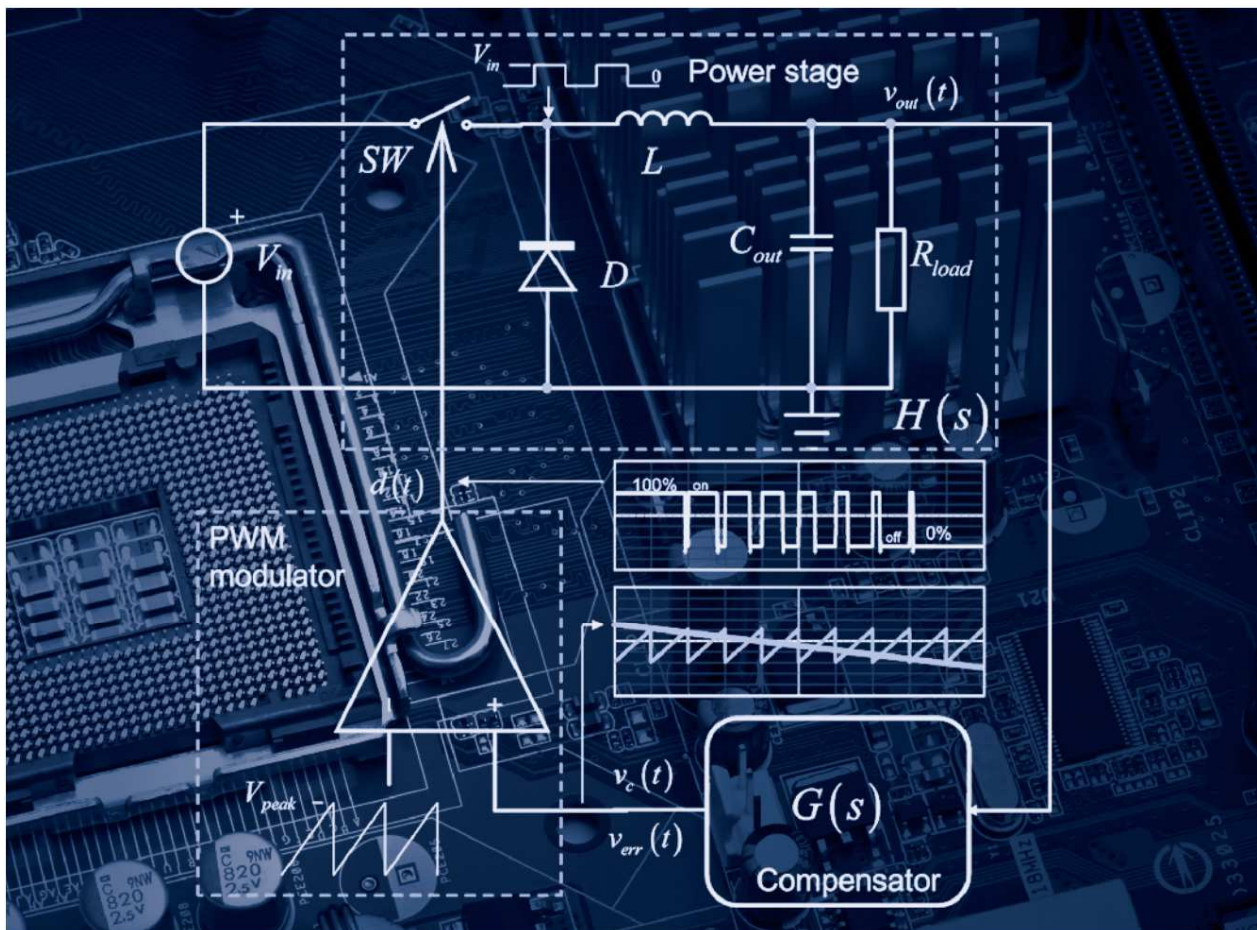


# DESIGNING CONTROL LOOPS for LINEAR and SWITCHING POWER SUPPLIES

## A TUTORIAL GUIDE



CHRISTOPHE BASSO

## CHAPTER 1

Basics of Loop Control	1
1.1 Open-Loop Systems	1
1.1.1 Perturbations	3
1.2 The Necessity of Control—Closed-Loop Systems	4
1.3 Notions of Time Constants	6
1.3.1 Working with Time Constants	7
1.3.2 The Proportional Term	9
1.3.3 The Derivative Term	10
1.3.4 The Integral Term	11
1.3.5 Combining the Factors	12
1.4 Performance of a Feedback Control System	12
1.4.1 Transient or Steady State?	13
1.4.2 The Step	15
1.4.3 The Sinusoidal Sweep	16
1.4.4 The Bode Plot	17
1.5 Transfer Functions	19
1.5.1 The Laplace Transform	20
1.5.2 Excitation and Response Signals	22
1.5.3 A Quick Example	23
1.5.4 Combining Transfer Functions with Bode Plots	25
1.6 Conclusion	27
Selected Bibliography	27

## CHAPTER 2

Transfer Functions	29
2.1 Expressing Transfer Functions	29
2.1.1 Writing Transfer Functions the Right Way	31
2.1.2 The 0-db Crossover Pole	32
2.2 Solving for the Roots	32
2.2.1 Poles and Zeros Found by Inspection	35
2.2.2 Poles, Zeros, and Time Constants	36

2.3	Transient Response and Roots	39
2.3.1	When the Roots Are Moving	43
2.4	S-Plane and Transient Response	49
2.4.1	Roots Trajectories in the Complex Plane	54
2.5	Zeros in the Right Half Plane	56
2.5.1	A Two-Step Conversion Process	56
2.5.2	The Inductor Current Slew-Rate Is the Limit	58
2.5.3	An Average Model to Visualize RHP Zero Effects	60
2.5.4	The Right Half Plane Zero in the Boost Converter	62
2.6	Conclusion	66
	References	66
	Appendix 2A: Determining a Bridge Input Impedance	67
	Reference	69
	Appendix 2B: Plotting Evans Loci with Mathcad	70
	Appendix 2C: Heaviside Expansion Formulas	71
	Reference	74
	Appendix 2D: Plotting a Right Half Plane Zero with SPICE	74

## CHAPTER 3

	Stability Criteria of a Control System	77
3.1	Building An Oscillator	77
3.1.1	Theory at Work	79
3.2	Stability Criteria	82
3.2.1	Gain Margin and Conditional Stability	84
3.2.2	Minimum Versus Nonminimum-Phase Functions	87
3.2.3	Nyquist Plots	89
3.2.4	Extracting the Basic Information from the Nyquist Plot	91
3.2.5	Modulus Margin	93
3.3	Transient Response, Quality Factor, and Phase Margin	97
3.3.1	A Second-Order System, the RLC Circuit	97
3.3.2	Transient Response of a Second-Order System	101
3.3.3	Phase Margin and Quality Factor	110
3.3.4	Opening the Loop to Measure the Phase Margin	117
3.3.5	The Phase Margin of a Switching Converter	120
3.3.6	Considering a Delay in the Conversion Process	122
3.3.7	The Delay in the Laplace Domain	127
3.3.8	Delay Margin versus Phase Margin	130
3.4	Selecting the Crossover Frequency	133
3.4.1	A Simplified Buck Converter	135
3.4.2	The Output Impedance in Closed-Loop Conditions	138
3.4.3	The Closed-Loop Output Impedance at Crossover	142
3.4.4	Scaling the Reference to Obtain the Desired Output	143
3.4.5	Increasing the Crossover Frequency Further	149
3.5	Conclusion	150
	References	151

## CHAPTER 4

Compensation	153
4.1 The PID Compensator	153
4.1.1 The PID Expressions in the Laplace Domain	155
4.1.2 Practical Implementation of a PID Compensator	157
4.1.3 Practical Implementation of a PI Compensator	161
4.1.4 The PID at Work in a Buck Converter	163
4.1.5 The Buck Converter Transient Response with the PID Compensation	170
4.1.6 The Setpoint Is Fixed: We Have a Regulator!	171
4.1.7 A Peaky Output Impedance Plot	174
4.2 Stabilizing the Converter with Poles-Zeros Placement	176
4.2.1 A Simple Step-by-Step Technique	177
4.2.2 The Plant Transfer Function	178
4.2.3 Canceling the Static Error with an Integrator	179
4.2.4 Adjusting the Gain with the Integrator: The Type 1	182
4.2.5 Locally Boosting the Phase at Crossover	183
4.2.6 Placing Poles and Zeros to Create Phase Boost	185
4.2.7 Create Phase Boost up to $90^\circ$ with a Single Pole/Zero Pair	189
4.2.8 Mid-Band Gain Adjustment with the Single Pole/Zero Pair: The Type 2	191
4.2.9 Design Example with a Type 2	192
4.2.10 Create Phase Boost up to $180^\circ$ with a Double Pole/Zero Pair	194
4.2.11 Mid-Band Gain Adjustment with the Double Pole/Zero Pair: The Type 3	197
4.2.12 Design Example with a Type 3	199
4.2.13 Selecting the Right Compensator Type	200
4.2.14 The Type 3 at Work with a Buck Converter	201
4.3 Output Impedance Shaping	210
4.3.1 Making the Output Impedance Resistive	212
4.4 Conclusion	221
References	222
Appendix 4A: The Buck Output Impedance with Fast Analytical Techniques	222
Reference	227
Appendix 4B: The Quality Factor from a Bode Plot with Group Delay	227
Appendix 4C: The Phase Display in Simulators or Mathematical Solvers	230
Calculating the Tangent	232
Accounting for the Quadrant	234
Improving the Arctangent Function	236
Phase Display in a SPICE Simulator	237
Conclusion	242
Reference	243
Appendix 4D: Impact of Open-Loop Gain and Origin Pole on OpAmp-Based Transfer Functions	243
The Integrator Case	248
Appendix 4E: Summary of Compensator Configurations	252

## CHAPTER 5

Operational Amplifiers-Based Compensators	253
5.1 Type 1: An Origin Pole	253
5.1.1 A Design Example	255
5.2 Type 2: An Origin Pole, plus a Pole/Zero Pair	257
5.2.1 A Design Example	260
5.3 Type 2a: An Origin Pole plus a Zero	262
5.3.1 A Design Example	263
5.4 Type 2b: Some Static Gain plus a Pole	264
5.4.1 A Design Example	266
5.5 Type 2: Isolation with an Optocoupler	267
5.5.1 Optocoupler and Op Amp: the Direct Connection, Common Emitter	269
5.5.2 A Design Example	271
5.5.3 Optocoupler and Op Amp: The Direct Connection, Common Collector	273
5.5.4 Optocoupler and Op Amp: The Direct Connection Common Emitter and UC384X	275
5.5.5 Optocoupler and Op Amp: Pull Down with Fast Lane	276
5.5.6 A Design Example	279
5.5.7 Optocoupler and Op Amp: Pull-Down with Fast Lane, Common Emitter, and UC384X	280
5.5.8 Optocoupler and Op Amp: Pull Down Without Fast Lane	283
5.5.9 A Design Example	285
5.5.10 Optocoupler and Op Amp: A Dual-Loop Approach in CC-CV Applications	288
5.5.11 A Design Example	293
5.6 The Type 2: Pole and Zero are Coincident to Create an Isolated Type 1	299
5.6.1 A Design Example	301
5.7 The Type 2: A Slightly Different Arrangement	303
5.8 The Type 3: An Origin Pole, a Pole/Zero Pair	308
5.8.1 A Design Example	313
5.9 The Type 3: Isolation with an Optocoupler	315
5.9.1 Optocoupler and Op Amp: The Direct Connection, Common Collector	315
5.9.2 A Design Example	317
5.9.3 Optocoupler and Op Amp: The Direct Connection, Common Emitter	319
5.9.4 Optocoupler and Op Amp: The Direct Connection, Common Emitter, and UC384X	321
5.9.5 Optocoupler and Op Amp: Pull-Down with Fast Lane	322
5.9.6 A Design Example	326
5.9.7 Optocoupler and Op Amp: Pull Down without Fast Lane	328
5.9.8 A Design Example	332
5.10 Conclusion	335
References	335

Appendix 5A: Summary Pictures	335
Appendix 5B: Automating Components Calculations with $k$ Factor	340
Type 1	340
Type 2	341
Type 3	342
Reference	344
Appendix 5C: The Optocoupler	346
Transmitting Light	346
Current Transfer Ratio	347
The Optocoupler Pole	348
Extracting the Optocoupler Pole	350
Watch for the LED Dynamic Resistance	351
Good Design Practices	354
References	355

## CHAPTER 6

Operational Transconductance Amplifier–Based Compensators	357
6.1 The Type 1: An Origin Pole	358
6.1.1 A Design Example	359
6.2 The Type 2: An Origin Pole plus a Pole/Zero Pair	360
6.2.1 A Design Example	364
6.3 Optocoupler and OTA: A Buffered Connection	365
6.3.1 A Design Example	368
6.4 The Type 3: An Origin Pole and a Pole/Zero Pair	370
6.4.1 A Design Example	377
6.5 Conclusion	380
Appendix 6A: Summary Pictures	380
References	381

## CHAPTER 7

TL431-Based Compensators	383
7.1 A Bandgap-Based Component	383
7.1.1 The Reference Voltage	385
7.1.2 The Need for Bias Current	387
7.2 Biasing the TL431: The Impact on the Gain	390
7.3 Biasing the TL431: A Different Arrangement	392
7.4 Biasing the TL431: Component Limits	395
7.5 The Fast Lane Is the Problem	396
7.6 Disabling the Fast Lane	397
7.7 The Type 1: An Origin Pole, Common-Emitter Configuration	399
7.7.1 A Design Example	402
7.8 The Type 1: Common-Collector Configuration	403
7.9 The Type 2: An Origin Pole plus a Pole/Zero Pair	403
7.9.1 A Design Example	407
7.10 The Type 2: Common-Emitter Configuration and UC384X	408
7.11 The Type 2: Common-Collector Configuration and UC384X	411

7.12	The Type 2: Disabling the Fast Lane	411
7.12.1	A Design Example	413
7.13	The Type 3: An Origin Pole plus a Double Pole/Zero Pair	415
7.13.1	A Design Example	423
7.14	The Type 3: An Origin Pole plus a Double Pole/Zero Pair—No Fast Lane	424
7.14.1	A Design Example	429
7.15	Testing the Ac Responses on a Bench	431
7.16	Isolated Zener-Based Compensator	434
7.16.1	A Design Example	436
7.17	Nonisolated Zener-Based Compensator	441
7.18	Nonisolated Zener-Based Compensator: A Lower Cost Version	443
7.19	Conclusion	445
	References	445
	Appendix 7A: Summary Pictures	445
	Appendix 7B: Second Stage <i>LC</i> Filter	448
	A Simplified Approach	449
	Simulation at Work	450
	References	454

## CHAPTER 8

	Shunt Regulator–Based Compensators	455
8.1	The Type 2: An Origin Pole plus a Pole/Zero Pair	456
8.1.1	A Design Example	460
8.2	The Type 3: An Origin Pole plus a Double Pole/Zero Pair	466
8.2.1	A Design Example	468
8.3	The Type 3: An Origin Pole plus a Double Pole/Zero Pair—No Fast Lane	471
8.3.1	A Design Example	474
8.4	Isolated Zener-Based Compensator	476
8.4.1	A Design Example	480
8.5	Conclusion	483
	References	483
	Appendix 8A: Summary Pictures	484

## CHAPTER 9

	Measurements and Design Examples	487
9.1	Measuring the Control System Transfer Function	487
9.1.1	Opening the Loop with Bias Point Loss	488
9.1.2	Power Stage Transfer Function without Bias Point Loss	492
9.1.3	Opening the Loop in ac Only	493
9.1.4	Voltage Variations at the Injection Points	496
9.1.5	Impedances at the Injection Points	504
9.1.6	Buffering the Data	505
9.2	Design Example 1: A Forward dc-dc Converter	509
9.2.1	Moving Parameters	509
9.2.2	The Electrical Schematic	511

9.2.3	Extracting the Power Stage Transfer Response	514
9.2.4	Compensating the Converter	515
9.3	Design Example 2: A Linear Regulator	519
9.3.1	Extracting the Power Stage Transfer Function	520
9.3.2	Crossover Frequency Selection and Compensation	521
9.3.3	Testing the Transient Response	527
9.4	Design Example 3: A CCM Voltage-Mode Boost Converter	528
9.4.1	The Power Stage Transfer Function	529
9.4.2	Compensating the Converter	533
	Strategy 1	535
	Strategy 2	535
9.4.3	Plotting the Loop Gain	537
9.5	Design Example 4: A Primary-Regulated Flyback Converter	539
9.5.1	Deriving the Transfer Function	540
9.5.2	Verifying the Equations	544
9.5.3	Stabilizing the Converter	545
9.6	Design Example 5: Input Filter Compensation	552
9.6.1	A Negative Incremental Resistance	553
9.6.2	Building an Oscillator	554
9.6.3	Taming the Oscillations	556
9.7	Conclusion	562
	References	562

# DESIGNING CONTROL LOOPS for LINEAR and SWITCHING POWER SUPPLIES

## A TUTORIAL GUIDE

CHRISTOPHE BASSO

Loop control is an essential area of electronics engineering that today's professionals need to master. Rather than delving into extensive theory, this practical book focuses on what engineers really need to know for compensating or stabilizing a given control system. Readers can turn instantly to practical sections with numerous design examples and ready-made formulas to help them with their projects in the field. Supported with over 450 illustrations and more than 1,500 equations, this authoritative volume:

- Demonstrates how to conduct analysis of control systems and provides extensive details on practical compensators;
- Helps engineers measure their system, showing how to verify whether or not a prototype is stable and features enough design margin;
- Explains how to secure high-volume production by bench-verified safety margins;
- Covers the underpinnings and principles of control loops, so readers can gain a more complete understanding of the material.

**Christophe Basso** is a product engineering director at ON Semiconductor in Toulouse, France. He received his B.S.E.E. in electronics from Montpellier University and his M.S.E.E. in power electronics from the National Polytechnic Institute of Toulouse. A senior member of the IEEE, Mr. Basso is recognized expert, patent holder, and author in the field.

Include bar code

ISBN 13: 978-1-60807-557-7  
ISBN 10: 1-60807-557-5



**ARTECH HOUSE**

BOSTON | LONDON

[www.artechhouse.com](http://www.artechhouse.com)