Designing Control Loops for Linear and Switching Power Supplies: A Tutorial Guide

Christophe Basso – October 2012
Last update March 3rd 2014

Corrections of typos, mistakes and errors found by readers or by the author himself.
Special thanks go to Mr Tomas Gubek from Czech Republic who really scrutinized the text line by line and caught a lot of typos and errors!

Page 9: Please note that the rise time is measured from 10 to 90 percent of the output waveform, $y(t)$, in the case of the damped response. For an under-damped response, like what we will study in Chapter 3, the rise time is measured from 0 to 100 percent.
Contributed by Krishnakumar Gopalakrishnan, May 2013

Page 34: equation (2.34) is reversed: $Q = \frac{\sqrt{10.25}}{5} \approx 0.64$

Contributed by Tomas Gubek, October 2013

Page 37: …in (2.42) its denominator has indeed the dimension of a time constant.

Page 56: 10th line from the top: …before transmitting it to the load (not source)
Contributed by Tomas Gubek, October 2013

Page 61: Figure 2.25: lower side: the label is not $v_{out}(t)$ but must be $i_{out}(t)$
Contributed by Tomas Gubek, October 2013

Page 62: Figure 2.26: upper side: the 200 µs label must be 300 µs.
Contributed by Tomas Gubek, October 2013

Page 65: Figure 2.27, caption: …if the zero of the numerator would lie…
Contributed by Tomas Gubek, October 2013

Page 65: in Figure 2.27, the total phase lag reaches 180° and not -180°

Page 68: some of the expression could include brackets to avoid confusion:

$$Z_{in}(s) = \frac{1}{sC} + R_4 \parallel (R_3 + R_2 \parallel R_1) = \frac{1 + sC\left[R_4 \parallel (R_3 + R_2 \parallel R_1)\right]}{sC} \qquad (2.136)$$

$$\omega_{z_1} = \frac{1}{sC\left[R_4 \parallel (R_3 + R_2 \parallel R_1)\right]} \qquad (2.138)$$

Contributed by Raymond Carr, February 2014

Page 69: the final equation should be labeled (2.142) and one of its terms subscript is wrong

$$Z_{in}(s) = R_1 + (R_3 + R_4) \parallel R_2 \frac{1 + sC\left[R_4 \parallel (R_3 + R_2 \parallel R_1)\right]}{1 + sC\left[R_1 + R_3 \parallel (R_4 + R_2)\right]} \qquad (2.142)$$

Contributed by Raymond Carr, February 2014

Page 73: Equation (2.160) should be $\mathcal{L}^{-1}\left\{\frac{1+s}{s^2+4}\right\} = -\frac{1-2j}{4j}e^{-2jt} + \frac{1+2j}{4j}e^{2jt}$

Contributed by Tomas Gubek, October 2013

Page 81: in Figure 3.5, the middle graph caption should be 29.32 dB and not 29.6 dB

Page 84: in Figure 3.7, the phase margin symbol should be φ_m and not ϕ_m

Page 84: in Figure 3.7, the lower right comment should be $\angle T(f) = -180°$

Page 98: Equation (3.32) should be $Q = \frac{1}{2\zeta} = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{1}{RC\omega_0} = \frac{L\omega_o}{R}$
Contributed by Tomas Gubek, October 2013

Page 99: last bullet, $Q > 0.5$, it should be corrected to: $Q > 0.5$ or $\zeta < 1$:
Contributed by Tomas Gubek, October 2013

Page 105: in (3.50) and (3.51), the Greek letter is sigma while it should be zeta:

$$t_r = \frac{\pi - \cos^{-1}(\zeta)}{\omega_0\sqrt{1-\zeta^2}} \tag{3.50}$$

$$\lim_{\zeta \to 0} \frac{\pi - \cos^{-1}(\zeta)}{\omega_0\sqrt{1-\zeta^2}} \approx \frac{\pi - \frac{\pi}{2}}{\omega_0} \approx \frac{1.6}{\omega_0} \tag{3.51}$$

Contributed by Tomas Gubek, October 2013

Page 107: Figure 3.26, caption: …ratio when lower than 1.
Contributed by Tomas Gubek, October 2013

Page 118: in the text, above Figure 3.33: …as sources that add and subtract…
Contributed by Tomas Gubek, October 2013

Page 118: the fifth reference is missing, it should be:

5. B. Erisman, R. Redl, "Optimizing the Load Transient Response of the Buck Converter", APEC'1998 proceedings, p. 170-176, vol. 1

Contributed by Tomas Gubek, October 2013

Page 155: equation dimension of (4.7) is wrong, it must be: $V_D(s) = \varepsilon(s)\tau_d s = \varepsilon(s)\frac{s}{\omega_{z_1}}$

Contributed by Tomas Gubek, October 2013

Page 157: …more friendly to us engineers than equation (4.8), isn't it?
Contributed by Tomas Gubek, October 2013

Page 166: … the output inductor (L_1) and the output capacitor (C_{out}) in Figure 4.11.
Contributed by Tomas Gubek, October 2013

Page 171: Terms in the ln quotient must be swapped, no impact on result:

$$Q = \sqrt{\left(\frac{\pi}{\ln k}\right)^2 + \frac{1}{4}} = \sqrt{\left(\frac{\pi}{\ln\frac{48.4}{21.5}}\right)^2 + \frac{1}{4}} = 3.9$$

Contributed by Tomas Gubek, October 2013

Page 181: in Figure 4.26, C_1 must be labeled 1 µF not 1 mF

Page 182: Equation (4.73) gives 1.4 Hz, not 14 Hz.
Contributed by Tomas Gubek, October 2013

Page 184: In equations (4.77) (4.78) and (4.79), this is arg $H(f_c)$ and not arg $T(f_c)$

$$\arg H(f_c) - 270° + boost = -360° + \varphi_m \qquad (4.77)$$

$$boost = -360° + \varphi_m - \arg H(f_c) + 270° = \varphi_m - \arg H(f_c) - 90° \qquad (4.78)$$

$$boost = \varphi_m - \arg H(f_c) - 90° = 70 + 71 - 90 = 51° \qquad (4.79)$$

Contributed by Tomas Gubek, October 2013

Page 194: Figure 4.39: 158° or -202° then 90° or -270° at the bottom
Contributed by Tomas Gubek, October 2013

Page 196: in the text, above (4.127): Suppose we need a phase boost of 120°, then…
Contributed by Tomas Gubek, October 2013

Page 200: in Figure 4.44, in this particular case, the label "146 Hz" is obviously misplaced and should occur before the 480-Hz label, at 0 dB.
Contributed by Tomas Gubek, October 2013

Page 203: in equation (4.140), it must be arg $H(f_c)$ and not arg $T(f_c)$

$$boost = \varphi_m - \arg H(f_c) - 90° = 70 + 134 - 90 = 114°$$

Contributed by Tomas Gubek, October 2013

Page 211: in Figure 4.57, $v_{out}(t)$ is the first curve on top, the square below is $i_{out}(t)$
Contributed by Tomas Gubek, October 2013

Page 215: in (4.159), we have 151 krad/s: $\omega_{p_G} = \omega_{z_1} = 151\,\text{krad/s}, f_{p_G} = f_{z_1} = 24.1\,\text{kHz}$
Contributed by Tomas Gubek, October 2013

Page 226: a small *s* should be in equation (4.190) and (4.191): $D(s) = \ldots$ and $Z_{out}(s) = \ldots$
Contributed by Tomas Gubek, October 2013

Page 226: (4.191) zero featuring the inductance must be reversed: $Z_{out}(s) = \ldots \dfrac{\left(1 + s\dfrac{L}{r_L}\right)(1+\ldots)}{\ldots}$
Contributed by Tomas Gubek, October 2013

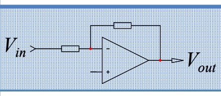
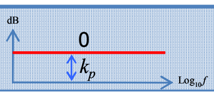
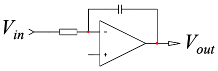
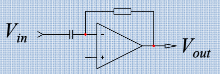
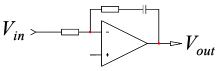
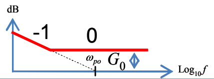
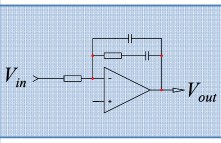
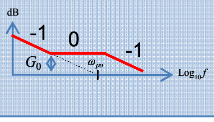
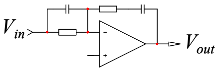
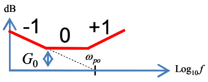
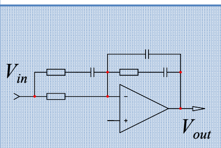
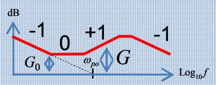
Page 250: in (4.261) the "-" sign must precede the parenthesis:

$$s_2 \approx \omega_0 \frac{-\left(1 - \dfrac{4Q^2}{2}\right) - 1}{2Q} = \omega_0 \left(\frac{2Q^2 - 2}{2Q}\right) \approx -\frac{\omega_0}{Q}$$

Contributed by Tomas Gubek, October 2013

Page 251: in Figure 4.98, the symbol next to the dB unit must be ° and not a crossed box!
Contributed by Tomas Gubek, October 2013

Page 252: in Table 4E.1, in expressions for PI, PI_2, PID and PID_2, to maintain a dimensionless expression, the term G_0 is actually ω_{po}/ω_{z_1}, the 0-dB crossover pole divided by the 1st zero. For clarity, G_0 can go and all expressions are divided by $-\frac{(\ldots)}{\frac{s}{\omega_{po}}(\ldots)}$. If you factor $\frac{s}{\omega_{z_1}}$ in the numerator, you have $\frac{\omega_{po}}{\omega_{z_1}}\frac{1+\frac{\omega_{z_1}}{s}}{\ldots}=G_0\frac{1+\frac{\omega_{z_1}}{s}}{\ldots}$ where the mid-band gain G_0 is now dimensionless.

Action Mode	Basic Element	Transfer Function	Implementation	Bode Plot $\lvert G(s)\rvert$	Type
Proportional	P	$G(s)=-k_p$			
Integral	I	$G(s)=-k_i\frac{1}{s}$			1
Derivative	D	$G(s)=-sk_d$			
Proportional Integral	PI	$G(s)=-G_0\left(1+\omega_{z_1}/s\right)$			2a
Proportional Integral + 1st-order lag	PI_1	$G(s)=-G_0\frac{1+\omega_{z_1}/s}{1+s/\omega_{p_1}}$			2
Proportional Integral Derivative	PID	$G(s)=-G_0\left(1+\omega_{z_1}/s\right)\left(1+s/\omega_{z_2}\right)$			3a
Proportional Integral Derivative + 2nd order lag	PID_2	$G(s)=-G_0\frac{\left(1+\omega_{z_1}/s\right)\left(1+s/\omega_{z_2}\right)}{\left(1+s/\omega_{p_1}\right)\left(1+s/\omega_{p_2}\right)}$ $G_0=\frac{\omega_{po}}{\omega_{z_1}}$			3

Contributed by Tomas Gubek, October 2013

Page 255: below equation (5.7): According to (5.5), to *amplify* the input signal by…
Contributed by Tomas Gubek, January 2014

Page 266: Figure 5.12, caption …; this is the type *2b* argument.
Contributed by Tomas Gubek, January 2014

Page 274: something went wrong here: $G_0=G_1G_2$
Contributed by Tomas Gubek, January 2014

Page 296: in Figure 5.34, caption: …Here, the *current* loop chain is not represented.

Page 300: …but also in the mid-*band* gain definition.
Contributed by Tomas Gubek, January 2014

Page 301: Suppose we need to create an attenuation of 20 dB at 10 Hz.

Page 303: Figure 5.40 is wrong. The right picture should be this one:

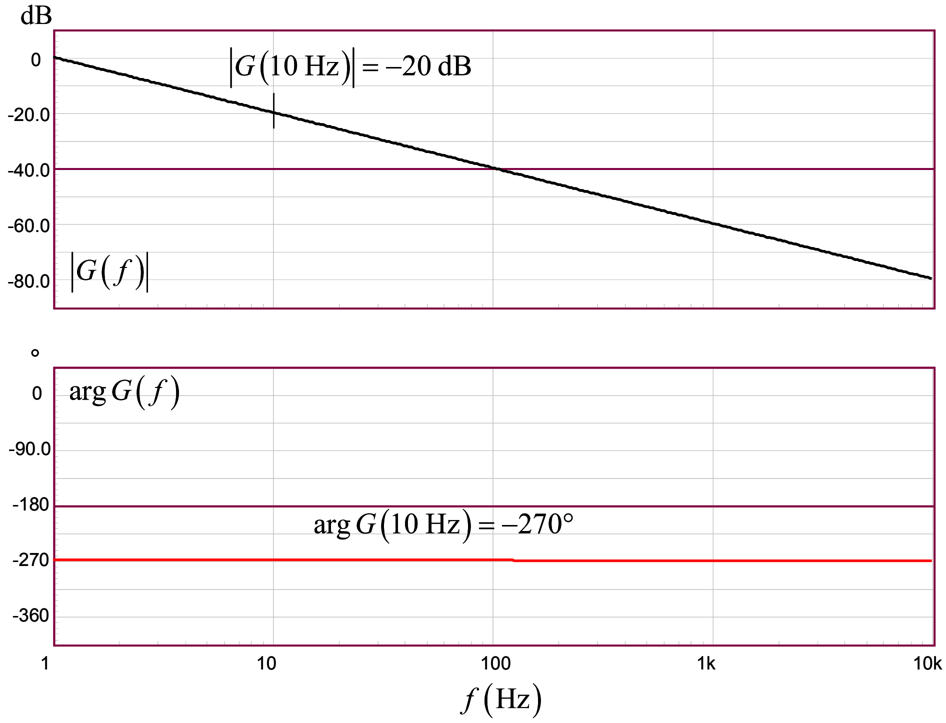


Figure 5.40: These ac results show the correct attenuation value at 10 Hz.
Contributed by Tomas Gubek, January 2014

Page 306: the text below equation (5.194) must be replaced up to *…than in first.*

Expressions and definitions now differ from what we originally derived for the classical type 2 compensator. In (5.13), assuming C_2 is much smaller than C_1, then the gain G_0 is defined by (5.22). In the above expressions, however, assuming than R_2 is much smaller than R_1, the gain G_0 in (5.189) simplifies to $\approx C_1/C_2$. If we equate both expressions (we want a similar mid-band gain with both configurations) and extract C_2, we have $C_2 = C_1 R_1/R_2$. As R_2 is smaller than R_1, then C_2 will be much larger than C_1. Therefore, as the entire current defined by (5.185) will cross C_2 at start-up, we can expect a longer charging time than with the traditional type 2 configuration.

Contributed by Tomas Gubek, January 2014

Page 307: the text after *…and 6.5 Hz* must be updated as below:

For the first case, Figure 5-5, C_1 equals 138 nF and C_2 is 16 nF. As expected, for a similar pole/zero arrangement, the second configuration (Figure 5-43) leads to a C_2 value of 154 nF.

Contributed by Tomas Gubek, January 2014

Page 310: in equation (5.209), R_{upper} is R_1: $C_3 = \frac{f_{p_2} - f_{z_2}}{2\pi R_1 f_{p_2} f_{z_2}}$

Contributed by Tomas Gubek, January 2014

Page 313: in equation (5.234), R_{upper} is R_1: $C_3 = \frac{f_{p_2} - f_{z_2}}{2\pi R_1 f_{p_2} f_{z_2}} = \frac{32.5k - 769}{6.28 \times 10k \times 32.5k \times 769} = 20\text{ nF}$

Contributed by Tomas Gubek, January 2014

Page 317: in equation (5.246), R_{upper} is R_1: $C_3 = \frac{f_{p_1} - f_{z_2}}{2\pi R_1 f_{p_1} f_{z_2}}$

Contributed by Tomas Gubek, January 2014

Page 321: in equation (5.259), $R_{pulldown}$ is R_{pullup}
Contributed by Tomas Gubek, January 2014

Page 332: …the phase must be boosted by 150°.
Contributed by Tomas Gubek, January 2014

Page 344: in the text below equation (5.362): …similar to that of the type 3 definition in (4.123) that Mr. Venable purposely squared:

$$k_{venable} = \left[\tan\left(\frac{boost}{4} + 45\right)\right]^2 \qquad (5.363)$$

Page 345: Figure 5.71:

$$k = \tan\left(\frac{boost}{2} + 45\right)$$

Page 351: The sentence is a bit misleading I believe. I meant that the peak amplitude decreases by 1.5 division. Perhaps it is simpler like that: …*increase it until the modulation occupies 7 divisions peak to peak. This point corresponds to a 3-dB drop from the reference point at 100 Hz*:
Contributed by Tomas Gubek, January 2014

Page 358: equation (6.6) needs to be cleaned up: $V_{(-)}(s) = V_{out}(s)\frac{R_{lower}}{R_{lower} + R_1}$

Contributed by Tomas Gubek, January 2014

Page 377: yes, the ratio between the 5-V output and the 2.5-V reference is 2, not 2.5! Therefore (6.90) is $boost_{5V} = 2\tan^{-1}\sqrt{2} - 90° = 19.5°$.
This would not allow a phase boost larger than 90°+19.5°=109.5°.
Contributed by Tomas Gubek, January 2014

Page 385: In figure 7.2, the bandgap…
Contributed by Tomas Gubek, January 2014

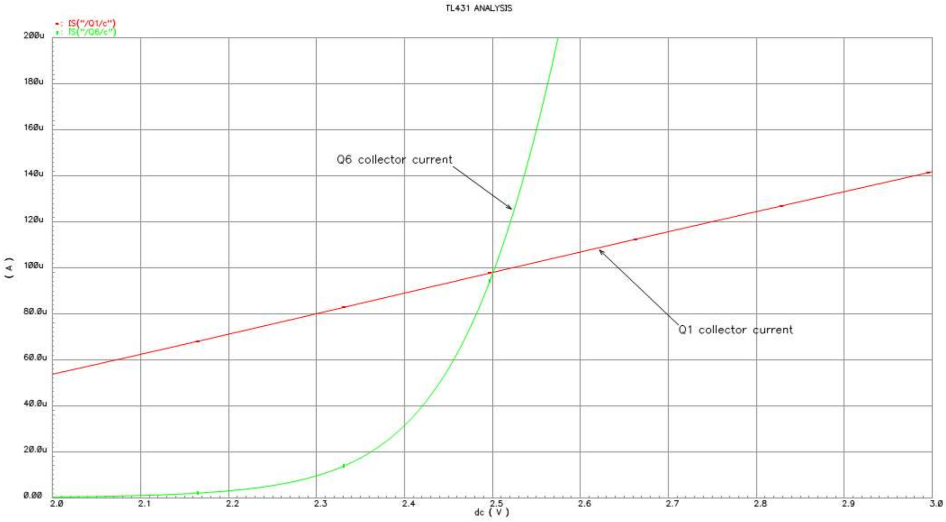
Page 386: After equation (7.12): This is the value displayed in Figure 7-2 over the *ref* node.
Contributed by Tomas Gubek, January 2014

Page 387: the paragraph below 7.1.2 needs a slight correction:

…working as a differential amplifier. However, the key point is the transconductance path from the V_{ref} node to Q_6 collector (also to Q_9 collector) that is much higher than the transconductance affecting the same V_{ref} node to Q_1 collector. We can show that the first transconductance involving Q_6 (or Q_9) is an exponential function while that involving Q_1 is a linear function. So when the loop leaves equilibrium and forces an increase of V_{ref}, Q_6 (Q_9) conducts more current than Q_1 and the cathode-anode voltage goes down via Q_{10} and Q_{11}.

Not for inclusion:

The below figure shows how these currents diverge when the 2.5-V reference level is left. Equilibrium is reached at V_{ref} equals 2.5 V, both transistors sink the exact same current and the TL431 cathode-anode voltage does not change. If V_{ref} increases, current in Q_6 increases at a significantly larger pace than that of Q_1, upsetting equilibrium: V_{KA} goes down.



Book section highlighted by Tomas Gubek, January 2014
Figure update kindly contributed by Petr Kadanka, January 2014

Page 388: Figure 7.4: of course, the "µ" had to transform into m… Yes, you should read 300 µV and 600 µA.

Page 394: In (7.26) the term V_f should be replace by 1.
Contributed by Tomas Gubek, January 2014

Page 414: the sentence below (7.95) should be: As the total capacitance is 618.3 nF…
Contributed by Tomas Gubek, January 2014

Page 433: Figure 7.35: of course, the "µ" had to transform into m… Yes, you should read 1000 µF and 0.1 µF for the 2 caps.

Page 437: the first parameter should be I_{Zbias}.
Contributed by Tomas Gubek, January 2014

Page 443: …Q_1 (if V_{out} decreases)
Contributed by Tomas Gubek, January 2014

Page 445: Figure 7.47: the sign ≤ has gone in the right side of R_{LED}.
Page 446: Figure 7.49: the sign ≤ has gone in the right side of R_{LED}.

Page 455: middle of the page: …account for *his* presence… → for *its* presence…

Page 455: in (8.2), 0.017 should be 0.018
Contributed by Tomas Gubek, January 2014

Page 495: some of the signs have gone during the print:
Figure 9.8, a minus sign is missing close the second arrow vertically pointing to the circle.

Page 499: the sign has gone during the print:
Figure 9.12, a minus sign is missing in the triangle, it is $-G(s)$ of course.
Contributed by Tomas Gubek, January 2014

Page 500: a question mark is in the middle of the sentence and has nothing to do here.
…at point B in relation? to…
…case, is delayed by 90°.
Contributed by Tomas Gubek, January 2014

Page 504: equation 9.26: the numerator is not Z_{out} of course, but Z_{in}:

$$T(s)=\frac{V_{err}(s)}{V_c(s)}=-G(s)H(s)\frac{Z_{in}(s)}{Z_{out}(s)+Z_{in}(s)}$$

Contributed by Thoralf Rosahl, February 2013

Page 514: equation 9.43, the denominator R_3 should obviously be the result of 9.42 (1.35 kΩ).

$$G_0=\frac{R_{pullup}\mathrm{CTR}_{\max}}{R_{3,\max}}=\frac{3.3k\times1.4}{1.35k}=3.42\text{ or }10.7\,\mathrm{dB}$$

In the text, …result found in (9.43) : 10.7 dB minimum gain.
Contributed by Tomas Gubek, February 2014

Page 515: in the text, 2nd paragraph, there is a reference to a source B_1 that is not labeled in Figure 9.29. It is actually the source right to the input source V_6, (V(err)-0.6)/3…
Contributed by Tomas Gubek, February 2014

Page 529: in figure 9.41, this is 10 µs and not 10 ms.
Contributed by John Pearson, February 2013

Page 531: in the upper section, reference [17] is wrong and it should be [14]
Contributed by John Pearson, February 2013

Page 540: some subscripts have disappeared when going to print. In figures 9.47/9.48/9.49 and 9.50, the π in r_π is gone, as well as β in $\beta I_b(s)$. Figure 9.51 is ok though.

Page 542: oops, I goofed the equation by replacing r_π by h_{11}:

$$\omega_z=\frac{\beta}{C_b r_\pi}$$

Contributed by Tomas Gubek, February 2014

Page 543: the sentence above (9.115), …and solving for the base current, we have:
Contributed by Tomas Gubek, February 2014

Page 543: in the sentence (9.116), this is R_{FB} not RFB.
Contributed by Tomas Gubek, February 2014

Page 550: to match equations below, in the upper component list $\beta \approx 73$.
Contributed by Tomas Gubek, February 2014

Page 555: in (9.149), it is $P_{R_1} = R_1 I_{R_1,rms}{}^2 = 0.377 \times 5.98^2 = 143.467\ \text{W}$
Contributed by Tomas Gubek, February 2014

Page 556: in (9.155) and (9.156), it is

$$Q = R\sqrt{\frac{C}{L}} \qquad (9.155)$$

$$Q = \frac{-R^2}{R-R}\sqrt{\frac{C}{L}} = \infty \qquad (9.155)$$

Contributed by Tomas Gubek, February 2014

Page 561: in Figures 9.69/9.70, C is 100 µF not 100 mF