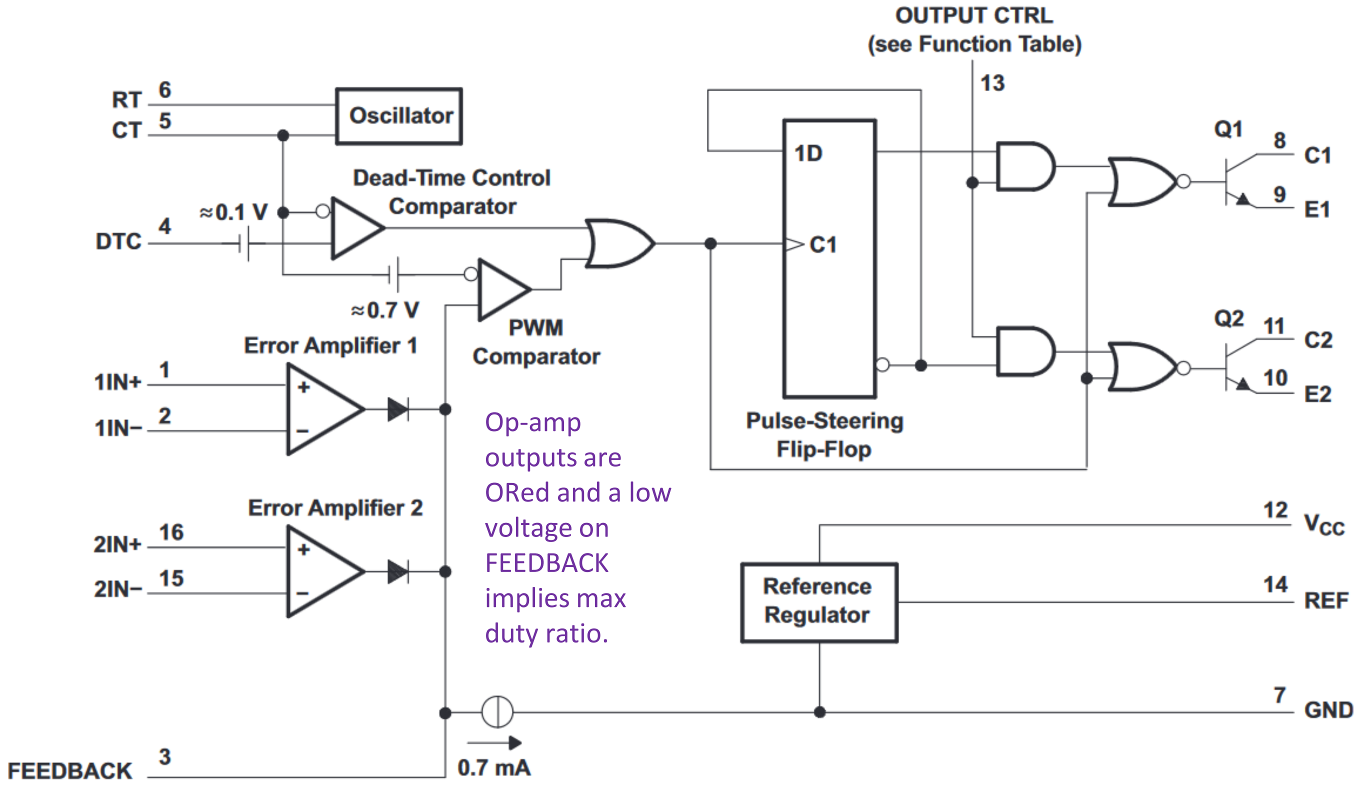
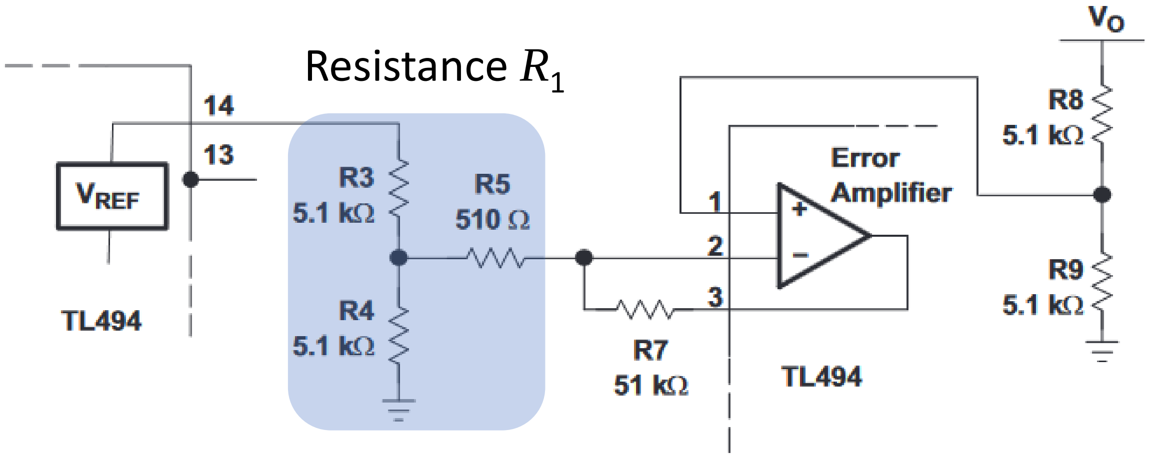
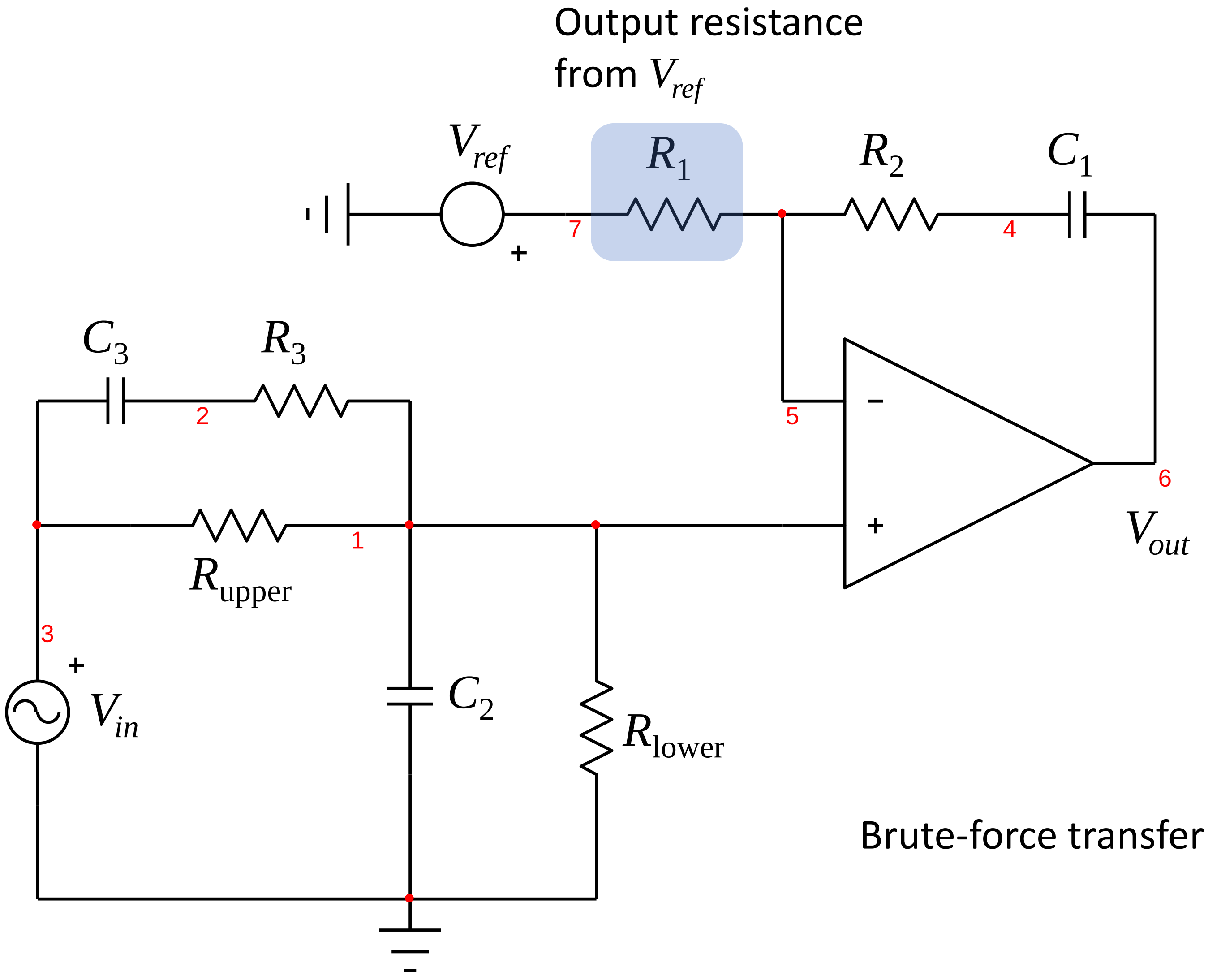




The TL494 hosts two op-amps wired in an uncommon configuration in which the error voltage at pin 3 *increases* to reduce the duty ratio. As such, the compensator can only be configured in a non-inverting configuration which is fairly unusual – and it's bad!

This is the recommended wiring diagram for the part where the reference voltage feeds the inverting pin while the non-inverting pin observes the regulated output.



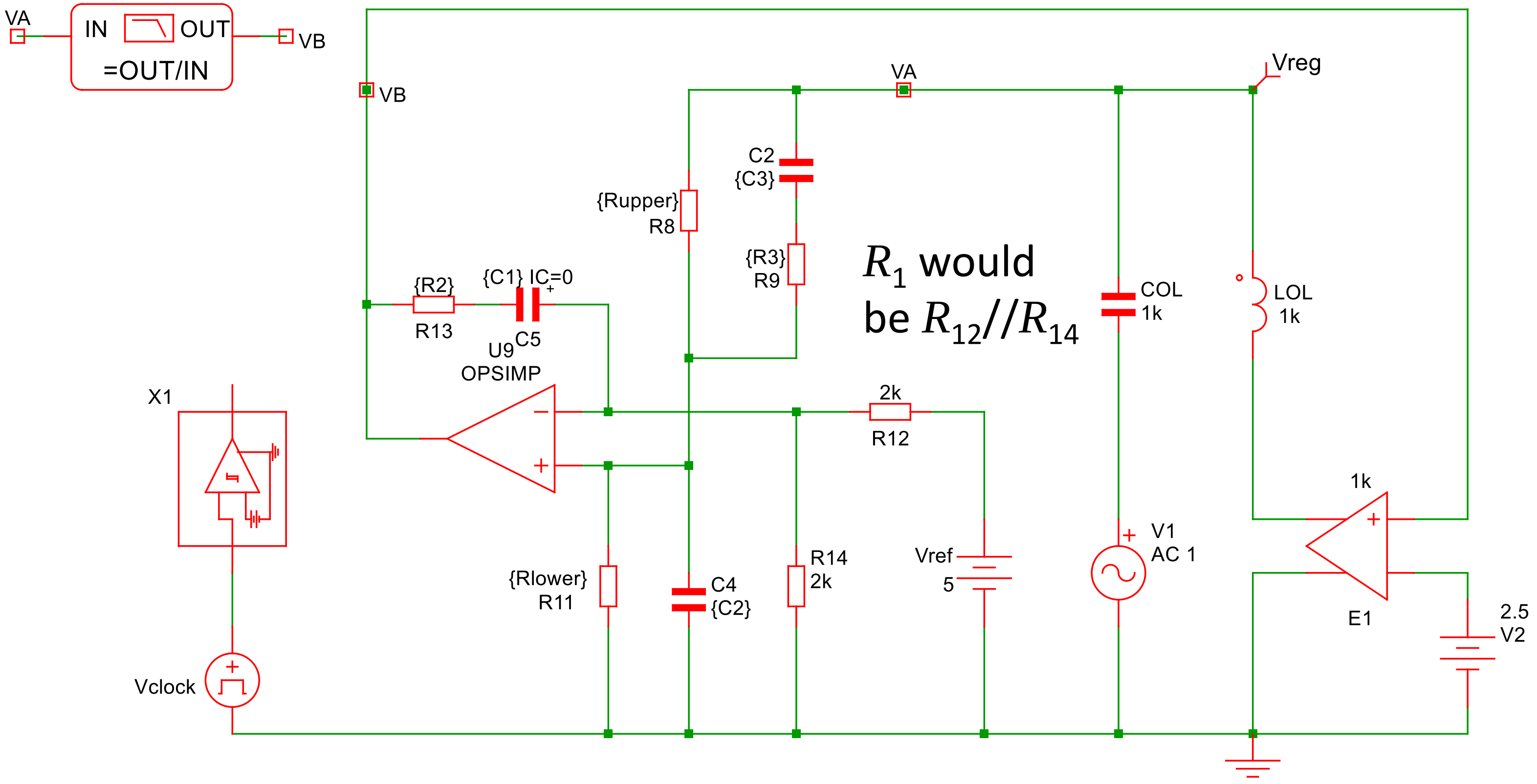
I have looked at various possibility to produce a type 3 compensator. The simplest I have found is to place the extra pole-zero across the upper-side resistor R_{upper}. Unfortunately, there is no virtual ground here and the resistive division ratio enters the picture as in type 3 made with an OTA.

Brute-force transfer function of the non-inverting type 3 compensator:

$$H_{ref}(s) := \frac{\left(\frac{1}{s \cdot C_2}\right) \parallel \left(R_{lower}\right)}{\left(R_{upper}\right) \parallel \left(R_3 + \frac{1}{s \cdot C_3}\right) + \left(\frac{1}{s \cdot C_2}\right) \parallel \left(R_{lower}\right)} \cdot \frac{1 + s \cdot C_1 \cdot \left(R_1 + R_2\right)}{s \cdot R_1 \cdot C_1}$$

OTA: operational transconductance amplifier

It always important to check the first raw expression versus simulated data to make sure the expression is sound before proceeding with more calculations:



R_1 would be $R_{12}//R_{14}$

This is an automated type-3 compensator.
Please press F11 to enter the power stage magnitude and phase as well as design goals. Check the computed values in: Simulator>Edit Netlist (after preprocess)

Christophe Basso.

```
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Vout=200
.VAR Ibias=250u
.VAR Vref=2.5
.VAR Rlower=Vref/Ibias
.VAR Rupper=(Vout-Vref)/Ibias
*
.VAR R2=22k
.VAR C1=22n
.VAR C2=330p
.VAR C3=470p
.VAR R3=22k
*
* Choose op amp characteristics *
*
.GLOBALVAR AOL=90 * open-loop gain in dB *
.GLOBALVAR POLE=30Meg * low-frequency pole *
.GLOBALVAR VHIGH=5 * upper output level *
.GLOBALVAR VLOW=100m * lower output level *
*
* Do not edit these lines *
.GLOBALVAR GAIN=10^(AOL/20)
.GLOBALVAR COL=1/(6.28*(GAIN/100u)*POLE)
.GLOBALVAR ROL=GAIN/100u
*
{ '*' }
{ '*' } Rupper = {Rupper}
{ '*' } Rlower = {Rlower}
{ '*' } R2 = {R2}
{ '*' } R3 = {R3}
{ '*' } C1 = {C1}
{ '*' } C2 = {C2}
{ '*' } C3 = {C3}
{ '*' }
```

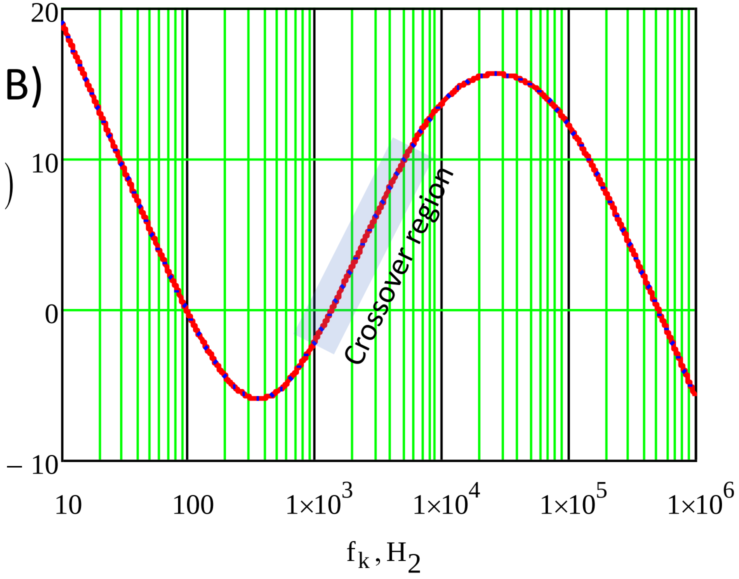
This is the magnitude graph

Brute-force expression

$20 \cdot \log\left(\left|H_{ref}\left(i \cdot 2\pi \cdot f_k\right)\right|\right)$

$H_2^{\langle 1 \rangle}$

SIMPLIS



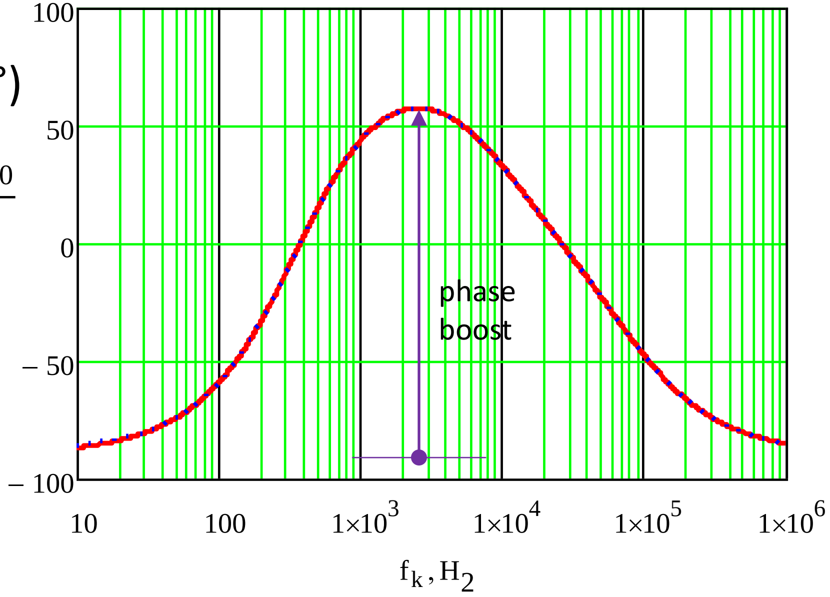
This is the phase graph

Brute-force expression

$\arg\left(H_{ref}\left(i \cdot 2\pi \cdot f_k\right)\right) \cdot \frac{180}{\pi}$

$H_2^{\langle 2 \rangle}$

SIMPLIS



Transfer function for s=0 $H_0 := \frac{R_{lower}}{R_{upper} + R_{lower}} = 0.0125$ $20 \cdot \log(H_0) = -38.0618$ dB

$\tau_3 := C_3 \cdot (R_3 + R_{upper} \parallel R_{lower}) = 14.98125 \cdot \mu s$

$\tau_{3a} := C_3 \cdot (R_3 + R_{lower}) = 15.04 \cdot \mu s$

$\tau_2 := C_2 \cdot (R_{upper} \parallel R_{lower}) = 3.25875 \cdot \mu s$

$\tau_{2a} := C_2 \cdot R_{lower} = 3.3 \cdot \mu s$

$b_1 := \tau_3 + \tau_2 = 18.24 \cdot \mu s$

$b_{1a} := C_3 \cdot (R_3 + R_{lower}) + C_2 \cdot R_{lower} = 1.834 \times 10^{-5} s$

$\tau_{23} := C_3 \cdot R_3 = 1.034 \times 10^{-5} s$

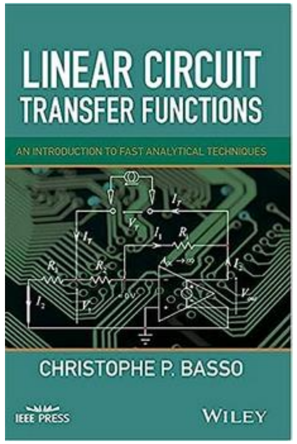
$b_2 := \tau_2 \cdot \tau_{23} = 3.36955 \times 10^{-5} \cdot ms^2$

$b_{2a} := C_2 \cdot R_{lower} \cdot C_3 \cdot R_3 = 3.4122 \times 10^{-5} \cdot ms^2$

$D_1(s) := 1 + s \cdot b_1 + s^2 \cdot b_2$

The exercise now lies in re-writing the brute-force expression in a meaningful way in which poles and zeroes are explicitly factored for design purposes: this is a design-oriented approach or D-OA.

See my book on fast analytical circuits techniques



$$Q := \frac{\sqrt{b_2}}{b_1} = 0.31824$$ Not really a low-Q

It is difficult to find an approximate factored expression whose denominator matches the second-order polynomial form. If we consider a low-Q, then the approximation holds.

$$\omega_0 := \frac{1}{\sqrt{b_2}} = 1.72272\times 10^5 \frac{1}{s}$$

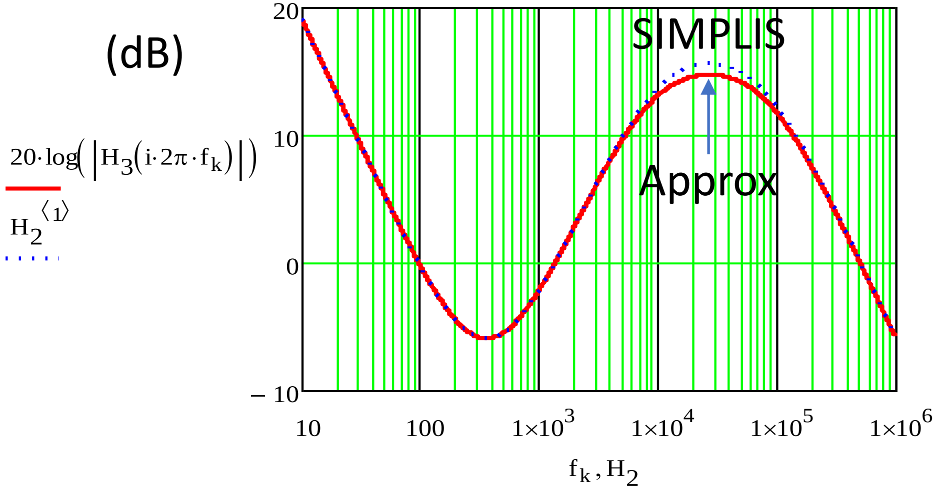
$$f_0 := \frac{\omega_0}{2\cdot\pi} = 2.74179\times 10^4 \frac{1}{s}$$

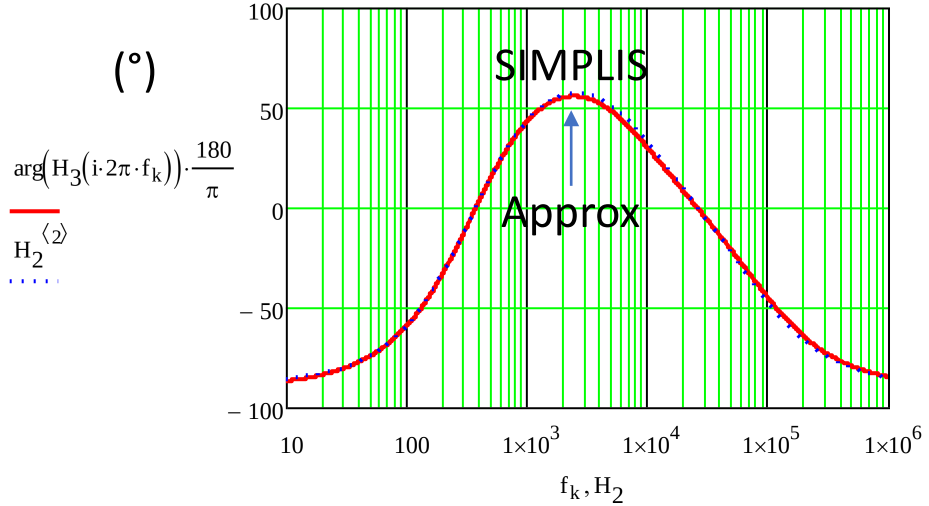
$$\omega_{p1} := \frac{1}{b_1} \qquad f_{p1} := \frac{\omega_{p1}}{2\pi} = 8.7256\times 10^3\cdot \mathrm{Hz} \qquad \omega_{p1a} := \frac{1}{C_3\cdot(R_3 + R_{lower}) + C_2\cdot R_{lower}} \qquad f_{p1a} := \frac{\omega_{p1a}}{2\pi} = 8.67802\times 10^3\cdot \mathrm{Hz}$$

$$\omega_{p2} := \frac{b_1}{b_2} \qquad f_{p2} := \frac{\omega_{p2}}{2\pi} = 86.15359\cdot \mathrm{kHz} \qquad \omega_{p2a} := \frac{\left[C_3\cdot(R_3 + R_{lower}) + C_2\cdot R_{lower}\right]}{(C_2\cdot R_{lower}\cdot C_3\cdot R_3)} \qquad f_{p2a} := \frac{\omega_{p2a}}{2\pi} = 85.5431\cdot \mathrm{kHz}$$

$$\omega_{z1} := \frac{1}{C_3\cdot(R_3 + R_{upper})} \qquad f_z := \frac{\omega_{z1}}{2\cdot\pi} = 417.02899\cdot \mathrm{Hz}$$

$$\omega_{z2} := \frac{1}{C_1\cdot(R_1 + R_2)} \qquad f_z := \frac{\omega_{z2}}{2\cdot\pi} = 314.53546\cdot \mathrm{Hz}$$





This is the approximation I came up to, with separate zeroes and poles:

1 zero — 1 inverted zero

$$H_3(s) := \frac{R_{lower}}{R_{upper} + R_{lower}}\cdot\frac{R_1 + R_2}{R_1}\cdot\frac{\left[1 + s\cdot\left[C_3\cdot(R_3 + R_{upper})\right]\right]\cdot\left[1 + \frac{1}{s\cdot C_1\cdot(R_1 + R_2)}\right]}{\left[1 + s\cdot\left[C_3\cdot(R_3 + R_{lower}) + C_2\cdot R_{lower}\right]\right]\cdot\left[1 + s\cdot\frac{(C_2\cdot R_{lower}\cdot C_3\cdot R_3)}{\left[C_3\cdot(R_3 + R_{lower}) + C_2\cdot R_{lower}\right]}\right]}$$

Gain at dc — 2 poles

From the previous expressions, below are the poles and zeroes of this compensator:

$$\omega_{z2} = \frac{1}{C_3\cdot(R_3 + R_{upper})}$$

$$\omega_{z1} = \frac{1}{C_1\cdot(R_1 + R_2)}$$

$$\omega_{p1} = \frac{1}{C_3\cdot(R_3 + R_{lower}) + C_2\cdot R_{lower}}$$

$$\omega_{p2} = \frac{[C_3\cdot(R_3 + R_{lower}) + C_2\cdot R_{lower}]}{(C_2\cdot R_{lower}\cdot C_3\cdot R_3)}$$

First, what matters is the gain at the selected crossover frequency which depends, for a type 3, on the poles and zeroes positions:

$$G_{fc} = \frac{R_{lower}}{R_{upper} + R_{lower}}\cdot\frac{R_1 + R_2}{R_1}\cdot\frac{\sqrt{1 + \left(\frac{f_{z1}}{f_c}\right)^2}\cdot\sqrt{1 + \left(\frac{f_c}{f_{z2}}\right)^2}}{\sqrt{1 + \left(\frac{f_c}{f_{p1}}\right)^2}\cdot\sqrt{1 + \left(\frac{f_c}{f_{p2}}\right)^2}}$$

R_{lower} and R_{upper} are selected based on the dc regulated level:

$I_b := 250\mu A$ $\quad V_{ref} := 1V$ $\quad V_{out} := 12V$

$$R_{upper} := \frac{V_{out} - V_{ref}}{I_b} = 4.4\times 10^4\,\Omega$$

$$R_{lower} := \frac{V_{ref}}{I_b} = 4\times 10^3\,\Omega$$

As with a type 3 designed with an operation transconductance amplifier (OTA), the resistive divider enters the picture and affects the maximum phase boost you can obtain. That is to say, you will have difficulty to spread ω_{z1} and f_{p1} while keeping positive components values. Besides, too low a f_{p2} also affects the roots polarity. F_{p2} will thus be placed at $F_{sw}/2$ or higher.

First, from the control-to-output transfer function, I position the poles and zeroes so that the phase boost at the selected crossover frequency f_c brings adequate phase and gain margins. Assume I have the following values:

$G_{fc} := 20$ dB

Wanted gain at crossover

$f_c := 1kHz$ $\quad f_{z1} := 500Hz$ $\quad f_{z2} := 300Hz$ $\quad f_{p1} := 3kHz$ $\quad f_{p2} := 60kHz$

$\omega_{z1} := 2\cdot\pi\cdot f_{z1}$ $\quad \omega_{z2} := 2\cdot\pi\cdot f_{z2}$ $\quad \omega_{p1} := 2\cdot\pi\cdot f_{p1}$ $\quad \omega_{p2} := 2\cdot\pi\cdot f_{p2}$

I first extract the value for R_2 while setting R_1 to an arbitrary value of 1 kΩ:

$$G_1 := 10^{\frac{G_{fc}}{20}} = 10$$

$$R_2 := R_1 \cdot \left[\frac{\sqrt{\frac{f_c^2}{f_{p1}^2} + 1} \cdot \sqrt{\frac{f_c^2}{f_{p2}^2} + 1}}{\sqrt{\frac{f_{z1}^2}{f_c^2} + 1} \cdot \sqrt{\frac{f_c^2}{f_{z2}^2} + 1}} \cdot \left(1 + \frac{R_{upper}}{R_{lower}} \right) \cdot G_1 - 1 \right] = 31.514 \cdot k\Omega$$

Capacitor C_1 then comes:

$$C_1 := \frac{1}{\omega_{z1} \cdot (R_1 + R_2)} = 9.79 \cdot nF$$

This is where it gets tricky as there are two real roots for obtaining values for R_3 and C_2:

$$R_{3a} := \frac{\sqrt{R_{lower}^2 \cdot \omega_{p1}^2 \cdot \omega_{p2}^2 - 2 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2}^2 \cdot \omega_{z1} + 4 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}^2 - 4 \cdot R_{upper}^2 \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}^2 + R_{upper}^2 \cdot \omega_{p2}^2 \cdot \omega_{z1}^2} - 2 \cdot R_{upper} \cdot \omega_{z1}^2 - R_{lower} \cdot \omega_{p1} \cdot \omega_{p2} + R_{upper} \cdot \omega_{p2} \cdot \omega_{z1}}{2 \cdot \left(\omega_{z1}^2 - \omega_{p2} \cdot \omega_{z1} + \omega_{p1} \cdot \omega_{p2} \right)} = 2.615 \times 10^3 \, \Omega$$

$$R_{3b} := -\frac{2 \cdot R_{upper} \cdot \omega_{z1}^2 + \sqrt{R_{lower}^2 \cdot \omega_{p1}^2 \cdot \omega_{p2}^2 - 2 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2}^2 \cdot \omega_{z1} + 4 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}^2 - 4 \cdot R_{upper}^2 \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}^2 + R_{upper}^2 \cdot \omega_{p2}^2 \cdot \omega_{z1}^2} + R_{lower} \cdot \omega_{p1} \cdot \omega_{p2} - R_{upper} \cdot \omega_{p2} \cdot \omega_{z1}}{2 \cdot \left(\omega_{z1}^2 - \omega_{p2} \cdot \omega_{z1} + \omega_{p1} \cdot \omega_{p2} \right)} = 1.232 \times 10^3 \, \Omega$$

$$C_{2a} := \frac{\sqrt{R_{lower}^2 \cdot \omega_{p1}^2 \cdot \omega_{p2}^2 - 2 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2}^2 \cdot \omega_{z1} + 4 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}^2 - 4 \cdot R_{upper}^2 \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}^2 + R_{upper}^2 \cdot \omega_{p2}^2 \cdot \omega_{z1}^2} - R_{lower} \cdot \omega_{p1} \cdot \omega_{p2} + R_{upper} \cdot \omega_{p2} \cdot \omega_{z1}}{2 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}} = 4.058 \cdot nF$$

$$C_{2b} := -\frac{\sqrt{R_{lower}^2 \cdot \omega_{p1}^2 \cdot \omega_{p2}^2 - 2 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2}^2 \cdot \omega_{z1} + 4 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}^2 - 4 \cdot R_{upper}^2 \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}^2 + R_{upper}^2 \cdot \omega_{p2}^2 \cdot \omega_{z1}^2} + R_{lower} \cdot \omega_{p1} \cdot \omega_{p2} - R_{upper} \cdot \omega_{p2} \cdot \omega_{z1}}{2 \cdot R_{lower} \cdot R_{upper} \cdot \omega_{p1} \cdot \omega_{p2} \cdot \omega_{z1}} = 1.97 \cdot nF$$

I am now combining R_{3a} and C_{2a} then R_{3b} et C_{2b}. In two different expressions and see the one approaching the reference one.

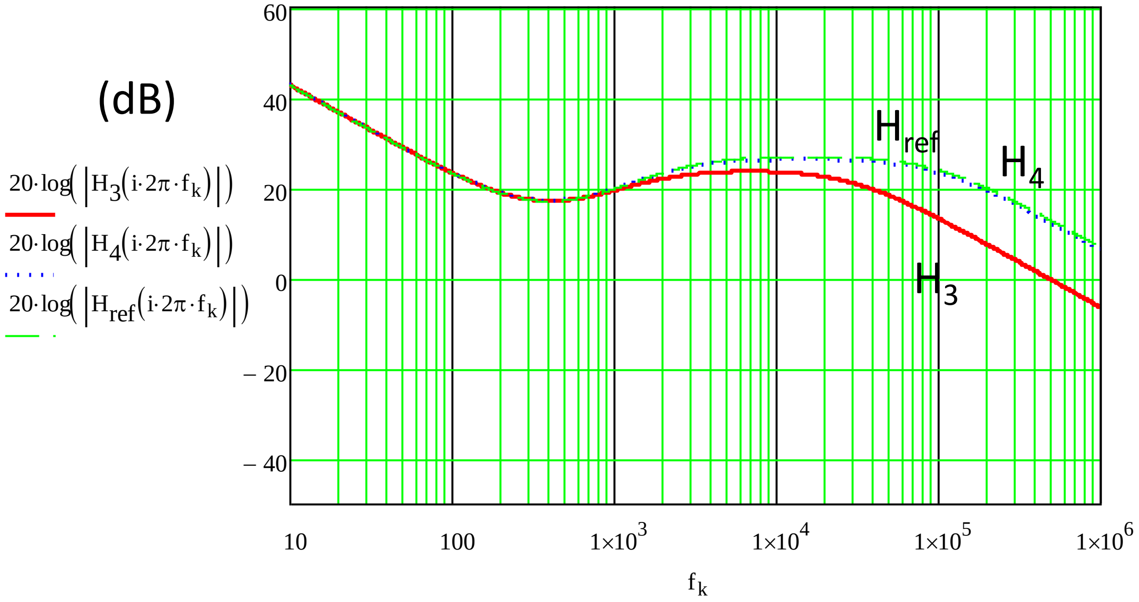
$$C_{3a} := \frac{1}{\omega_{z2} \cdot (R_{3a} + R_{upper})} = 11.381 \cdot nF$$

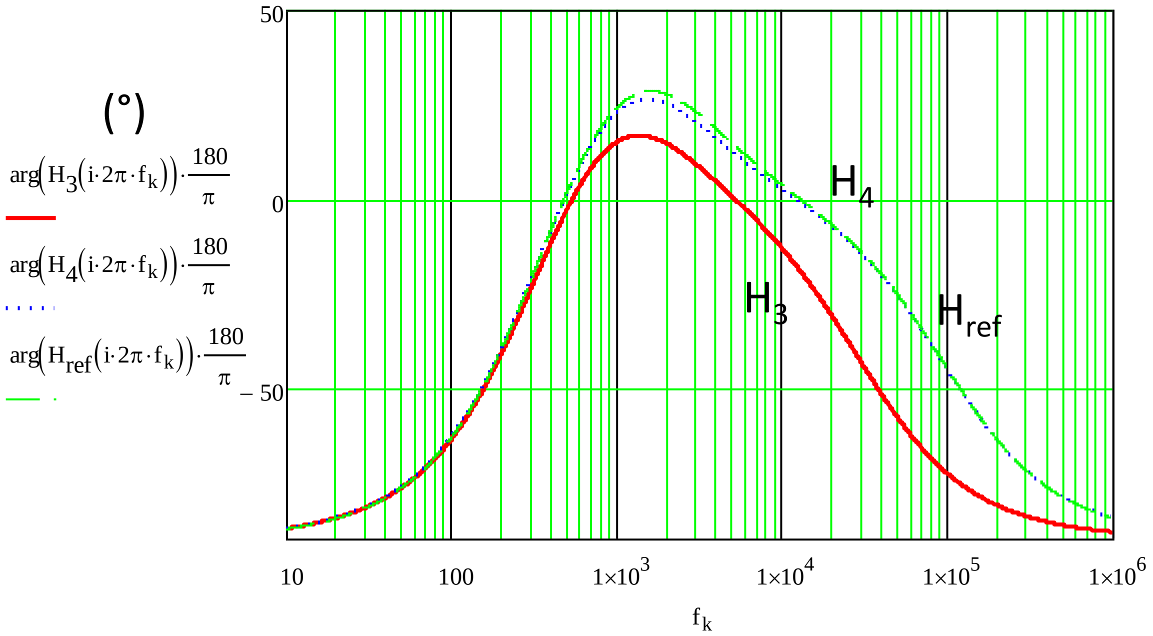
$$C_{3b} := \frac{1}{\omega_{z2} \cdot (R_{3b} + R_{upper})} = 11.729 \cdot nF$$

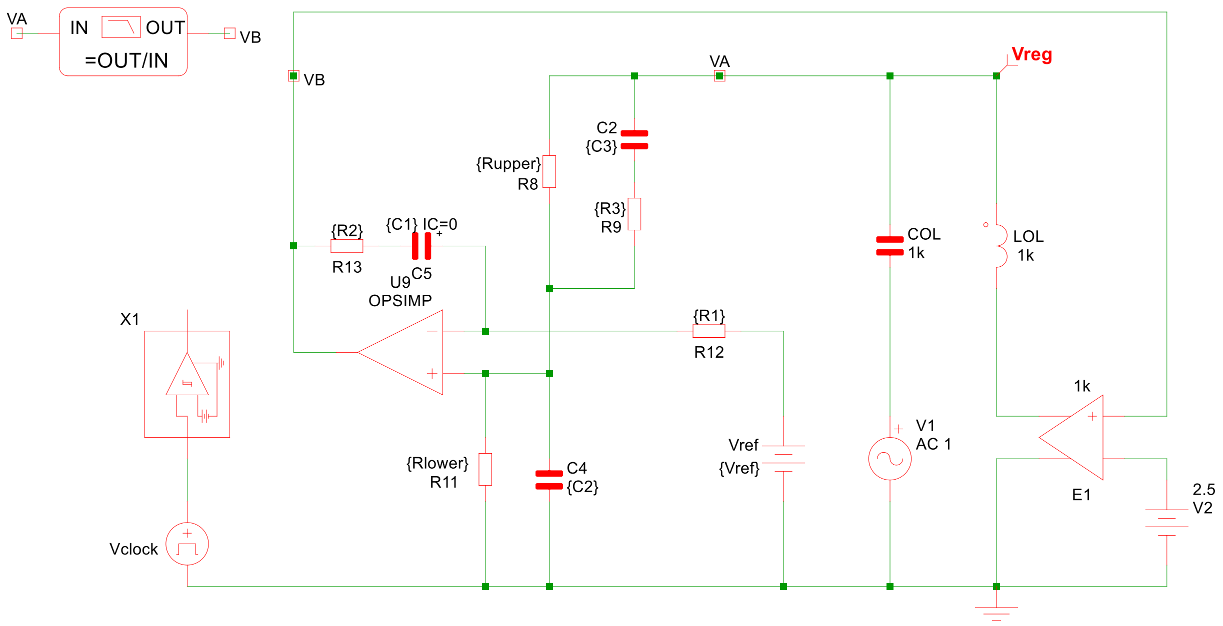
$$H_3(s) := \frac{R_{lower}}{R_{upper} + R_{lower}} \cdot \frac{R_1 + R_2}{R_1} \cdot \frac{\left[1 + s\left[C_{3a} \cdot (R_{3a} + R_{upper})\right]\right] \cdot \left[1 + \frac{1}{s \cdot C_1 \cdot (R_1 + R_2)}\right]}{\left[1 + s\left[C_{3a} \cdot (R_{3a} + R_{lower}) + C_{2a} \cdot R_{lower}\right]\right] \cdot \left[1 + s \cdot \frac{(C_{2a} \cdot R_{lower} \cdot C_{3a} \cdot R_{3a})}{\left[C_{3a} \cdot (R_{3a} + R_{lower}) + C_{2a} \cdot R_{lower}\right]}\right]}$$

$$H_4(s) := \frac{R_{lower}}{R_{upper} + R_{lower}} \cdot \frac{R_1 + R_2}{R_1} \cdot \frac{\left[1 + s\left[C_{3b} \cdot (R_{3b} + R_{upper})\right]\right] \cdot \left[1 + \frac{1}{s \cdot C_1 \cdot (R_1 + R_2)}\right]}{\left[1 + s\left[C_{3b} \cdot (R_{3b} + R_{lower}) + C_{2b} \cdot R_{lower}\right]\right] \cdot \left[1 + s \cdot \frac{(C_{2b} \cdot R_{lower} \cdot C_{3b} \cdot R_{3b})}{\left[C_{3b} \cdot (R_{3b} + R_{lower}) + C_{2b} \cdot R_{lower}\right]}\right]}$$

In this particular example, the best response is that obtained from H_4 which uses R_{3b} and C_{2b}.

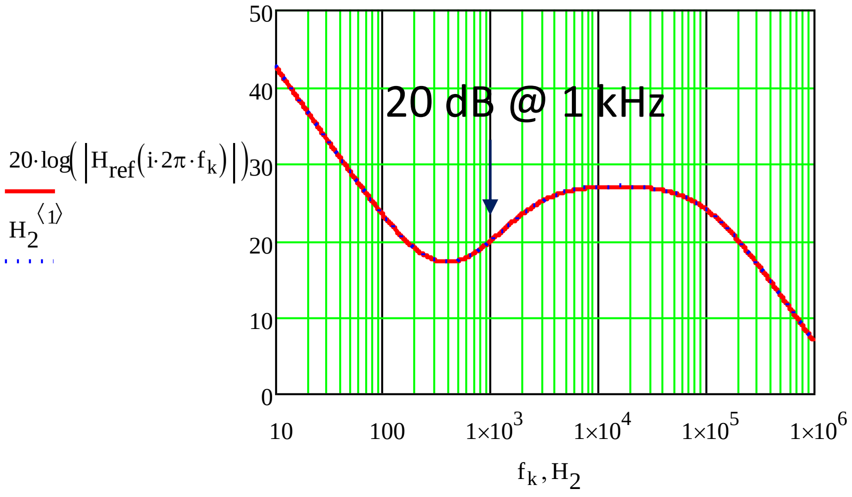


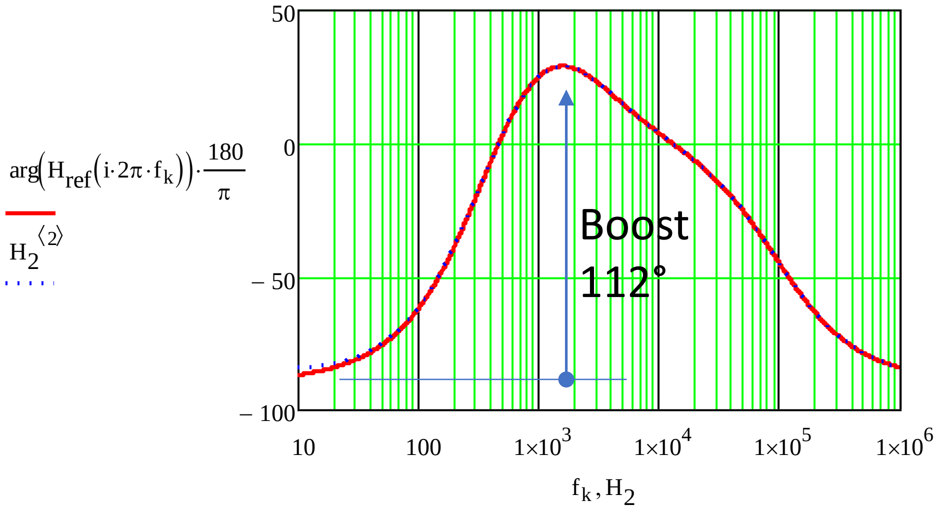


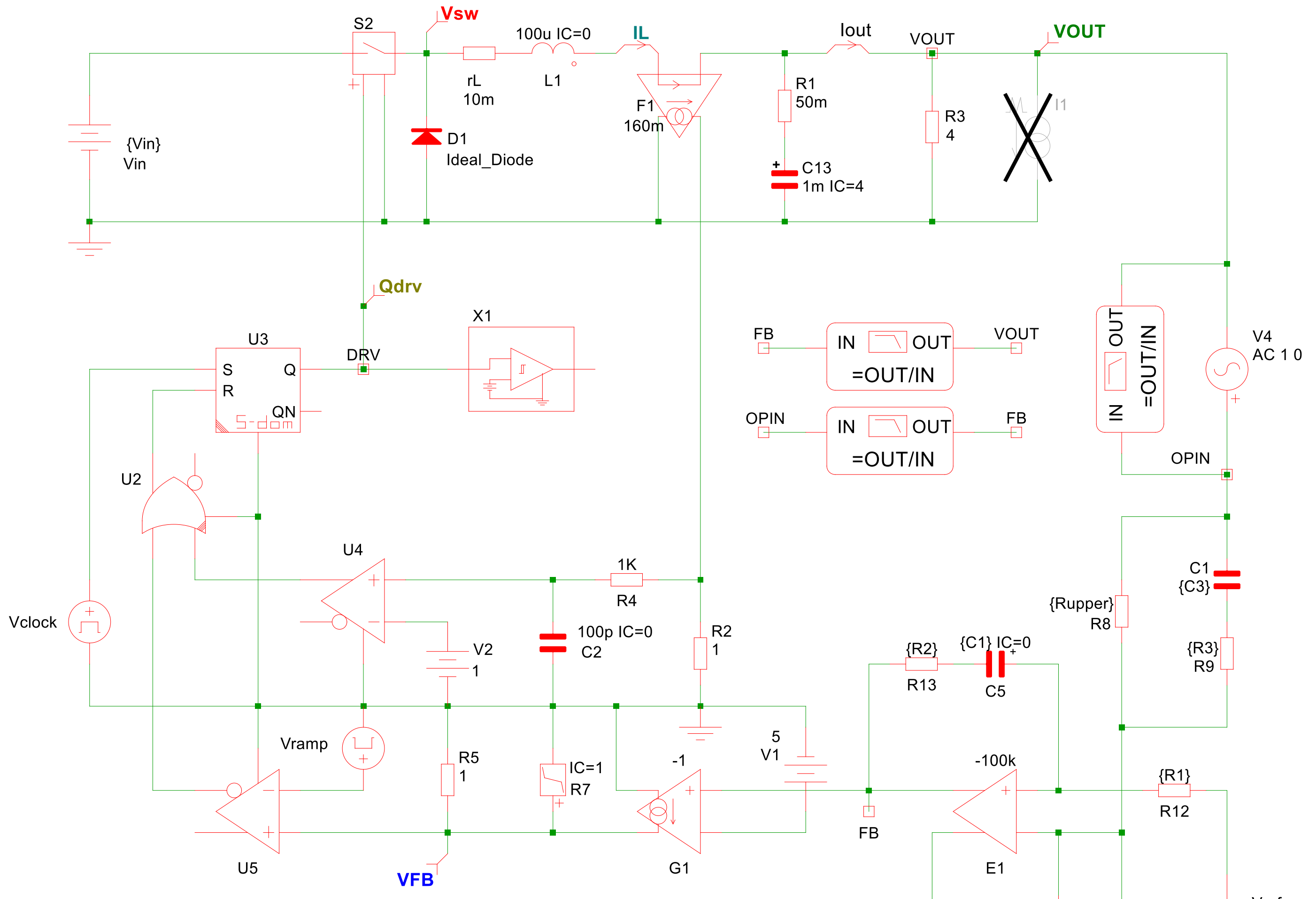



```
*
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Vout=12
.VAR Ibias=250u
.VAR Vref=1
.VAR Rlower=Vref/Ibias
.VAR Rupper=(Vout-Vref)/Ibias
*
.VAR R1=1k
.VAR R2=31.5k
.VAR C1=9.8n
.VAR C2=2n
.VAR C3=11.8n
.VAR R3=1.2k
*
```

The SIMPLIS templates confirms the response matches the Mathcad expression and provides the wanted 20-dB gain at 1 kHz with a 112° phase boost at that frequency.





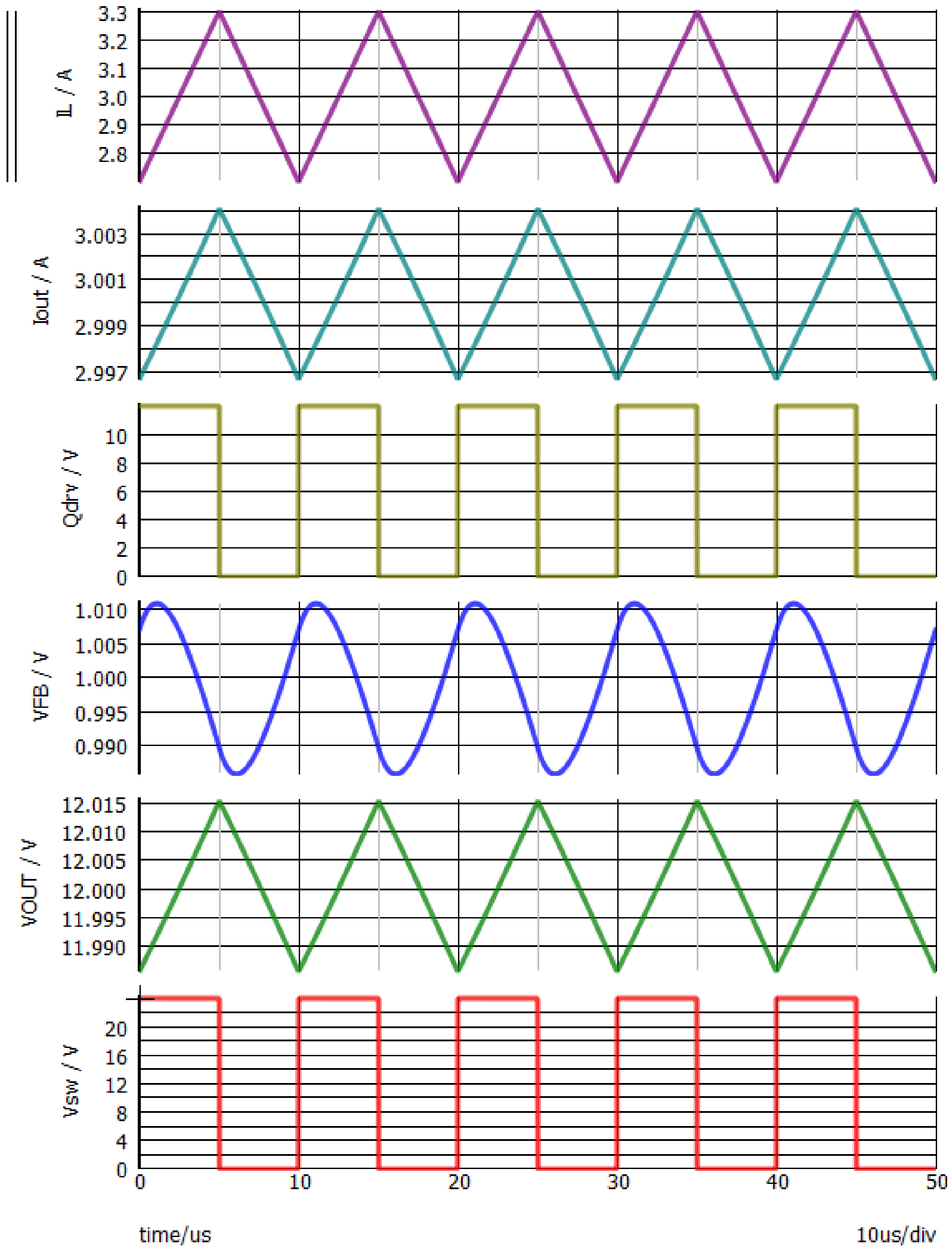


*
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Vin=24
.VAR Vout=12
.VAR Ibias=250u
.VAR Vref=1
.VAR Rlower=Vref/Ibias
.VAR Rupper=(Vout-Vref)/Ibias
*
.VAR R1=1k
.VAR R2=1.1k
.VAR C1=153n
.VAR C2=2n
.VAR C3=11.8n
.VAR R3=1.2k
*
{ '*' }
{ '*' } Rupper = {Rupper}
{ '*' } Rlower = {Rlower}
{ '*' } R2 = {R2}
{ '*' } R3 = {R3}
{ '*' } C1 = {C1}
{ '*' } C2 = {C2}
{ '*' } C3 = {C3}
{ '*' }

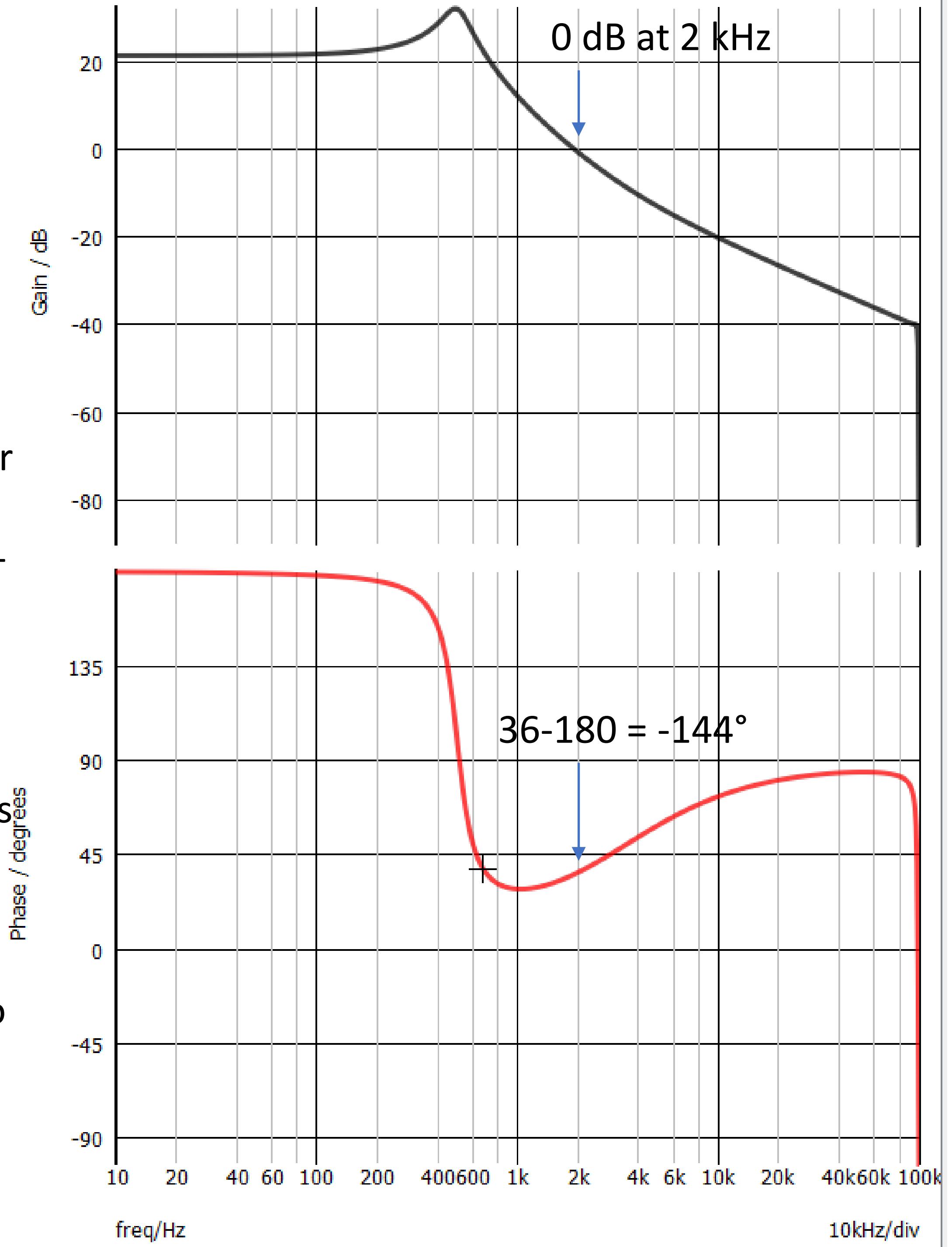
This is a fixed-frequency voltage-mode-controlled buck converter delivering 12 V 3 A from a 24-V source. Enable the 6-ohm load for ac analysis and disable the PWL source (right-click after selection) to see the transient response. Check Simulator>Edit Netlist (after preprocess) to see the calculated component values. This converter uses a non-inverting compensator as with the TL494.

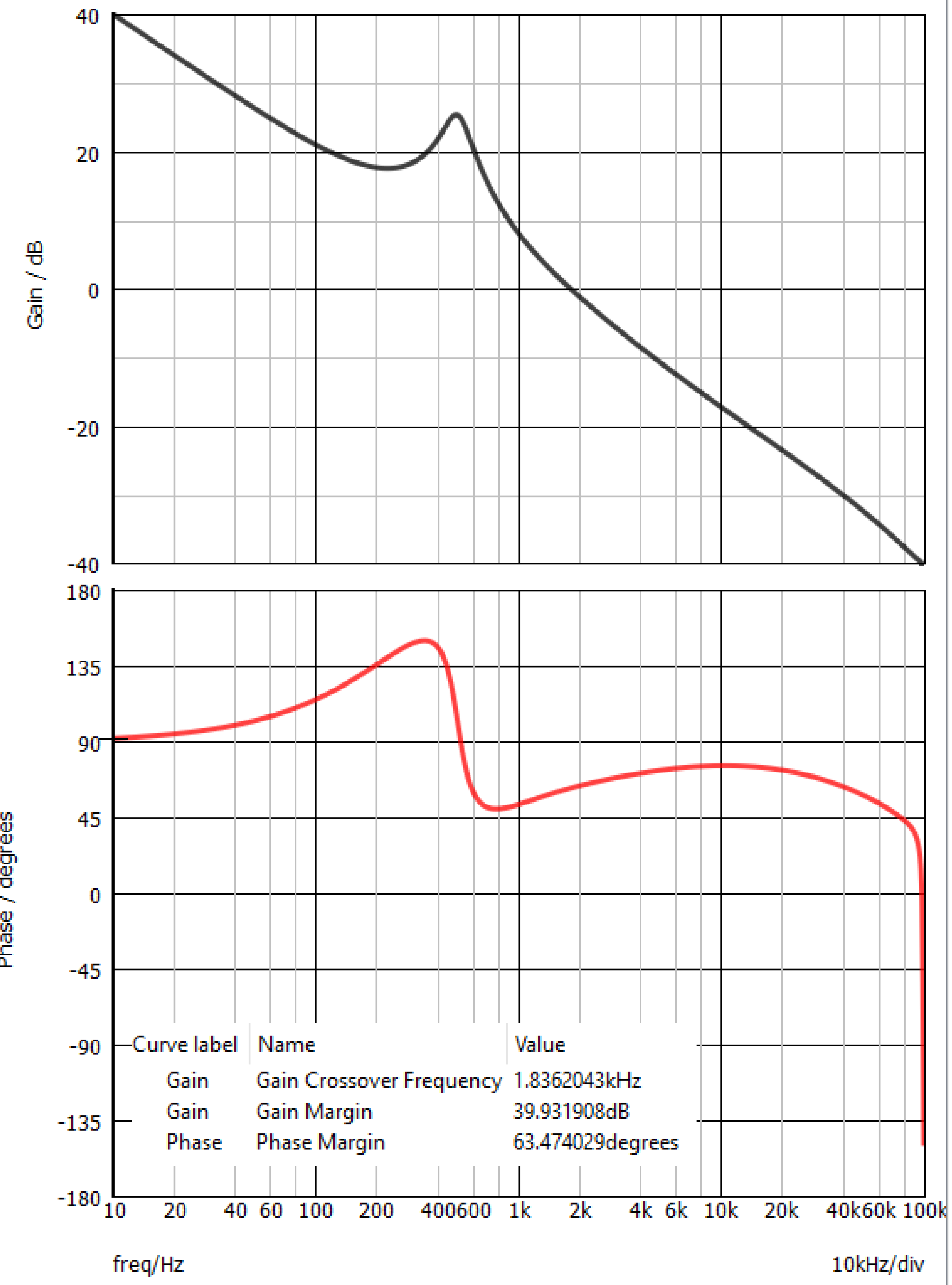
- Christophe Basso - Transfer Functions of Switching Converters -

This is a typical voltage-mode buck converter to which the non-inverting compensator has been added. An inverting block is included to reflect the TL494 reversed control law.

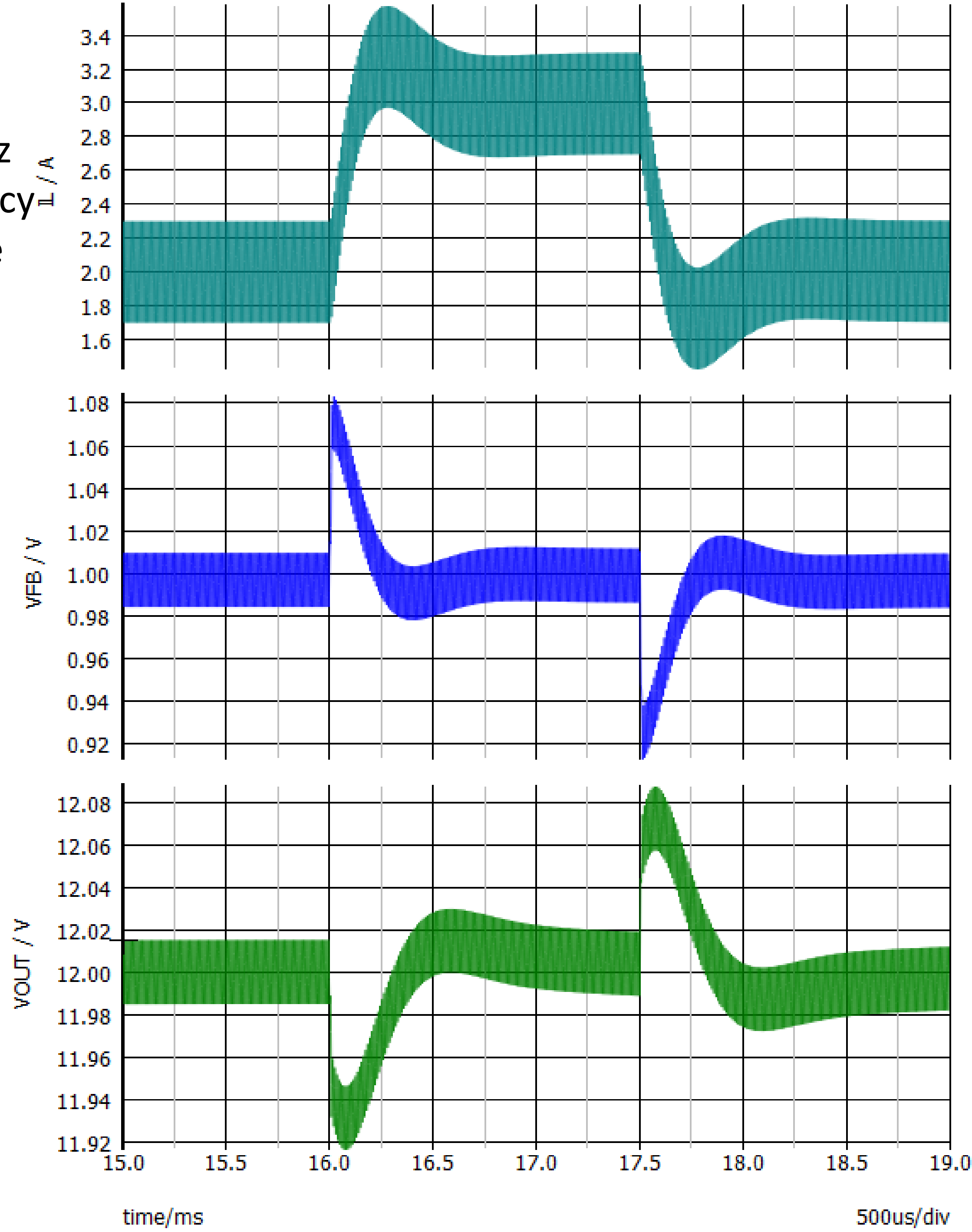


The transient simulation confirms the correct operating point (12 V from the 24-V input) and the control-to-output transfer function is obtained. For a 2-kHz crossover frequency, the gain is 0 dB and the phase lag is 144°. Place zeroes around the resonant frequency and adjust the pole to obtain a good phase margin.





The loop gain confirms the 2-kHz crossover frequency with a good phase margin. Stability with a step load is good



Stabilizing a switching converter operated with a TL494 requires a non-inverting compensator. Determining the components values to obtain the exact transfer function that is wanted from this non-inverting structure remains a difficult exercise and only an approximate form is proposed here. The configuration does not offer the flexibility you can obtain with a classical op-amp-based type 3 and that is the reason I recommend to stay away from this circuit. If you must use this circuitry, be well aware of its limitations when placing the poles and zeroes as negative component values can arise, indicating this is a dead-end and you need to go through another iteration.