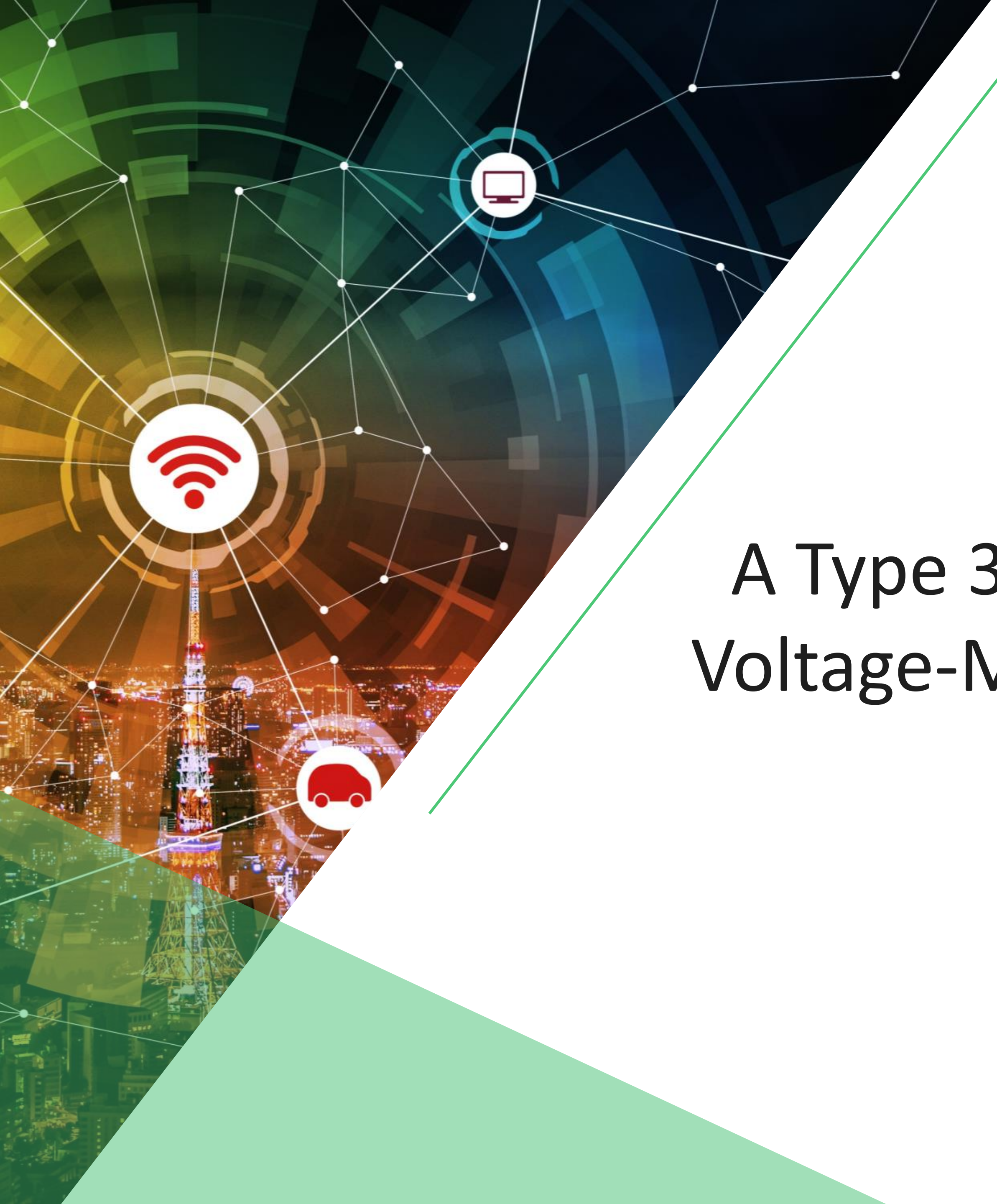


A Type 3 OTA in the Compensation of a Voltage-Mode-Controlled Buck Converter

Christophe Basso

Business Development Manager

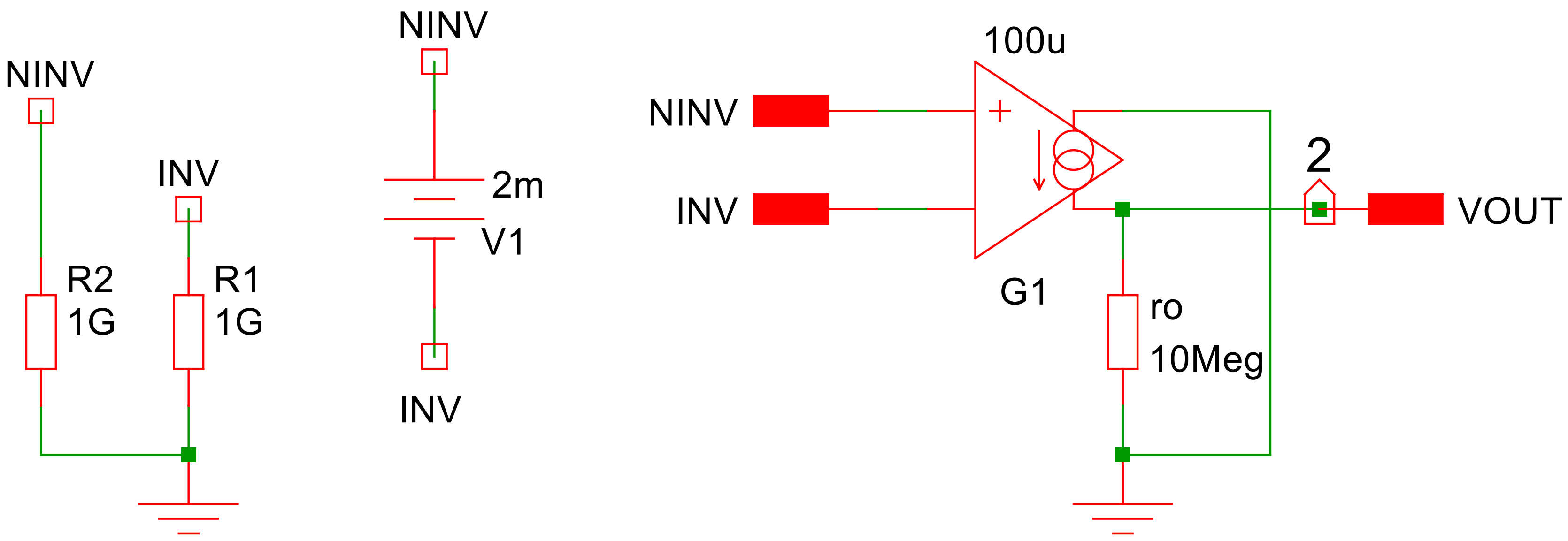
IEEE Senior Member

February 2023 – Rev 0.11

The Operational Transconductance Amplifier

- An OTA converts an error voltage (V) into an output current (A)
- The transconductance g_m in Siemens (S) links the differential voltage with the output current
- The open-loop gain depends on g_m and the output resistance of the OTA r_o

✓ An OTA can be assimilated as a voltage-controlled current-source, G suffix in SPICE



SI — not SI

g_m = 100 µS or 100 µmhos

Open-loop gain

$$A_{OL} = g_m r_o$$
$$= 100u \times 10Meg = 1000 \text{ or } 60 \text{ dB}$$

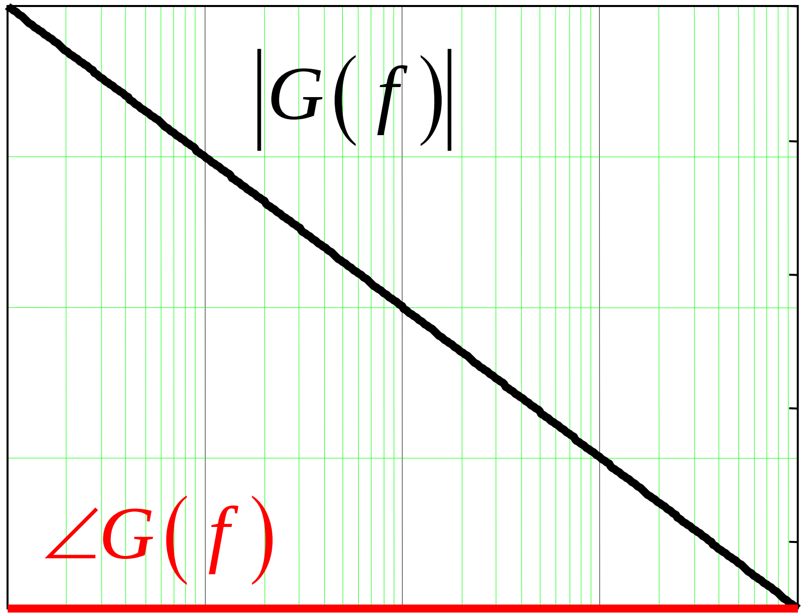
Three Possible Compensators

- Three possible compensators are available depending on the wanted phase boost

✓ Each of them includes a pole at the origin for high dc gain

Type 1

$$G(s) = -\frac{1}{\dfrac{s}{\omega_{po}}}$$



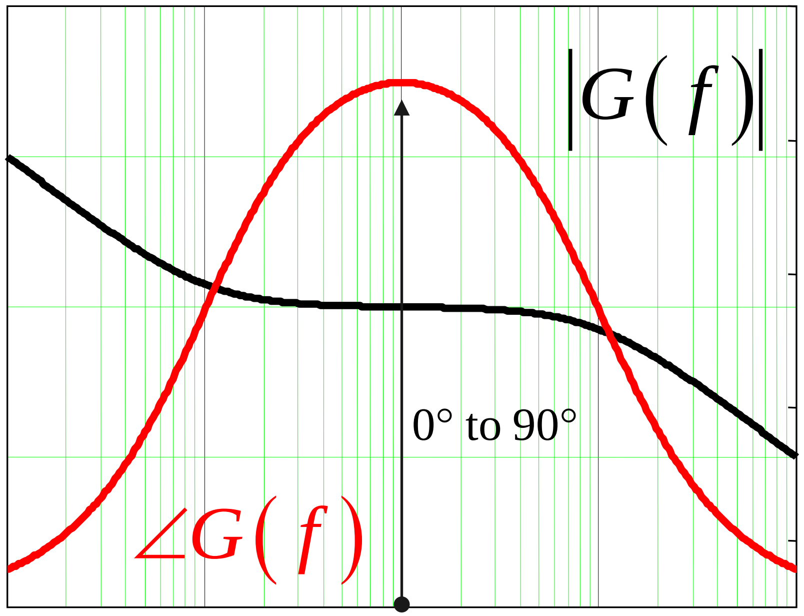
0° phase boost

Type 2

$$G(s) = -G_0 \frac{1+\dfrac{\omega_z}{s}}{1+\dfrac{s}{\omega_p}}$$

Inverted zero ($\frac{\omega_z}{s}$)

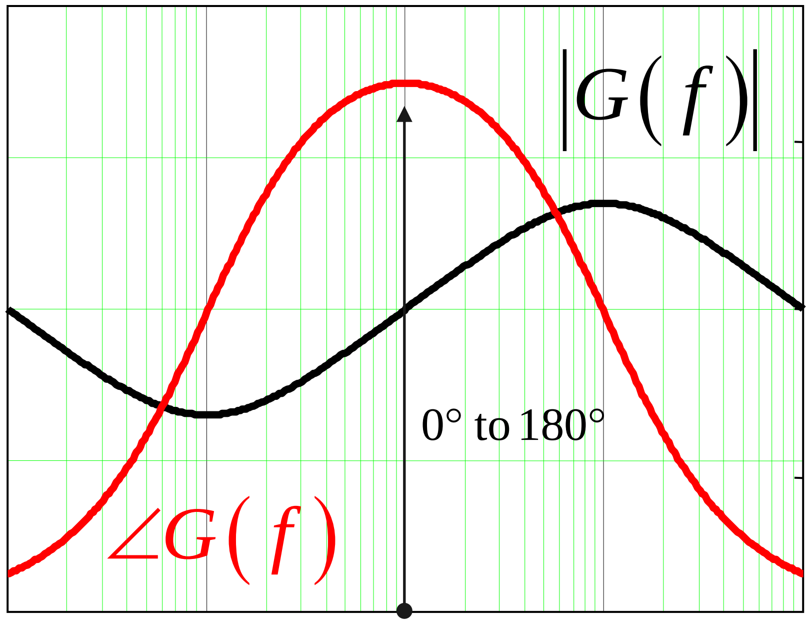
Mid-band gain (G_0)



Up to 90° phase boost

Type 3

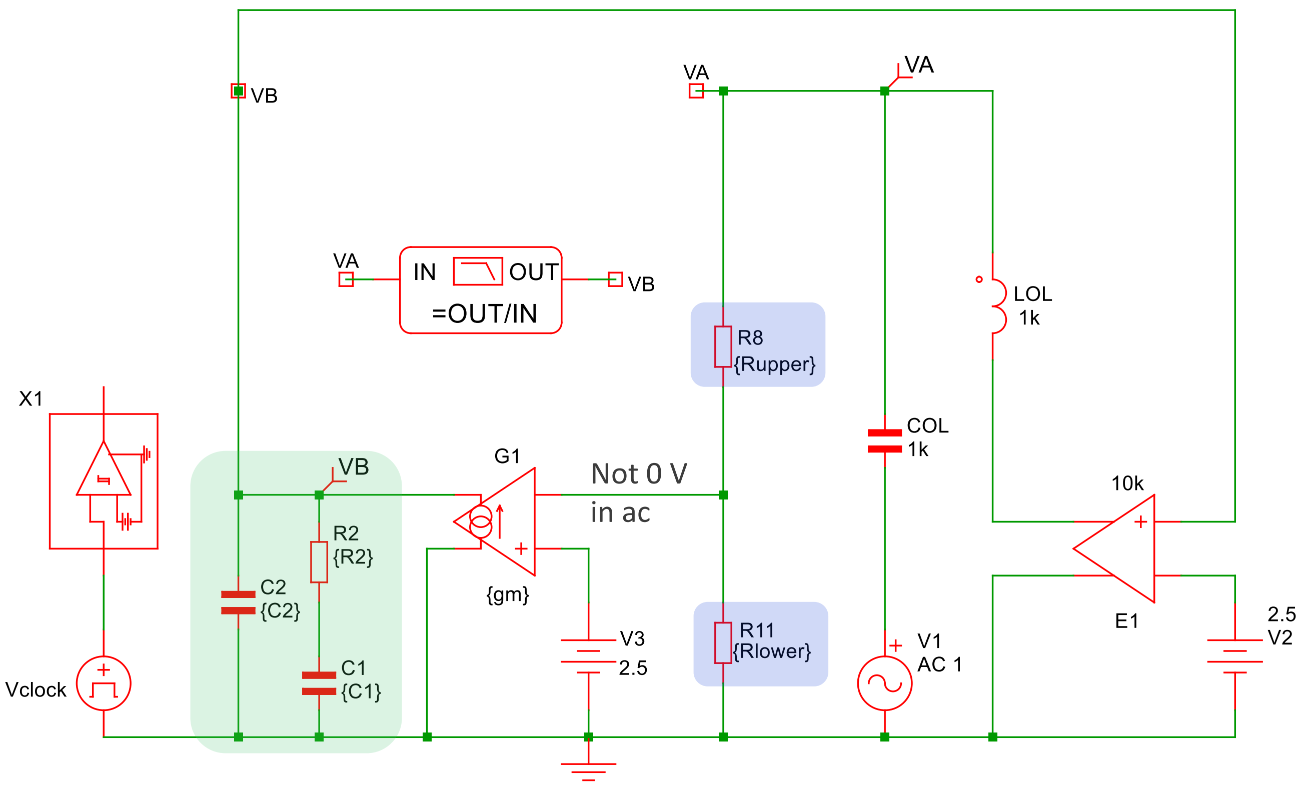
$$G(s) = -G_0 \frac{\left(1+\dfrac{\omega_{z_1}}{s}\right)\left(1+\dfrac{s}{\omega_{z_2}}\right)}{\left(1+\dfrac{s}{\omega_{p_1}}\right)\left(1+\dfrac{s}{\omega_{p_2}}\right)}$$



Up to 180° phase boost

Building a Compensator

- The compensation network for a type 2 compensator is loading the OTA
- Design formulas are different than with an op-amp: there is no virtual ground



$$G(s) = -\frac{R_2 C_1}{C_1 + C_2}\,\frac{g_m R_{lower}}{R_{lower} + R_{upper}}\,\frac{\sqrt{1+\left(f_z/f\right)^2}}{\sqrt{1+\left(f/f_p\right)^2}}$$

$$\omega_z = \frac{1}{R_2 C_1} \qquad \omega_p = \frac{1}{R_2\left(\frac{C_1 C_2}{C_1 + C_2}\right)}$$

$$R_2 = \frac{G_{f_c} f_p}{f_p - f_z}\,\frac{R_{lower} + R_1}{g_m R_1}\,\frac{\sqrt{1+\left(\frac{f}{f_p}\right)^2}}{\sqrt{1+\left(\frac{f_z}{f}\right)^2}}$$

C. Basso, Designing Compensators for the Control of Switching Power Supplies, APEC 2010 Professional Seminar

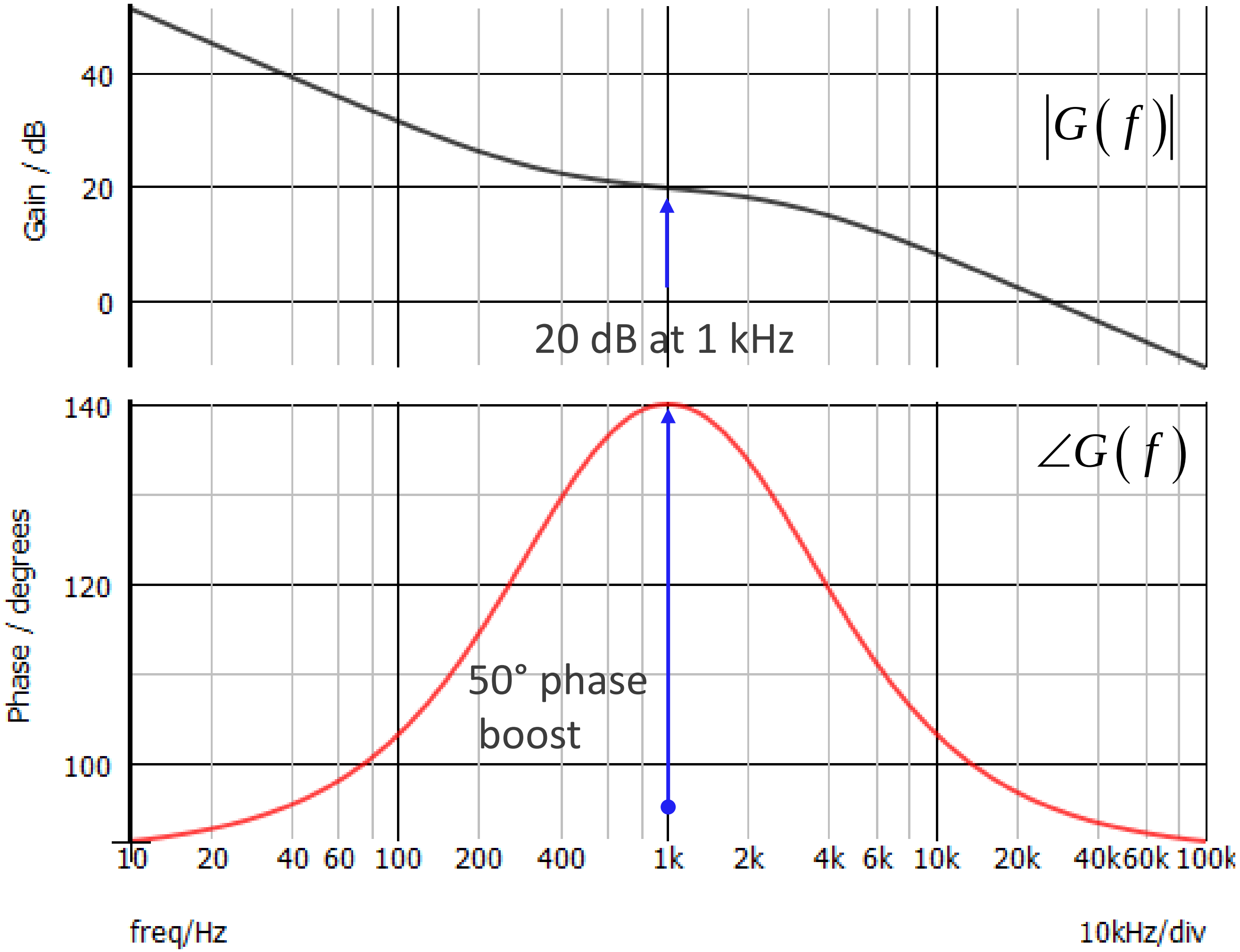
Simulating a Type 2 Compensator

- It is easy to automate the calculation based on the wanted characteristics

Extract from the plant

```
.VAR Gfc=-20 * magnitude at crossover *
.VAR PS=-70 * phase lag at crossover *
*
.VAR fc=1k * targetted crossover *
.VAR PM=70 * choose phase margin at crossover *
*
.VAR Vout=12
.VAR Ibias=250u
.VAR Vref1=2.5
.VAR Rlower={Vref1/Ibias}
.VAR Rupper={(Vout-Vref1)/Ibias}
*
.VAR gm=10u * transconductance in Siemens *
*
.VAR boost=PM-PS-90
.VAR G=10^(-Gfc/20)
.VAR k=tan((boost/2+45)*pi/180)
.VAR fp=fc*k
.VAR fz=fc/k
.VAR a=sqrt((fc^2/fp^2)+1)
.VAR b=sqrt((fz^2/fc^2)+1)
*
.VAR R2=(a/b)*(fp*G)*(Rlower+Rupper)/((fp-fz)*Rlower*gm)
.VAR C1=1/(2*pi*R2*fz)
.VAR C2=(Rlower*gm/(2*pi*fp*G*(Rlower+Rupper)))(b/a)
```

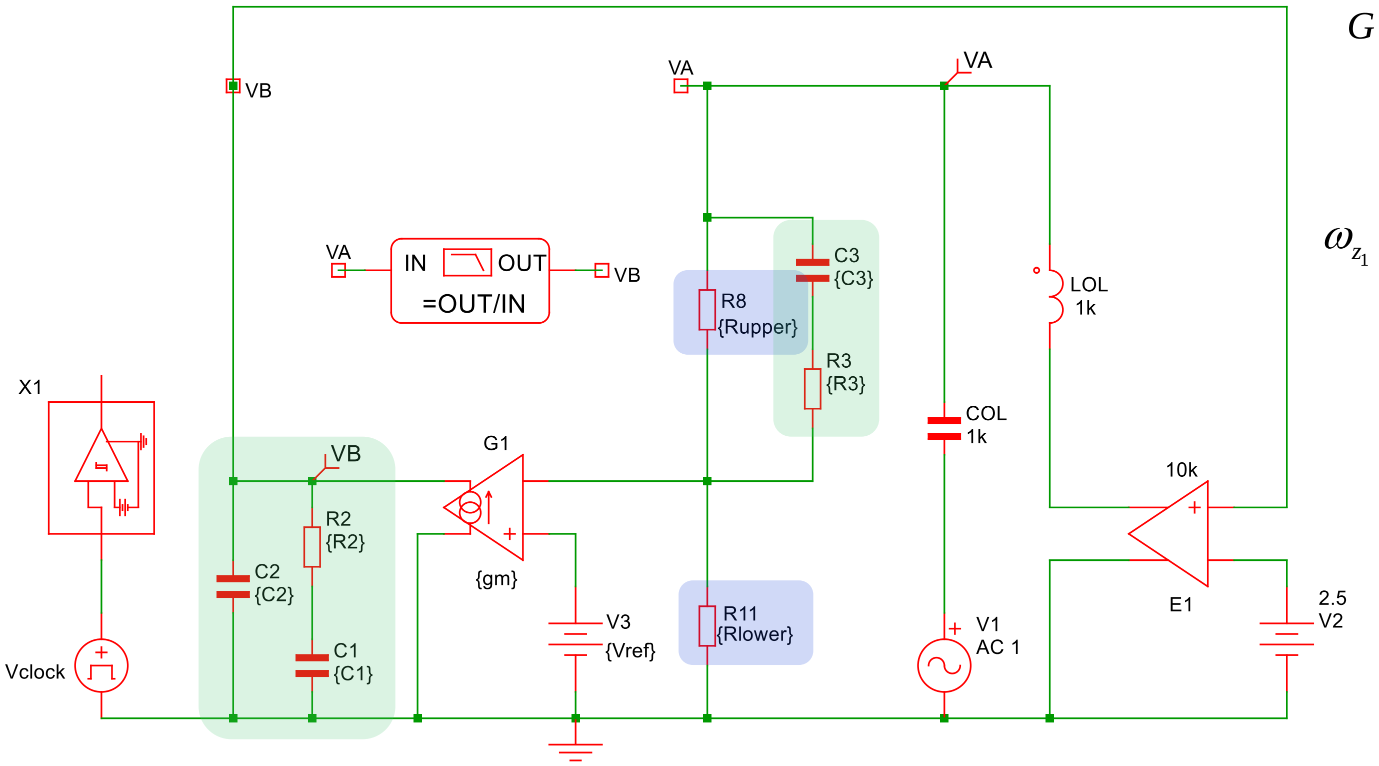
Design targets



A. Laprade, Enhanced OTA Models Improve Design of Feedback Compensation Networks, How2Power, July 2014

A Type 3 Compensator with an OTA

- The type 3 compensator is built by adding an RC network across the upper resistor
- The low-side resistance now plays a role in the absence of a virtual ground



$$G(s) = -\frac{R_{lower}\, g_m}{R_{lower}+R_{upper}} \frac{R_2 C_1}{C_1+C_2} \frac{sC_3\left(R_3+R_1\right)+1}{sC_3\left(\frac{R_{lower}R_1}{R_{lower}+R_1}+R_3\right)+1} \frac{\frac{1}{sR_2C_1}+1}{\left(1+sR_2\frac{C_1C_2}{C_1+C_2}\right)}$$

$$\omega_{z_1} = \frac{1}{R_2C_1} \quad \omega_{z_2} = \frac{1}{C_3\left(R_3+R_1\right)} \quad \omega_{p_1} = \frac{1}{R_2C_2} \quad \omega_{p_2} = \frac{1}{C_3\left(\frac{R_{lower}R_1}{R_{lower}+R_1}+R_3\right)}$$

Can be negative!

$$R_3 = \frac{f_{z_2}V_{out} - f_{p_2}V_{ref}}{V_{ref}V_{out}\left(f_{p_2}-f_{z_2}\right)} R_{lower}\left(V_{out}-V_{ref}\right)$$

$$f_{z_2}V_{out} - f_{p_2}V_{ref} = 0 \quad \Rightarrow \quad f_{z_2} > \frac{V_{ref}}{V_{out}} f_{p_2}$$

Simulation Example with a Type 3

- Assume we want a moderate phase boost at the selected crossover frequency

Extract from the plant

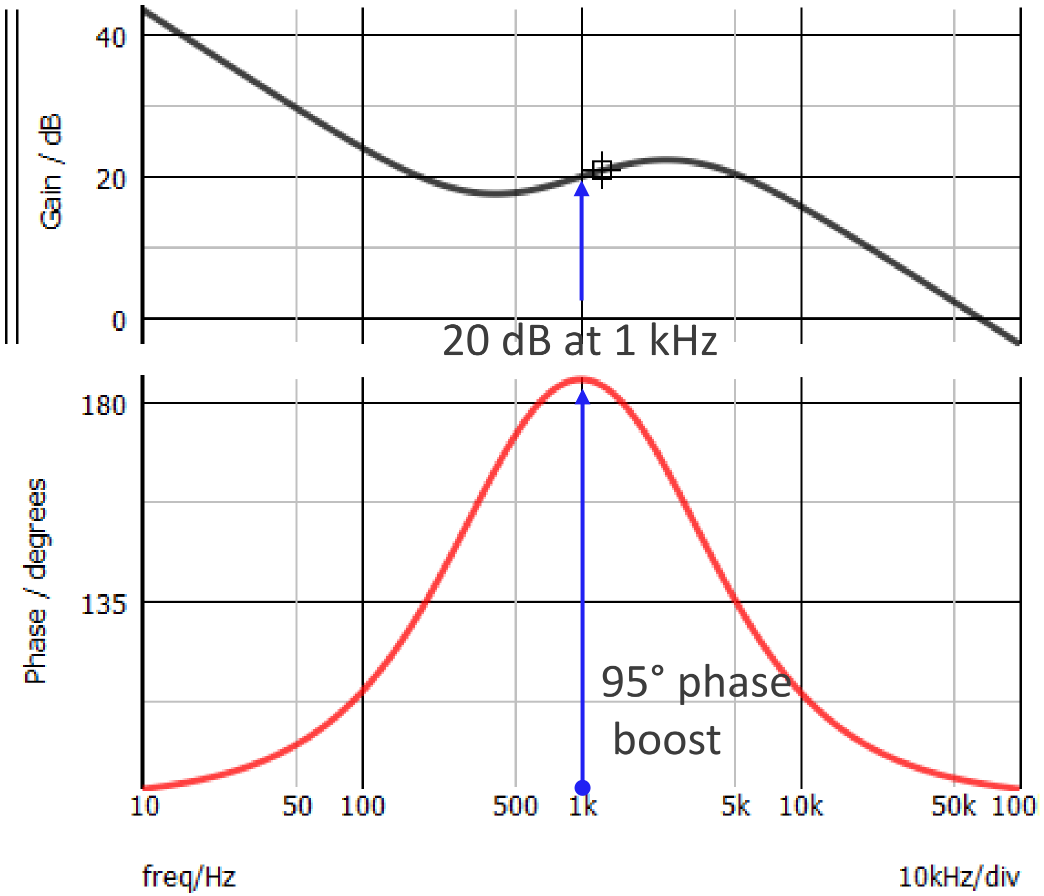
```
.VAR Gfc=-20 * magnitude at crossover *
.VAR PS=-135 * phase lag at crossover *
*
```

Design targets

```
.VAR fc=1k * targeted crossover *
.VAR PM=50 * choose phase margin at crossover *
*
.VAR Vout=19
.VAR Ibias=250u
.VAR Vref=2.5
.VAR Rlower={Vref/Ibias}
.VAR Rupper={(Vout-Vref)/Ibias}
*
.VAR gm=10u * transconductance in Siemens *
*
.VAR G={10^(-Gfc/20)}
.VAR boost=PM-PS-90
.VAR Kf=(tan((boost/4+45)*pi/180))^2
.VAR fz1=fc/sqrt(Kf)
.VAR fz2=fc/sqrt(Kf)
.VAR fp1=fc*sqrt(Kf)
.VAR fp2=fc*sqrt(Kf)
*
.VAR a=sqrt((fc^2/fp1^2)+1)
.VAR b=sqrt((fc^2/fp2^2)+1)
.VAR c=sqrt((fz1^2/fc^2)+1)
.VAR d=sqrt((fc^2/fz2^2)+1)
*
.VAR aa={((a*b)/(c*d))}
.VAR bb={(G*fp1*(Rupper+Rlower))/(Rlower*gm*(fp1-fz1))}
.VAR R2={aa*bb}
*
.VAR cc={((Rupper^2)*fz2)-Rupper*Rlower*(fp2-fz2)}
.VAR dd={(fp2-fz2)*(Rupper+Rlower)}
.VAR R3={cc/dd}
.VAR C1={1/(2*pi*fz1*R2)}
.VAR C2={C1/(2*pi*C1*R2*fp1-1)}
.VAR C3={1/(2*pi*fz2*(Rupper+R3))}
```

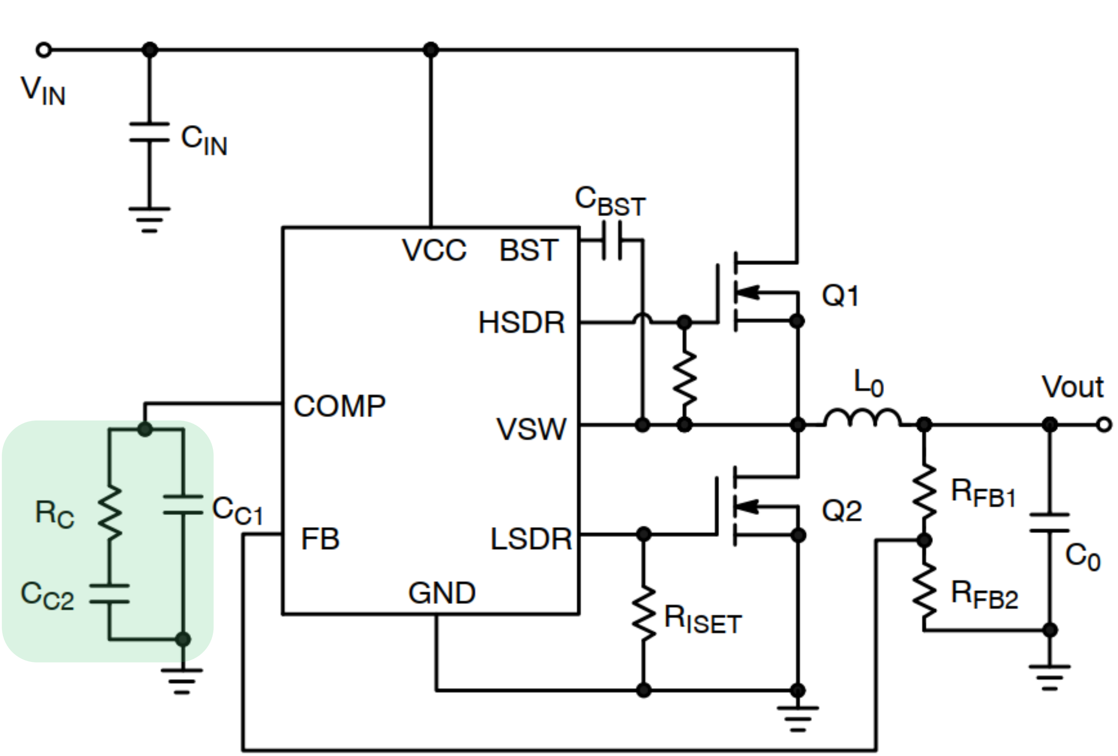
ok

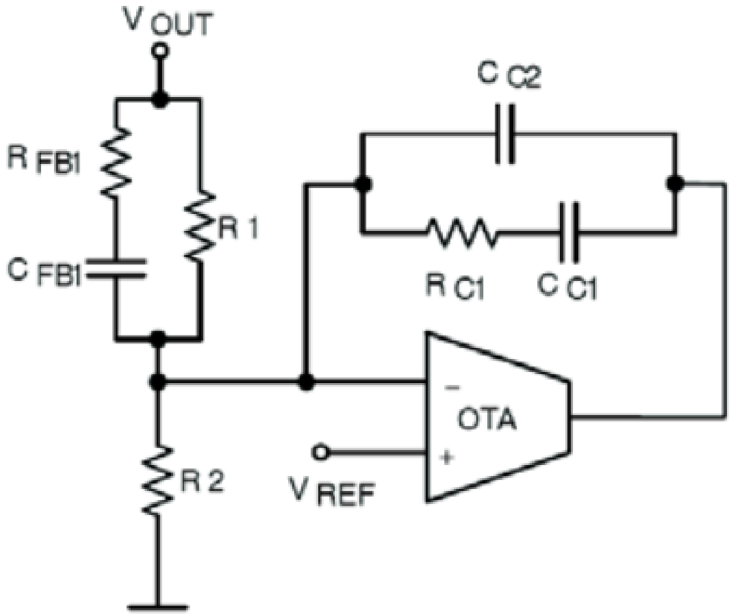
```
* Rupper = 66000
* Rlower = 10000
* R2 = 3482058.46126621
* R3 = 1527.79254332055
* C2 = 2.09414398805125e-11
* C1 = 1.17535722549486e-10
* C3 = 6.06070836599494e-09
* k = 6.61259030993665
* Boost = 95
* Fz1 = 388.87873185299
* Fz2 = 388.87873185299
* Fp1 = 2571.49573399153
* Fp2 = 2571.49573399153
*
```



Compensating a Buck Converter

- A buck converter operated in voltage-mode control is built around a NCP3020A
- The part operates at 300 or 600 kHz and features an on-board OTA
- ✓ The schematic shows a type 2 compensator or a type 3 with a feedback as in an op-amp



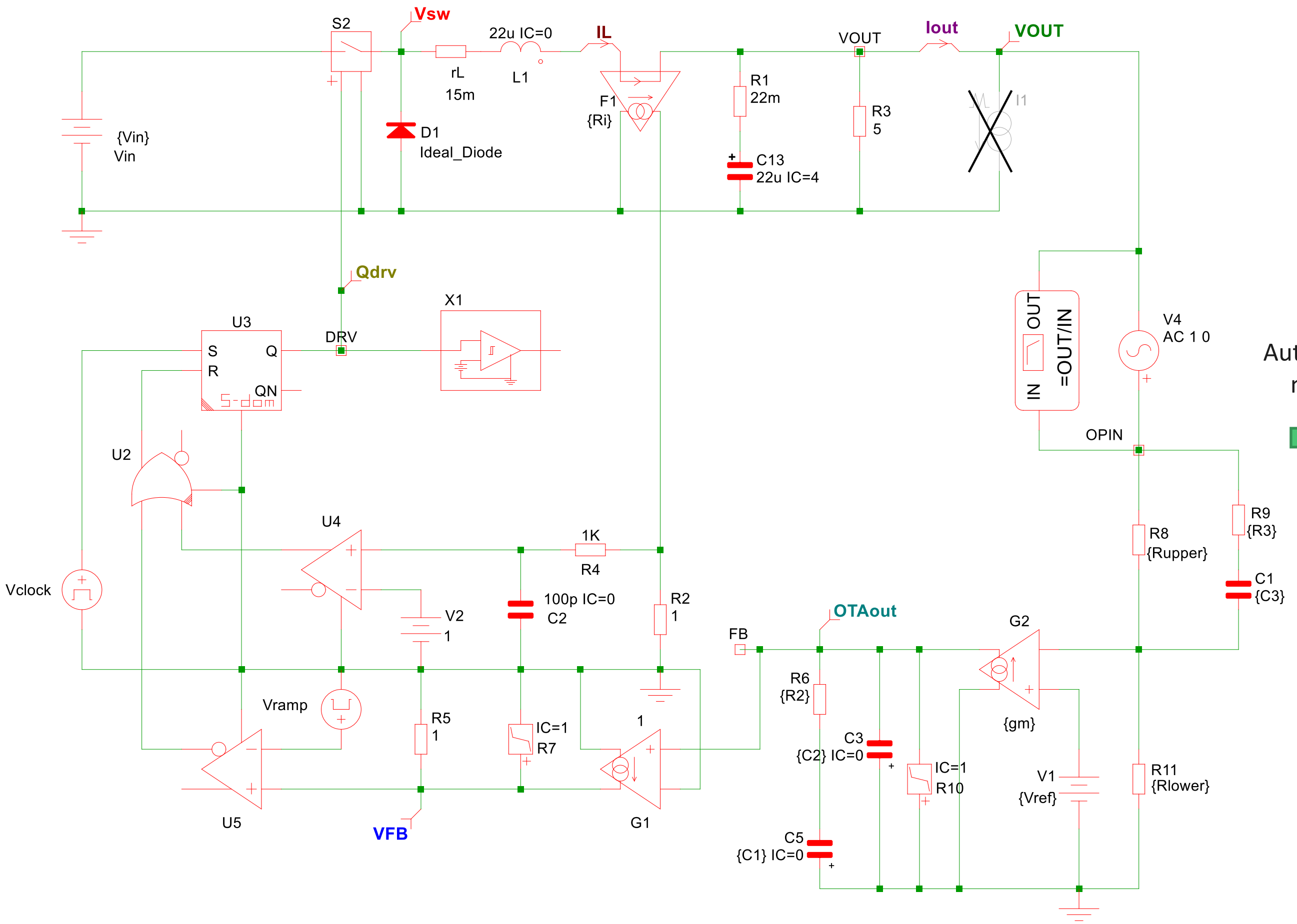


This structure is absolutely *not* recommended as it is almost impossible to freely place poles and zeroes!

Control-to-Output Transfer Function

- This is the starting point for any loop stabilization exercise

➤ How does a *stimulus* applied at the control pin propagate in the circuit to form the *response*?



Automated macro

```
*
.VAR Vin=24
.VAR Vout=12
.VAR L=22u
.VAR Ri=10m
*
.VAR Gfc=-0.0 * magnitude at crossover *
.VAR PS=-165 * phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.VAR fc=30k * targetted crossover *
.VAR PM=60 * choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Ibias=0.3m
.VAR Vref=0.6
.VAR Rlower={Vref/Ibias}
.VAR Rupper={(Vout-Vref)/Ibias}
*
* Capture the double zero position and one of the pole position *
*
* Choose OTA characteristics *
*
.VAR gm=1.4m ; transconductance in Siemens
*
*
* Do not edit the below lines *
*
.VAR G={10^(-Gfc/20)}
.VAR boost=PM-PS-90
.VAR Kf=(tan((boost/4+45)*pi/180))^2
*
*.VAR fz1=fc/sqrt(Kf)
*.VAR fp2=fc*sqrt(Kf)
*.VAR fz2=fc/sqrt(Kf)
*.VAR fp1=fc*sqrt(Kf)
*
.VAR fz1=2000 ; you can manually lower this zero to improve the PM in DCM
.VAR fz2=10k ; you can't move this second zero below Vref*fp2/Vout or R3 becomes negative
.VAR fp1=200k
.VAR fp2={0.9*fz2*Vout/Vref}
*
.VAR a=sqrt((fc^2/fp1^2)+1)
.VAR b=sqrt((fc^2/fp2^2)+1)
.VAR c=sqrt((fz1^2/fc^2)+1)
.VAR d=sqrt((fc^2/fz2^2)+1)
*
.VAR aa={((a*b)/(c*d))}
.VAR bb={(G*fp1*(Rupper+Rlower))/(Rlower*gm*(fp1-fz1))}
*
.VAR R2={aa*bb}
.VAR cc={((Rupper^2)*fz2)-Rupper*Rlower*(fp2-fz2)}
.VAR dd={(fp2-fz2)*(Rupper+Rlower)}
.VAR R3={cc/dd}
.VAR C1={1/(2*pi*fz1*R2)}
.VAR C2={C1/(2*pi*C1*R2*fp1-1)}
.VAR C3={1/(2*pi*fz2*(Rupper+R3))}
*
```

- The macro automates the calculation process and delivers values
- Check R_3 is always positive. If not, the second zero is too low

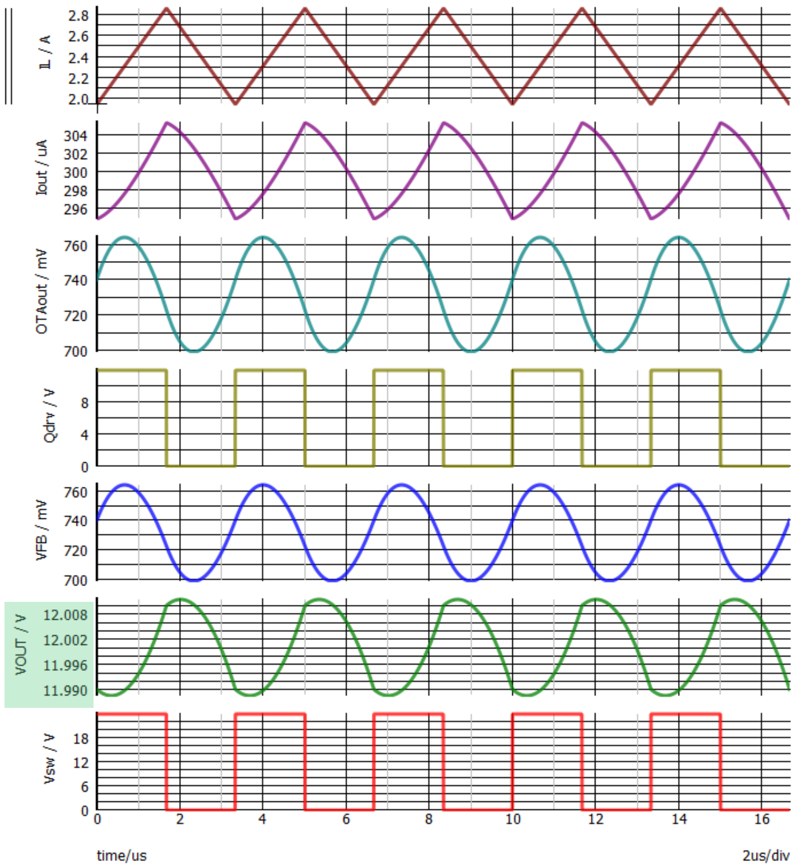
Ok! →

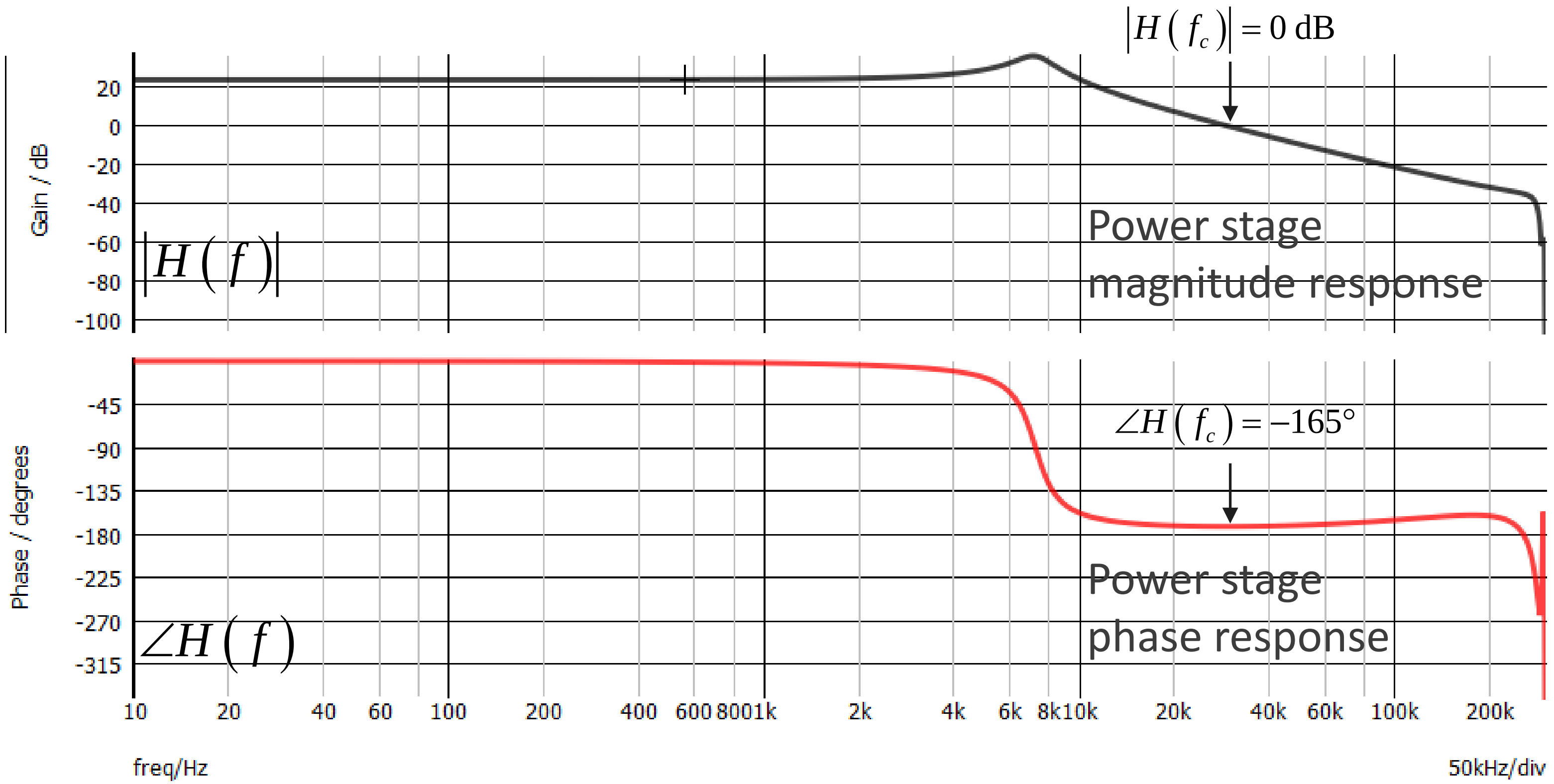
```
*
* Rupper = 38000
* Rlower = 2000
* R2 = 4667.50804156356
* R3 = 223.529411764706
* C2 = 1.72214560048019e-10
* C1 = 1.70492414447539e-08
* C3 = 4.16379506396156e-10
* k = 25.2741423690882
* Boost = 135
* Fz1 = 2000
* Fz2 = 10000
* Fp1 = 200000
* Fp2 = 180000
*
```

Simulator>Edit Netlist (after preprocess)

Extracting Data from the Bode Plot

- Run the SIMPLIS model and plot the control-to-output transfer function $\hat{v}_{out}/\hat{v}_{err}$
- Select a crossover frequency and extract the gain and phase values at f_c
- ➤ Check the correct operating point, e.g. V_{out} = 12 V at the considered bias condition

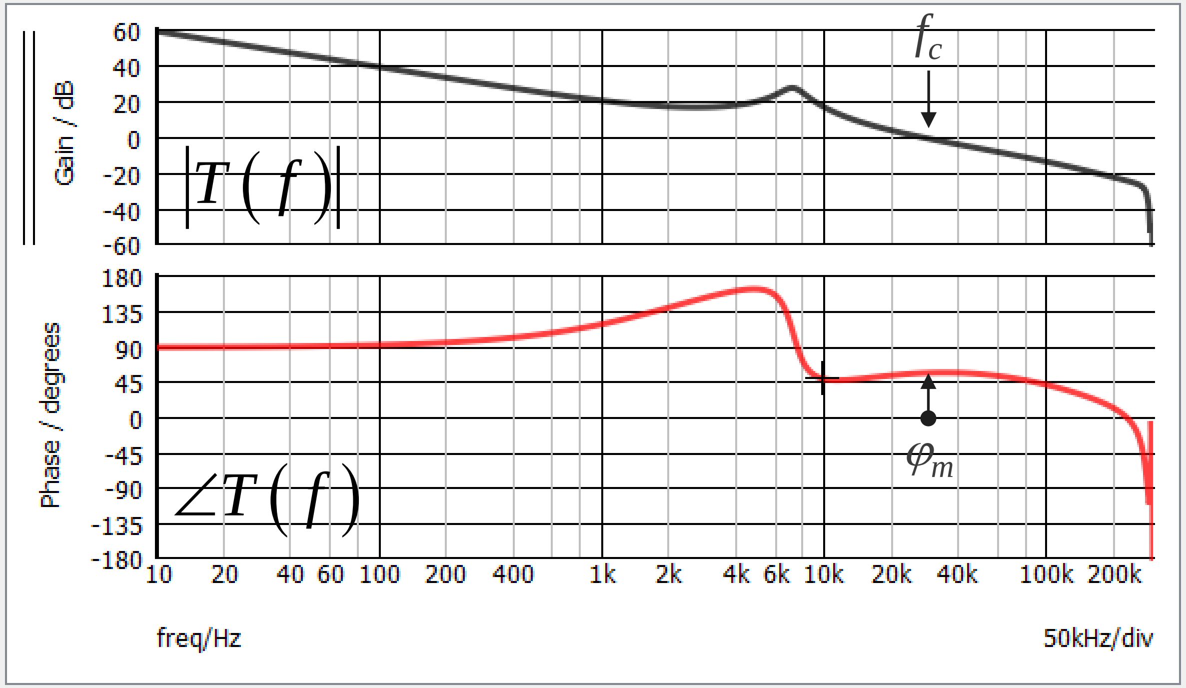




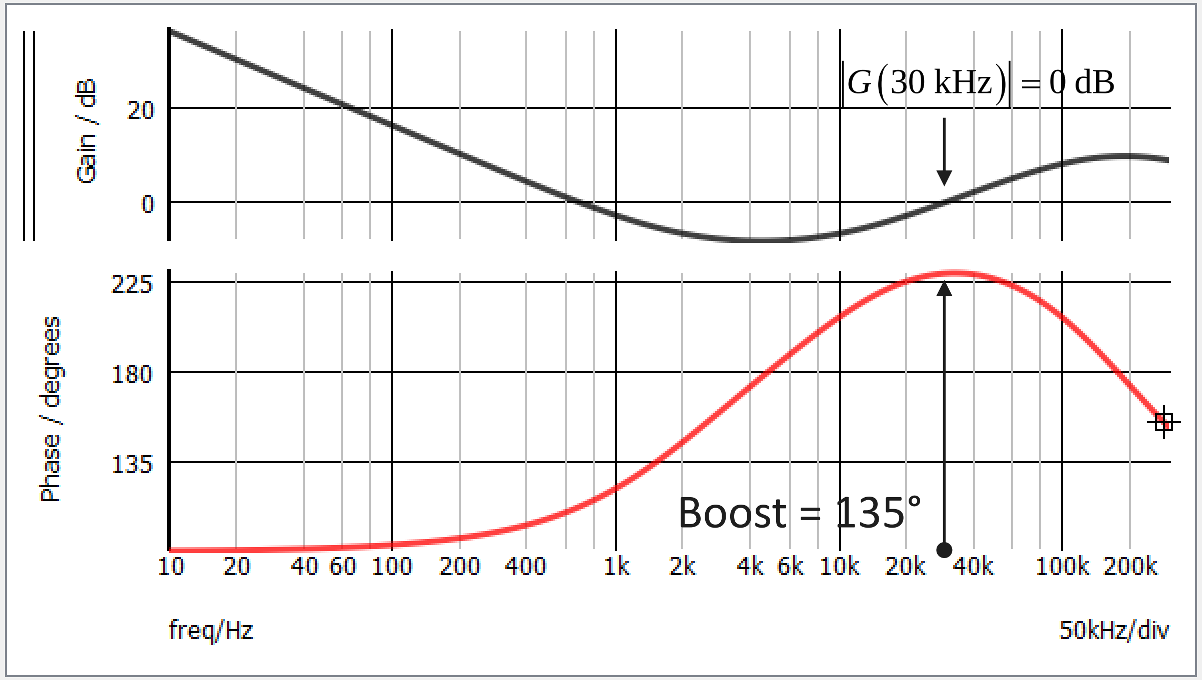
- The compensator must exhibit a unity gain at 30 kHz
- It must boost the phase by 135° at 30 kHz for a PM of 60°

Compensated Converter

- The compensator has been designed with the recommended compensation strategy
- The crossover frequency and phase/gain margins are within adequate limits



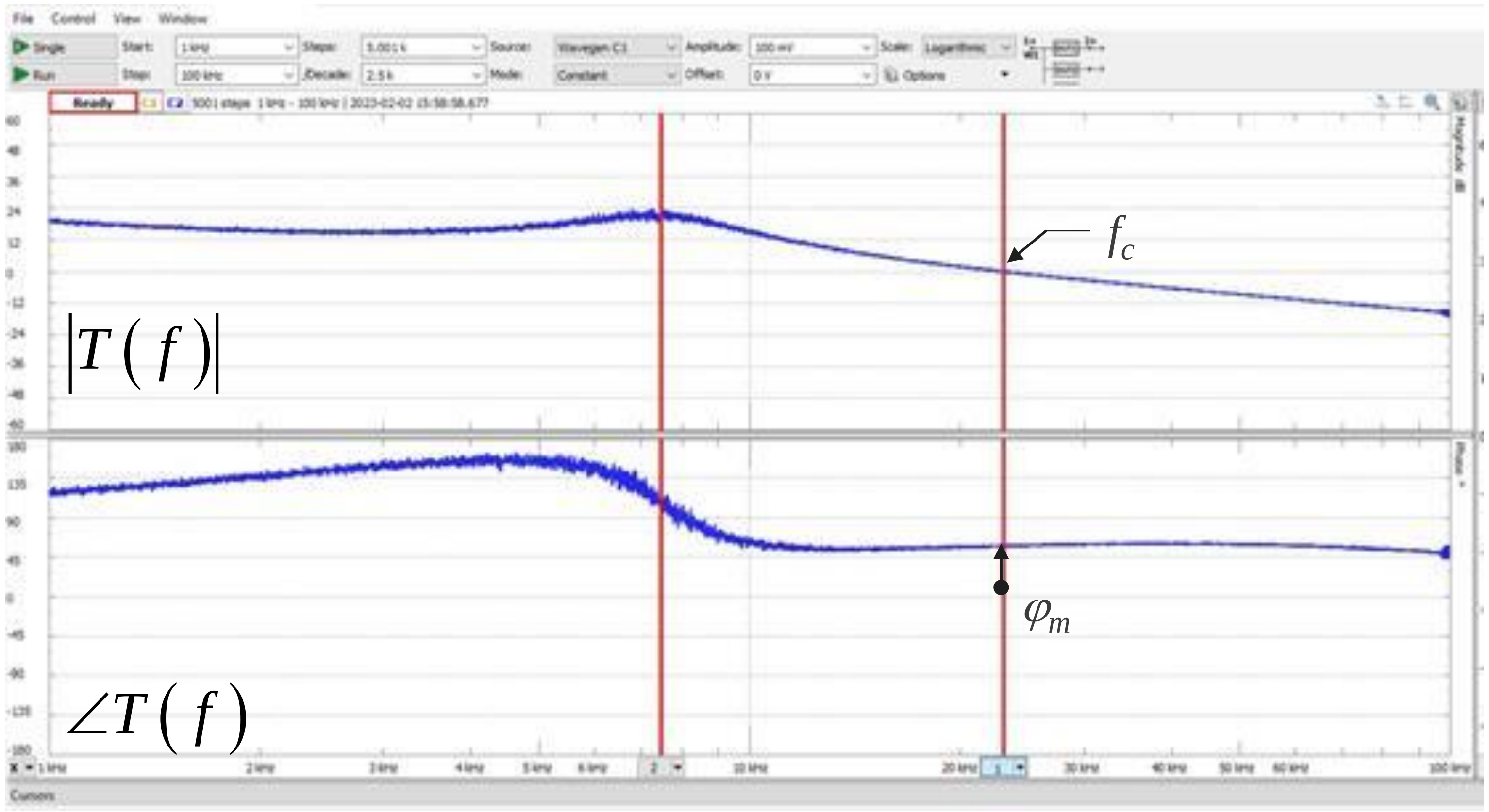
Curve label	Name	Value
Gain	Gain Crossover Frequency	28.4498kHz
Gain	Gain Margin	24.03851dB
Phase	Phase Margin	57.508971degrees

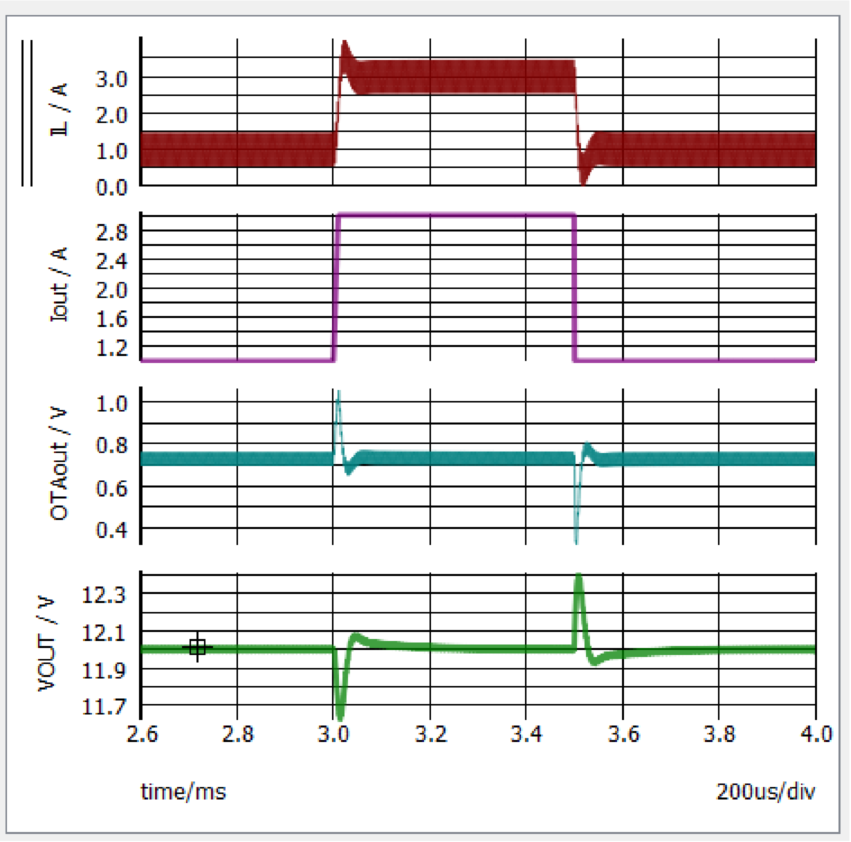


- Type 3 compensator response as built by the OTA:
- ✓ The gain is unity at 30 kHz
- ✓ The phase boost meets the 135° target

Practical Experiments

- Checking the loop on the prototype is a crucial step for the validation process
- Small-signal response agrees with simulation and simulated load-step shows good performance





Conclusion

- Different compensator types exist depending on the needed phase boost
- The operational transconductance amplifier (OTA) lends itself well for a type 2 compensator
- A type 3 is more difficult to implement with an OTA but doable with precautions
  - A classical op-amp-like feedback across the OTA is highly unadvised
  - Installing a RC network across the upper divider resistor is the way to go
- Simulations and practical experiments prove the validity of the approach