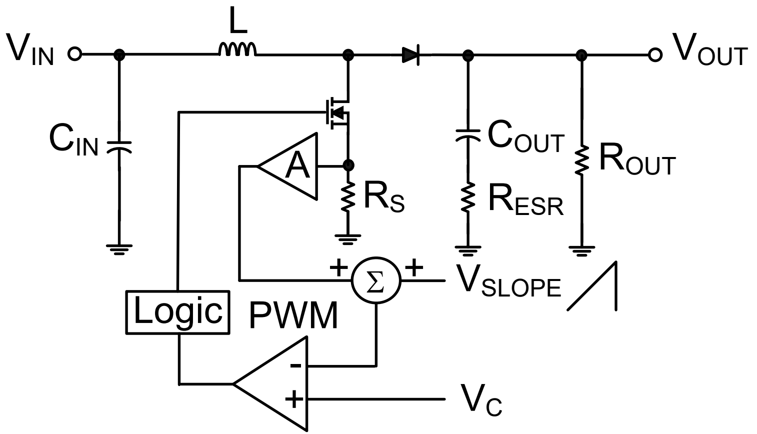
$$F_h(s) = \frac{1}{1 + \frac{s}{\omega_n \cdot Q_p} + \left(\frac{s}{\omega_n}\right)^2}$$

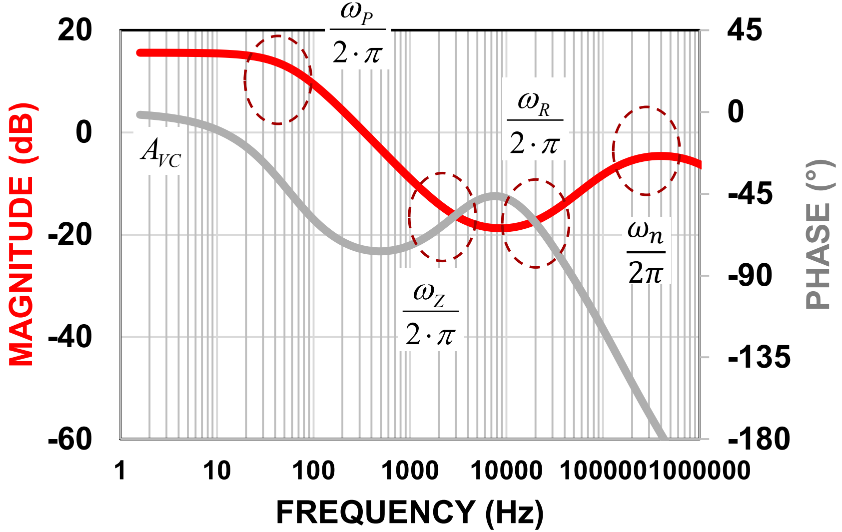
$$\omega_n = \frac{\omega_{fsw}}{2}$$

at D = 0.5

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

Current-mode boost power stage





$$R_i = A\cdot R_S$$

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

$$\omega_n = \frac{\omega_{fsw}}{2}$$

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

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

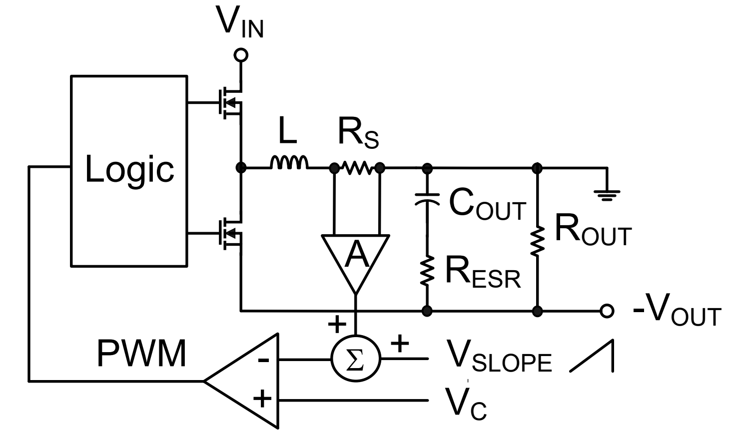
at D = 0.5

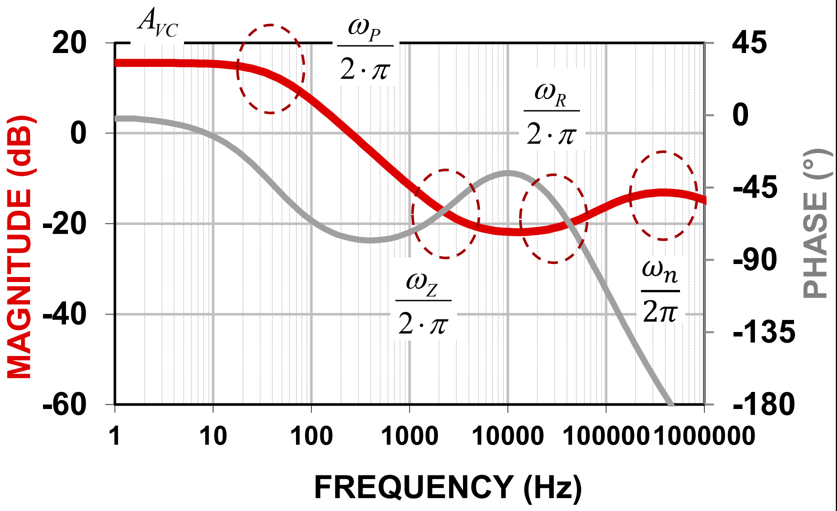
$$\omega_P \approx \frac{2}{C_{OUT}\cdot R_{OUT}}$$

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

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

Current-mode buck-boost power stage





$$R_i = A \cdot R_S$$

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

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

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

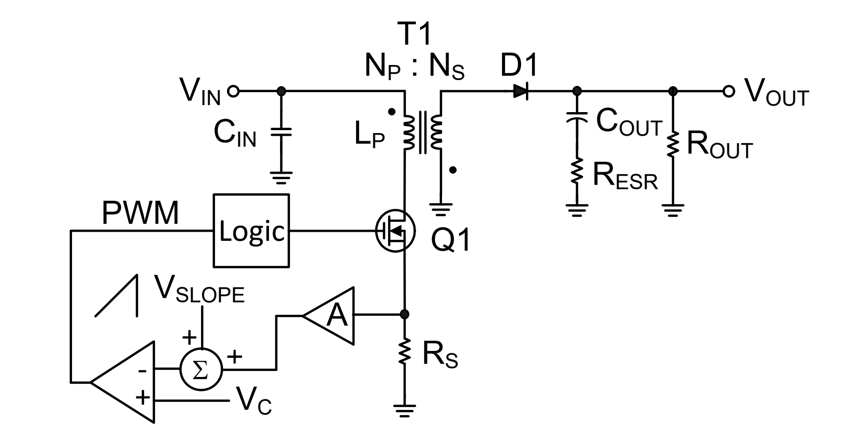
at D = 0.5

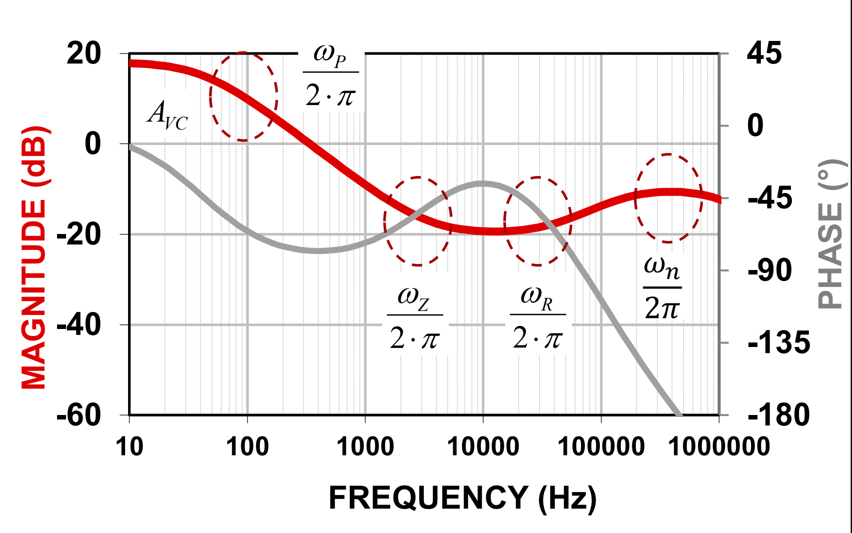
$$\omega_P \approx \frac{1+D}{C_{OUT} \cdot R_{OUT}}$$

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

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

Current-mode flyback power stage





$$R_i = A \cdot R_S$$

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

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

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

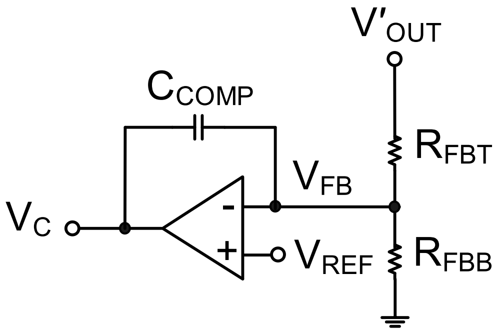
at D = 0.5

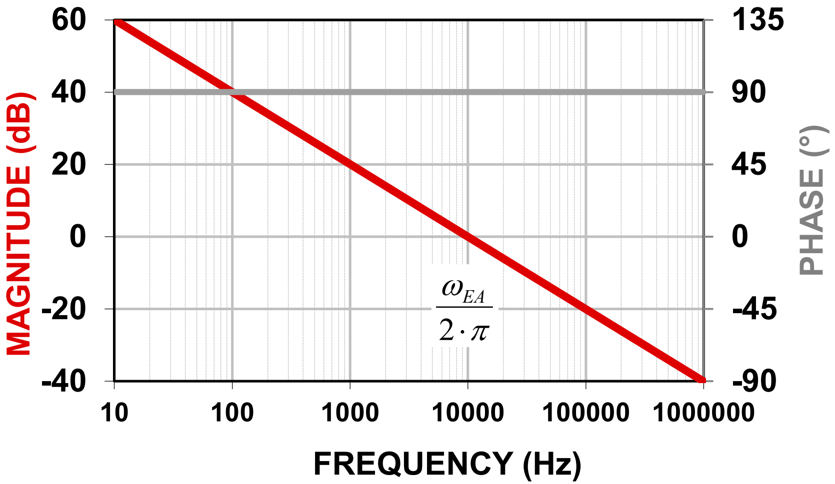
$$\omega_P \approx \frac{1+D}{C_{OUT} \cdot R_{OUT}}$$

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

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

Type I error amplifier

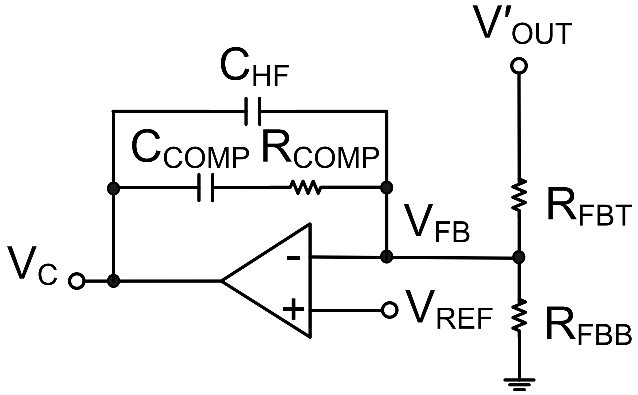




$$\omega_{EA} = \frac{1}{R_{FBT} \cdot C_{COMP}}$$

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

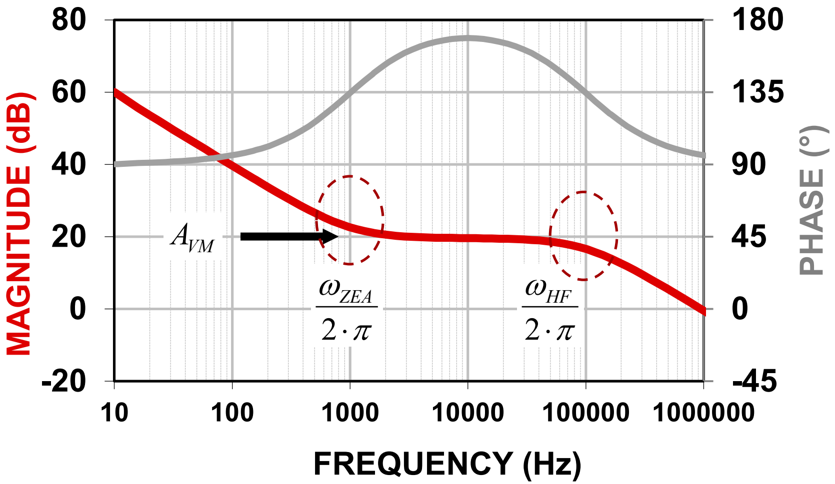
Type II error amplifier



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

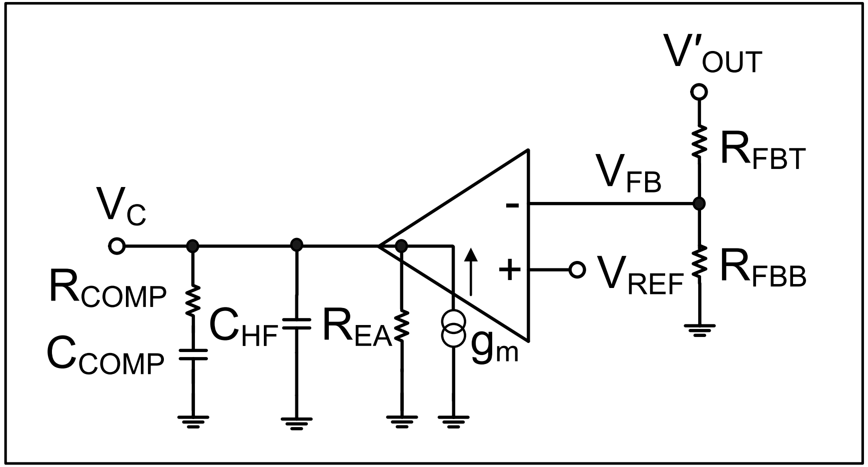
$$\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}}$$

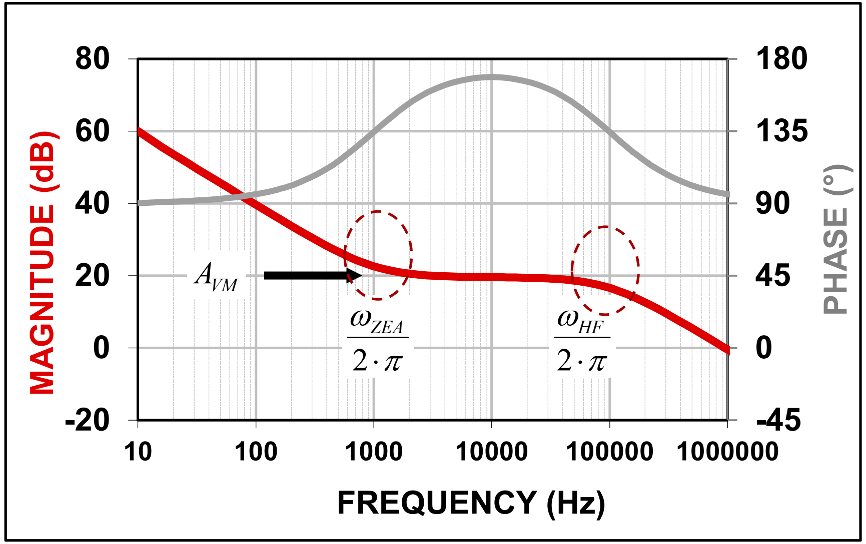
Assumption: $C_{COMP} >> C_{HF}$



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

Type II transconductance amplifier





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

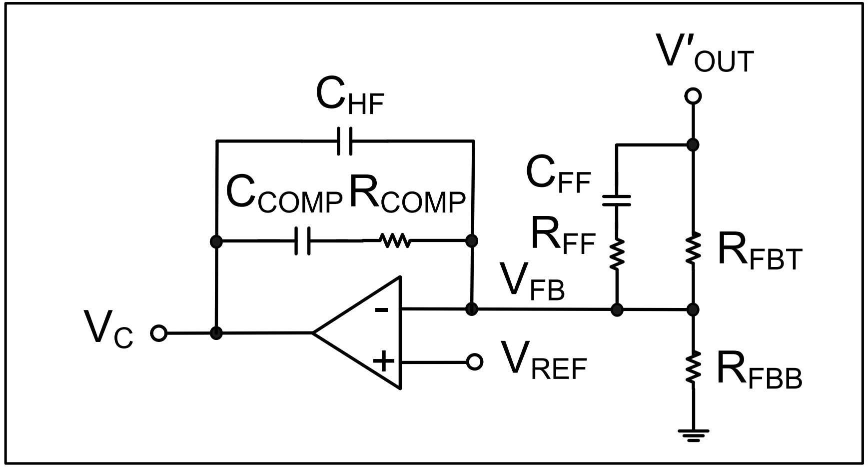
$$\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}} \qquad K_{FB} = \frac{R_{FBB}}{R_{FBB} + R_{FBT}}$$

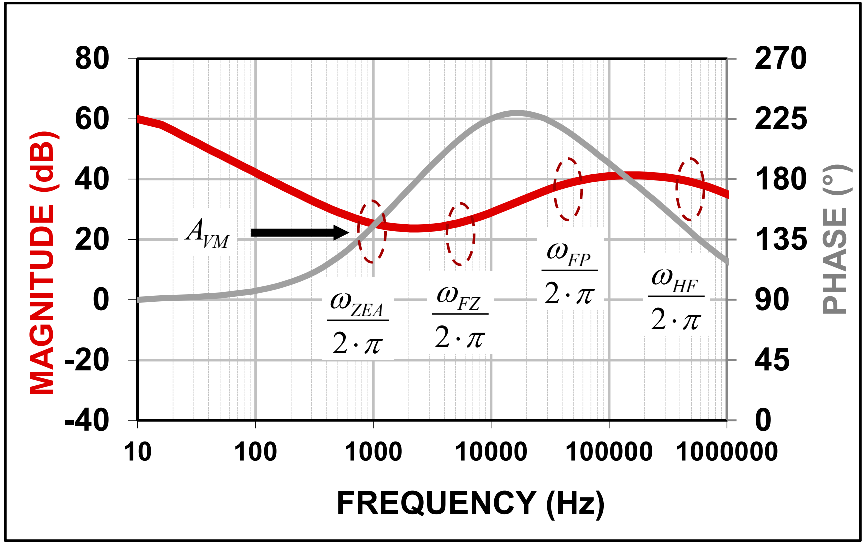
$$\omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}} \qquad A_{OL} = g_m \cdot R_{EA}$$

Assumptions: $C_{COMP} >> C_{HF}$ & $R_{EA} >> R_{COMP}$

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

Type III error amplifier





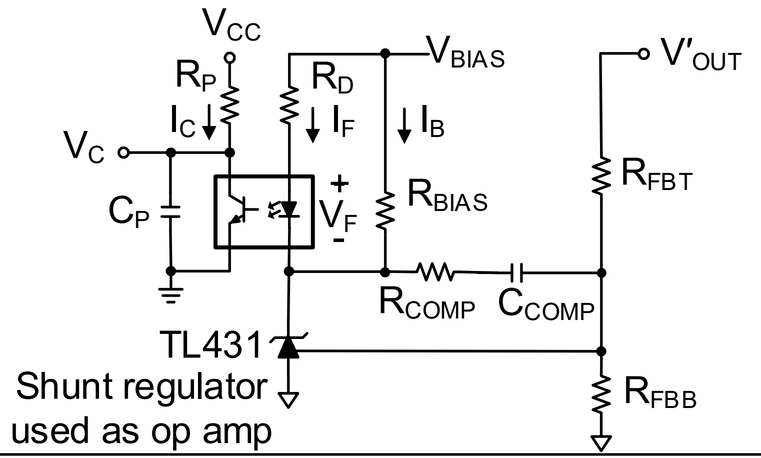
$$A_{VM} \approx \frac{R_{COMP}}{R_{FBT}} \qquad \omega_{ZEA} = \frac{1}{R_{COMP}\cdot C_{COMP}} \qquad \omega_{FP} = \frac{1}{R_{FF}\cdot C_{FF}}$$

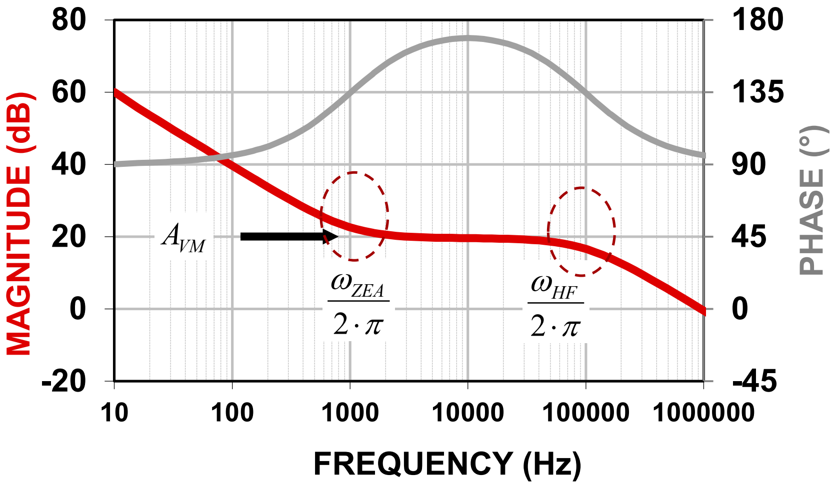
$$\omega_{FZ} \approx \frac{1}{R_{FBT}\cdot C_{FF}} \qquad \omega_{HF} \approx \frac{1}{R_{COMP}\cdot C_{HF}}$$

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

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

Type II isolated feedback with fixed bias



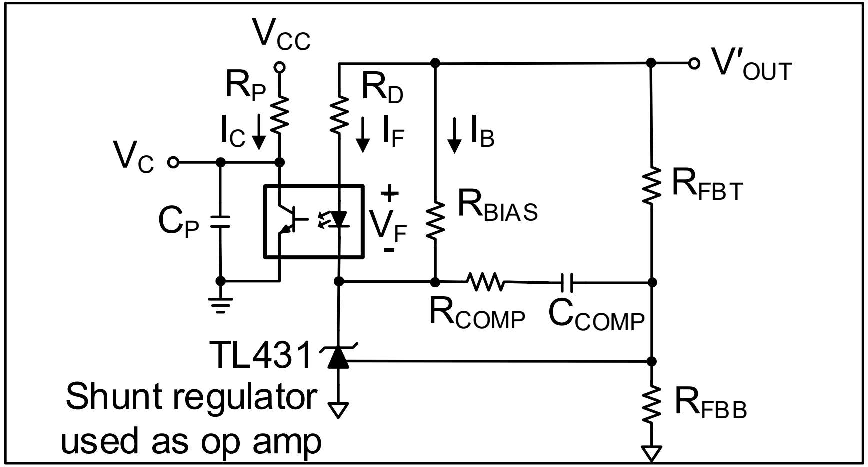


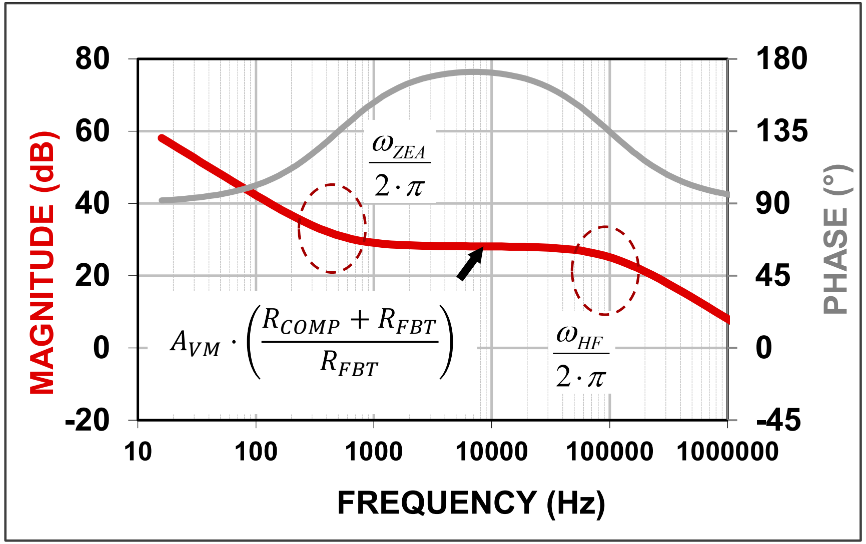
$$A_{VM} = CTR \cdot \frac{R_P}{R_D} \qquad CTR = \frac{I_C}{I_F}$$

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

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

Type II isolated feedback with Vout bias





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

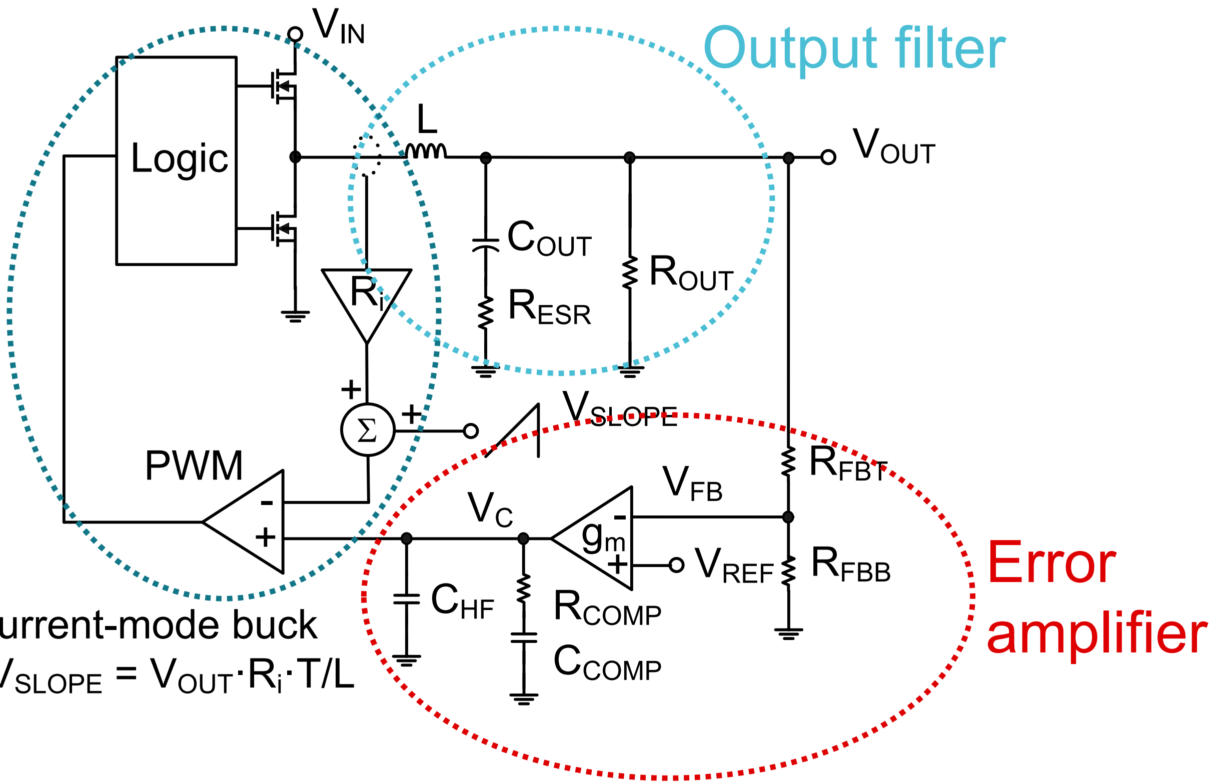
$$\omega_{ZEA} = \frac{1}{(R_{COMP} + R_{FBT}) \cdot C_{COMP}} \qquad \omega_{HF} = \frac{1}{R_P \cdot C_P}$$

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

Current-mode buck

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

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



Peak current-mode buck

Optimal $V_{SLOPE} = V_{OUT} \cdot R_i \cdot T/L$

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:

  $\omega_{HF} = \omega_Z$

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

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

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

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

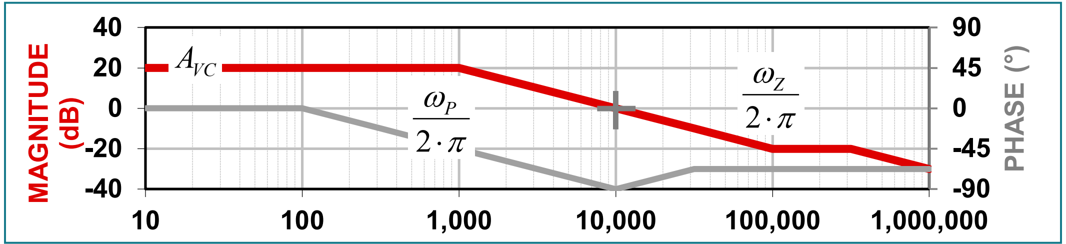
$$C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}$$

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

Current-mode buck compensation results

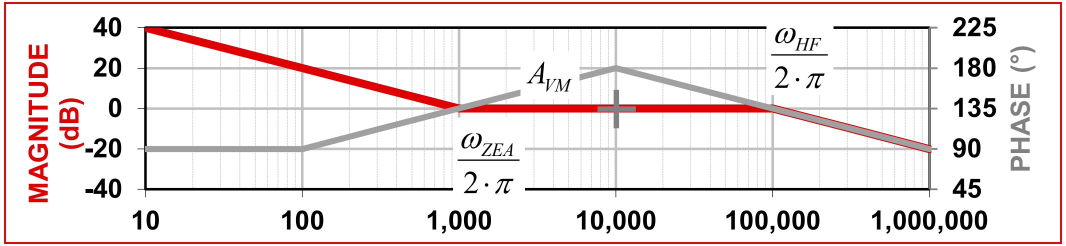
Power stage

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



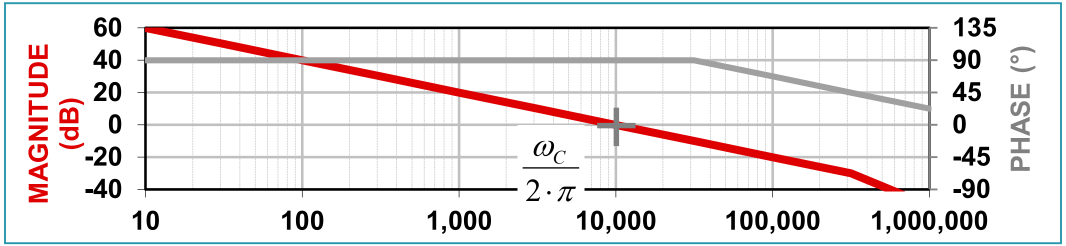
Error amplifier

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



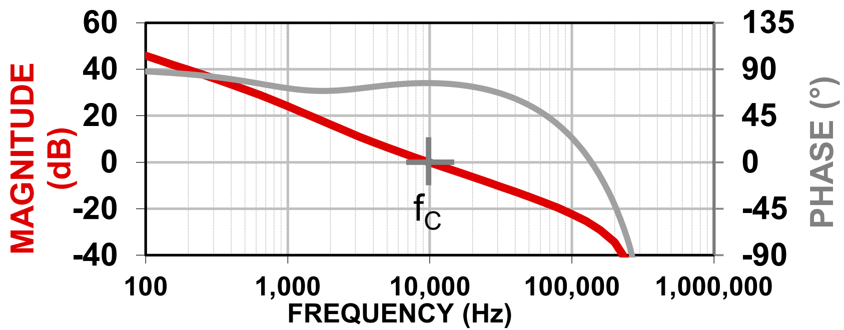
Control loop

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

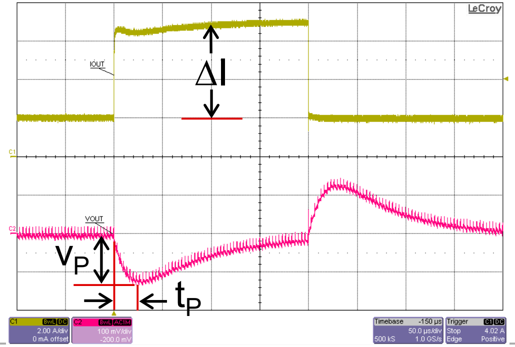


Bandwidth vs transient response

Current-mode bandwidth



Current-mode transient response



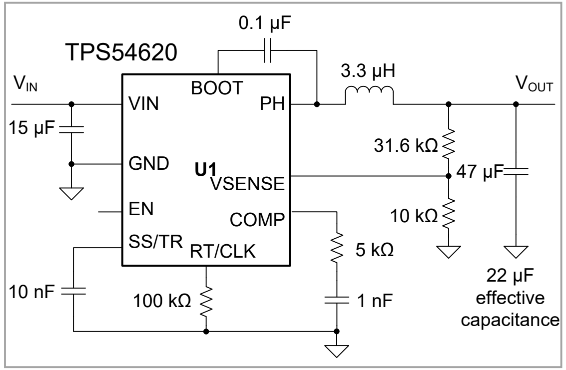
With no ESR, slew rate or duty cycle limiting: $t_P = \frac{1}{4 \cdot f_C}$ $\quad t_P = \frac{1}{4 \cdot 10kHz} = 25\mu s$

Current-mode single pole approximation: $V_P = \frac{\Delta I}{2 \cdot \pi \cdot f_C \cdot C_{OUT}}$ $\quad V_P = \frac{5A}{2 \cdot \pi \cdot 10kHz \cdot 440\mu F} = 180mV$

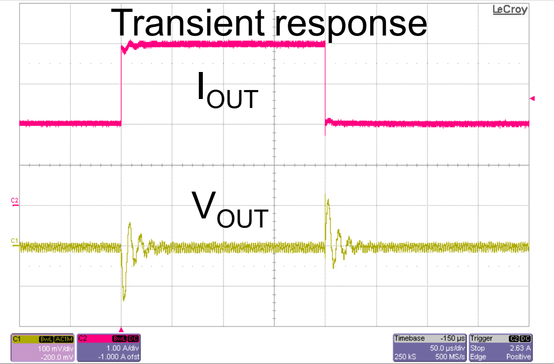
Current-mode critically damped: $V_P = \frac{\Delta I}{e \cdot \pi \cdot f_C \cdot C_{OUT}}$ $\quad V_P = \frac{5A}{e \cdot \pi \cdot 10kHz \cdot 440\mu F} = 130mV$ shown above

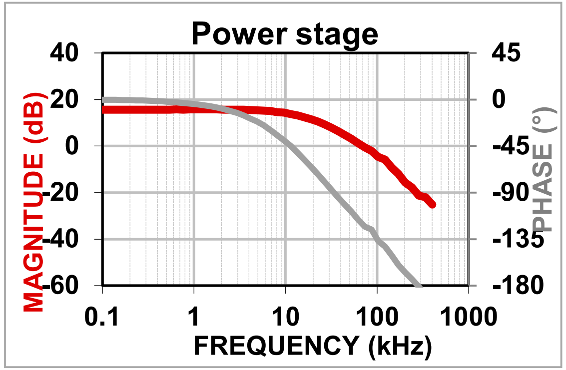
Voltage-mode: $V_P = \frac{\Delta I}{8 \cdot f_C \cdot C_{OUT}}$ $\quad V_P = \frac{5A}{8 \cdot 10kHz \cdot 440\mu F} = 140mV$

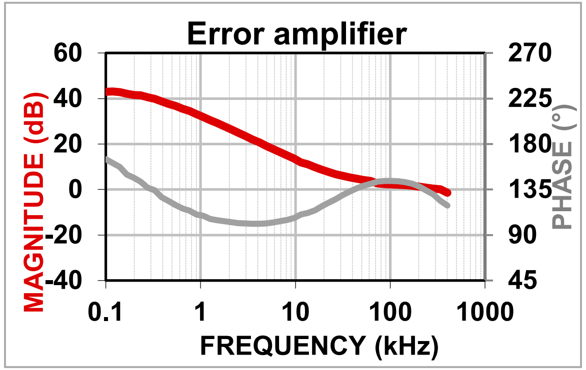
Switching regulator with poor compensation

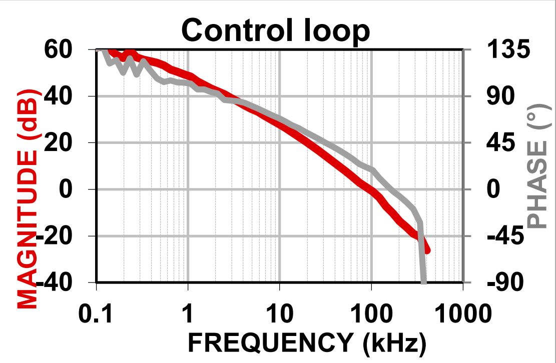


- Power stage: phase at –180° indicates high internal slope compensation
- Error amplifier: zero appears high and mid-band gain is 3 dB
- Control loop: f_C is 95 kHz with only 20° phase margin

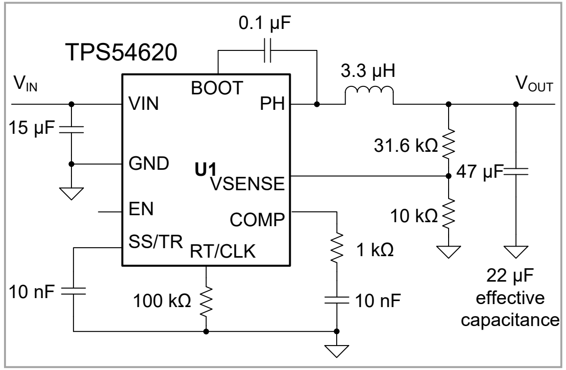




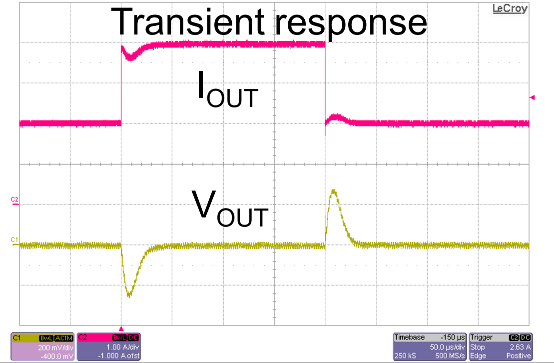


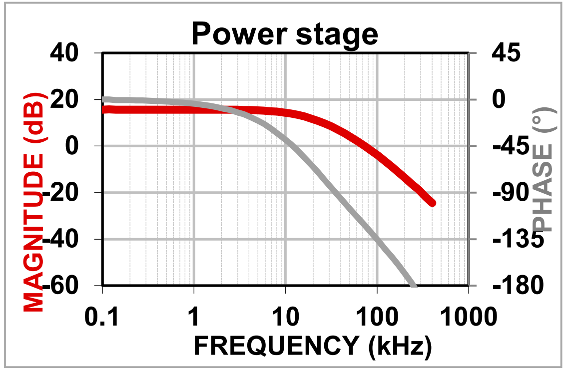


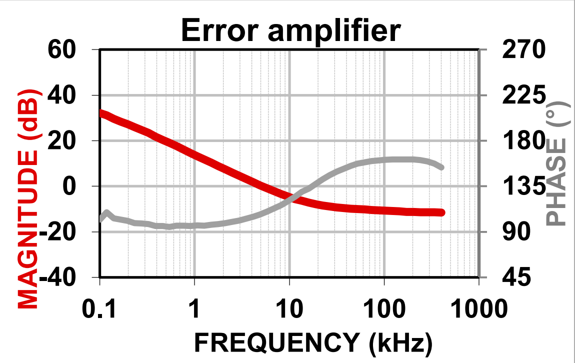
Switching regulator with revised compensation

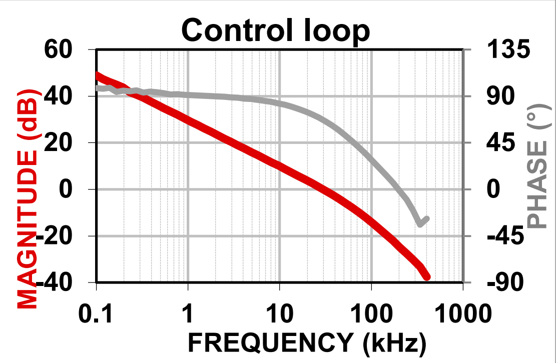


- Power stage: cannot change slope compensation
- Error amplifier: decrease R_{COMP} and rescale C_{COMP}
- Control loop: now f_C is 30 kHz with 67° phase margin



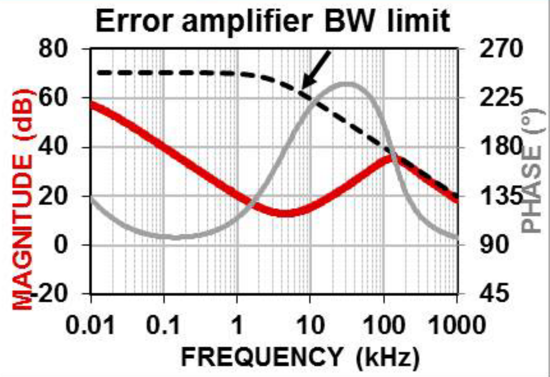






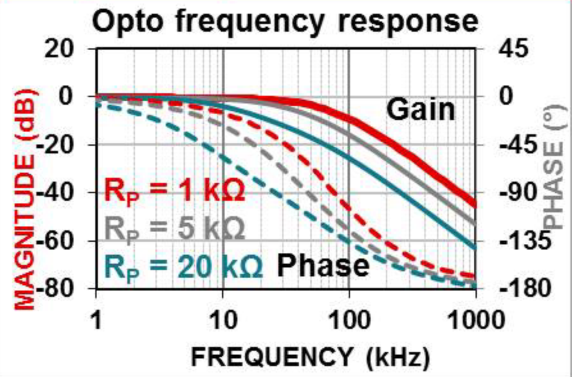
Practical limitations

Error amplifier bandwidth



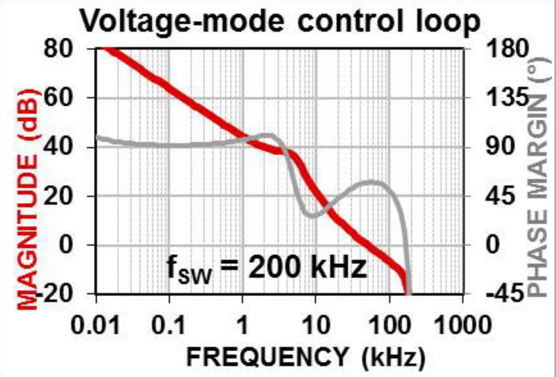
- Error amp BW can limit maximum f_C
- Wider BW op amp needed for voltage-mode due to Type III compensation

Optocoupler bandwidth



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

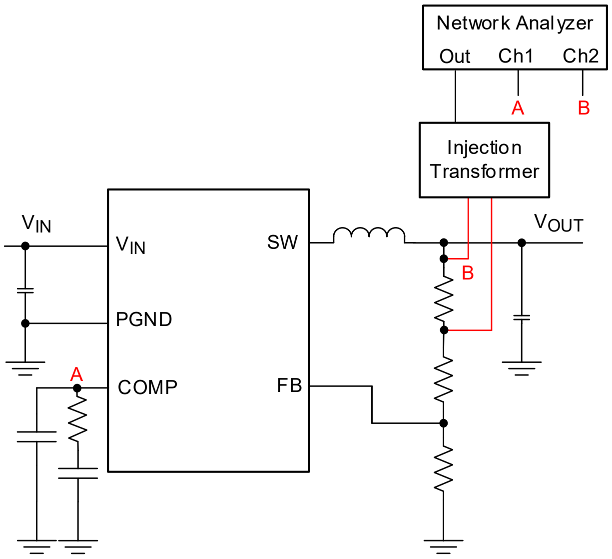
Switching frequency



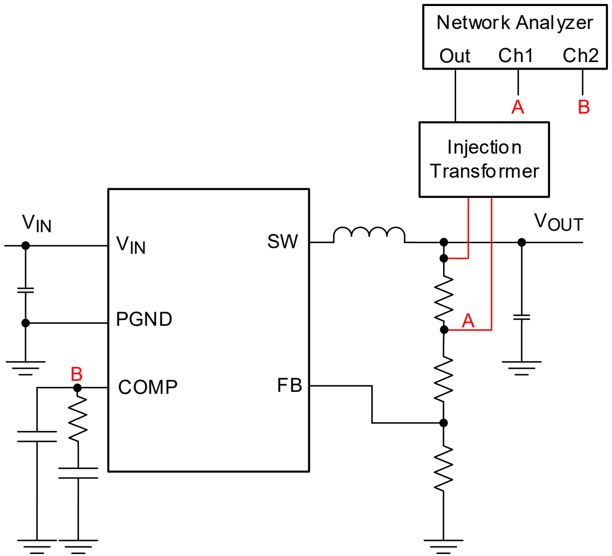
- Maximum f_C is a fraction of f_{SW}
- Rule of thumb is 1/5 to 1/10 of f_{SW}

Measuring transfer functions

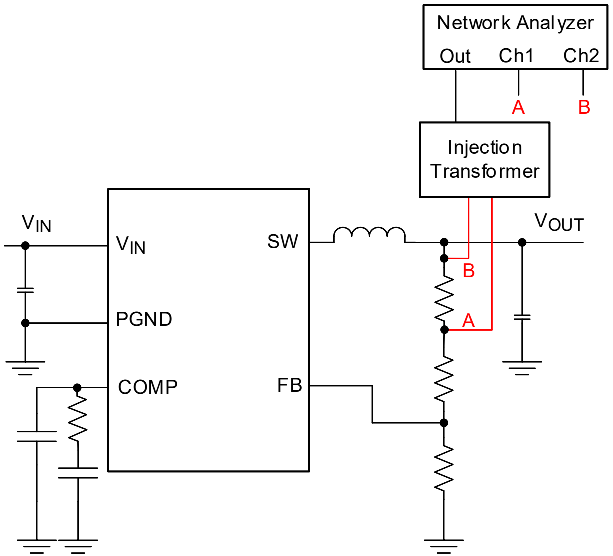
Power stage



Compensator

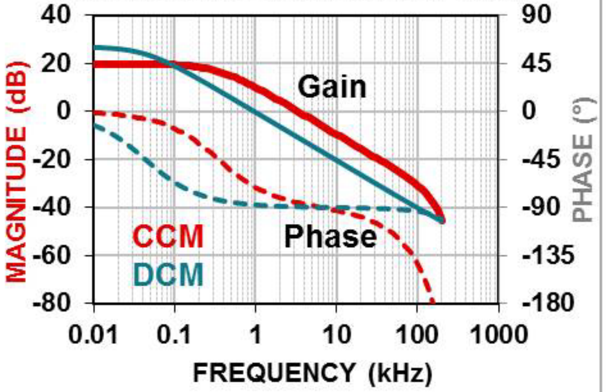


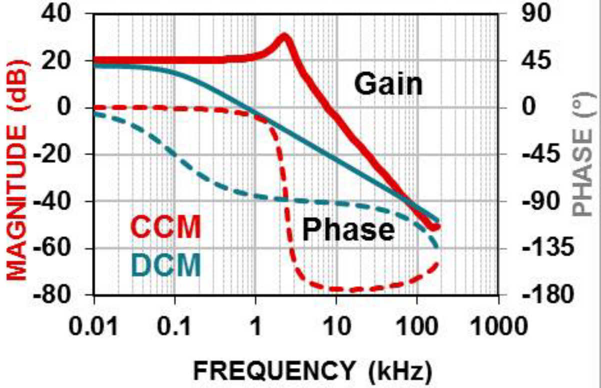
Closed loop



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

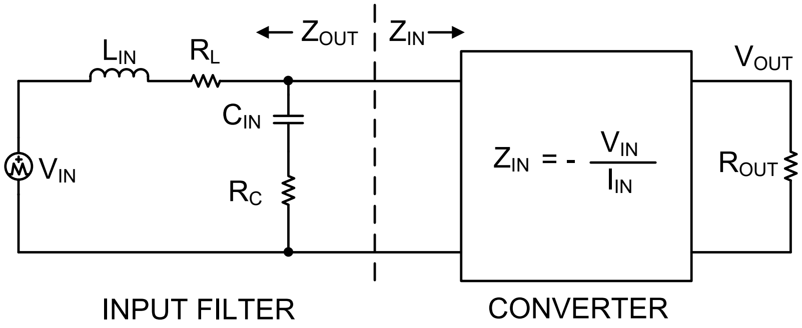
$$D = \frac{\sqrt{2 \cdot L \cdot f_{SW} \cdot I_{OUT} \cdot (V_{OUT} - V_{IN})}}{V_{IN}}$$

- Buck-boost

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

Filter considerations

Input filter stability

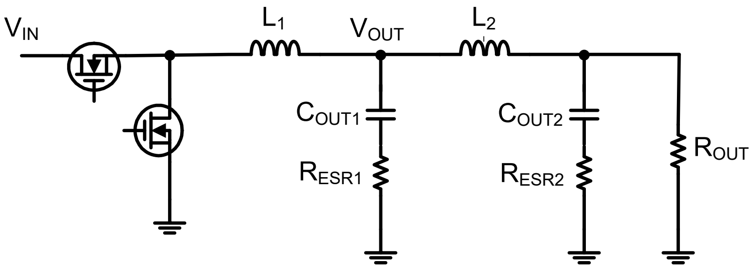


For stability: Filter Z_{OUT} << Converter Z_{IN}

- 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 Ray Ridley
- "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