

Contents

Preface	xi
About the Author	xii
1. BUCK CONVERTER	1
1.1. BUCK CONVERTER IN CCM	1
1.1.1. Basic Operation in CCM	1
1.1.2. Static Analysis of the Buck converter in CCM	3
1.1.3. Dynamic Analysis of the Buck converter in CCM	4
1.1.4. Inductor Current and Output Voltage Ripples in CCM	9
1.1.5. CCM-DCM Boundary Condition	10
1.2. BUCK CONVERTER IN DCM	11
1.2.1. Basic Operation in DCM	11
1.2.2. Static Analysis of the Buck converter in DCM	13
1.2.3. Output Voltage Ripple in DCM	14
1.2.4. Dynamic Analysis of the Buck converter in DCM	15
1.3. SMALL-SIGNAL EQUIVALENT CIRCUIT OF A DC-DC CONVERTER	19
1.4. SUMMARY	20
1.4.1. Summary of Buck Converter in CCM	21
1.4.2. Summary of Buck Converter in DCM	21
2. BOOST CONVERTER	23
2.1. BOOST CONVERTER IN CCM	23
2.1.1. Basic Operation in CCM	23
2.1.2. Static Analysis of the Boost Converter in CCM	25
2.1.3. Dynamic Analysis of the Boost Converter in CCM	26
2.1.4. Inductor Current and Output Voltage Ripples in CCM	31
2.1.5. CCM-DCM Boundary Condition	31
2.2. BOOST CONVERTER IN DCM	32
2.2.1. Basic Operation in DCM	32
2.2.2. Static Analysis of the Boost Converter in DCM	35
2.2.3. Output Voltage Ripple in DCM	35
2.2.4. Dynamic Analysis of the Boost Converter in DCM	36
2.3. SUMMARY	40
2.3.1. Summary of Boost Converter in CCM	40
2.3.2. Summary of Boost Converter in DCM	41

3.	BUCK-BOOST CONVERTER	43
3.1.	BUCK-BOOST CONVERTER IN CCM	43
3.1.1.	Basic Operation in CCM	43
3.1.2.	Static Analysis of the Buck-Boost Converter in CCM	45
3.1.3.	Dynamic Analysis of the Buck-Boost Converter in CCM	46
3.1.4.	Inductor Current and Output Voltage Ripples in CCM	50
3.1.5.	CCM-DCM Boundary Condition	51
3.2.	BUCK-BOOST CONVERTER IN DCM	51
3.2.1.	Basic Operation in DCM	51
3.2.2.	Static Analysis of the Buck-Boost Converter in DCM	54
3.2.3.	Output Voltage Ripple in DCM	54
3.2.4.	Dynamic Analysis of the Buck-Boost Converter in DCM	55
3.3.	SUMMARY	59
3.3.1.	Summary of Buck-Boost Converter in CCM	59
3.3.2.	Summary of Buck-Boost Converter in DCM	60
4.	FLYBACK CONVERTER	61
4.1.	FLYBACK CONVERTER IN CCM	61
4.1.1.	Basic Operation in CCM	61
4.1.2.	Static Analysis of the Flyback Converter in CCM	65
4.1.3.	Dynamic Analysis of the Flyback Converter in CCM	66
4.1.4.	Inductor Current and Output Voltage Ripples in CCM	70
4.1.5.	CCM-DCM Boundary Condition	71
4.2.	FLYBACK CONVERTER IN DCM	71
4.2.1.	Basic Operation in DCM	71
4.2.2.	Static Analysis of the Flyback Converter in DCM	74
4.2.3.	Output Voltage Ripple in DCM	75
4.2.4.	Dynamic Analysis of the Flyback Converter in DCM	76
4.3.	SUMMARY	80
4.3.1.	Summary of Flyback Converter in CCM	80
4.3.2.	Summary of Flyback Converter in DCM	81

5.	FORWARD CONVERTER	83
5.1.	FORWARD CONVERTER IN CCM	83
5.1.1.	Basic Operation in CCM	83
5.1.2.	Static Analysis of the Forward Converter in CCM	86
5.1.3.	Simplified Averaged Circuit of the Forward Converter in CCM	87
5.1.4.	Dynamic Analysis of the Forward Converter in CCM	88
5.1.5.	Inductor Current and Output Voltage Ripples in CCM	93
5.1.6.	CCM-DCM Boundary Condition	93
5.2.	FORWARD CONVERTER IN DCM	94
5.2.1.	Basic Operation in DCM	94
5.2.2.	Static Analysis of the Forward Converter in DCM	97
5.2.3.	Output Voltage Ripple in CCM	97
5.2.4.	Dynamic Analysis of the Forward Converter in DCM	98
5.3.	SUMMARY	102
5.3.1.	Summary of Forward Converter in CCM	102
5.3.2.	Summary of Forward Converter in DCM	103
6.	HALF-BRIDGE CONVERTER	105
6.1.	HALF-BRIDGE CONVERTER IN CCM	105
6.1.1.	Basic Operation in CCM	105
6.1.2.	Static Analysis of the Half-Bridge Converter in CCM	108
6.1.3.	Simplified Averaged Circuit in CCM	108
6.1.4.	Dynamic Analysis of the Half-Bridge Converter in CCM	110
6.1.5.	Inductor Current and Output Voltage Ripples in CCM	114
6.1.6.	CCM-DCM Boundary Condition	115
6.2.	HALF-BRIDGE CONVERTER IN DCM	115
6.2.1.	Basic Operation in DCM	115
6.2.2.	Static Analysis of the Half-Bridge Converter in DCM	118
6.2.3.	Output Voltage Ripple in CCM	119
6.2.4.	Dynamic Analysis of the Half-Bridge Converter in DCM	119
6.3.	SUMMARY	123
6.3.1.	Summary of Half-Bridge Converter in CCM	123
6.3.2.	Summary of Half-Bridge Converter in DCM	124

7.	FULL-BRIDGE AND PUSH-PULL CONVERTER	127
7.1.	FULL-BRIDGE CONVERTER IN CCM	127
7.1.1.	Basic Operation in CCM	127
7.1.2.	Simplified Averaged Circuit in CCM	129
7.2.	FULL-BRIDGE CONVERTER IN DCM	130
7.2.1.	Basic Operation in DCM	130
7.2.2.	Simplified Averaged Circuit in DCM	131
7.3.	PUSH-PULL CONVERTER IN CCM	132
7.4.	PUSH-PULL CONVERTER IN DCM	134
7.5.	SUMMARY	135
7.5.1.	Summary of Full-Bridge and Push-Pull Converters in CCM	135
7.5.2.	Summary of Full-Bridge and Push-Pull Converters in DCM	136
8.	COMPENSATOR IMPLEMENTATION	137
8.1.	INTRODUCTION	137
8.2.	TYPE I COMPENSATOR	143
8.3.	TYPE II COMPENSATOR	145
8.4.	TYPE II COMPENSATOR WITH AN ADDITIONAL POLE	147
8.5.	OPA-BASED TYPE III COMPENSATOR	149
8.6.	OTA-BASED TYPE III COMPENSATOR	152
8.7.	EFFECT OF AMPLIFIER RESPONSE	154
8.7.1.	Effect of OPA Frequency Response	154
8.7.2.	Effect of OTA Frequency Response	175
8.8.	OPTO-ISOLATED COMPENSATORS	160
8.9.	TL431-BASED COMPENSATORS	163
8.9.1.	Non-Isolated TL431-Based Compensators	165
8.9.2.	Isolated TL431-Based Compensators	166
8.10.	EXAMPLES OF COMPENSATOR DESIGN	168
8.10.1.	Design of a Type II Compensator for a Voltage-Mode Buck Converter	169
8.10.2.	Design of a Type III Compensator for a Voltage-Mode Buck Converter	177

9.	CONTROL OF DC-DC CONVERTERS	181
9.1.	INTRODUCTION	181
9.2.	VOLTAGE-MODE CONTROL	182
9.2.1.	Introduction	182
9.2.2.	Difference Equations	183
9.2.3.	Modelling of PWM Modulator Including Sampling Effect	184
9.2.4.	Modelling of Loop Delay	192
9.3.	CURRENT-MODE CONTROL	195
9.3.1.	Introduction	195
9.3.2.	Dynamic Modelling of Current-Mode Control	197
9.3.3.	Example of Current-Mode Control Dynamic Response	202
9.4.	HYSTERETIC CONTROL	206
9.4.1.	Introduction	206
9.4.2.	Hysteretic Current Control	207
9.4.3.	Hysteretic Voltage Control	214
9.5.	ON-TIME CONTROL	217
9.5.1.	Introduction	217
9.5.2.	On-Time Current Control	217
9.5.3.	Constant On-Time Voltage Control	223
9.5.4.	Constant On-Time Voltage Control with Input Voltage Feedforward	228
9.6.	OFF-TIME CONTROL	228
9.6.1.	Introduction	228
9.6.2.	Off-Time Current Control	228
9.6.3.	Constant Off-Time Voltage Control	235
9.7.	SUMMARY OF CONTROL METHOD FEATURES	240
10.	SIMULATION OF DC-DC CONVERTERS	241
10.1.	INTRODUCTION	241
10.2.	SIMULATION OF THE ACTUAL CONVERTER	244
10.2.1.	Transient Simulation	244
10.2.2.	Duty Cycle to Output Voltage Frequency Response	246
10.2.3.	Audio Susceptibility Frequency Response	247
10.2.4.	Input Impedance Frequency Response	249
10.2.5.	Output Impedance Frequency Response	251

10.3.	SIMULATION OF THE AVERAGED CIRCUIT	253
10.3.1.	Transient Simulation	253
10.3.2.	Duty Cycle to Output Voltage Frequency Response	255
10.3.3.	Audio Susceptibility Frequency Response	256
10.3.4.	Input Impedance Frequency Response	258
10.3.5.	Output Impedance Frequency Response	260
10.4.	SIMULATION OF THE SMALL-SIGNAL AVERAGED CIRCUIT	262
10.4.1.	Duty Cycle to Output Voltage Frequency Response	262
10.4.2.	Audio Susceptibility Frequency Response	264
10.4.3.	Input Impedance Frequency Response	265
10.4.4.	Output Impedance Frequency Response	265
10.5.	SIMULATION OF POWER CONVERTER USING QSPICE	267
	INTRODUCTION	
	TYPE I COMPENSATOR	
	TYPE II COMPENSATOR	
	TYPE II COMPENSATOR WITH AN ADJUSTABLE ZERO	
	OTA-BASED TYPE II COMPENSATOR	
	EFFECT OF AMPLIFIER RESPONSE	
8.7.1.	Effect of OPA Frequency Response	
8.7.2.	Effect of OTA Frequency Response	
	OPTIMIZED COMPENSATOR DESIGN	
	TI-BASED COMPENSATORS	
8.9.1.	Non-Isolated Buck Converter	
8.9.2.	Isolated Buck Converter	
	EXAMPLES OF COMPENSATOR DESIGN	
8.10.1.	Design of Buck Converter	
8.10.2.	Design of Buck Converter with Voltage Feedback	
8.10.3.	Audio Susceptibility Frequency Response	
8.10.4.	Input Impedance Frequency Response	
8.10.5.	Output Impedance Frequency Response	