

# Designing Control Loops for Linear and Switching Power Supplies: A Tutorial Guide – 2<sup>nd</sup> print

Christophe Basso – April 2014  
Last update October 2023

Corrections of typos, mistakes and errors found by readers or by the author himself.

**Page 12:** figure 1.13, a “-“ sign is missing at the end of the vertical arrow, below the first summation circle.

Contributed by Ken Shirriff, April 2014

**Page 13:** ...value. **After** a certain time designated as...

Contributed by Ken Shirriff, April 2014

**Page 13:** ...be approximated **by** a linear system...

Contributed by Ken Shirriff, April 2014

**Page 16:** a possible test fixture... not text fixture

Contributed by Ken Shirriff, April 2014

**Page 16:** figure 1.17, ...(amplitude-phase couples) **are** recorded at each frequency step.

Contributed by Ken Shirriff, April 2014

**Page 17:** The decibel, one tenth of a bel not a bell.

Contributed by Ken Shirriff, April 2014

**Page 17:** ...compress the  $x$  and  $y$  **axes**.

Contributed by Ken Shirriff, April 2014

**Page 17:** End of the page: ... the ratio increase between the second point and the starting point.

Contributed by Ahmed Yousef, September 2015

**Page 18:** ...the corner frequency is the frequency **at which** the transfer function magnitude...

Contributed by Ken Shirriff, April 2014

**Page 18:** above equation (1.18), last bullet: ...in other words,

$$S = \frac{y_2 - y_1}{x_2 - x_1} = \frac{y_2 - y_1}{\log_{10} f_2 - \log_{10} f_1} \quad (1.18)$$

(1.19) needs an update as well:

$$S = \frac{-20}{\log_{10} \left( \frac{10f_1}{f_1} \right)} = -20 \text{ dB/dec} \quad (1.19)$$

**Page 19:** ...of its **terminal's** voltage (actually...

Contributed by Ken Shirriff, April 2014

**Page 19:** Second paragraph: A first-order system exhibits an up or down slope of 1 or -1, respectively, implying...

Contributed by Ahmed Yousef, September 2015

**Page 20:** ...into a two-dimensional **plane**, the complex...

Contributed by Ken Shirriff, April 2014

**Page 20:** ...and  $Y(s)$  are **functions** of a complex...

Contributed by Ken Shirriff, April 2014

**Page 20:** ...that positive time only **remove comma** is considered (the function is said...)

Contributed by Ken Shirriff, April 2014

**Page 22:** Figure 1.20: ...by  $s$  **after** going through...

Contributed by Ken Shirriff, April 2014

**Page 25:** Figure 1.22: capacitor  $C_1$  should be 0.1  $\mu\text{F}$  in the Mathcad sheet.

Contributed by Ken Shirriff, April 2014

**Page 26:** Figure 1.24: when combining **asymptotic** responses,...

Contributed by Ken Shirriff, April 2014

**Page 52:** in Figure 2.16, all subscripts should be  $s_p$  and not  $s_z$ .

Contributed by Martin Svensson, April 2014

**Page 48:** In equation (2.90), the real parts have to be updated when the capacitor ESR goes to zero:

$$s_1 = -4.8k + j31.4k$$

$$s_2 = -4.8k - j31.4k$$

Contributed by Ahmed Yousef, September 2015

**Page 48:** As a result, the resonant frequency definition must also change but the result is unaffected:

$$\omega_0 = |s_1| = |s_2| = \sqrt{(4.8k)^2 + (31.4k)^2} = 31.73 \text{ krad/s or } 5.05 \text{ kHz}$$

Contributed by Ahmed Yousef, September 2015

**Page 51:** End of bullet 4: It is important to note that if the real part is 0, we have imaginary pole pairs of the form  $p_i = \pm j\omega$ .

Contributed by Ahmed Yousef, September 2015

**Page 55:** 3<sup>rd</sup> paragraph, second line: ...move to the right-half-*plane* section.

Contributed by Felix Lieberium, July 2022

**Page 57:** above (2.105) of course, “surface” has a different meaning in English: ...circulating in the load is the area of  $A_0$ , averaged...

**Page 58:** below Figure 2.22: In theory, the new *area*,  $A_1$ , should be...

**Page 60:** a typo in (2.113), the square in the denominators is missing.

$$\Delta I_L = \frac{V_{in}}{R_{load}} \left[ \frac{1}{(1-D_1)^2} - \frac{1}{(1-D_0)^2} \right] = \frac{10}{240} \left[ \frac{1}{(1-0.59)^2} - \frac{1}{(1-0.583)^2} \right] = 8.25 \text{ mA}$$

$$dt = \frac{8.25m}{160u} = 51.6 \mu\text{s}$$

In the text below, replace 10.6  $\mu\text{s}$  by 51.6  $\mu\text{s}$ .

Contributed by Orestis Polychronakis, February 2015

**Page 60:** below (2.112): Brought back to the inductor *current* change...

Contributed by Felix Lieberum, July 2022

**Page 86:** figure 3.9: the shift in magnitude is closer to 20 dB than 25.

Contributed by Felix Lieberum, July 2022

**Page 89:** Line 2: In  $\epsilon$  many theory books, ...

Contributed by Felix Lieberum, July 2022

**Page 128:** don't know why the 3 disappeared in expression (3.149):

$$-\omega\tau \approx -2 \left[ \frac{\omega}{\omega_\tau} - \frac{\left(\frac{\omega}{\omega_\tau}\right)^3}{3} + \frac{\left(\frac{\omega}{\omega_\tau}\right)^5}{5} \right]$$

Contributed by Jobe Chen, June 2020

**Page 145:** in equation (3.189), the term  $V_{out}(s)$  has disappeared from the equation:

$$\frac{V_{err}(s)}{V_{out}(s)} = -\frac{Z_f(s)}{R_{upper}}$$

Contributed by T L, September 2022

**Page 159:** the denominator in equation (4.2) is not homogeneous and the  $\omega_{p1}$  term has to go:

$$N = \frac{\omega_{p1}^2}{\omega_{p1}\omega_{z1} + \omega_{p1}\omega_{z2} - \omega_{z1}\omega_{z2}} - 1$$

This is a typo and the rest of the formulas is sound.

**Page 194:** a square is missing in the numerator and the division is by 2 to comply with the SPICE simulation. The final result is correct though:

$$|H(10k)| = H_0 \frac{\sqrt{1 + \left(\frac{f_c}{f_{z1}}\right)^2}}{\sqrt{\left(1 - \frac{f_c^2}{f_0^2}\right)^2 + \left(\frac{f_c}{f_0 Q}\right)^2}} = \frac{10}{2} \frac{\sqrt{1 + \left(\frac{10k}{10.3k}\right)^2}}{\sqrt{\left(1 - \frac{10k^2}{1.24k^2}\right)^2 + \left(\frac{10k}{1.24k \times 1.45}\right)^2}} = 0.108 \text{ or } -19.3 \text{ dB}$$

**Page 215:** equation (4.156) is suspicious. I actually took it from the paper referenced in [8] and included it without thinking it could be wrong. If you replace the definitions of the terms in  $a$  as defined page 214, you find  $a$  equals 0. I was alerted by a student, Siyu He, about this strange result and I decided to re-derive the equation myself. Develop (4.153) and rearrange the polynomial form, factoring  $s$  and  $s^2$ . You should find

$$G(s) = \frac{R_0 - r_C}{H_0 r_C} \frac{1 + s \left( \frac{QR_0 \omega_0 \omega_{z_1} - r_C \omega_{z_1} \omega_{z_2} + QR_0 \omega_0 \omega_{z_2}}{Q \omega_0 \omega_{z_1} \omega_{z_2} (R_0 - r_C)} \right) + s^2 \frac{R_0 \omega_0^2 - r_C \omega_{z_1} \omega_{z_2}}{\omega_0^2 \omega_{z_1} \omega_{z_2} (R_0 - r_C)}}{1 + s \left( \frac{H_0 Q r_C \omega_0^2 \omega_{z_2}}{H_0 Q r_C \omega_0^2 \omega_{z_1} \omega_{z_2}} \right)}$$

after simplification we have

$$G(s) = \frac{R_0 - r_C}{H_0 r_C} \frac{1 + s \left( \frac{QR_0 \omega_0 \omega_{z_1} - r_C \omega_{z_1} \omega_{z_2} + QR_0 \omega_0 \omega_{z_2}}{Q \omega_0 \omega_{z_1} \omega_{z_2} (R_0 - r_C)} \right) + s^2 \frac{R_0 \omega_0^2 - r_C \omega_{z_1} \omega_{z_2}}{\omega_0^2 \omega_{z_1} \omega_{z_2} (R_0 - r_C)}}{1 + \frac{s}{\omega_{z_1}}} = K_0 \frac{1 + a_1 s + a_2 s^2}{1 + \frac{s}{\omega_{z_1}}}$$

Considering a dominant low-frequency pole given by  $1/a_1$ , then the numerator simplifies to

$$G(s) \approx K_0 \frac{1 + s \left( \frac{R_0 (\omega_{z_1} + \omega_{z_2})}{\omega_{z_1} \omega_{z_2} (R_0 - r_C)} \right)}{1 + \frac{s}{\omega_{z_1}}} = K_0 \frac{1 + \frac{s}{\omega_{z_G}}}{1 + \frac{s}{\omega_{p_G}}}$$

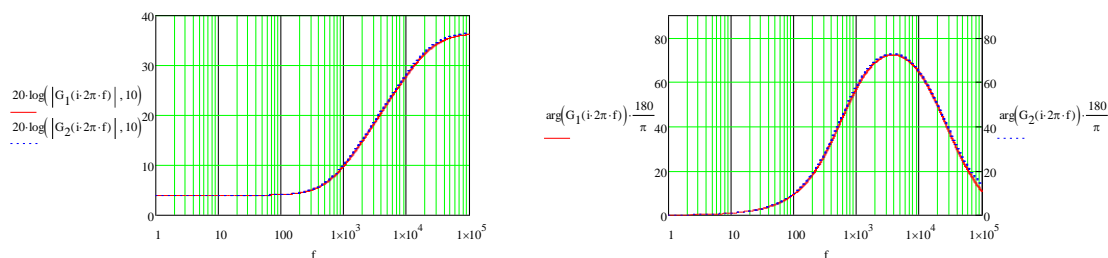
with

$$K_0 = \frac{R_0 - r_C}{H_0 r_C}$$

$$\omega_{z_G} = \frac{\omega_{z_1} \omega_{z_2}}{\omega_{z_1} + \omega_{z_2}} \frac{R_0 - r_C}{R_0}$$

$$\omega_{p_G} = \omega_{z_1}$$

The response comparing (4.153) in  $G_1(s)$  and the above equation in  $G_2(s)$  is shown below



Motivated by Siyu He, April 2015

**Page 273:** above 5.5.3: ...of the whole chain  $\neq$  is now  $90^\circ$ ...

**Page 286:** Equation (5.127) returns a wrong value:

$$G_2 = \frac{10^{\frac{-10}{20}}}{0.88} = 0.359 \quad (5.127)$$

And the two equations below then need an update also:

$$R_2 = R_1 G_2 = 38k \times 0.359 = 13.6 \text{ k}\Omega \quad (5.128)$$

$$C_1 = \frac{1}{2\pi f_z R_2} = \frac{1}{6.28 \times 1.8k \times 13.6k} = 6.5 \text{ nF} \quad (5.129)$$

Contributed by Dmitriy, March 2020

**Page 325:** equation (5.282), the value for the pole in  $C_2$  equation is  $f_{p1}$

$$C_2 = \frac{1}{2\pi R_{pullup} f_{p1}} \quad (5.282)$$

Contributed by X.H Zhu, October 2023

**Page 327:** equation (5.294), the value for the pole in  $C_2$  equation is  $f_{p1}$  but the value is unchanged as the 2 poles are coincident.

Contributed by X.H Zhu, October 2023

**Page 330:** equation (5.301), this is  $V_{err}(s)/V_{out}(s) = \dots$  and not  $V_{op}(s)/V_{out}(s)$

Contributed by Raymond Carr, July 2014

**Pages 339/340:** the value for the pole in  $C_2$  equation is  $f_{p1}$

**Page 364:** The selected OTA offers a 100- $\mu$ S transconductance and not 199- $\mu$ S

Contributed by Dmitriy, March 2020

**Page 398:** The  $R_{LED}$  maximum value...

Contributed by Felix Lieberium, July 2022

**Page 400:** The capacitor in formula (7.41) is  $C_2$  not  $C_1$

$$V_{err}(s) = -I_C(s) \frac{R_{pullup} \frac{1}{sC_2}}{R_{pullup} + \frac{1}{sC_2}} = -I_C(s) R_{pullup} \frac{1}{1 + sR_{pullup} C_2}$$

Contributed by Felix Lieberium, July 2022

**Page 417:** figure 7.25, the magnitude and phase are read at 20 Hz, not 1 kHz.

$$|G(20 \text{ Hz})| = -18.8 \text{ dB} \quad \text{and} \quad \arg G(20 \text{ Hz}) = -213^\circ$$

Contributed by Nicola Rosano, May 2020

**Page 421:** it is  $f_{p1}$  in (7.114)

$$C_2 = \frac{1}{2\pi R_{pullup} f_{p1}}$$

**Page 421:** it is  $f_{p1}$  in (7.124)

$$C_2 = \frac{1}{2\pi R_{pullup} f_{p1}} = \frac{1}{6.28 \times 20k \times 3.7k} = 2.15 \text{ nF}$$

**Page 430:** there is one typo in the application equation but those shown in Figure 7.33 macro are correct. The error lies in the value passed for  $G$  in (7.153). It should be 0.316 which corresponds to the 10-dB attenuation wanted at crossover.

$$R_2 = \frac{0.316 \times 38k \times 1.8k}{20k \times 0.3} \times \frac{\sqrt{1 + \left(\frac{1k}{4.5k}\right)^2} \sqrt{1 + \left(\frac{1k}{4.5k}\right)^2}}{\sqrt{1 + \left(\frac{221}{1k}\right)^2} \sqrt{1 + \left(\frac{1k}{221}\right)^2}} = 799 \Omega \quad (7.153)$$

$$C_1 = \frac{1}{2\pi f_{z1} R_2} = \frac{1}{6.28 \times 221 \times 799} \approx 900 \text{ nF} \quad (7.155)$$

$$C_2 = \frac{1}{2\pi f_{p1} R_{pullup}} = \frac{1}{6.28 \times 4.5k \times 20k} \approx 1.8 \text{ nF} \quad (7.156)$$

After several exchanges with Nicola and Dmitriy! The Mathcad sheet shows the values and the final Bode plot:

----- Components calculation according to the book, p429 -----

boost = 130°     $R_1 = 38 \text{ k}\Omega$      $R_{LED} = 1.8 \text{ k}\Omega$      $R_{pullup} = 20 \text{ k}\Omega$     CTR = 0.3     $C_1$

$\frac{G_0}{\omega} = 10 \left( \frac{f_c}{20} \right) = 0.316$

$f_{p12} = \frac{f_c}{\tan\left(45^\circ - \frac{\text{boost}}{4}\right)} = 4.511 \text{ kHz}$

$f_{z12} = \frac{f_c^2}{f_{p12}} = 221.695 \text{ Hz}$

$f_{p1} = f_{p12} = 4.511 \text{ kHz}$      $f_{z1} = f_{z12} = 221.695 \text{ Hz}$

$f_{p2} = f_{p12} = 4.511 \text{ kHz}$      $f_{z2} = f_{z12} = 221.695 \text{ Hz}$

$R_2 = \frac{G R_1 R_{LED} \sqrt{1 + \left(\frac{f_c}{f_{p1}}\right)^2} \sqrt{1 + \left(\frac{f_c}{f_{p2}}\right)^2}}{R_{pullup} \text{ CTR} \sqrt{1 + \left(\frac{f_{z1}}{f_c}\right)^2} \sqrt{1 + \left(\frac{f_{z2}}{f_c}\right)^2}} = 799.208 \Omega$

$R_3 = \frac{R_1 f_{z2}}{f_{p2} - f_{z2}} = 1.964 \text{ k}\Omega$

$C_3 = \frac{1}{2\pi \cdot f_{z1} \cdot R_2} = 898.266 \text{ nF}$

$C_4 = \frac{1}{2\pi \cdot f_{p1} \cdot R_{pullup}} = 1.764 \text{ nF}$

$C_5 = \frac{f_{p2} - f_{z2}}{2\pi \cdot R_1 \cdot f_{p2} \cdot f_{z2}} = 17.964 \text{ nF}$

$C_{10} = \frac{R_2 \cdot R_{pullup} \cdot \text{CTR}}{R_{LED} \cdot R_1} = 0.07$

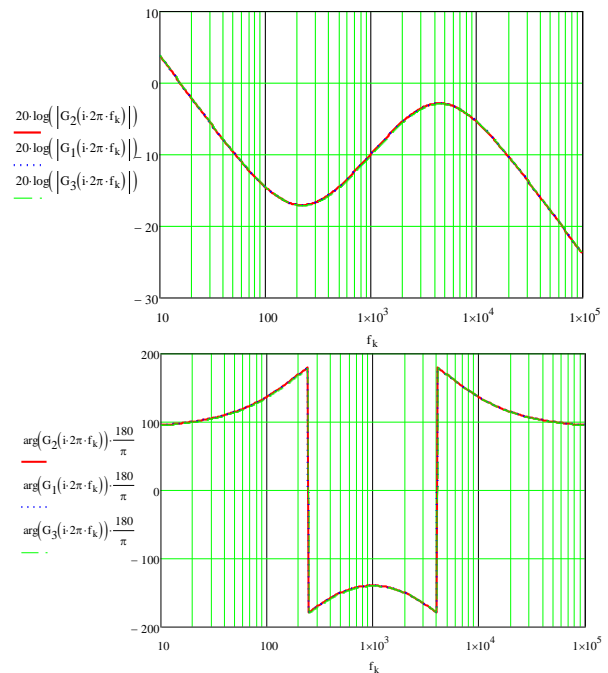
$G_2(s) = \frac{R_2 \cdot R_{pullup} \cdot \text{CTR} \left(1 + \frac{1}{s \cdot R_2 \cdot C_1}\right) \left[1 + s \cdot C_3 \cdot (R_1 + R_3)\right]}{R_{LED} \cdot R_1 \left(1 + s \cdot R_{pullup} \cdot C_2\right) \left(1 + s \cdot R_3 \cdot C_3\right)}$      $f_{\omega} = 1 \text{ kHz}$

$20 \log\left(\left|G_2(i \cdot 2\pi \cdot f_k)\right|\right) = -10 \quad \text{atan}\left(\frac{f_c}{f_{z1}}\right) + \text{atan}\left(\frac{f_c}{f_{z2}}\right) - 2 \cdot \text{atan}\left(\frac{f_c}{f_{p12}}\right) = 130^\circ$

$f_{z1a} = \frac{1}{2\pi \cdot R_2 \cdot C_1} = 221.695 \text{ Hz}$      $f_{z2a} = \frac{1}{2\pi \cdot R_3 \cdot (R_1 + R_3)} = 221.695 \text{ Hz}$

$f_{p1a} = \frac{1}{2\pi \cdot R_{pullup} \cdot C_2} = 4.511 \text{ kHz}$      $f_{p2a} = \frac{1}{2\pi \cdot R_3 \cdot C_3} = 4.511 \text{ kHz}$

$$G_3(s) := -G_{00} \frac{1 + \frac{2\pi \cdot f_{z1}}{s} \left(1 + \frac{s}{2\pi \cdot f_{z2}}\right)}{1 + \frac{s}{2\pi \cdot f_{p1}} \left(1 + \frac{s}{2\pi \cdot f_{p2}}\right)}$$



The formulas were good in the IsSpice sheet but went wrong once copied in the book.

**Page 445:** in Figure 7.47 and Figure 7.48, the resistance involved in calculating  $C_{opto}$  is  $R_{pullup}$  considering the configuration.

Contributed by Felix Lieberum, July 2022

**Page 506:** 8<sup>th</sup> line: ...characterize the other one (*fast* lane) by...

**Page 532:** equation (9.78), a square is missing in the denominator

$$|H(f)| = 20 \text{Log}_{10} \left[ H_0 \frac{\sqrt{1 + \left(\frac{f}{f_{z_1}}\right)^2} \sqrt{1 + \left(\frac{f}{f_{z_2}}\right)^2}}{\sqrt{\left(1 - \left(\frac{f}{f_0}\right)^2\right)^2 + \left(\frac{f}{f_0 Q}\right)^2}} \right]$$

Contributed by Edwin Marte, April 2015

**Page 534:** equation (9.85) went wrong and should be corrected:

$$|G(f)| \approx 20 \cdot \text{Log}_{10} \left[ \frac{R_2}{R_1} \frac{\sqrt{1 + \left(\frac{f_{z_1}}{f}\right)^2} \sqrt{1 + \left(\frac{f}{f_{z_2}}\right)^2}}{\sqrt{1 + \left(\frac{f}{f_{p_1}}\right)^2} \sqrt{1 + \left(\frac{f}{f_{p_2}}\right)^2}} \right]$$

Contributed by Raymond Carr, October 2014