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Loop Stabilization with NCP1060

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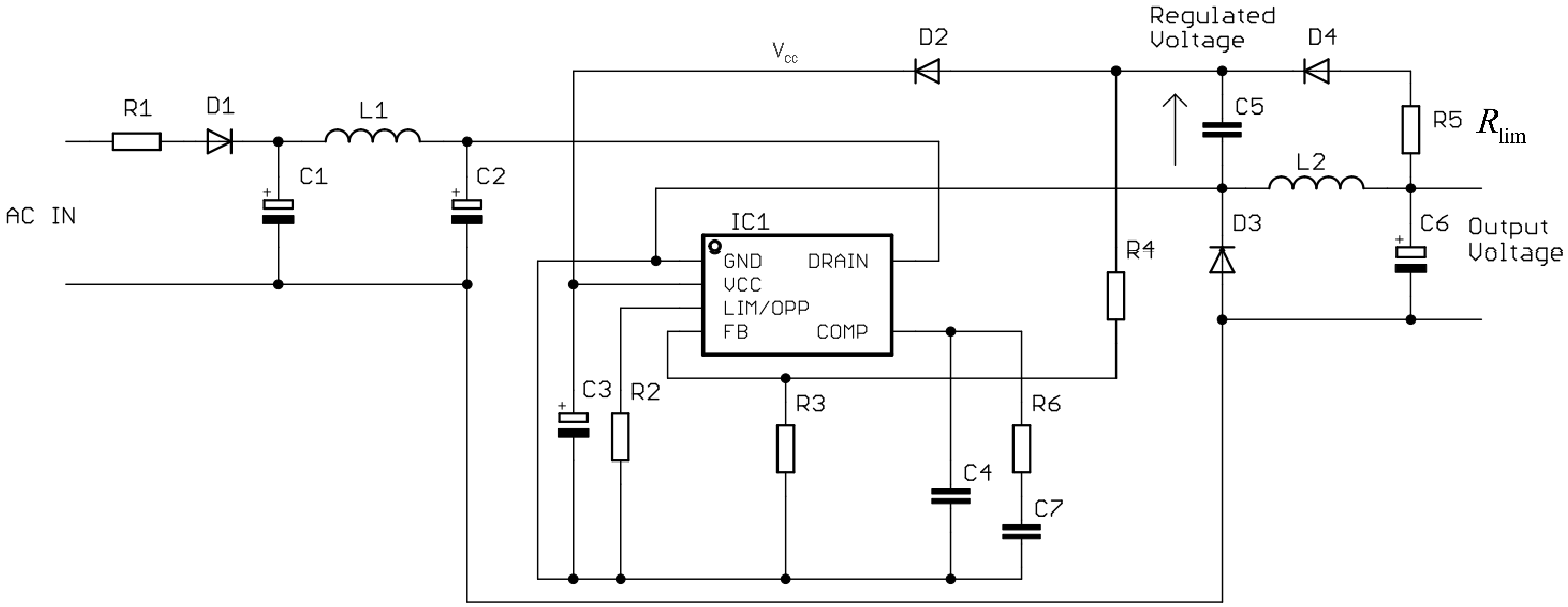
Application Schematic

The NCP1060 lends itself well to building non-isolated buck converters. The feedback is made by reconstructing the output voltage V_{out} during the off-time period. This voltage is then internally compared to perform regulation.



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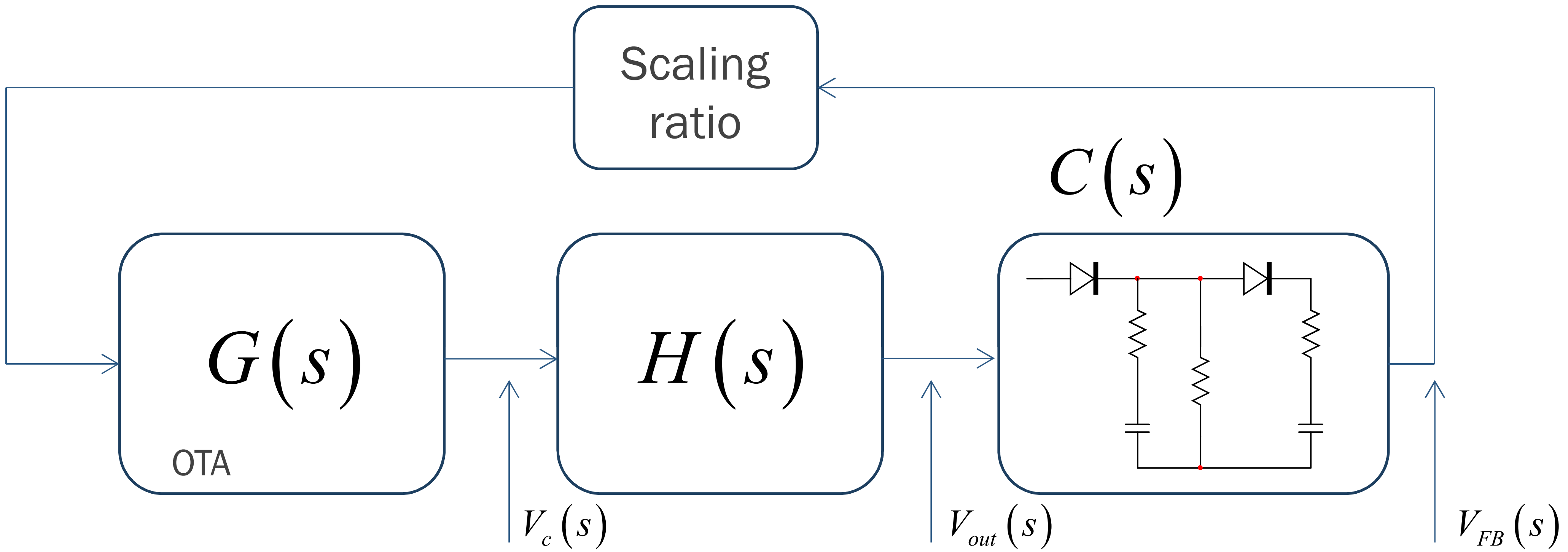
Small-Signal Model

Before attempting to stabilize any converter, we need its control-to-output transfer function $H(s)$. However, in our case, we do not directly observe V_{out} but an image of it, adding a second transfer function.



The second transfer function $C(s)$ is cascaded with that of the plant to form the dynamic response we need. From this response and based on the requirement (crossover frequency and phase margin), we can deduce a compensation strategy.

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The Power Plant Dynamic Response

The plant control-to-output transfer function is that of a CCM-operated current-mode buck converter:

$$H(s) \approx H_0 \frac{1+\dfrac{s}{\omega_{z_1}}}{1+\dfrac{s}{\omega_{p_1}}} \frac{1}{1+\dfrac{s}{\omega_n Q}+\left(\dfrac{s}{\omega_n}\right)^2} \qquad H_0 = \frac{R}{R_i}\frac{1}{1+\dfrac{RT_{sw}}{L}\left[m_c(1-D)-0.5\right]} \qquad \omega_{z_1} = \frac{1}{r_C C}$$

$$\omega_{p_1} = \frac{1}{RC}+\frac{T_{sw}}{LC}\left[m_c(1-D)-0.5\right] \qquad \omega_n = \frac{\pi}{T_{sw}} \qquad Q = \frac{1}{\pi\left[m_c(1-D)-0.5\right]} \qquad m_c = 1+\frac{S_e}{S_n}$$

Artificial ramp

Inductor on slope

In NCP1060, with have:

$R_i = 300\ \mathrm{m\Omega}$ $\quad S_a = 8.4\ \mathrm{mA/\mu s}$ 1060/60 kHz $\quad S_a = 14\ \mathrm{mA/\mu s}$ 1060/100 kHz

$S_a = 15.6\ \mathrm{mA/\mu s}$ 1063/60 kHz $\quad S_a = 26\ \mathrm{mA/\mu s}$ 1063/100 kHz

R. B. Ridley, *A new Continuous-Time Model for CM Control*, IEEE Transactions of Power Electronics, Vol. 6, April 1991

Operating Conditions – Power Stage Alone

$F_{sw} := 60kHz$ $L_1 := 1mH$ $R_L := 30\Omega$ $V_{in} := 125V$ $V_{out} := 14V$

$r_C := 0.2\Omega$ $C_{out} := 20\mu F$ $T_{sw} := \frac{1}{F_{sw}} = 16.667\mu s$

$T_{sw} := \frac{1}{F_{sw}}$ $S_e := \frac{V_{in} - V_{out}}{L_1} = 111\frac{kA}{s}$ $S_a := 8.4\frac{mA}{\mu s}$ $R_i := 0.3\Omega$

$m_c := 1 + \frac{S_a}{S_e} = 1.076$ $D := \frac{V_{out}}{V_{in}} = 11.2\%$ $H_{div} := 0.078$

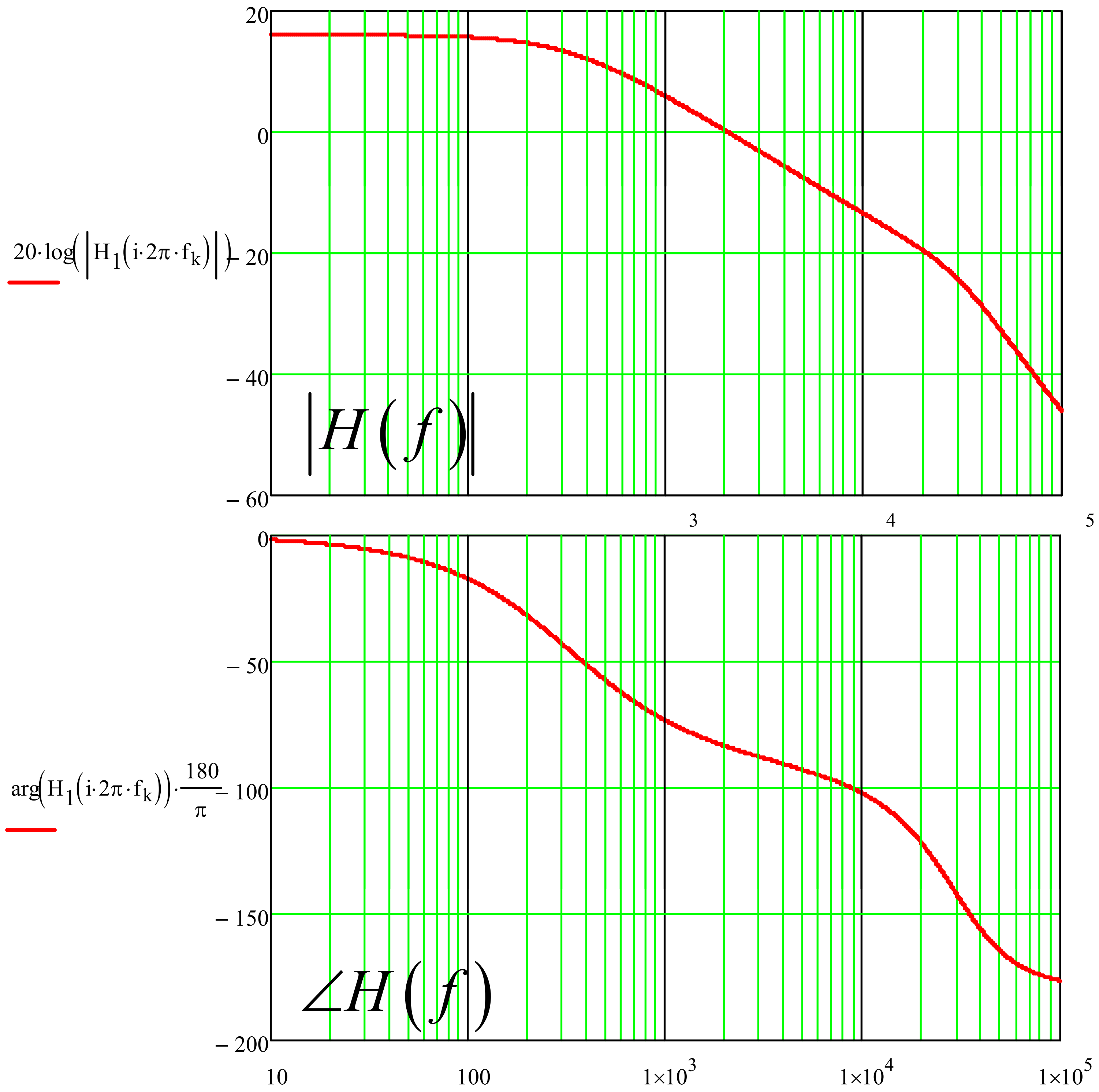
$$H_0 := H_{div}\cdot\frac{R_L}{R_i}\cdot\frac{1}{1 + \frac{R_L \cdot T_{sw}}{L_1}\cdot\left[m_c\cdot(1-D) - 0.5\right]} \qquad 20\cdot\log(H_0) = 16.061 \quad \text{dB}$$

Internal divider

$$\omega_{z1} := \frac{1}{r_C \cdot C_{out}} \qquad \omega_{p1} := \frac{1}{R_L \cdot C_{out}} + \frac{T_{sw}}{L_1 \cdot C_{out}}\cdot\left[m_c\cdot(1-D) - 0.5\right]$$

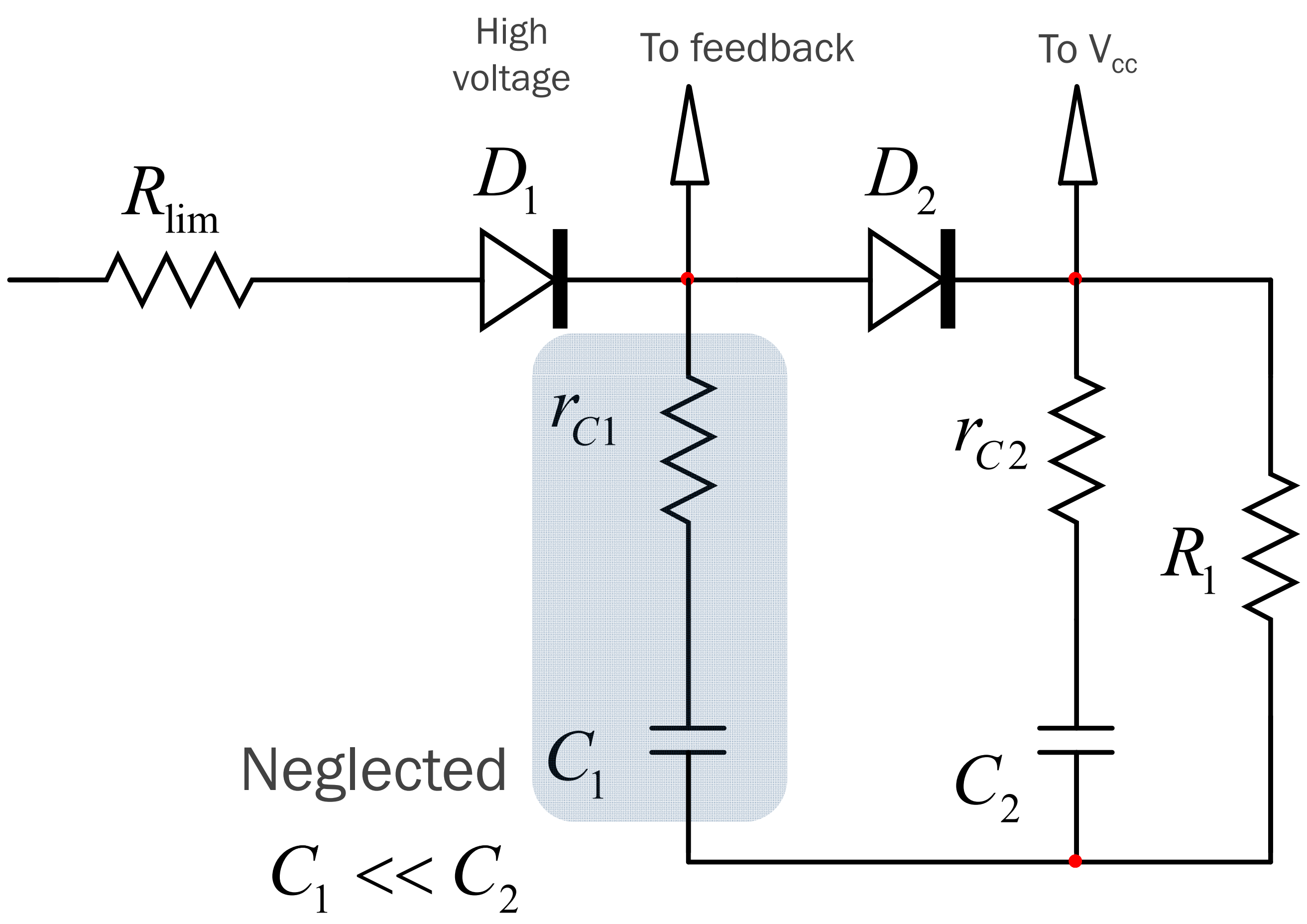
$$\omega_n := \frac{\pi}{T_{sw}} \qquad Q_p := \frac{1}{\pi\cdot\left[m_c\cdot(1-D) - 0.5\right]} = 0.699$$

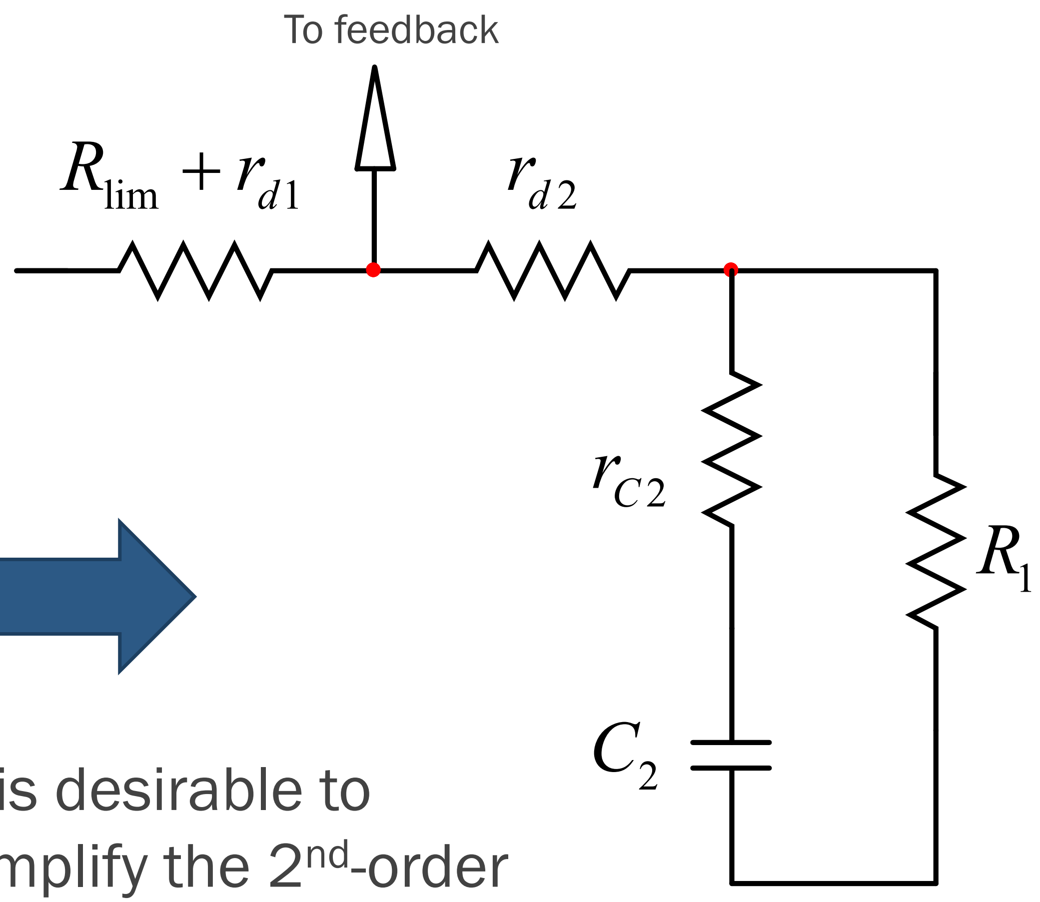
$$H_1(s) := H_0\cdot\frac{1 + \frac{s}{\omega_{z1}}}{1 + \frac{s}{\omega_{p1}}}\cdot\frac{1}{1 + \frac{s}{\omega_n \cdot Q_p} + \left(\frac{s}{\omega_n}\right)^2}$$



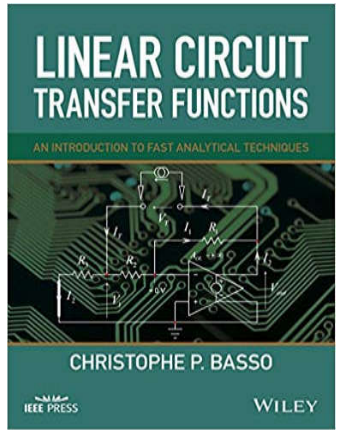
Output Voltage Image

The circuit does not regulate V_{out} directly but an image obtained during the freewheeling operation. The rectifying diode is affected by a dynamic resistance r_d. The whole thing is then loaded by the V_{cc} capacitor and the IC consumption.





It is desirable to simplify the 2nd-order circuitry to a 1st-order circuit for analysis.



Apply the FACTs!

$$C(s) = C_0 \frac{1 + \frac{s}{\omega_{z_2}}}{1 + \frac{s}{\omega_{p_2}}}$$

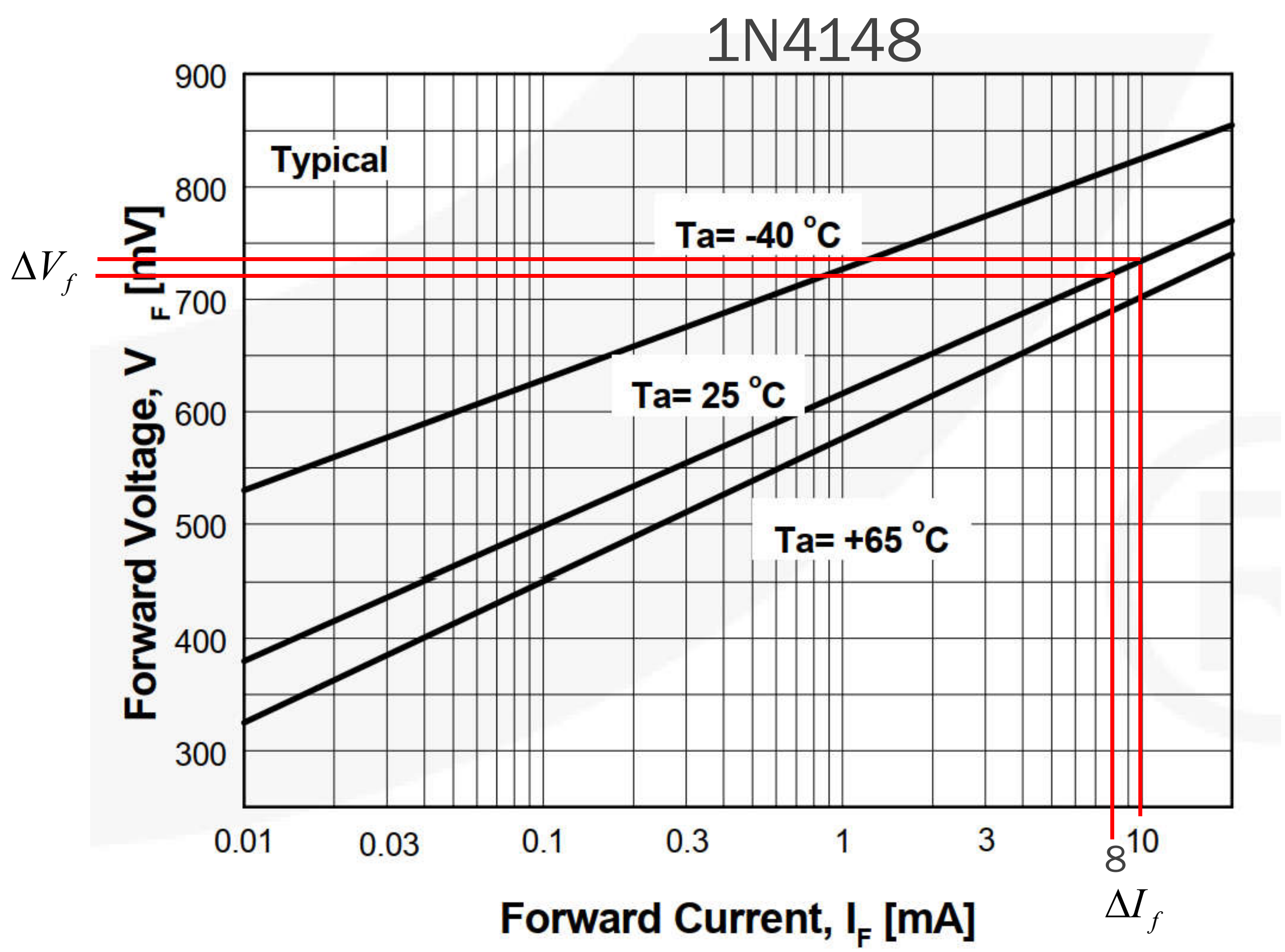
$$C_0 = \frac{R_1 + r_{d2}}{(R_{\lim} + r_{d1}) + r_{d2} + R_1}$$

$$\omega_{z_2} = \frac{1}{C_2 \left[r_{C2} + r_{d2} \parallel R_1 \right]}$$

$$\omega_{p_2} = \frac{1}{\left[R_1 \parallel (r_{d1} + R_{\lim} + r_{d2}) + r_{C2} \right] C_2}$$

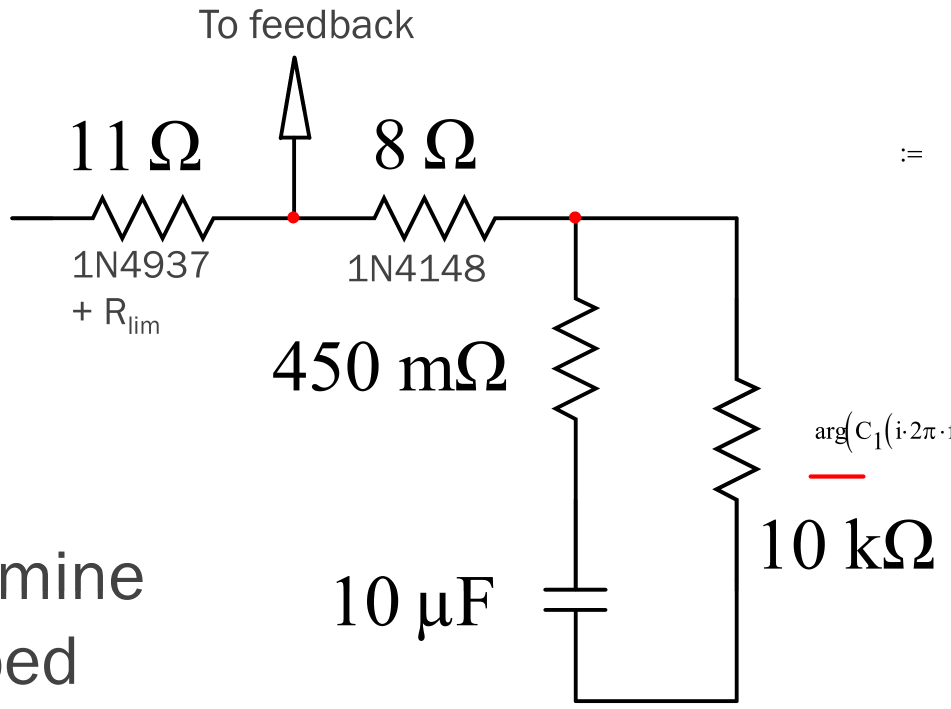
Extracting the Diode Dynamic Resistance

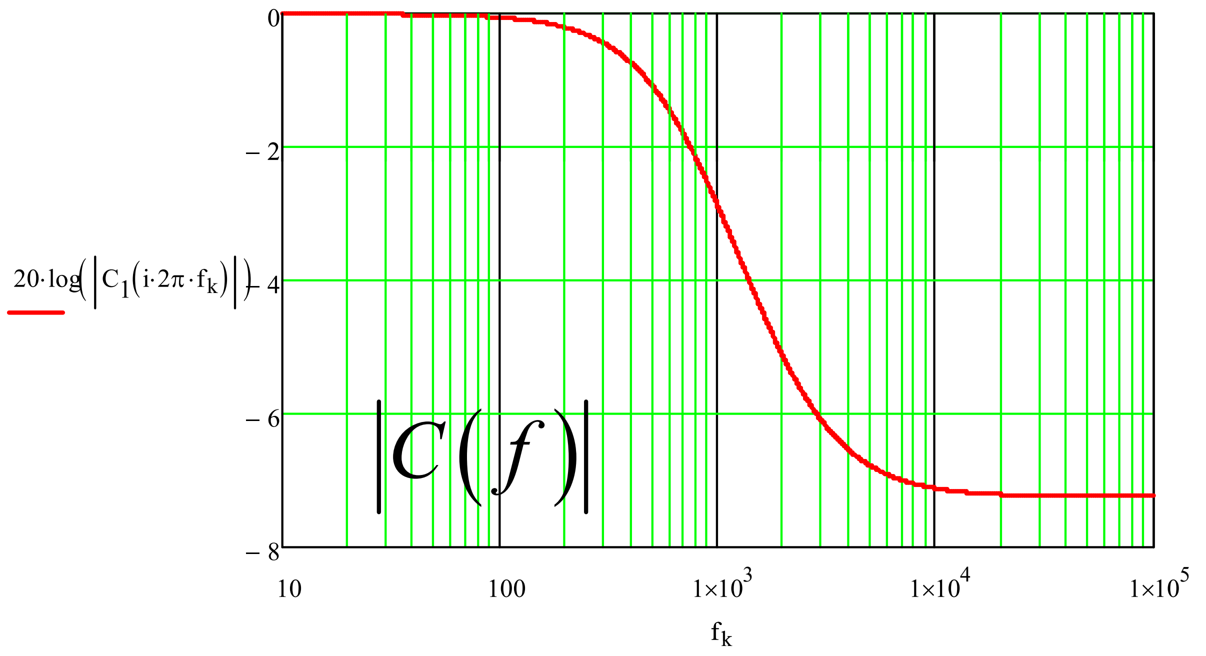
You have to know the rectifying diode dynamic resistance to calculate $C(s)$:

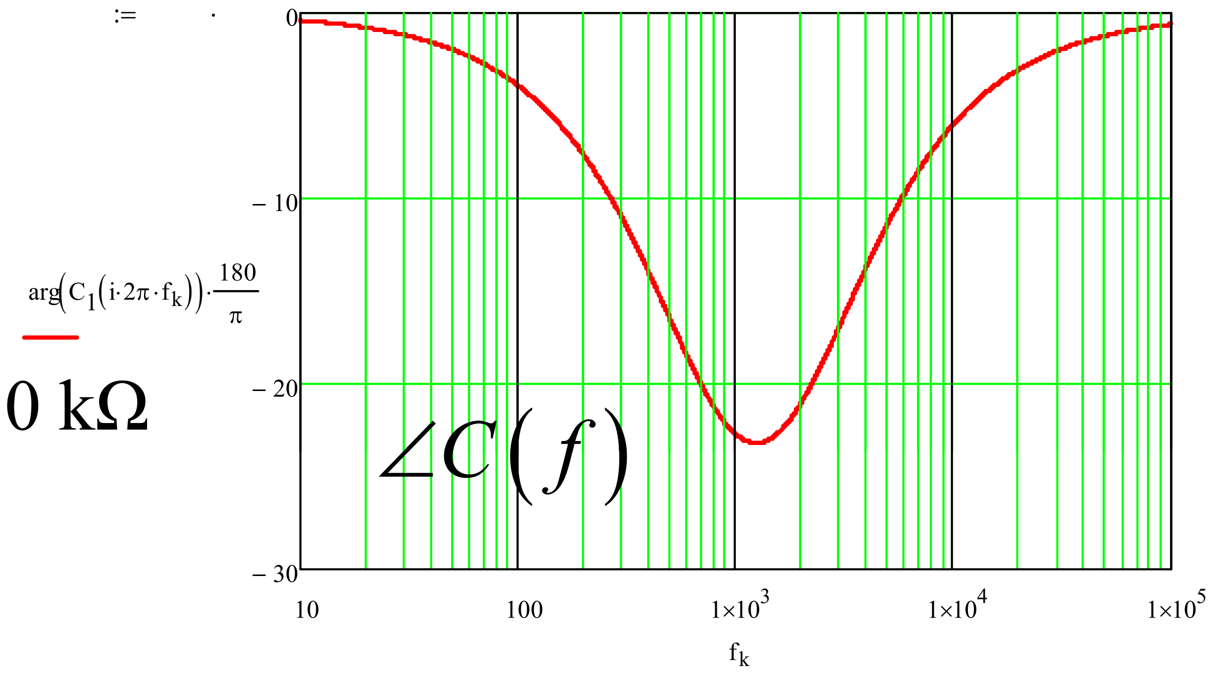


1N4148:

$$r_d = \frac{\Delta V_f}{\Delta I_f} = \frac{16m}{2m} = 8\ \Omega$$





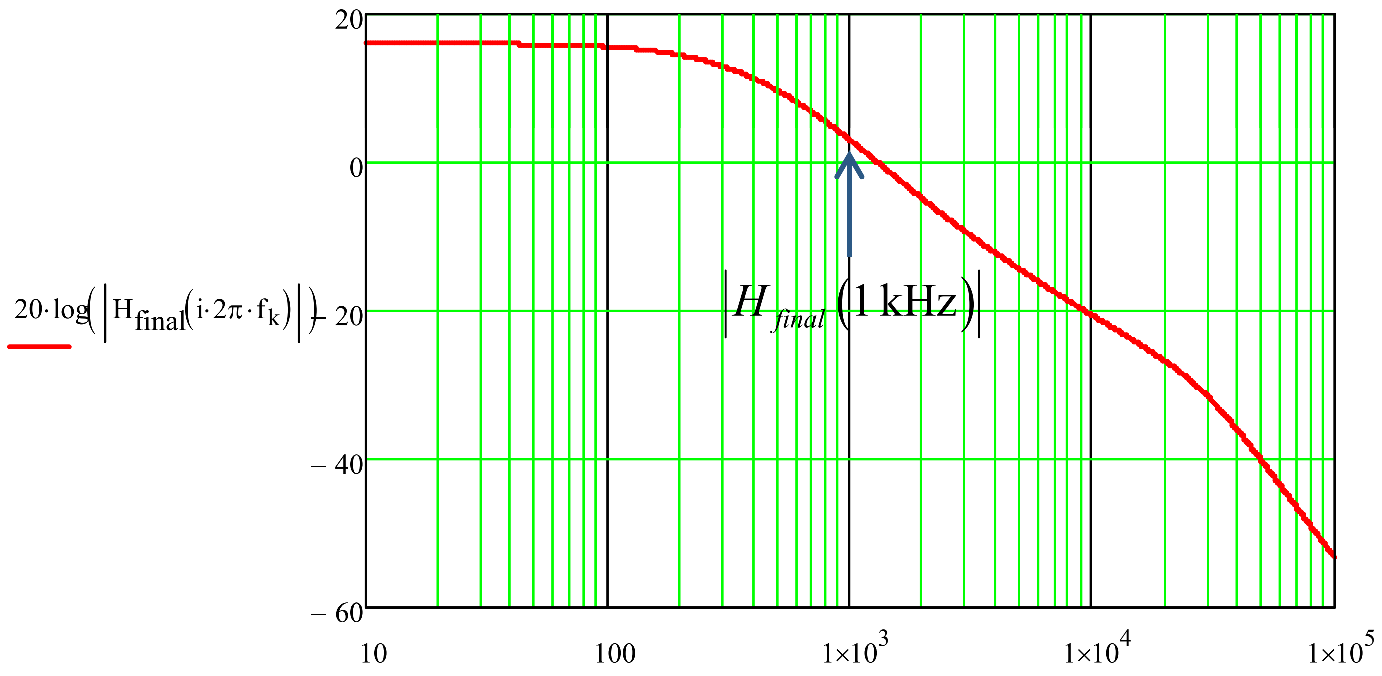


The 1N4937 resistance is difficult to determine at low I_d. It is assumed to be 1 Ω and lumped into an 11-Ω term considering 10 Ω for R_{lim}.

The Control-to-Output Transfer Function

The final transfer function is the cascading of the plant expression with the extra filter going to the feedback pin:

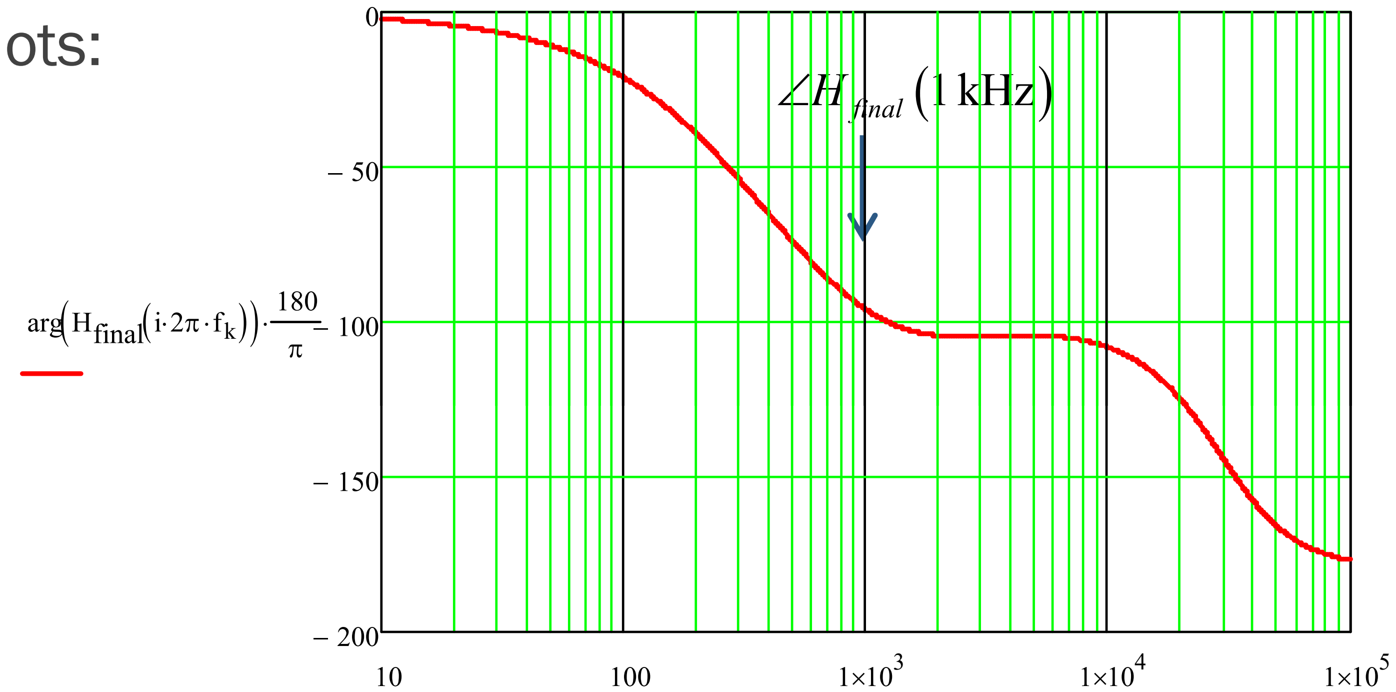
$$H_{final}(s) \approx H_0 \frac{1+\frac{s}{\omega_{z_1}}}{1+\frac{s}{\omega_{p_1}}} \frac{1}{1+\frac{s}{\omega_n Q}+\left(\frac{s}{\omega_n}\right)^2} C_0 \frac{1+\frac{s}{\omega_{z_2}}}{1+\frac{s}{\omega_{p_2}}}$$



Select a 1-kHz crossover frequency and extract data from the plots:

$$\left|H_{final}(1\,\text{kHz})\right| = 3\text{ dB} \longrightarrow G_{f_c}$$

$$\angle H_{final}(1\,\text{kHz}) \approx -96° \longrightarrow pf_c$$



Choose a phase margin goal, PM=70° for instance

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Determine how to Position Poles and Zeroes

The *k* factor method works well for current-controlled power converters:

$$G_{10} = 10^{\frac{-G_{f_c}}{20}} \approx 0.71$$

$$boost = pm - \left(pf_c\right) - 90° = 70° - \left(-96°\right) - 90° \approx 76° \qquad k = \tan\left(\frac{boost}{2} + 45°\right) = 8.123$$

$$f_z = \frac{f_c}{k} = 123\ \text{Hz} \qquad f_p = k \cdot f_c = 8.1\ \text{kHz}$$

$$C_1 = \frac{1}{2\pi f_z R_2} \approx 835\ \text{nF}$$

Resistive divider network

$$R_2 = \frac{G_{10} f_p}{f_p - f_z} \frac{R_{lower} + R_1}{R_{lower} g_m} \frac{\sqrt{1 + \left(\frac{f_c}{f_p}\right)^2}}{\sqrt{1 + \left(\frac{f_z}{f_c}\right)^2}} = 1.5\ \text{k}\Omega$$

$$C_2 = \frac{R_{lower} g_m}{2\pi f_p G_{10}\left(R_{lower} + R_1\right)} \frac{\sqrt{1 + \left(\frac{f_z}{f_c}\right)^2}}{\sqrt{1 + \left(\frac{f_c}{f_p}\right)^2}} = 12.8\ \text{nF}$$

D. Venable, *The k Factor: a New Mathematical Tool for Stability Analysis and Synthesis*, Proceedings of Powercon 10, 1983

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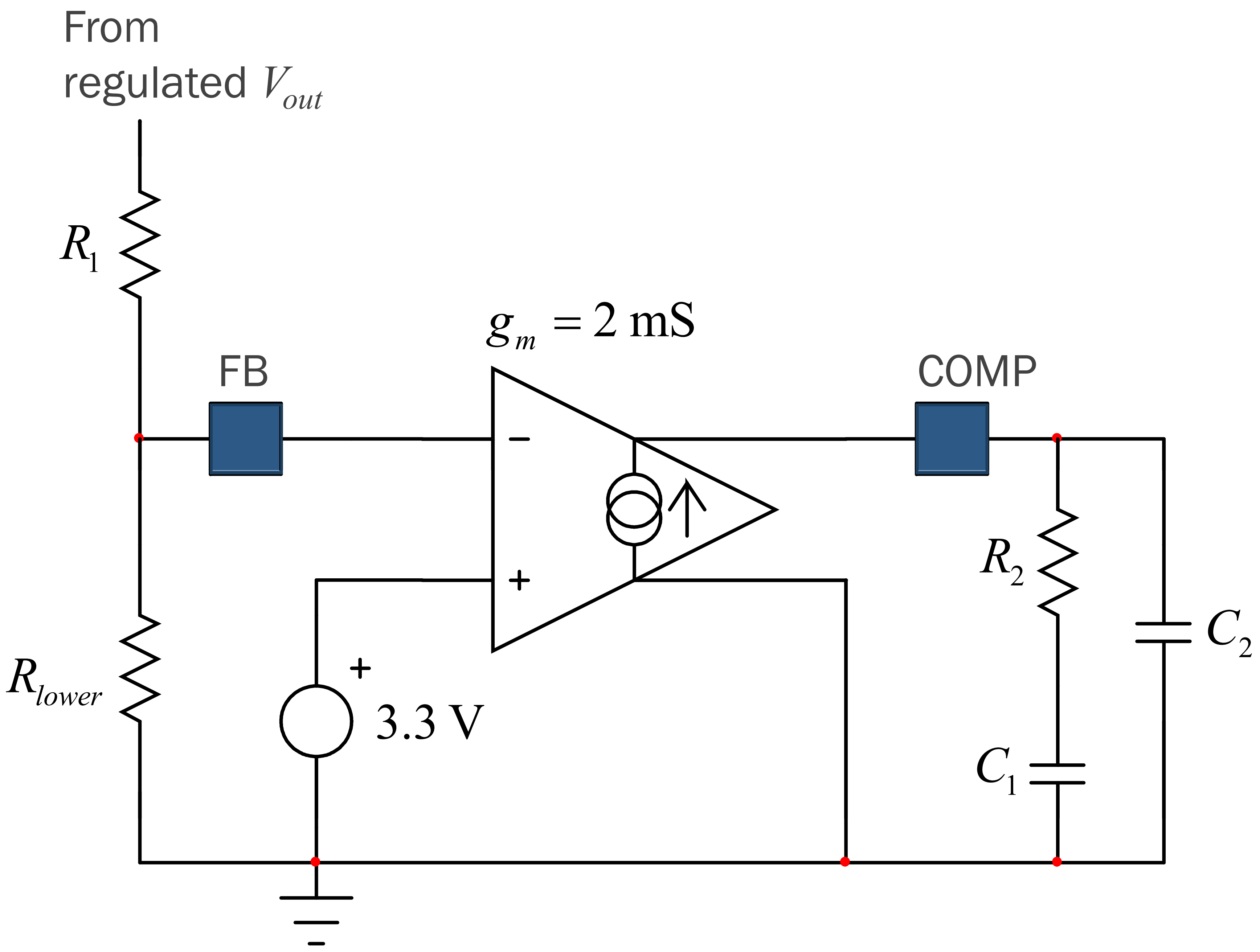
Type 2 Transfer Function with an OTA



$$G(s) = -G_0 \frac{1+\dfrac{\omega_z}{s}}{1+\dfrac{s}{\omega_p}} \qquad \omega_z = \frac{1}{R_2 C_1}$$

$$\omega_p = \frac{1}{R_2\left(\dfrac{C_1 C_2}{C_1 + C_2}\right)} \qquad G_0 = \frac{R_2 C_1}{C_1 + C_2}\frac{g_m R_{lower}}{R_{lower} + R_1}$$

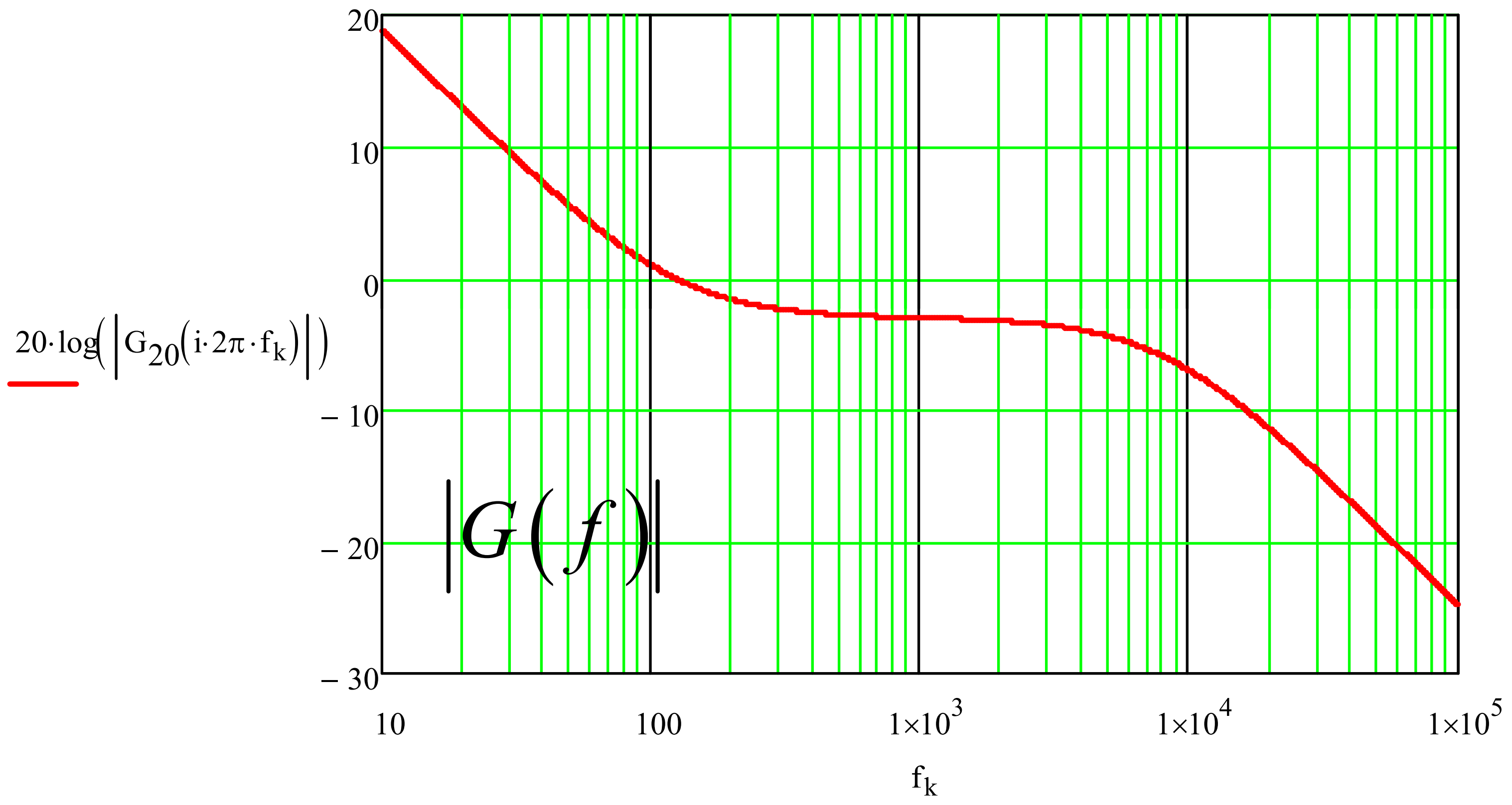
Select R_2 to compensate gain/attenuation at f_c

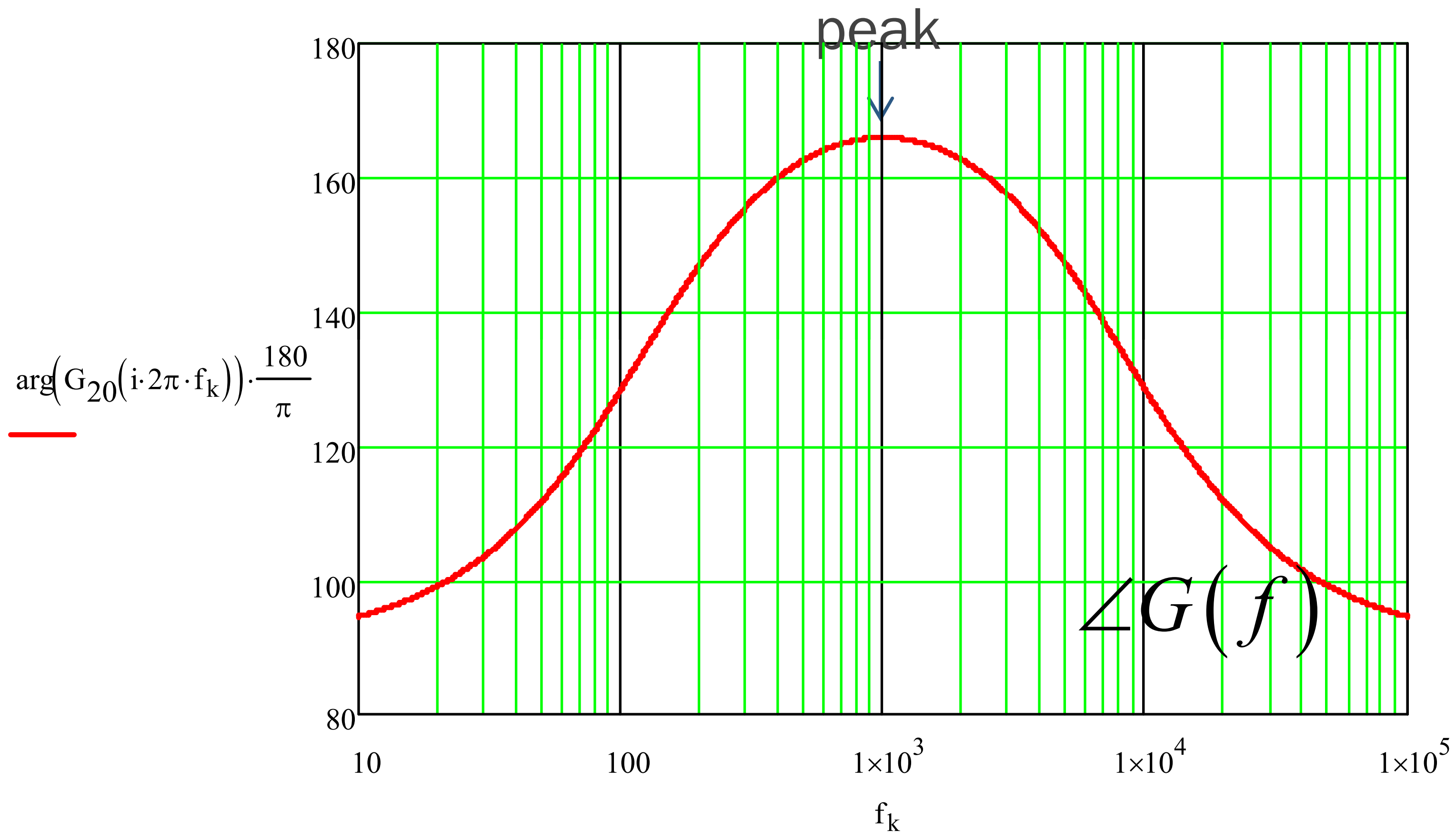
$$R_2 = \frac{G_{10} f_p}{f_p - f_z}\frac{R_{lower} + R_1}{g_m R_1}\frac{\sqrt{1+\left(\dfrac{f}{f_p}\right)^2}}{\sqrt{1+\left(\dfrac{f_z}{f}\right)^2}}$$

C. Basso, *Designing Control Loops for Linear and Switching Power Supplies*, Artech House 2012

Dynamic Response of the Type-2 Compensator

The phase response is boosted between the zero and the pole. The peak occurs at the selected crossover frequency.





Plot the loop gain

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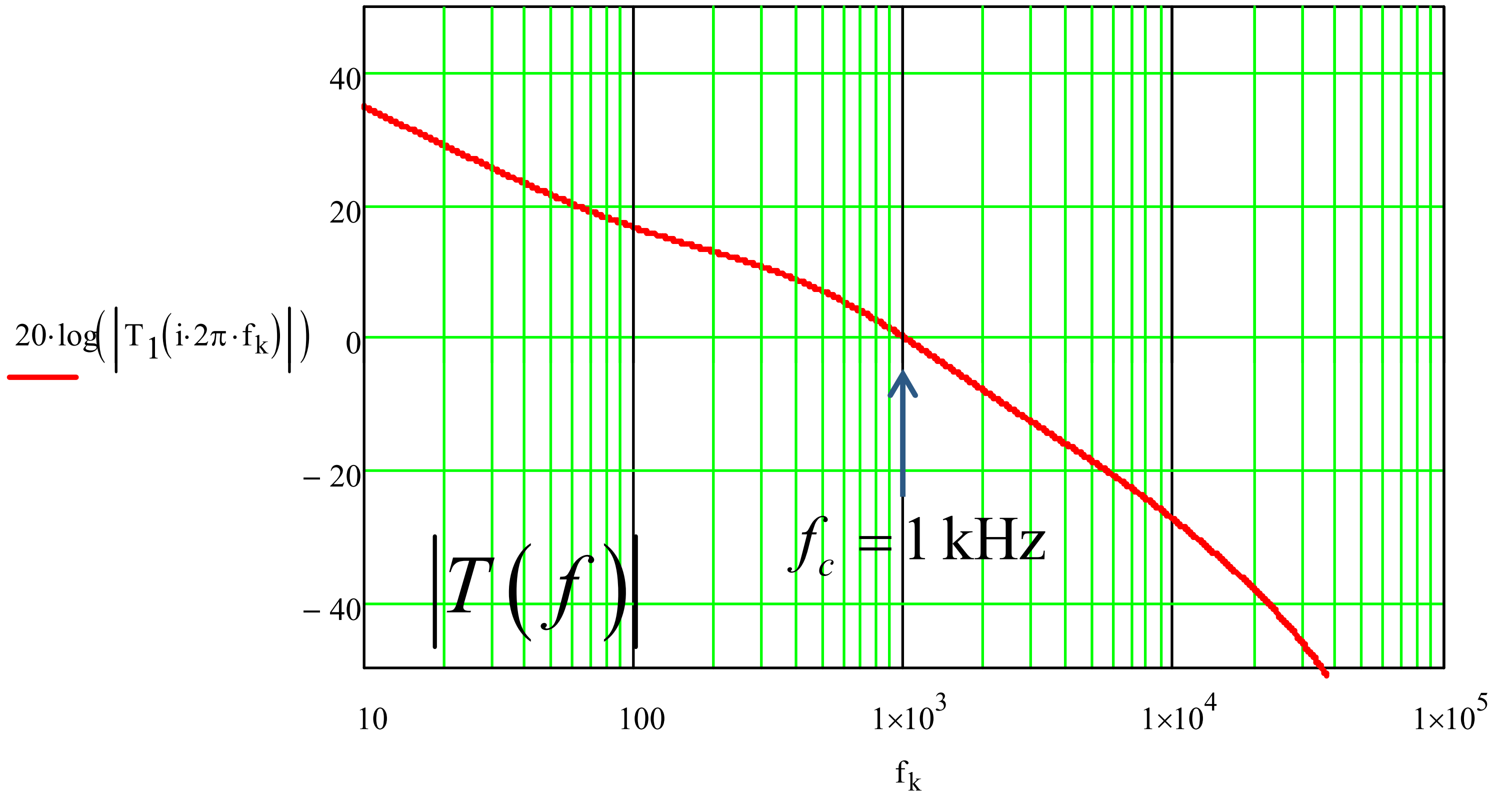
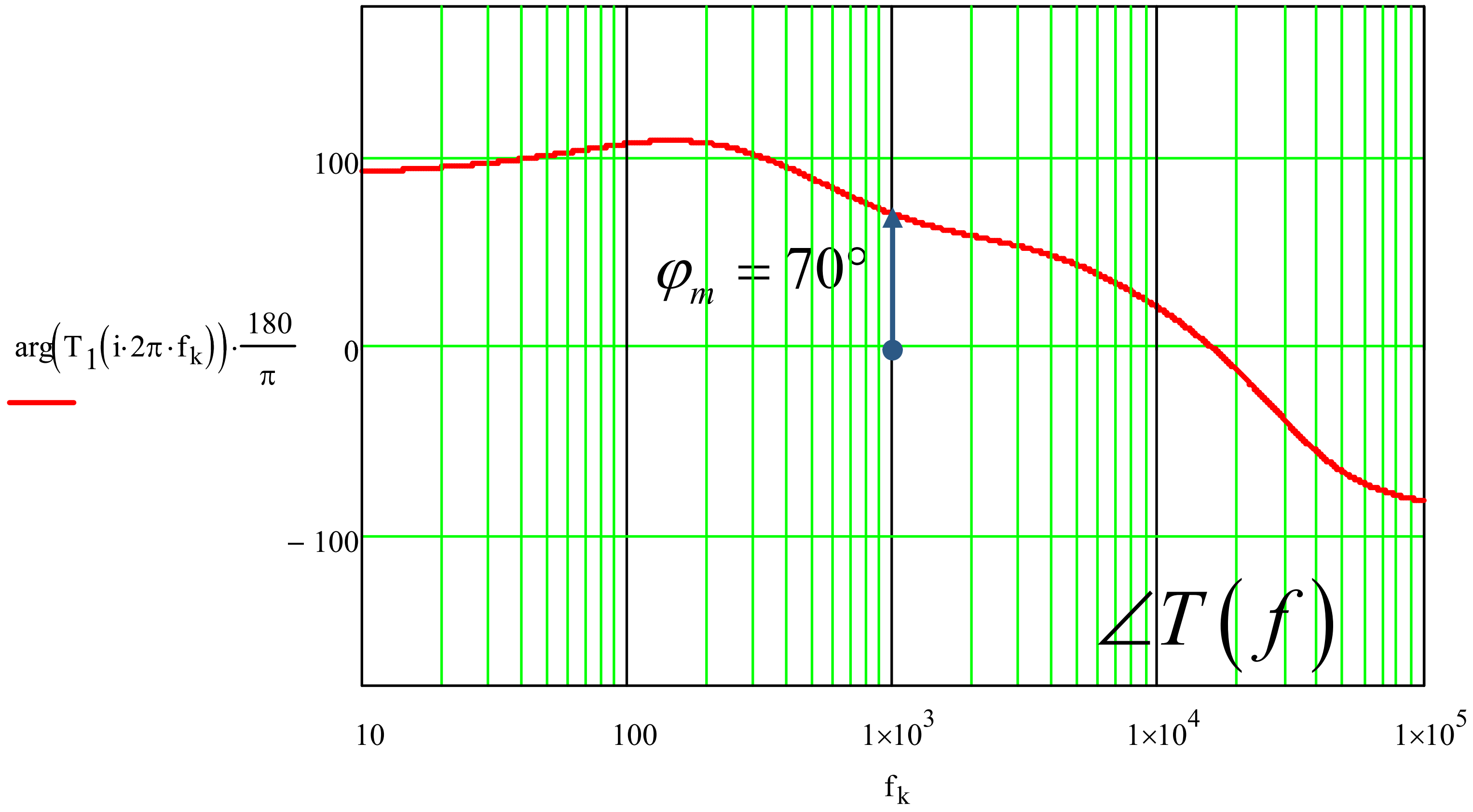
Plot the Compensated Loop Gain

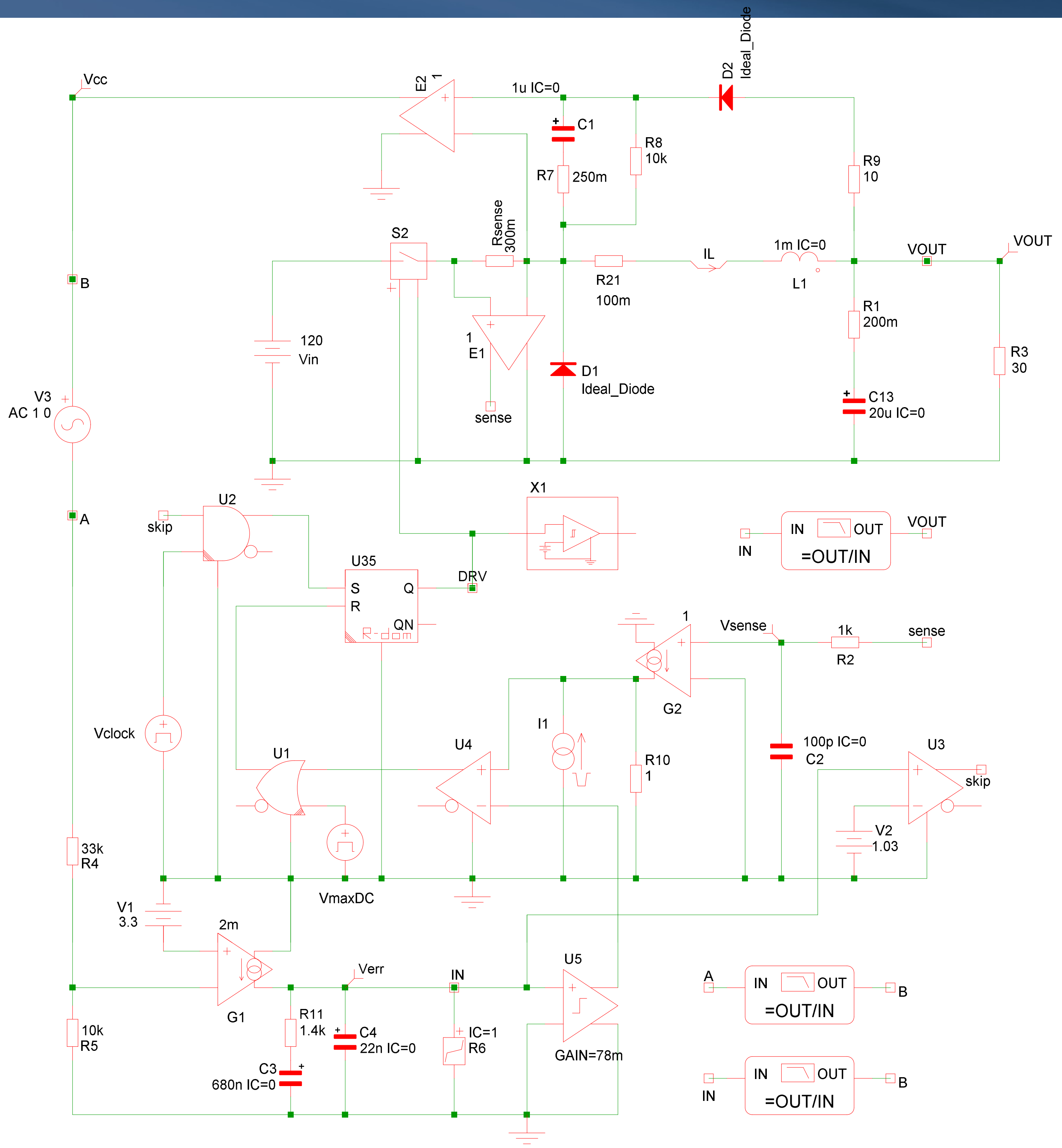
The loop gain is obtained by cascading the plant transfer function with the compensator transfer function

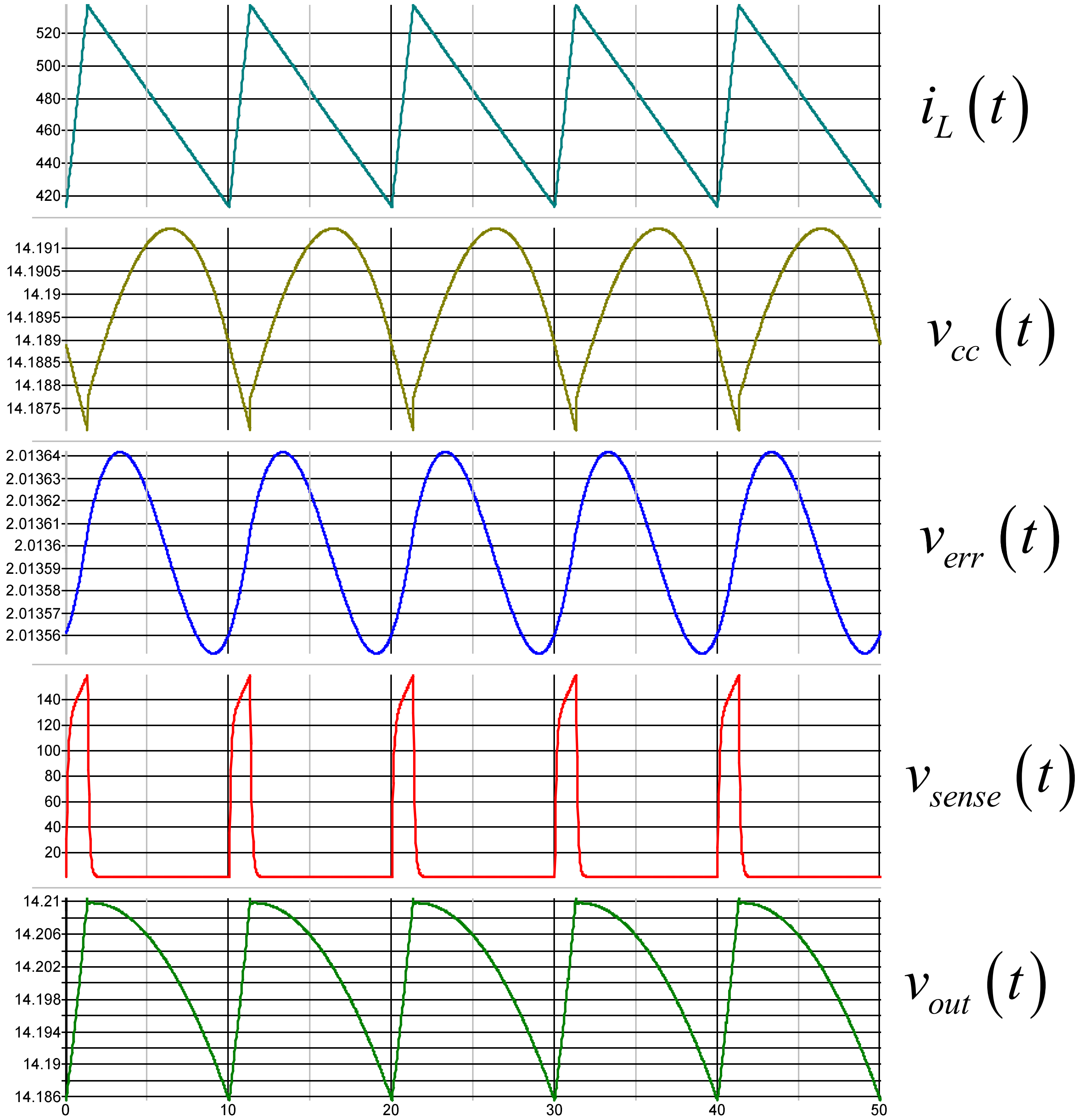
$$T(s) = H(s)C(s)G(s)$$



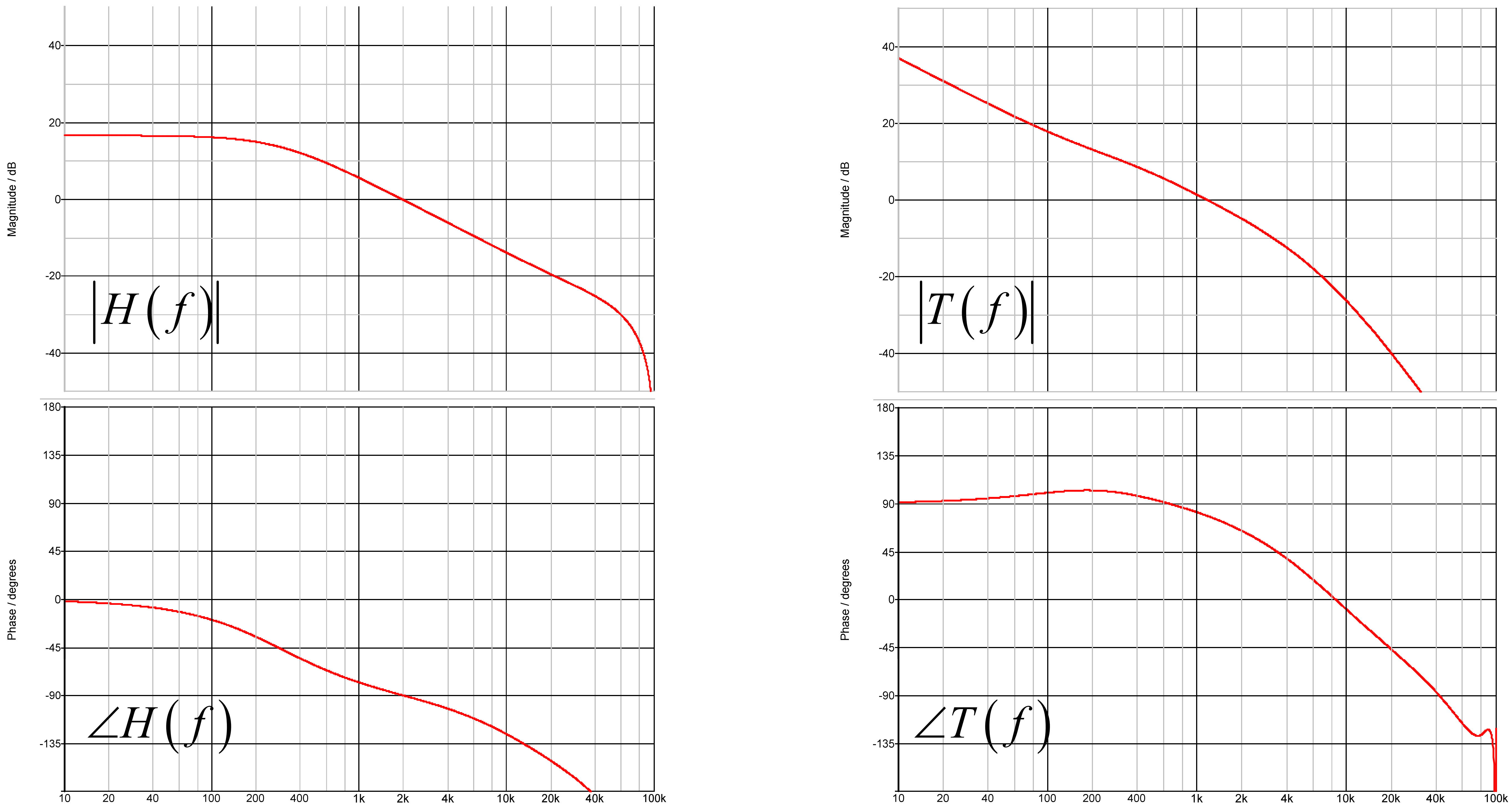


Simulate with SIMPLIS®





Check Plant and Loop Gains



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Conclusion

❑ The compensation of the NCP1060 in a CCM-operated buck converter is done via a few steps

1. Determine the control-to-output transfer function (with Mathcad® or SIMPLIS®)
2. Extract the magnitude and phase at the selected crossover frequency
3. Build a type-2 compensator with the built-in OTA
4. Check the complete loop gain $T(s)$ at different operating conditions
5. Sweep all parasitics (ESRs, capacitor etc.) and check there is always a sufficiently-high phase margin