

Power Supply Design Seminar

# Switch-mode power converter compensation made easy

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# Switch-mode power converter compensation made easy

Louis Diana

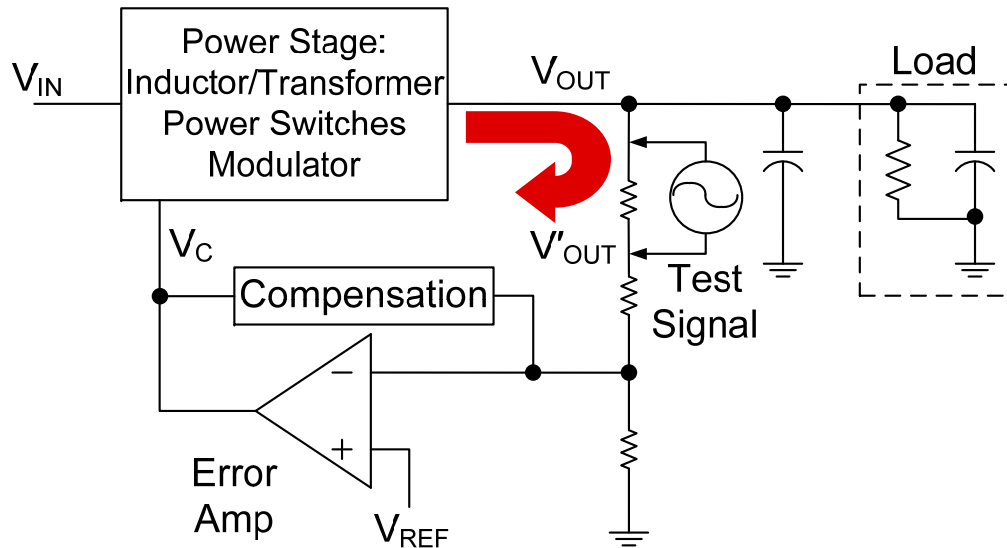
Robert Sheehan

# 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

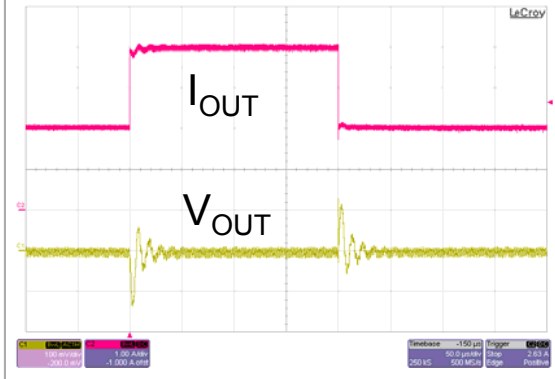
Why do we need feedback and why do we need compensation?



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

# Control loop response

## Poor transient response

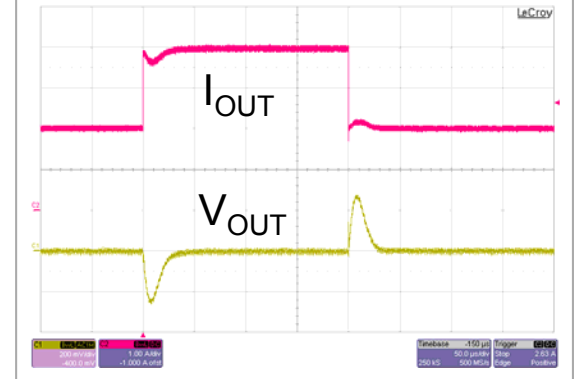


- Response is under-damped causing oscillatory behavior

## Objective

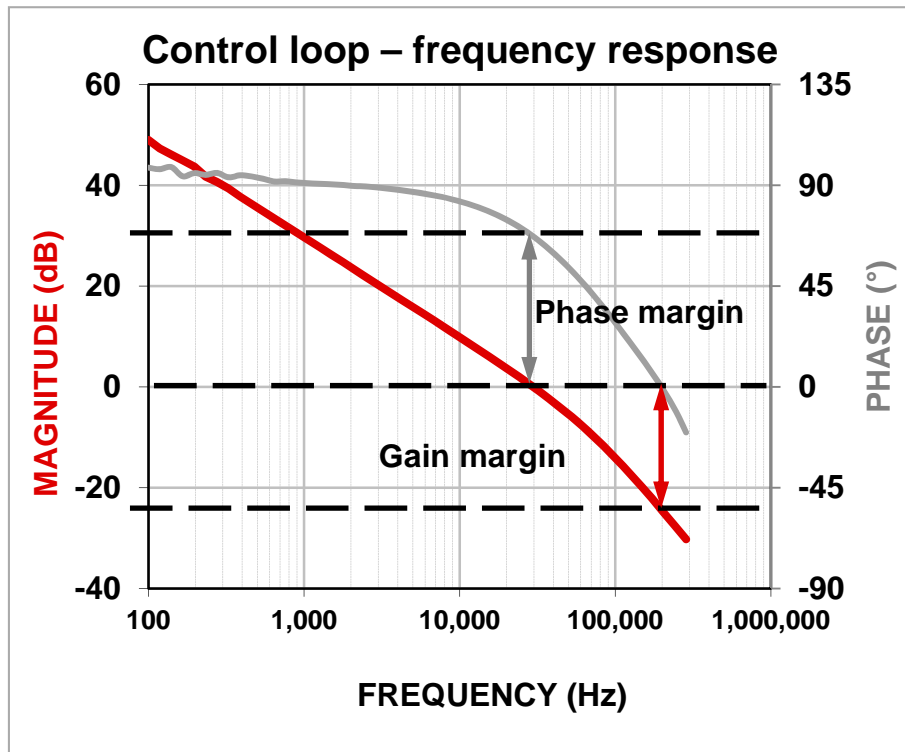
- Maximize crossover frequency for fastest transient response
- Adjust compensation for best settling behavior

## Good transient response



- Response is well damped with good settling behavior

# Phase margin and gain margin



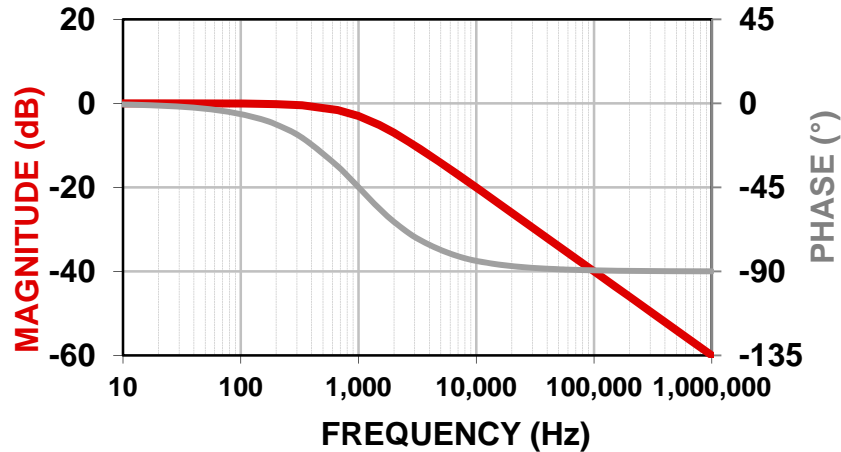
## Phase margin and stability

- Sufficient phase margin is needed to prevent oscillation ( $45^\circ$  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

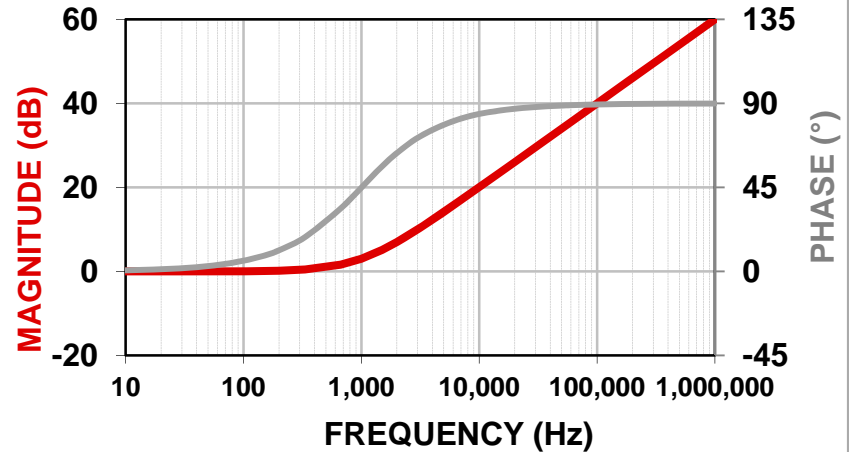
## Pole

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



## Zero

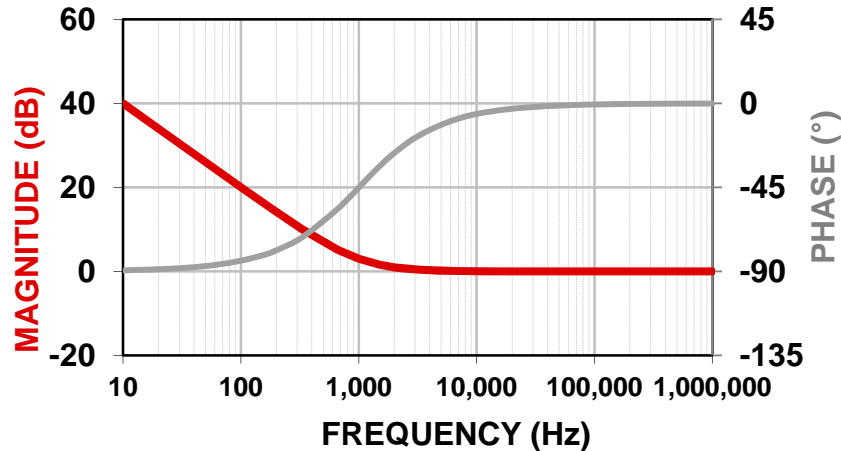
$$H(s) = \frac{1 + \frac{s}{\omega_z}}{1}$$



# Inverted and right-half-plane zeros

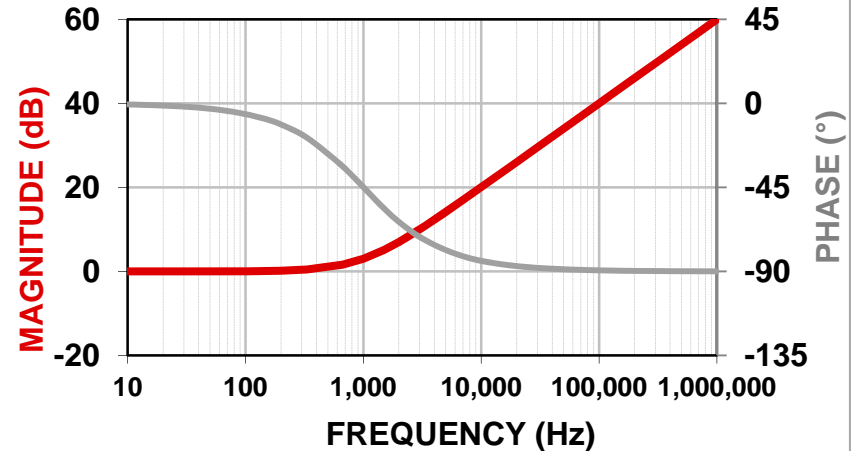
## Inverted zero

$$H(s) = \frac{1 + \frac{\omega_z}{s}}{1}$$



## Right-half-plane zero

$$H(s) = \frac{1 - \frac{s}{\omega_z}}{1}$$

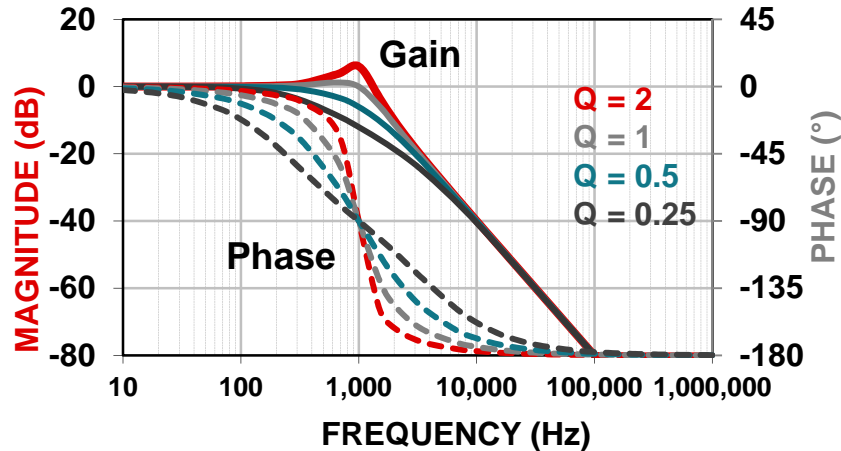




# Complex conjugate pole and ESR zero

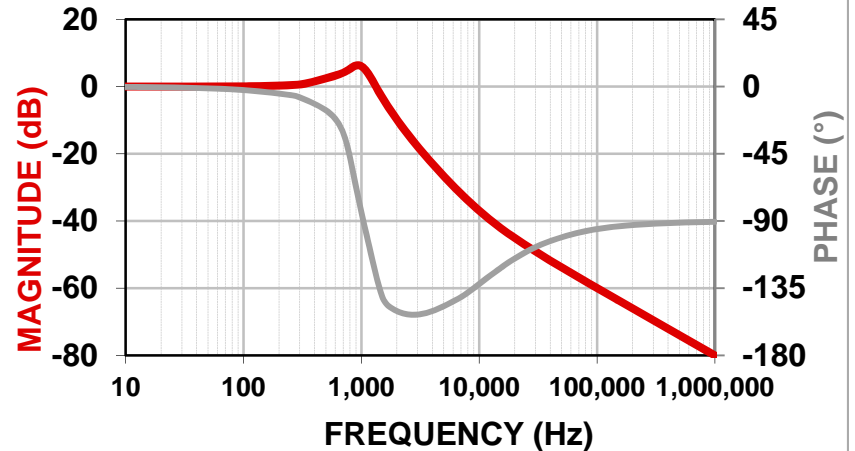
## Complex conjugate pole

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



## With ESR zero

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



# Control methods and operating modes

## Control methods

- Voltage-mode control
- Current-mode control

## Operating modes

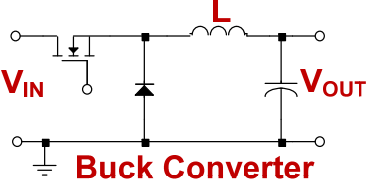
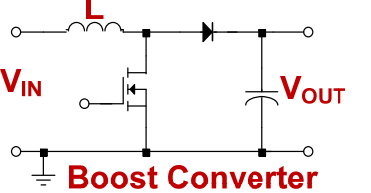
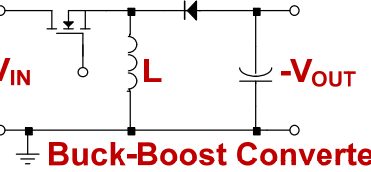
- Fixed frequency
- Continuous conduction-mode (CCM)

## Switching frequency and period

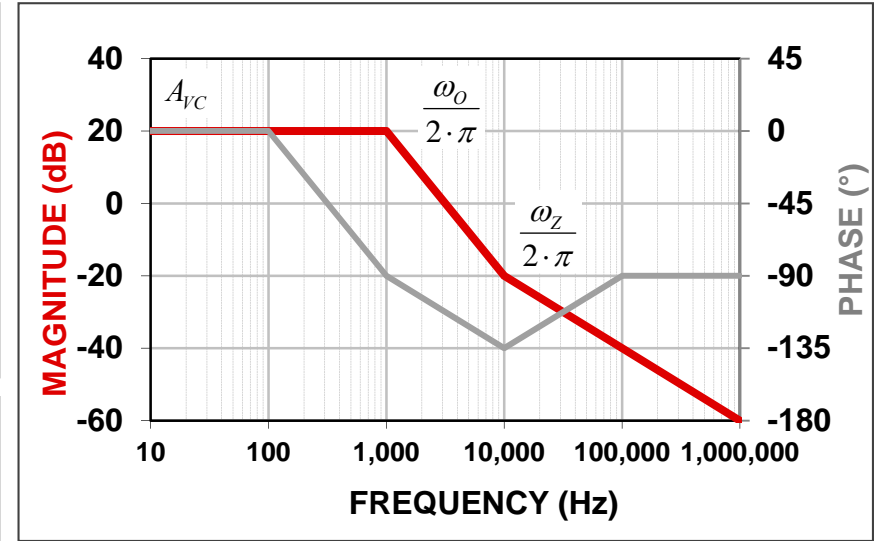
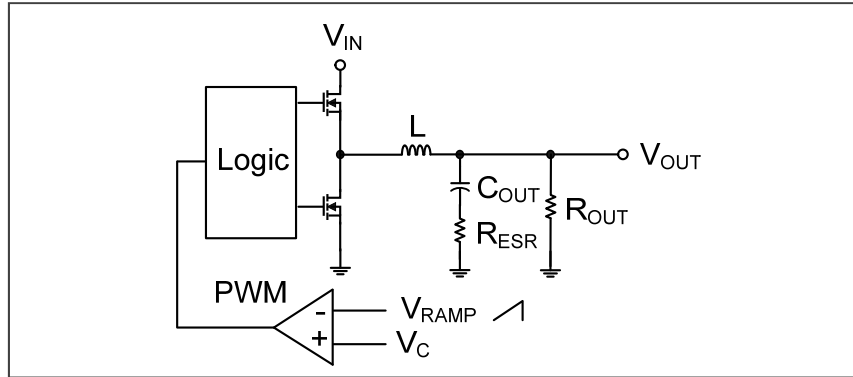
- Switching frequency –  $f_{SW}$
- Switching period –  $T$

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

# Buck, boost and buck-boost derived topologies

<p>Buck, forward, push-pull, bridge</p>	 <p><b>Buck Converter</b></p> $V_{OUT} = V_{IN} \cdot D$	<ul style="list-style-type: none"> <li>• Forward</li> <li>• Two switch forward</li> <li>• Active clamp forward</li> <li>• Half bridge</li> </ul> $V_{OUT} = V_{IN} \cdot D \cdot \frac{N_S}{N_P}$	<ul style="list-style-type: none"> <li>• Push-pull</li> <li>• Full bridge</li> <li>• Phase-shifted full bridge</li> </ul> $V_{OUT} = V_{IN} \cdot 2 \cdot D \cdot \frac{N_S}{N_P}$
<p>Boost</p>	 <p><b>Boost Converter</b></p> $V_{OUT} = V_{IN} \cdot \frac{1}{D'}$	<ul style="list-style-type: none"> <li>• Boost topology</li> </ul>	<p>On-time duty cycle: D Off-time duty cycle: D' = 1 - D</p>
<p>Buck-boost, SEPIC, flyback</p>	 <p><b>Buck-Boost Converter</b></p> $V_{OUT} = V_{IN} \cdot \frac{D}{D'}$	<ul style="list-style-type: none"> <li>• Buck-boost derived topologies</li> <li>• SEPIC</li> <li>• Cuk</li> </ul>	<ul style="list-style-type: none"> <li>• Flyback</li> </ul> $V_{OUT} = V_{IN} \cdot \frac{D}{D'} \cdot \frac{N_S}{N_P}$

# Voltage-mode buck power stage

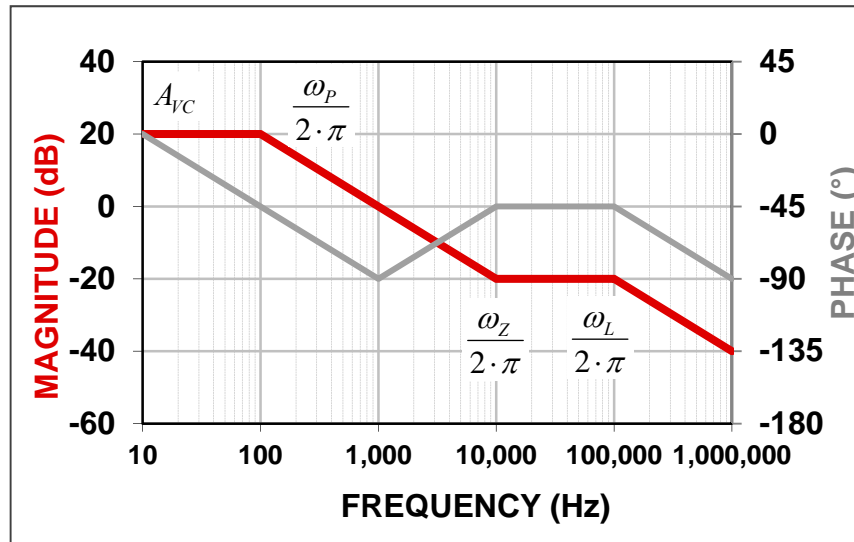
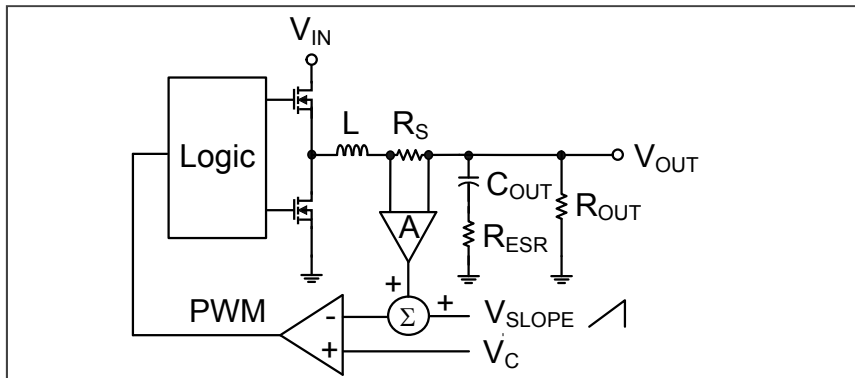


$$A_{VC} = \frac{V_{IN}}{V_{RAMP}} \qquad \omega_O = \frac{1}{\sqrt{L \cdot C_{OUT}}}$$

$$Q_O = \frac{R_{OUT}}{\sqrt{L/C_{OUT}}} \qquad \omega_Z = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

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

# Current-mode buck power stage



$$R_i = A \cdot R_S$$

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

$$A_{VC} \approx \frac{R_{OUT}}{R_i}$$

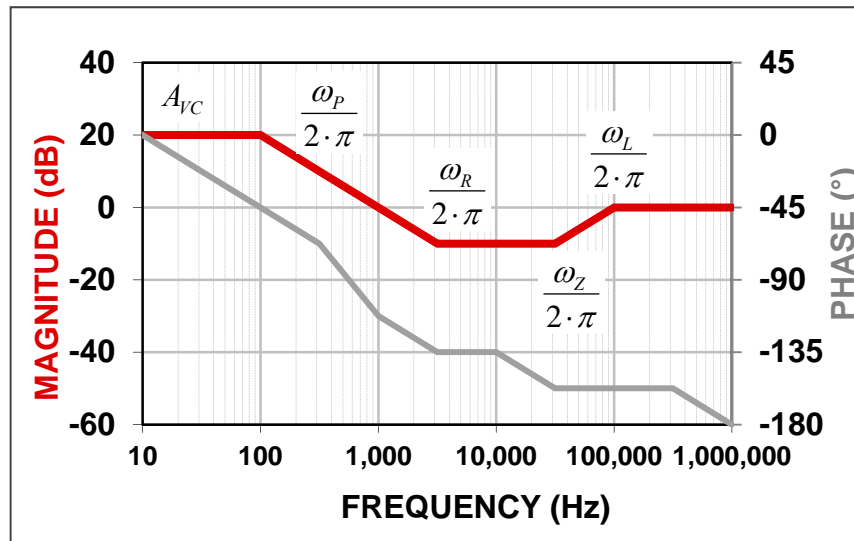
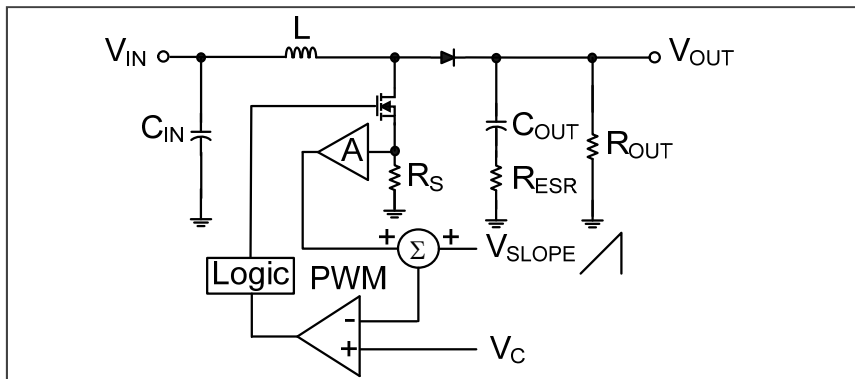
$$K_m \approx \frac{V_{IN}}{V_{SLOPE}} \quad \text{at } D = 0.5$$

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

$$\omega_L = \frac{K_m \cdot R_i}{L}$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_Z}}{\left(1 + \frac{s}{\omega_P}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$

# Current-mode boost power stage



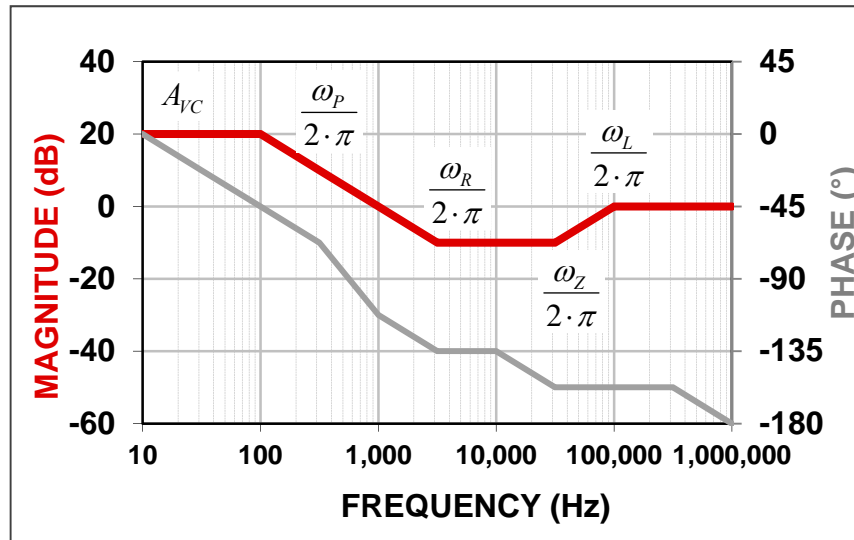
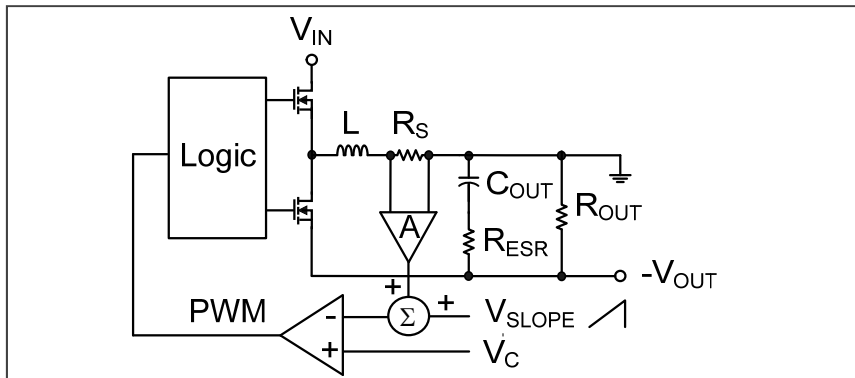
$$R_i = A \cdot R_S \quad \omega_R = \frac{R_{OUT} \cdot D'^2}{L} \quad \omega_L = \frac{K_m \cdot R_i}{L}$$

$$A_{VC} \approx \frac{R_{OUT} \cdot D'}{2 \cdot R_i} \quad \omega_Z = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

$$\omega_P \approx \frac{2}{C_{OUT} \cdot R_{OUT}} \quad K_m \approx \frac{V_{OUT}}{V_{SLOPE}} \quad \text{at } D = 0.5$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{\left(1 - \frac{s}{\omega_R}\right) \cdot \left(1 + \frac{s}{\omega_Z}\right)}{\left(1 + \frac{s}{\omega_P}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$

# Current-mode buck-boost power stage



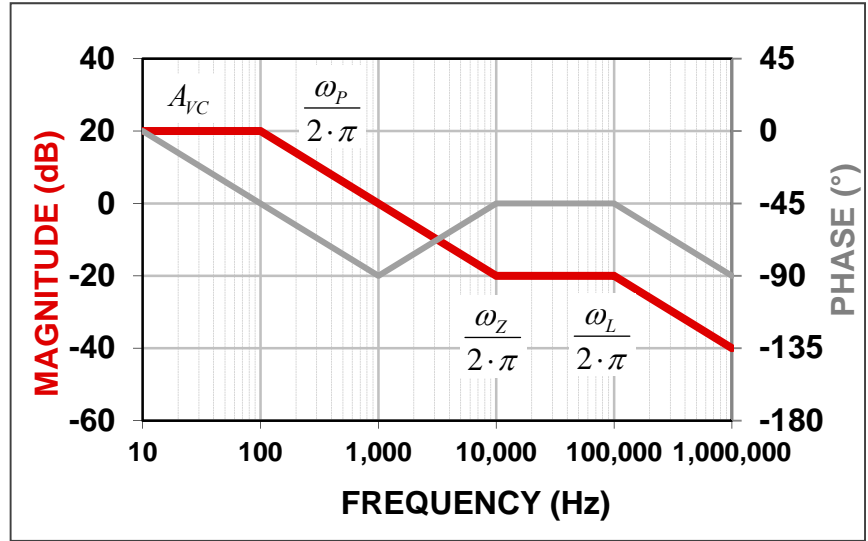
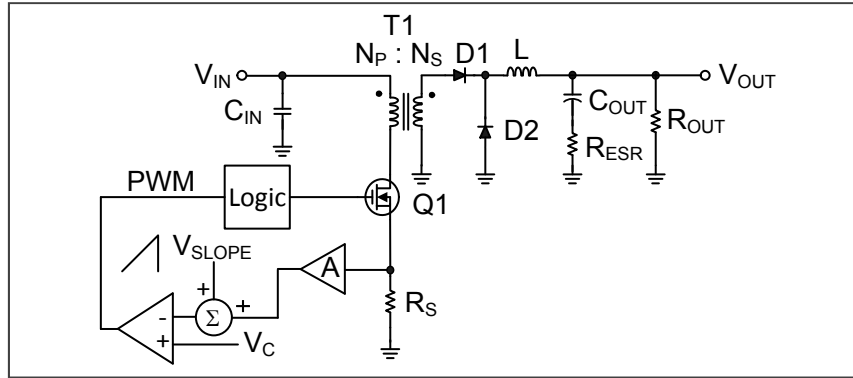
$$R_i = A \cdot R_S \qquad \omega_R = \frac{R_{OUT} \cdot D'^2}{L \cdot D} \qquad \omega_L = \frac{K_m \cdot R_i}{L}$$

$$A_{VC} \approx \frac{R_{OUT} \cdot D'}{(1+D) \cdot R_i} \qquad \omega_Z = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

$$\omega_P \approx \frac{1+D}{C_{OUT} \cdot R_{OUT}} \qquad K_m \approx \frac{V_{IN} + V_{OUT}}{V_{SLOPE}} \qquad \text{at } D = 0.5$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{\left(1 - \frac{s}{\omega_R}\right) \cdot \left(1 + \frac{s}{\omega_Z}\right)}{\left(1 + \frac{s}{\omega_P}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$

# Current-mode forward power stage



$$R_i = A \cdot R_S$$

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

$$A_{VC} \approx \frac{R_{OUT}}{R_i} \cdot \frac{N_P}{N_S}$$

$$K_m \approx \frac{V_{IN}}{V_{SLOPE}} \quad \text{at } D = 0.5$$

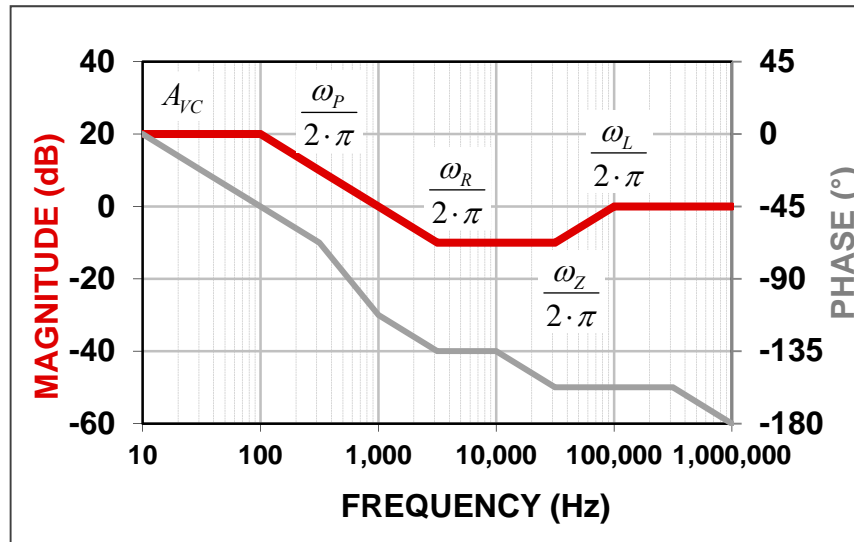
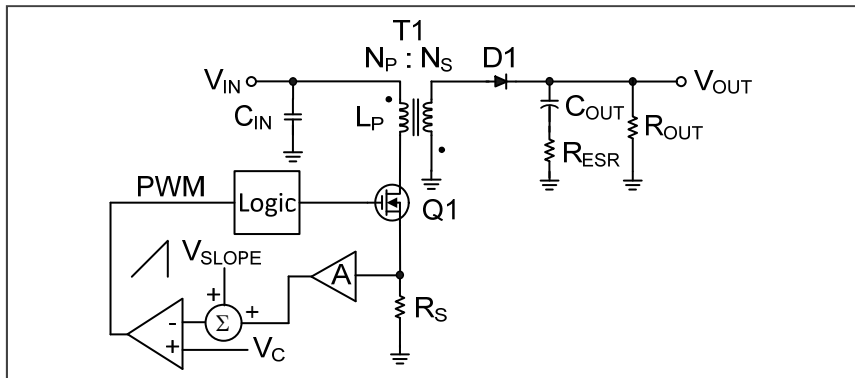
$$\omega_p \approx \frac{1}{C_{OUT} \cdot R_{OUT}}$$

$$\omega_L = \frac{K_m \cdot R_i}{L} \cdot \left( \frac{N_S}{N_P} \right)^2$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_Z}}{\left(1 + \frac{s}{\omega_P}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$



# Current-mode flyback power stage



$$R_i = A \cdot R_s$$

$$A_{VC} \approx \frac{R_{OUT} \cdot D'}{(1+D) \cdot R_i} \cdot \frac{N_P}{N_S}$$

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

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

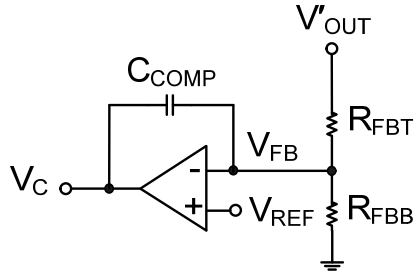
$$\omega_R = \frac{R_{OUT} \cdot D'^2}{L_P \cdot D} \cdot \left( \frac{N_P}{N_S} \right)^2$$

$$K_m \approx \frac{V_{IN} + V_{OUT} \cdot \frac{N_P}{N_S}}{V_{SLOPE}} \quad \text{at } D = 0.5$$

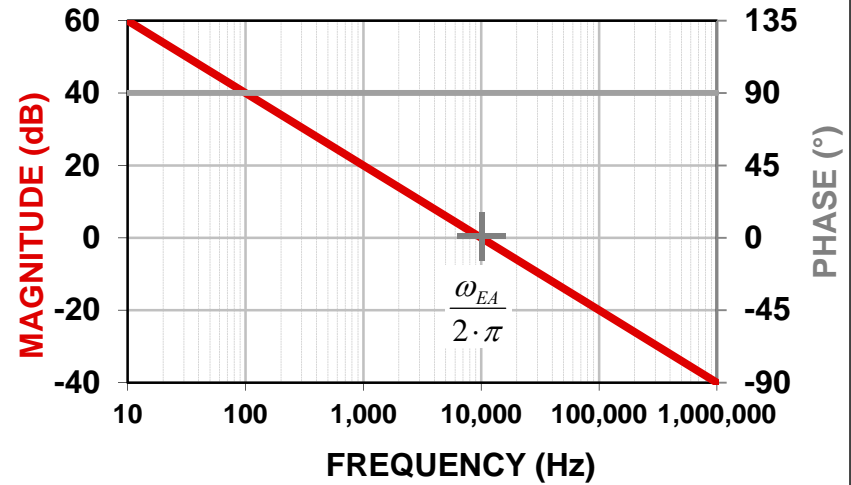
$$\omega_L = \frac{K_m \cdot R_i}{L_P}$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{\left(1 - \frac{s}{\omega_R}\right) \cdot \left(1 + \frac{s}{\omega_Z}\right)}{\left(1 + \frac{s}{\omega_p}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$

# Type I error amplifier

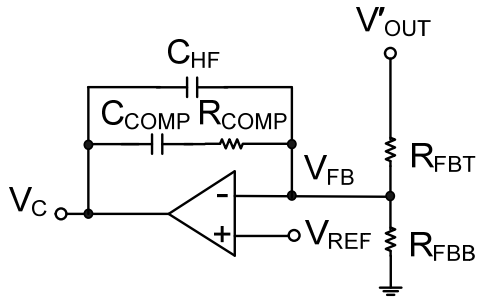


$$\omega_{EA} = \frac{1}{R_{FBT} \cdot C_{COMP}}$$



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

# Type II error amplifier

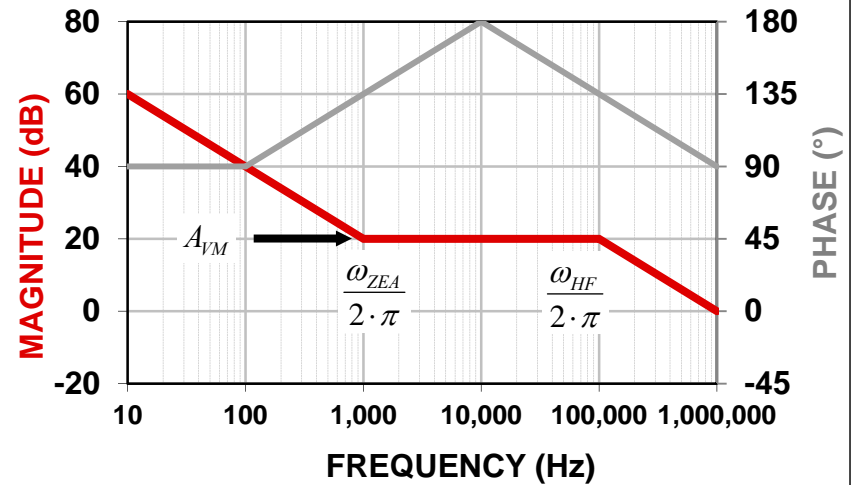


$$A_{VM} \approx \frac{R_{COMP}}{R_{FBT}}$$

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

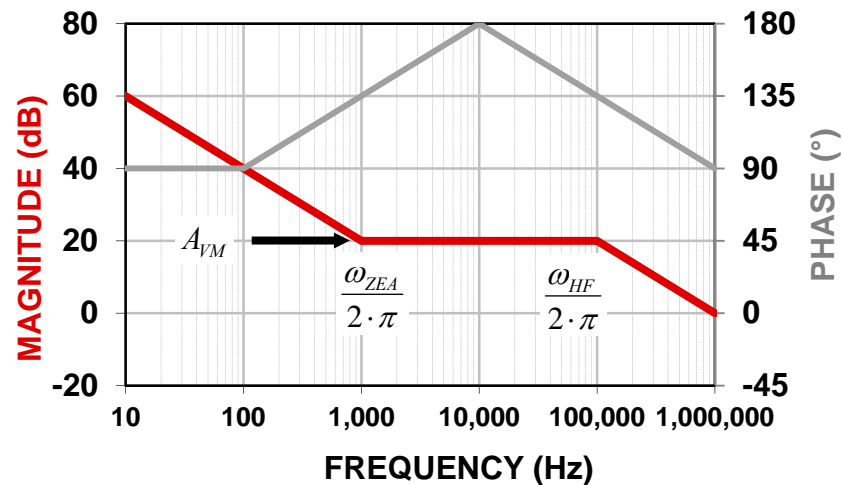
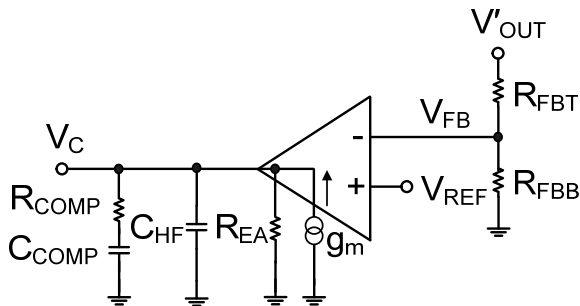
$$\omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}}$$

Assumption:  $C_{COMP} \gg C_{HF}$



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

# Type II transconductance amplifier



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

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

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

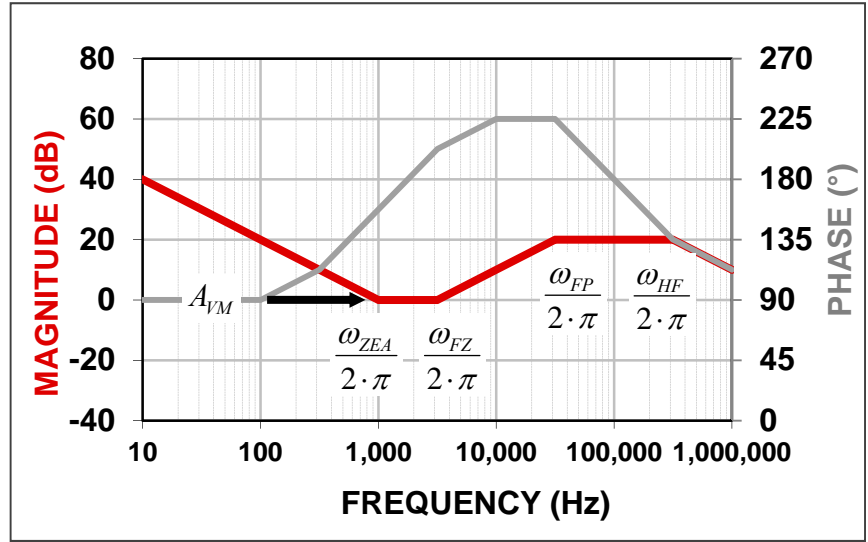
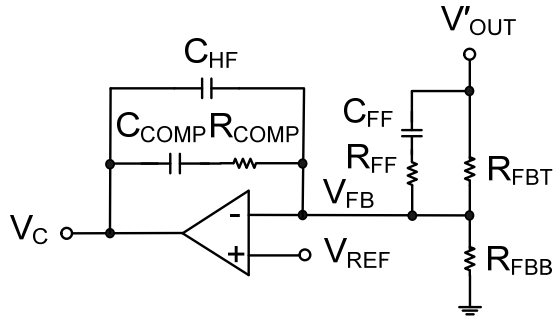
$$\omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}}$$

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

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

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

# Type III error amplifier



$$A_{VM} \approx \frac{R_{COMP}}{R_{FBT}}$$

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

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

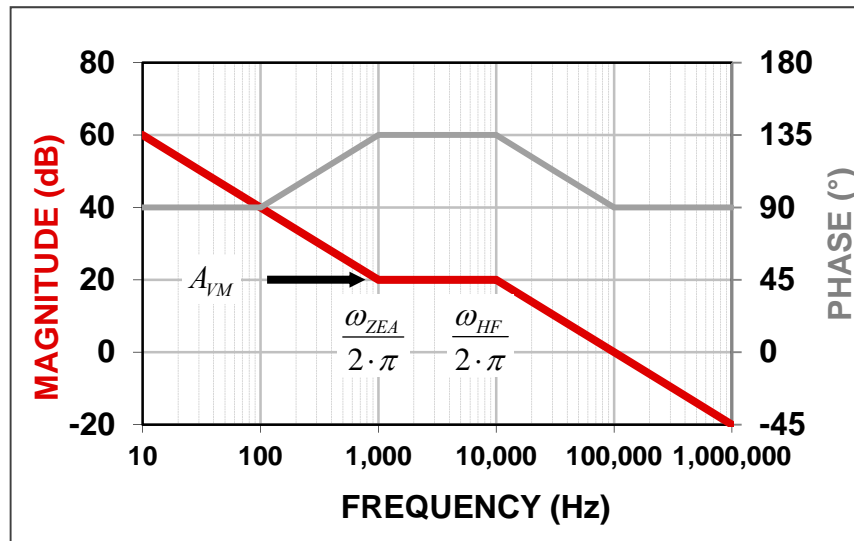
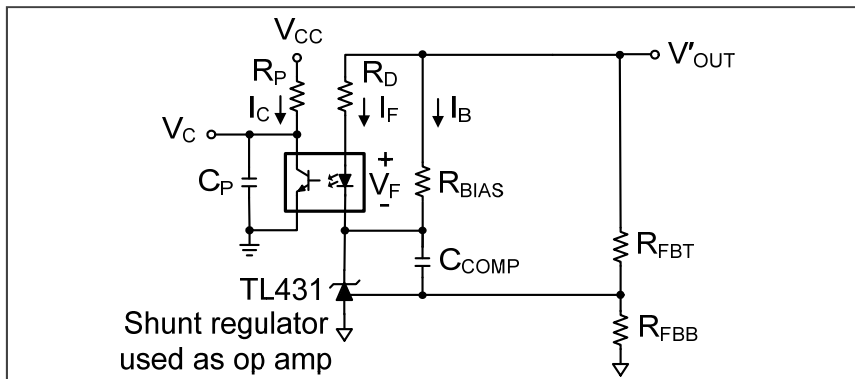
Assumptions:  $C_{COMP} \gg C_{HF}$  &  $R_{FBT} \gg R_{FF}$

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

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

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

# Isolated feedback with optocoupler



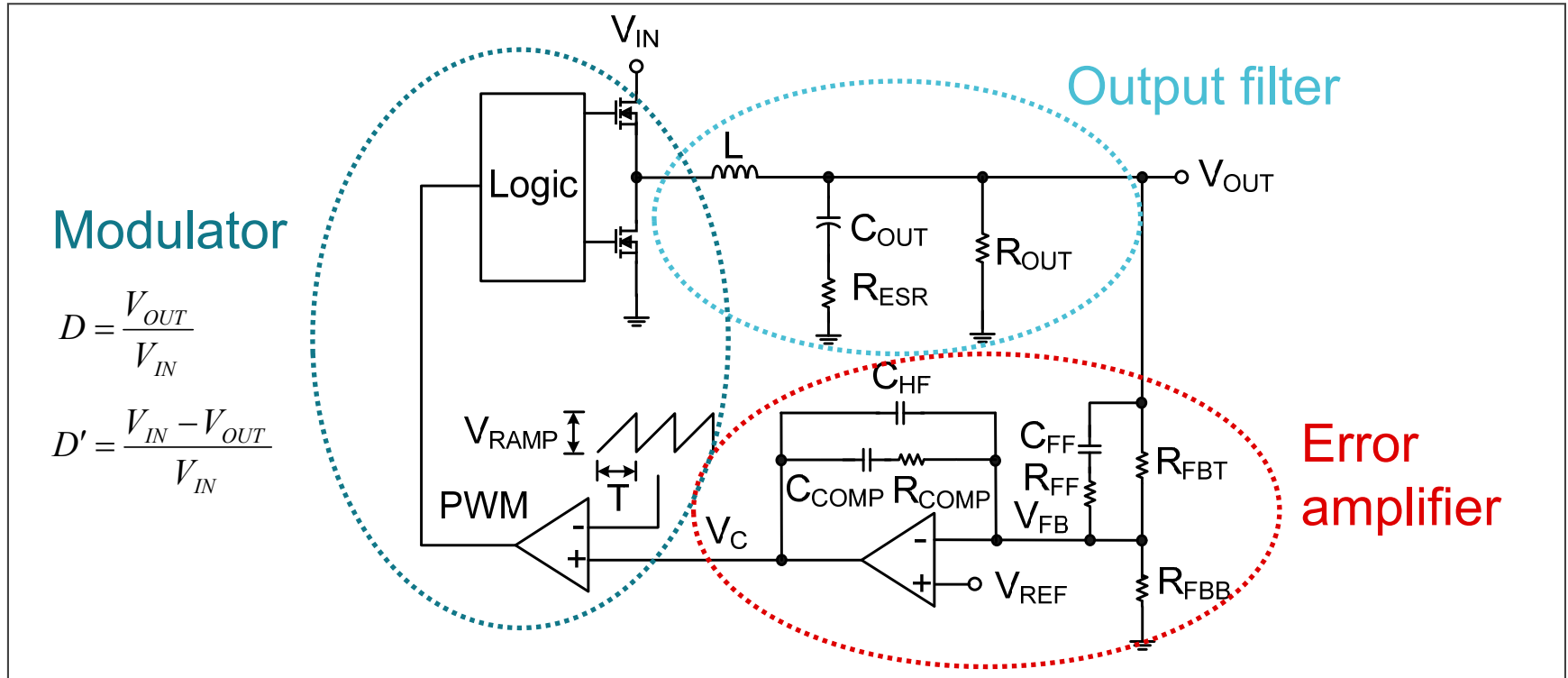
$$A_{VM} = CTR \cdot \frac{R_P}{R_D} \quad CTR = \frac{I_C}{I_F}$$

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

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

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

# Voltage-mode buck



# 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:  
$$\omega_{HF} = 2 \cdot \pi \cdot f_{SW}/2$$

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

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

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

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

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

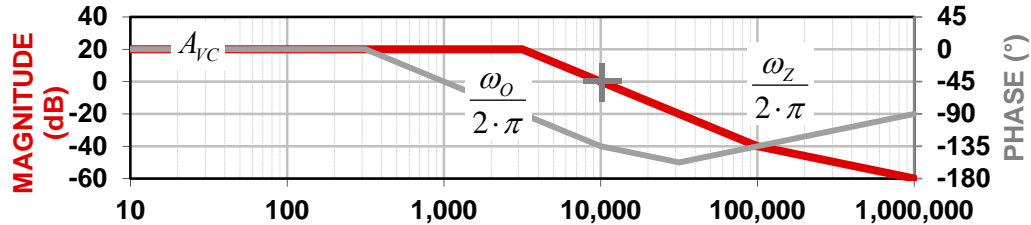
$$C_{HF} = \frac{1}{\omega_{HF} \cdot R_{COMP}}$$



# Voltage-mode buck compensation results

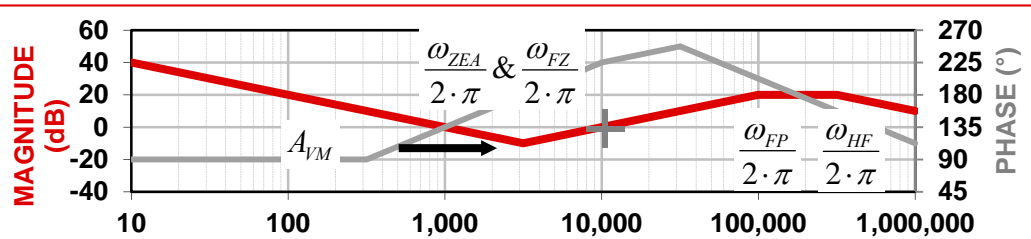
## Power stage

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



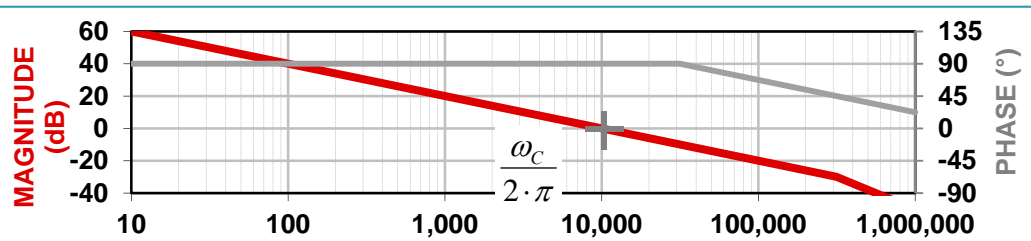
## Error amplifier

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



## Control loop

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

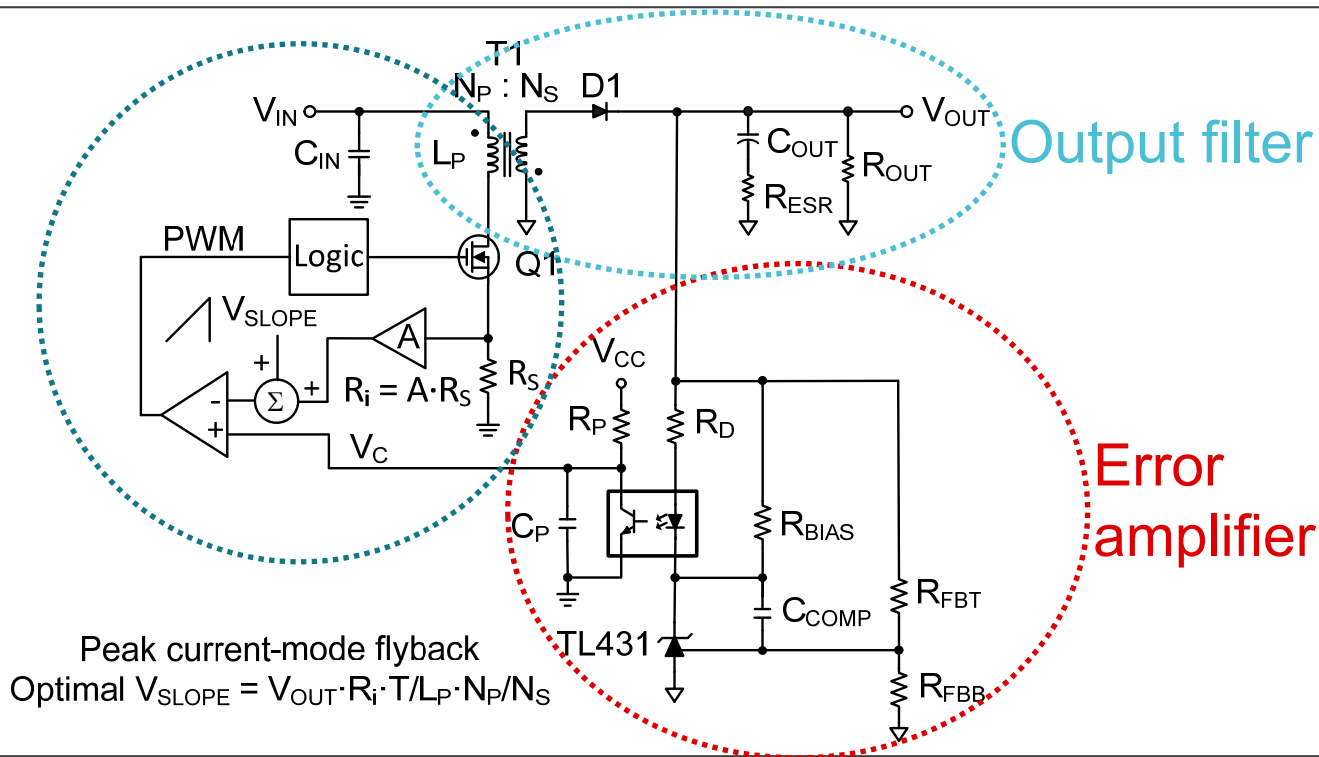


# Isolated current-mode flyback

## 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  $\omega_{ZEA}$  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:  
 $\omega_{HF} = \omega_R$  or  $\omega_Z$

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

$$\omega_R = \frac{R_{OUT} \cdot D'^2}{L_p \cdot D} \cdot \left( \frac{N_p}{N_s} \right)^2$$

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

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

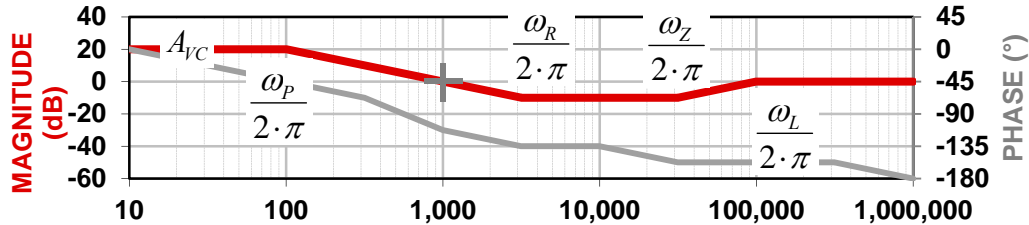
$$C_{COMP} = \frac{1}{R_{FBT} \cdot \omega_{ZEA}}$$

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

# Current-mode flyback compensation results

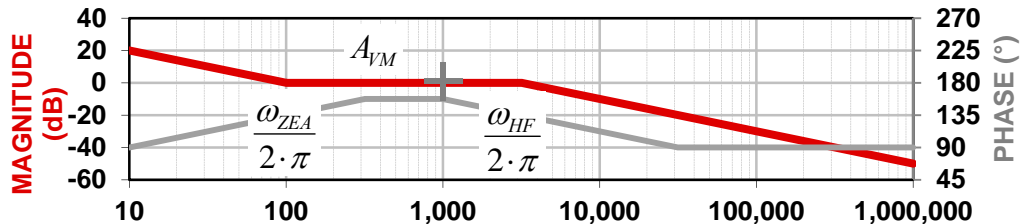
## Power stage

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{\left(1 - \frac{s}{\omega_R}\right) \cdot \left(1 + \frac{s}{\omega_Z}\right)}{\left(1 + \frac{s}{\omega_P}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$



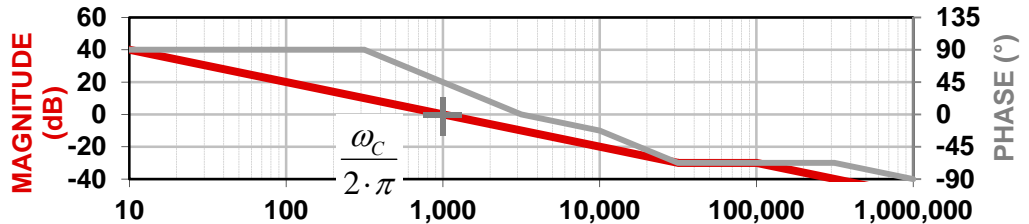
## Error amplifier

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



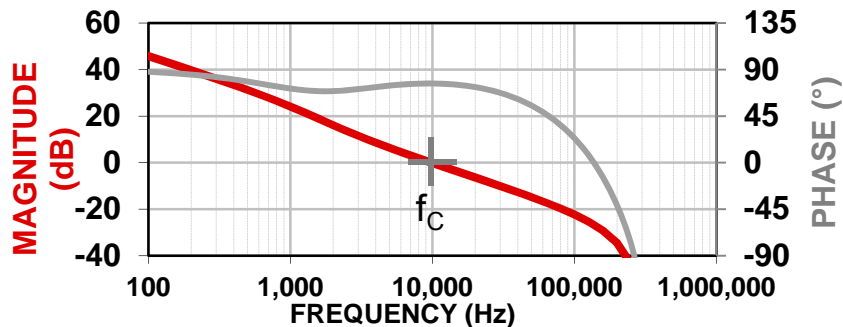
## Control loop

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

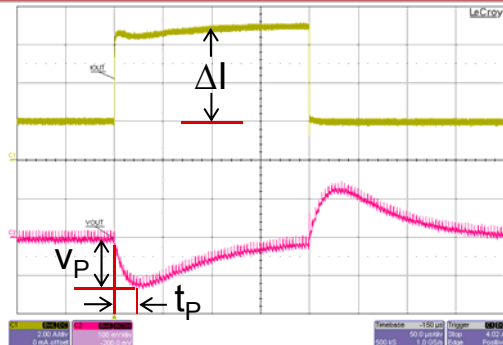


# Bandwidth vs. transient response

## Current-mode bandwidth



## Current-mode transient response



With no ESR, slew rate or duty cycle limiting:

Current-mode single pole approximation:

Current-mode critically damped:

Voltage-mode:

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

$$V_P = \frac{\Delta I}{2 \cdot \pi \cdot f_c \cdot C_{OUT}}$$

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

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

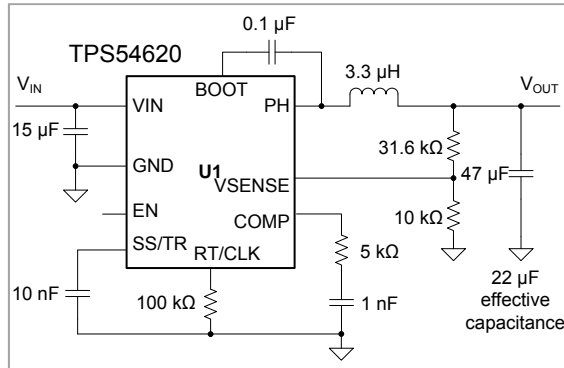
$$t_p = \frac{1}{4 \cdot 10\text{kHz}} = 25\mu\text{s}$$

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

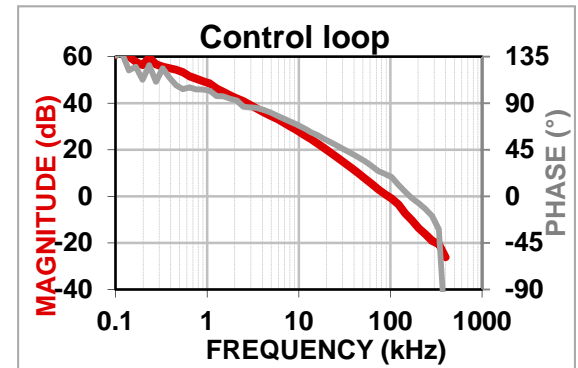
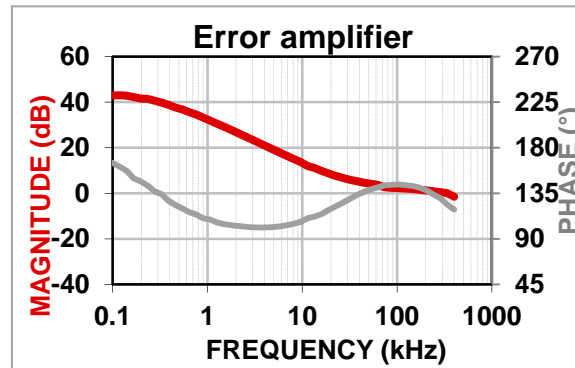
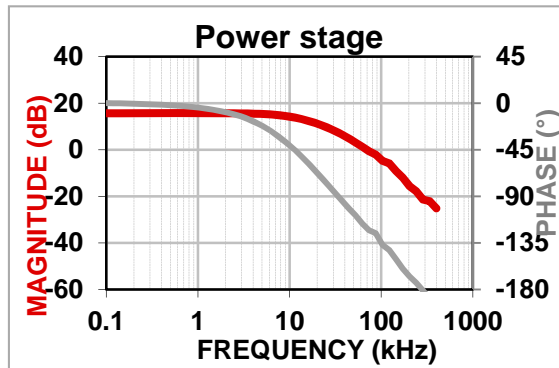
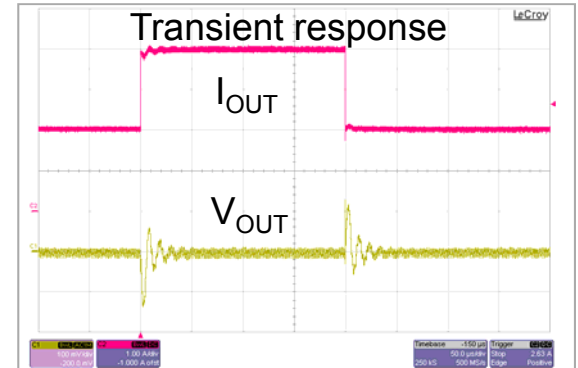
$$V_P = \frac{5\text{A}}{e \cdot \pi \cdot 10\text{kHz} \cdot 440\mu\text{F}} = 130\text{mV} \text{ shown above}$$

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

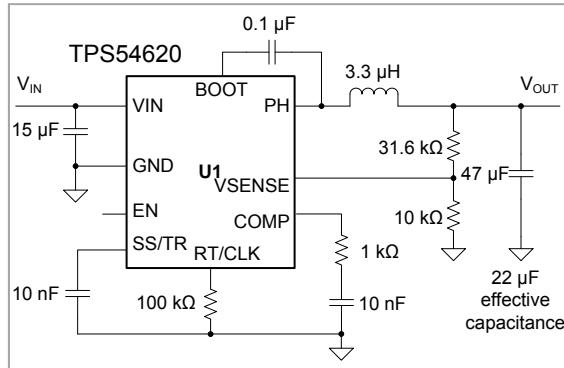
# Switching regulator with poor compensation



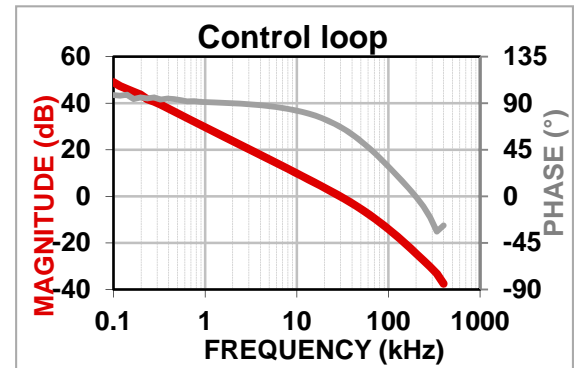
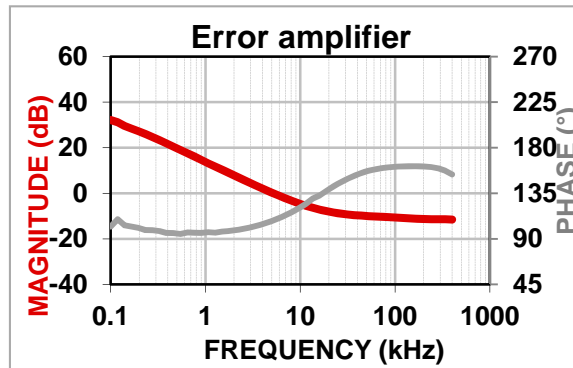
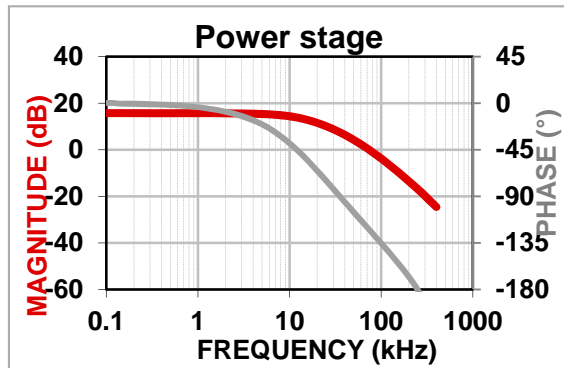
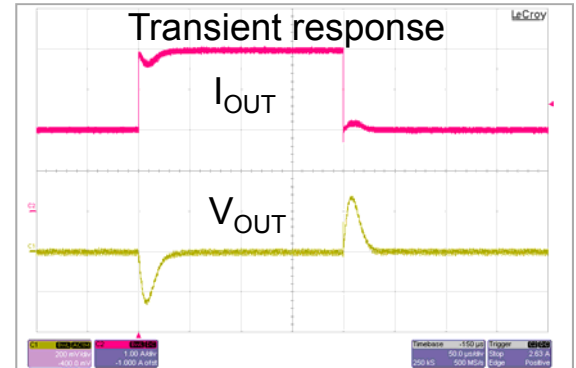
- Power stage: phase at  $-180^\circ$  indicates high internal slope compensation
- Error amplifier: zero appears high and mid-band gain is 3 dB
- Control loop:  $f_C$  is 95 kHz with only  $20^\circ$  phase margin



# Switching regulator with revised compensation

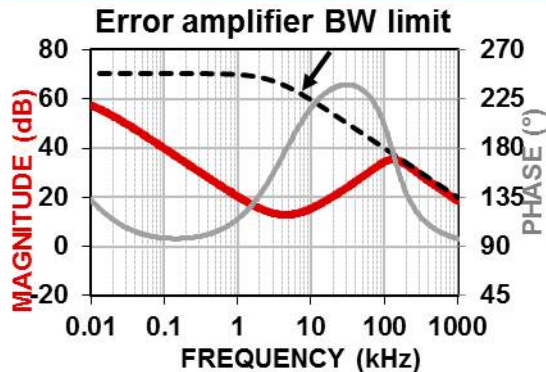


- Power stage: cannot change slope compensation
- Error amplifier: decrease  $R_{\text{COMP}}$  and rescale  $C_{\text{COMP}}$
- Control loop: now  $f_c$  is 30 kHz with  $67^\circ$  phase margin



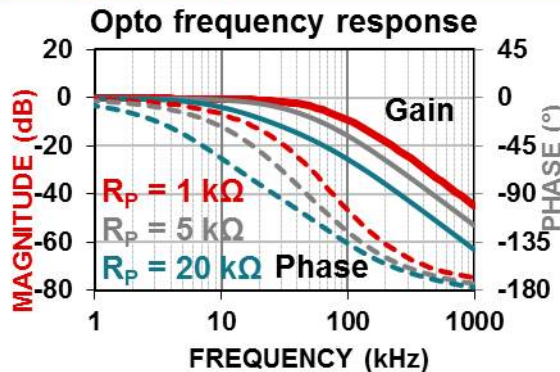
# Practical limitations

## Error amplifier bandwidth



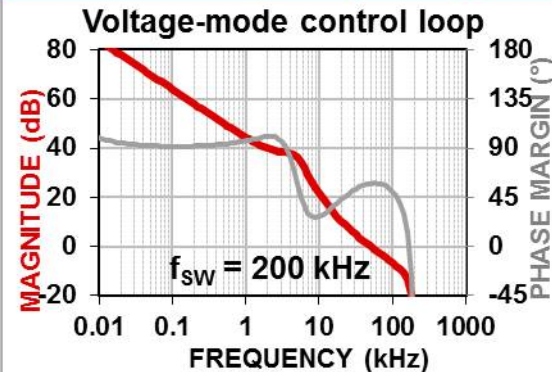
- Error amp BW can limit maximum  $f_c$
- Wider BW op amp needed for voltage-mode due to Type III compensation

## 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

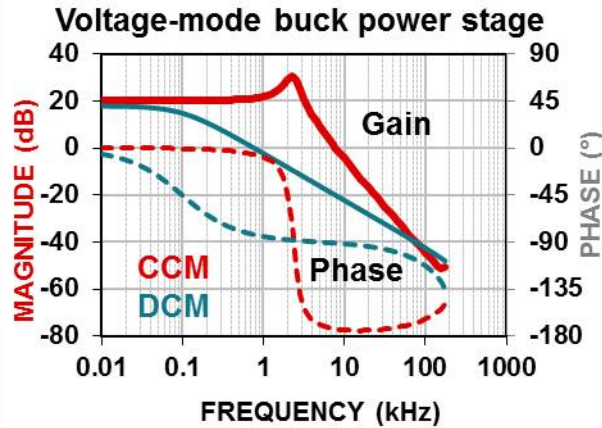
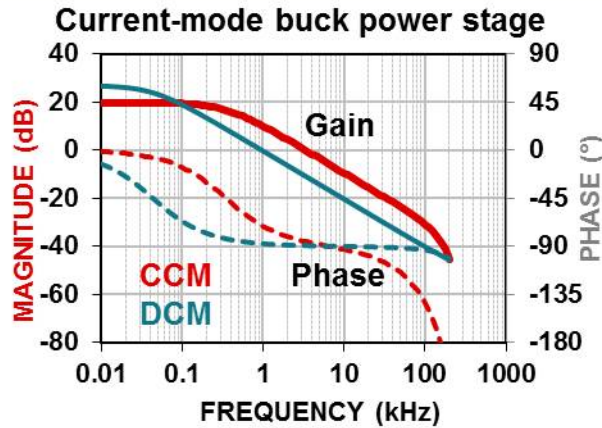


- Maximum  $f_c$  is a fraction of  $f_{sw}$
- Rule of thumb is 1/5 to 1/10 of  $f_{sw}$



# DCM vs. CCM characteristics

## Discontinuous vs. continuous conduction-mode



- 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

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

- Boost

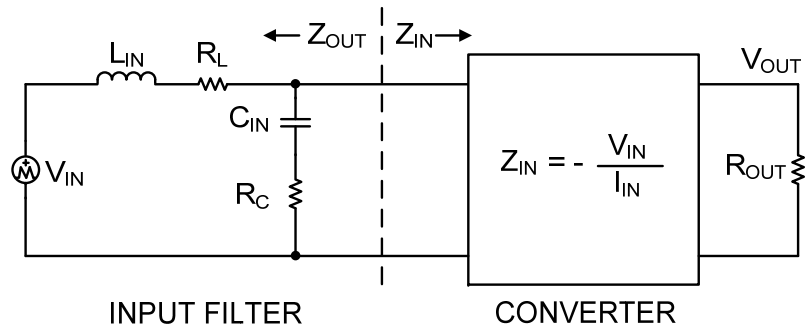
$$D = \frac{\sqrt{2 \cdot L \cdot f_{SW} \cdot I_{OUT} \cdot (V_{OUT} - V_{IN})}}{V_{IN}}$$

- Buck-boost

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

# Filter considerations

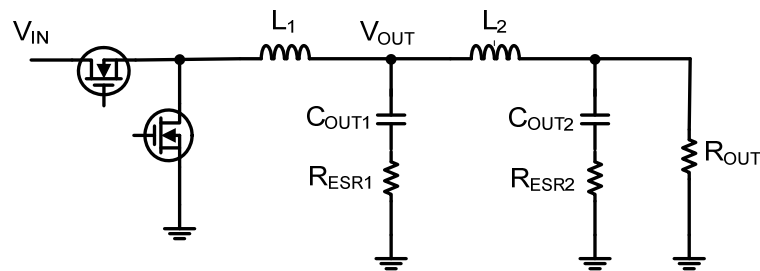
## Input filter stability



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
- Cancel with zeros and poles in the error amp
- Adjust the gain for best performance

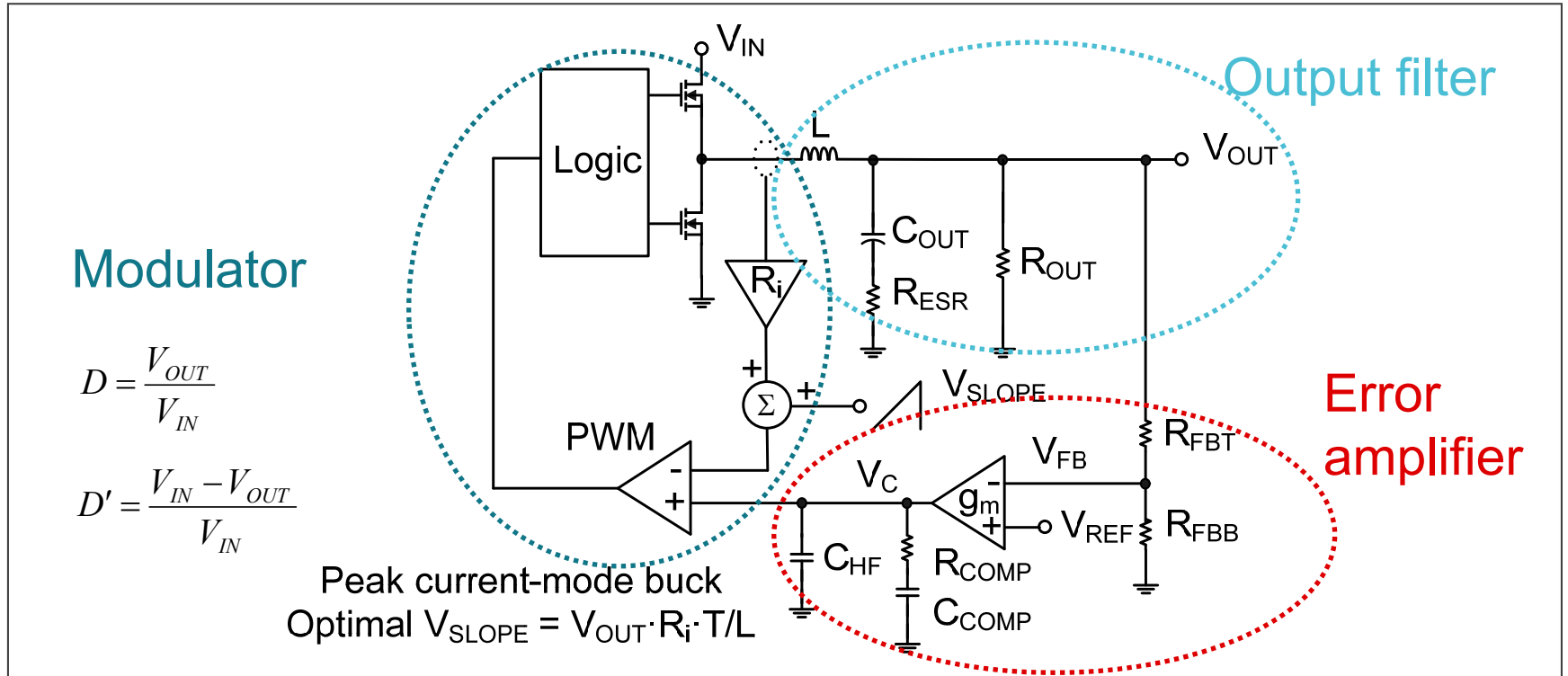
# Resources and references

- [“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
- [“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

# Appendix

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

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

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

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

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

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

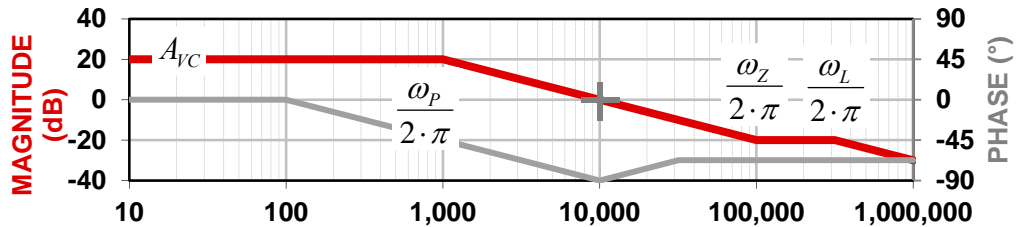
$$C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}$$

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

# Current-mode buck compensation results

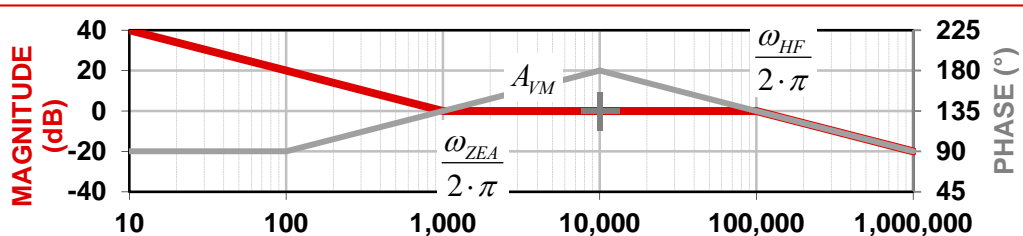
## Power stage

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_Z}}{\left(1 + \frac{s}{\omega_P}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$



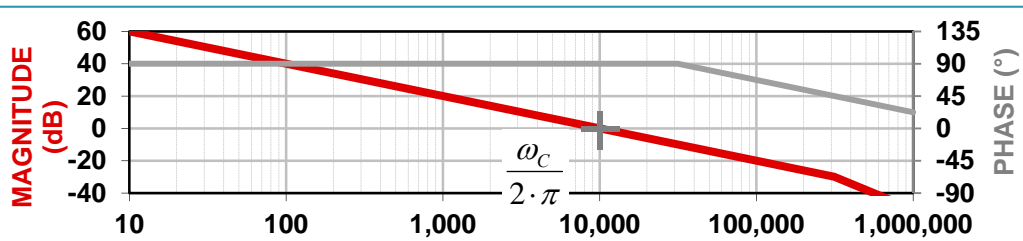
## Error amplifier

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



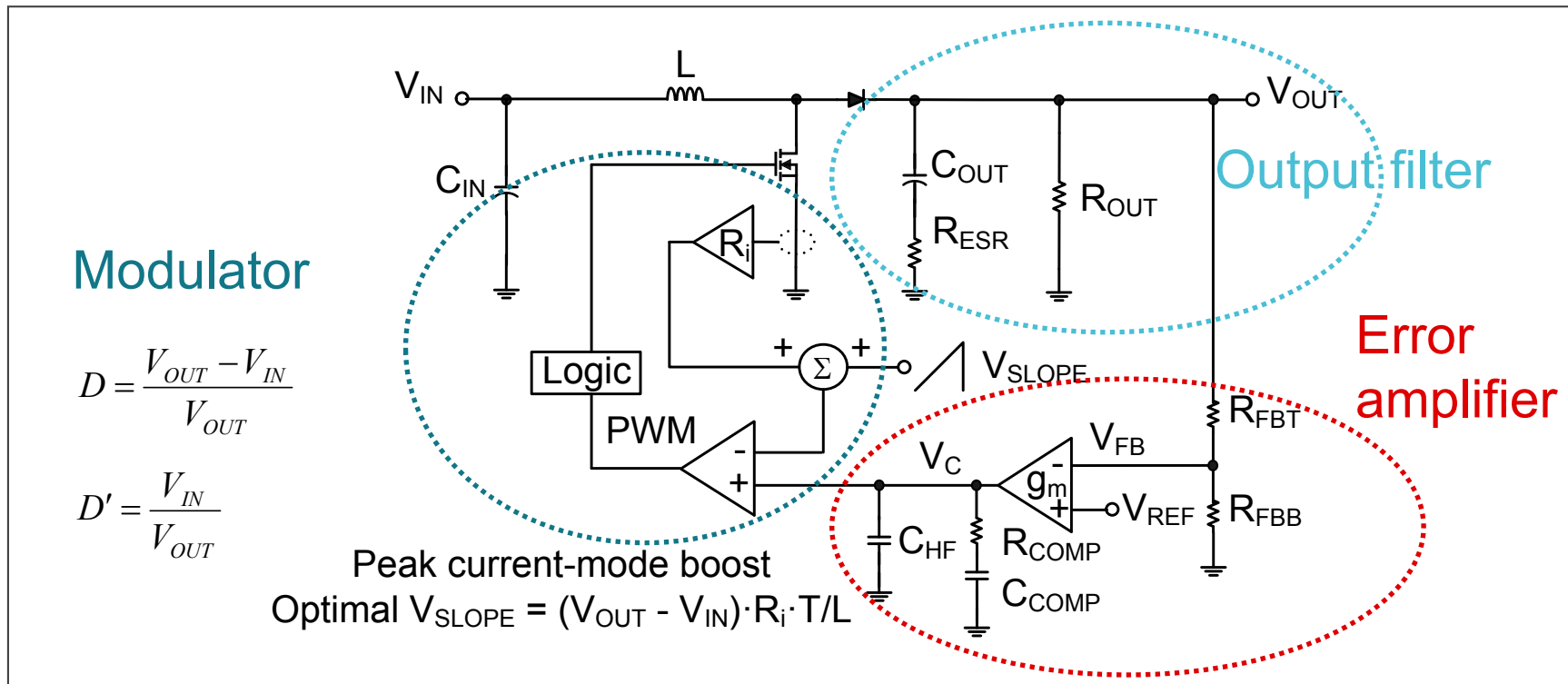
## Control loop

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





# Current-mode boost



# 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:  
 $\omega_{HF} = \omega_R$  or  $\omega_Z$

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

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

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

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

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

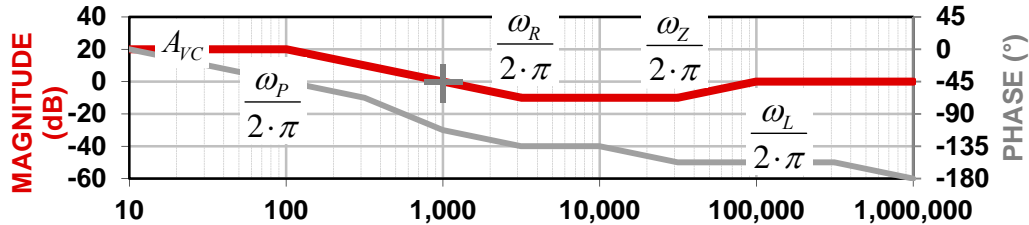
$$C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}$$

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

# Current-mode boost compensation results

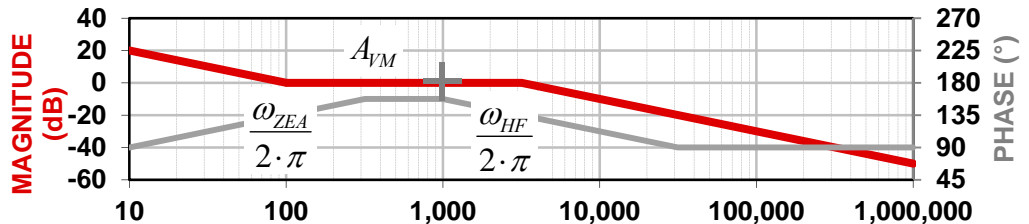
## Power stage

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{\left(1 - \frac{s}{\omega_R}\right) \cdot \left(1 + \frac{s}{\omega_Z}\right)}{\left(1 + \frac{s}{\omega_p}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$



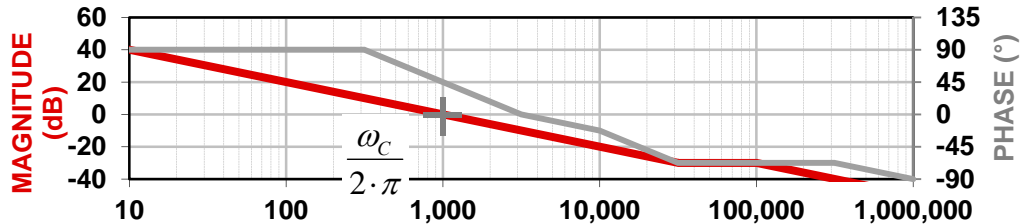
## Error amplifier

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

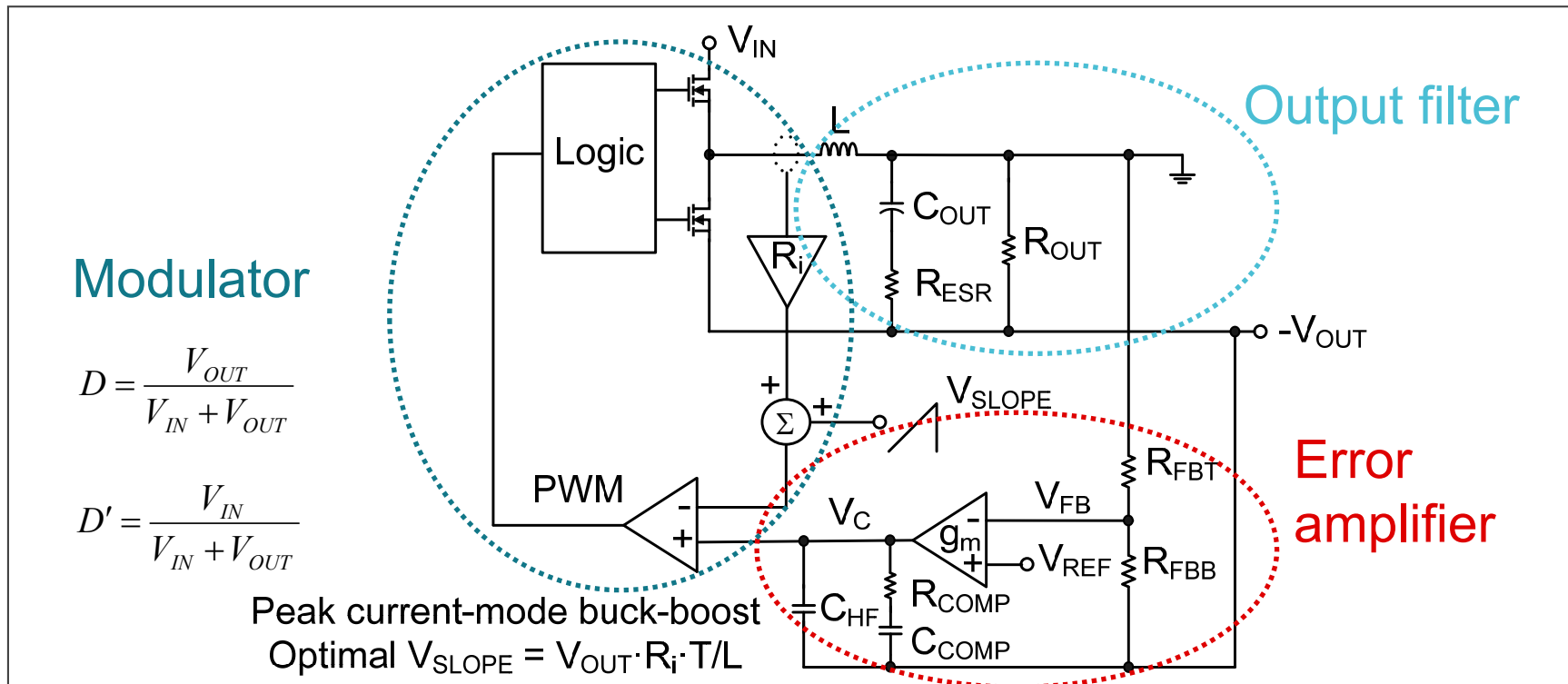


## Control loop

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



# 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  $\omega_{ZEA}$  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:  
 $\omega_{HF} = \omega_R$  or  $\omega_Z$

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

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

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

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

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

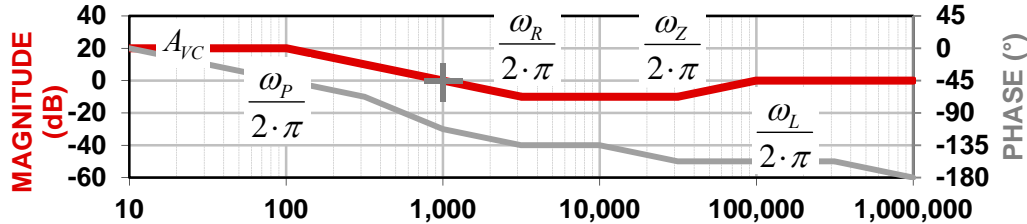
$$C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}$$

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

# Current-mode buck-boost compensation results

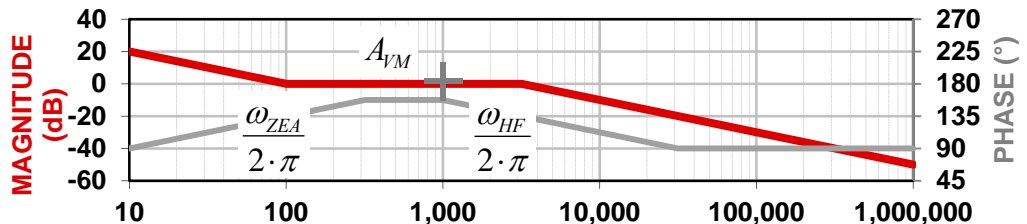
## Power stage

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{\left(1 - \frac{s}{\omega_R}\right) \cdot \left(1 + \frac{s}{\omega_Z}\right)}{\left(1 + \frac{s}{\omega_P}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$



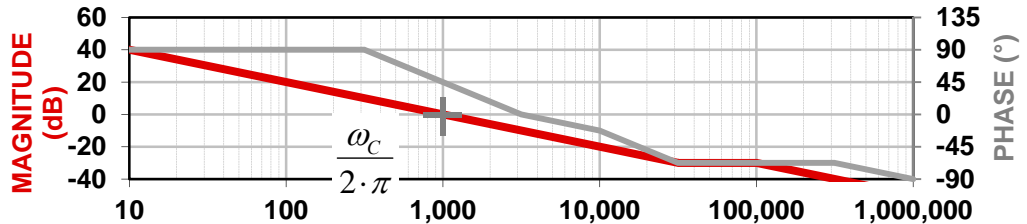
## Error amplifier

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



## Control loop

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



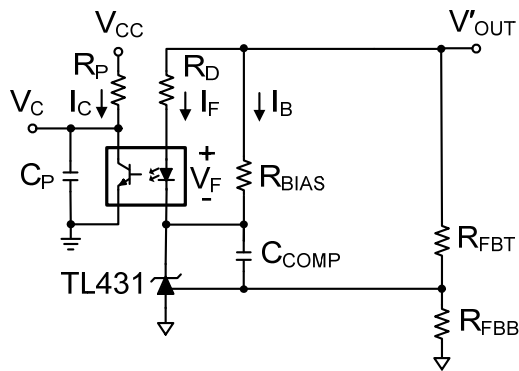
# Isolated compensation techniques

## Simplest method: Optocoupler with shunt regulator

- **CTR** – Current transfer ratio

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

- **C<sub>P</sub>** – Includes opto parasitic capacitance. This creates a pole with gain setting resistor R<sub>P</sub>

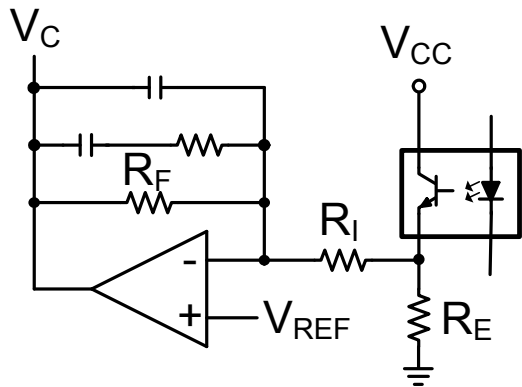


- **R<sub>D</sub>** – Connected to V<sub>OUT</sub> creates a feedback path even when C<sub>COMP</sub> rolls off the gain
- **TL431** – Cathode cannot pull lower than the reference voltage

$$\frac{\hat{v}_C}{\hat{v}'_{OUT}} \approx -CTR \cdot \frac{R_P}{R_D} \cdot \frac{1 + \frac{1}{s \cdot C_{COMP} \cdot R_{FBT}}}{1 + s \cdot C_P \cdot R_P}$$

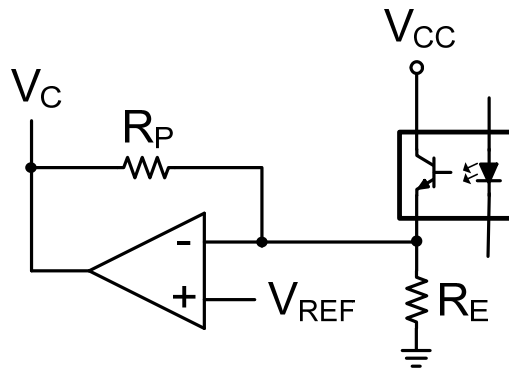
# Primary side compensation

## Primary side compensation



- Uses primary side inverting amplifier to implement frequency compensation

## High bandwidth configuration

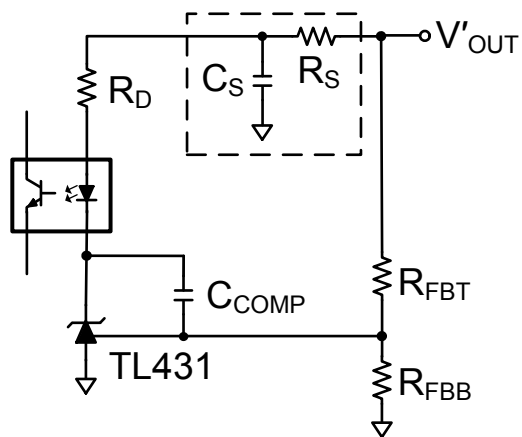


- Opto emitter is at virtual ground of  $V_{REF}$
- This minimizes pole due to opto parasitic capacitance



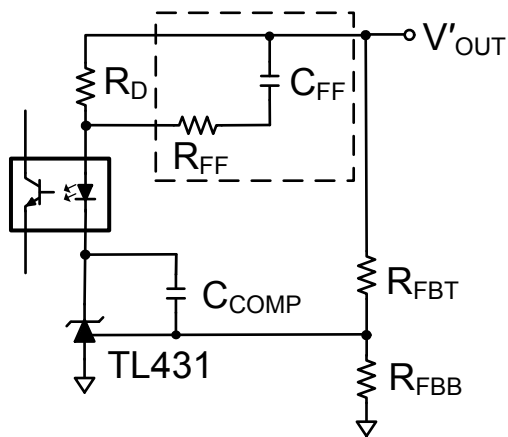
# Secondary side compensation

## ESR zero compensation



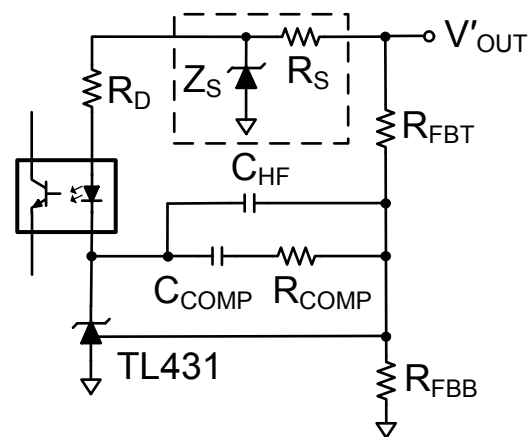
- An RC pole to the opto can be used to cancel the output capacitor ESR zero

## 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

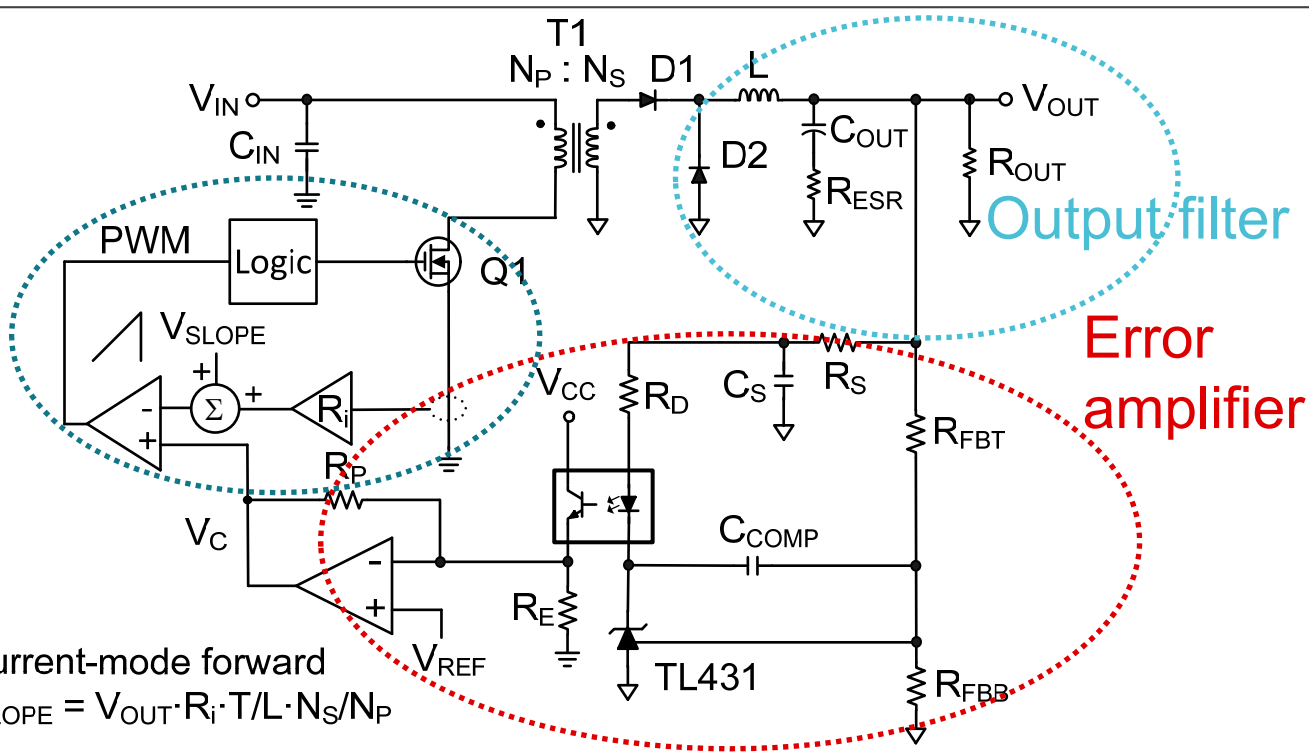
# Isolated current-mode forward

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

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

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

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

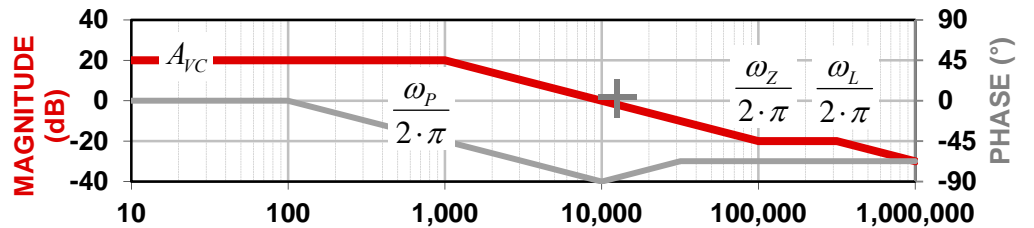
$$C_{\text{COMP}} = \frac{1}{R_{\text{FBT}} \cdot \omega_{\text{ZEA}}}$$

$$C_S = \frac{1}{R_S \cdot \omega_{\text{HF}}}$$

# Current-mode forward compensation results

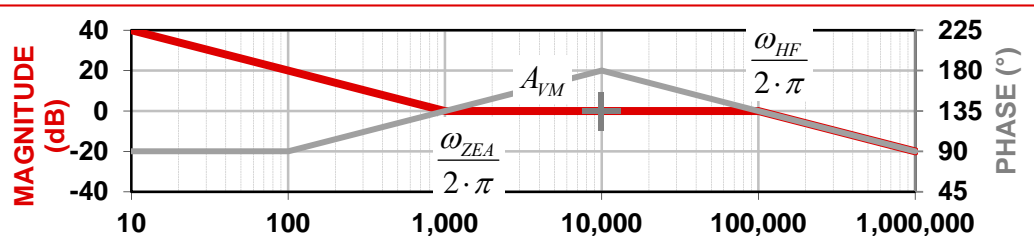
## Power stage

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_Z}}{\left(1 + \frac{s}{\omega_P}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$



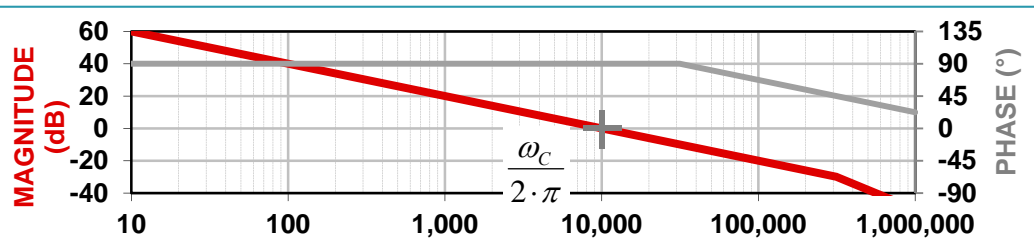
## Error amplifier

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



## Control loop

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



# TI Worldwide Technical Support

## Internet

### TI Semiconductor Product Information Center Home Page

[support.ti.com](http://support.ti.com)

### TI E2E™ Community Home Page

[e2e.ti.com](http://e2e.ti.com)

## Product Information Centers

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<b>Brazil</b>	Phone	0800-891-2616
<b>Mexico</b>	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	<a href="http://support.ti.com/sc/pic/americas.htm">support.ti.com/sc/pic/americas.htm</a>

### Europe, Middle East, and Africa

Phone	
European Free Call	00800-ASK-TEXAS (00800 275 83927)
International	+49 (0) 8161 80 2121
Russian Support	+7 (4) 95 98 10 701

**Note:** The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax	+ (49) (0) 8161 80 2045
Internet	<a href="http://www.ti.com/asktexas">www.ti.com/asktexas</a>
Direct Email	<a href="mailto:asktexas@ti.com">asktexas@ti.com</a>

### Japan

Phone	Domestic	0120-92-3326
Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	<a href="http://support.ti.com/sc/pic/japan.htm">support.ti.com/sc/pic/japan.htm</a>
	Domestic	<a href="http://www.tij.co.jp/pic">www.tij.co.jp/pic</a>

## Asia

Phone	
International	+91-80-41381665
Domestic	<a href="#">Toll-Free Number</a>

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Korea	080-551-2804
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New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
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International	+86-21-23073444
Fax	+8621-23073686
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