CONTENTS

Pref	Preface				
	PAF	RT I CIRCUITS FOR DC-TO-DC POWER CONVERSIO	N		
1	PWN	M Dc-to-Dc Power Conversion	3		
	1.1	PWM Dc-to-Dc Power Conversion	4		
		1.1.1 Dc-to-Dc Power Conversion	4		
		1.1.2 PWM Technique	6		
	1.2	Dc-to-Dc Power Conversion System	7		
	1.3	Features and Issues of PWM Dc-to-Dc Converter	8		
	1.4	Chapter Highlights	11		
		References	12		
2	Power Stage Components				
	2.1	Semiconductor Switches	13		
		2.1.1 MOSFETs	14		
		2.1.2 Diodes	15		
		2.1.3 MOSFET-Diode Pair as SPDT Switch	16		
	2.2	Energy Storage and Transfer Devices	17		
			yiii		

xiv CONTENTS

		2.2.1	Inductors	18
		2.2.2	Capacitors	26
		2.2.3	Transformers	31
	2.3	Switch	ing Circuits in Practice	39
		2.3.1	Solenoid Drive Circuits	39
		2.3.2	Capacitor Charging Circuit	45
	2.4	Summa	ry	50
		Referei	nces	51
		Proble	ms	52
3	Buck	(Conve	rter	71
	3.1	Ideal S	tep-Down Dc-to-Dc Power Conversion	72
	3.2	Buck C	Converter: Step-Down Dc-to-Dc Converter	74
		3.2.1	Evolution to Buck Converter	74
		3.2.2	Frequency-Domain Analysis	75
	3.3	Buck C	Converter in Start-Up Transient	78
		3.3.1	Piecewise Linear Analysis	78
		3.3.2	Start-up Response	78
	3.4	Buck C	Converter in Steady State	80
		3.4.1	Circuit Analysis Techniques	80
		3.4.2	Steady-State Analysis	82
		3.4.3	Estimation of Output Voltage Ripple	84
	3.5	Buck (Converter in Discontinuous Conduction Mode	89
		3.5.1	Origin of Discontinuous Conduction Mode Operation	90
		3.5.2	Conditions for DCM Operation	92
		3.5.3	Steady-State Operation in DCM	94
	3.6	Closed	-Loop Control of Buck Converter	99
		3.6.1	Closed-Loop Feedback Controller	99
		3.6.2	Responses of Closed-Loop Controlled Buck Converter	103
	3.7	Summ	ary	109
		Refere	nces	110
		Proble	ms	110
4	Dc-to-Dc Power Converter Circuits			
	4.1 Boost Co		Converter	124
		4.1.1	Evolution to Boost Converter	124
		4.1.2	Steady-State Analysis in CCM	126
		4.1.3	Steady-State Analysis in DCM	130

		4.1.4	Effects of Parasitic Resistance on Voltage Gain	132
	4.2	Buck/E	Boost Converter	135
		4.2.1	Evolution to Buck/Boost Converter	137
		4.2.2	Steady-State Analysis in CCM	137
		4.2.3	Steady-State Analysis in DCM	141
	4.3	Structu	re and Voltage Gain of Three Basic Converters	143
	4.4	Flybac	k Converter: Transformer-Isolated Buck/Boost Converter	145
		4.4.1	Evolution to Flyback Converter	145
		4.4.2	Steady-State Analysis in CCM	147
		4.4.3	Steady-State Analysis in DCM	150
	4.5	Bridge	-Type Buck-Derived Isolated Dc-to-Dc Converters	153
		4.5.1	Switch Network and Multi-Winding Transformer	154
		4.5.2	Full-Bridge Converter	157
		4.5.3	Half-Bridge Converter	163
		4.5.4	Push-Pull Converter	163
	4.6	Forwar	rd Converters	167
		4.6.1	Basic Operational Principles	167
		4.6.2	Tertiary-Winding Reset Forward Converter	172
		4.6.3	Two-Switch Forward Converter	177
	4.7	Summa	ary	177
		Refere	nces	180
		Proble	ms	181
-	NDT II	MODE	TIMO DVALANIOS AND DESIGNI OF DIVIN DO TO	D O
PA	ART II	MODE	LING, DYNAMICS, AND DESIGN OF PWM DC-TO- CONVERTERS	DC
_		DV		400
5	Mode	eling PV	WM Dc-to-Dc Converters	199
	5.1		ew of PWM Converter Modeling	200 202
	5.2	Averaging Power Stage Dynamics		
		5.2.1	State-Space Averaging	204
		5.2.2	Circuit Averaging	210
		5.2.3	Generalization of Circuit Averaging Technique	219
		5.2.4	Circuit Averaging and State-Space Averaging	220
	5.3	Linear	izing Averaged Power Stage Dynamics	221
		5.3.1	Linearization of Nonlinear Function and Small-Signal	
			Model	221
		5.3.2	Small-Signal Model for PWM Switch — PWM Switch	
			Model	223
		5.3.3	Small-Signal Model of Converter Power Stage	226

CONTENTS XV

xvi CONTENTS

	5.4	Frequei	ncy Response of Converter Power Stage	221
		5.4.1	Sinusoidal Response of Power Stage	228
		5.4.2	Frequency Response and s-Domain Small-Signal	
			Model of Power Stage	230
	5.5	Small-S	Signal Gain of PWM Block	232
	5.6	Small-S	Signal Model for PWM Dc-to-Dc Converters	234
		5.6.1	Voltage Feedback Circuit	234
		5.6.2	Small-Signal Model for PWM Converters	236
	5.7	Summa	ıry	238
		Referer	nces	239
		Probler	ns	239
6	Pow	er Stage	Transfer Functions	245
	6.1	Bode P	lot for Transfer Functions	245
		6.1.1	Basic Definitions	246
		6.1.2	Bode Plots for Multiplication Factors	248
		6.1.3	Bode Plot Construction for Transfer Functions	257
		6.1.4	Identification of Transfer Function from Bode Plot	262
	6.2	Power	Stage Transfer Functions of Buck Converter	264
		6.2.1	Input-to-Output Transfer Function	265
		6.2.2	Duty Ratio-to-Output Transfer Function	268
		6.2.3	Load Current-to-Output Transfer Function	270
	6.3	Power	Stage Transfer Functions of Boost Converter	271
		6.3.1	Input-to-Output Transfer Function	272
		6.3.2	Duty Ratio-to-Output Transfer Function and RHP Zero	273
		6.3.3	Load Current-to-Output Transfer Function	277
		6.3.4	Physical Origin of RHP Zero	278
	6.4	Power	Stage Transfer Functions of Buck/Boost Converter	281
	6.5	Empirical Methods for Small-Signal Analysis		
	6.6	6.6 Summary		286
		Refere	nces	287
		Proble	ms	289
7	Dynamic Performance of PWM Dc-to-Dc Converters			
	7.1	Stabili	ty	298
	7.2	Freque	ency-Domain Performance Criteria	301
		7.2.1	Loop Gain	301
		7.2.2	Audio-Susceptibility	302

			CONTENTS	XVII
		7.2.3	Output Impedance	303
	7.3	Time-I	Domain Performance Criteria	304
		7.3.1	Step Load Response	305
		7.3.2	Step Input Response	306
	7.4	Stabilit	ty of Dc-to-Dc Converters	307
		7.4.1	Stability of Linear Time-Invariant Systems	307
		7.4.2	Small-Signal Stability of Dc-to-Dc Converters	307
	7.5	Nyquis	st Criterion	308
	7.6	Relativ	e Stability: Gain Margin and Phase Margin	315
	7.7	Summa	ary	322
		Refere	nces	323
		Proble	ms	324
3	Clos	ed-Loop	o Performance and Feedback Compensation	331
	8.1	Asymp	ototic Analysis Method	332
		8.1.1	Concept of Asymptotic Analysis Method	332
		8.1.2	Examples of Asymptotic Analysis Method	334
	8.2	Freque	ncy-Domain Performance	339
		8.2.1	Audio-Susceptibility	340
		8.2.2	Output Impedance	343
	8.3	Voltage	e Feedback Compensation and Loop Gain	344
		8.3.1	Problems of Single Integrator	345
		8.3.2	Voltage Feedback Compensation	347
	8.4	Compe	ensation Design and Closed-Loop Performance	349
		8.4.1	Voltage Feedback Compensation and Loop Gain	349
		8.4.2	Feedback Compensation Design Guidelines	352
		8.4.3	Voltage Feedback Compensation and Closed-Loop	
			Performance	353
		8.4.4	Phase Margin and Closed-Loop Performance	367
		8.4.5	Compensation Zeros and Speed of Transient Responses	372
		8.4.6	Step Load Response	374
		8.4.7	Non-Minimum Phase System Case: Boost and	
			Buck/Boost Converters	379
	8.5	Summ	ary	383
		Refere	nces	385
		Proble	ms	385

9	Practical Considerations in Modeling, Analysis, and Design of PWM Converters 407					
	PWM Converters					
	9.1	Generalization of PWM Converter Model	408			
		9.1.1 Converter Modeling with Parasitic Resistances	408			
		9.1.2 Modeling and Analysis of PWM Converters in Do				
		Operation	415			
		9.1.3 Modeling of Isolated PWM Converters	425			
	9.2	Design and Analysis of Dc-to-Dc Converters with Practic	al			
		Source System	431			
		9.2.1 Audio-Susceptibility Analysis	432			
		9.2.2 Stability Analysis	434			
		9.2.3 Input Impedance of Regulated Dc-to-Dc Converte	er 441			
		9.2.4 Origin of Source-Impedance Induced Instability	446			
		9.2.5 Control Design with Source Impedance	447			
		9.2.6 Impacts of Source Impedance on Loop Gain and	i			
		Output Impedance	448			
	9.3	Consideration for Non-Resistive Load	449			
	9.4	Summary	452			
		References	453			
		Problems	454			
		PART III CURRENT MODE CONTROL				
10	Curr	ent Mode Control — Functional Basics and Cla	assical			
	Anal	lysis	465			
	10.1	Current Mode Control Basics	466			
		10.1.1 Evolution to Peak Current Mode Control	466			
		10.1.2 Benefits and Issues of Peak Current Mode Control	ol 475			
		10.1.3 Average Current Mode Control and Charge Control	col 476			
	10.2	Classical Analysis and Control Design Procedures	479			
		10.2.1 Small-Signal Model for Peak Current Mode Cont	rol 480			
		10.2.2 Loop Gain Analysis	486			
		10.2.3 Stability Analysis	489			
		10.2.4 Voltage Feedback Compensation	492			
		10.2.5 Control Design Procedures	497			
		10.2.6 Analysis of Converter Dynamics in DCM	507			
	10.3	Closed-Loop Performance of Peak Current Mode Control	509			
		10.3.1 Audio-Susceptibility Analysis	511			
		10.3.2 Output Impedance Analysis	516			

			CONTENTS	xix			
		10.3.3	Step Load Response Analysis	520			
	10.4	Current	Mode Control for Boost and Buck/Boost Converters	532			
		10.4.1	Stability Analysis and Control Design	532			
		10.4.2	Loop Gain Analysis	543			
	10.5	Summa		548			
		Referen		550			
		Problem	as	550			
11	Current Mode Control — Sampling Effects and New Control						
		ın Proce	· -	559			
	11.1	Samplin	ng Effects of Current Mode Control	560			
		11.1.1	Origin and Consequence of Sampling Effects	561			
		11.1.2	Modeling Methodology for Sampling Effects	564			
		11.1.3	Feedforward Gains	564			
		11.1.4	Complete s-Domain Model for Current Mode Control	565			
		11.1.5	Two Prevalent s-Domain Models for Current Mode				
			Control	565			
	11.2	Express	sions for s-Domain Model for Current Mode Control	568			
		11.2.1	Modified Small-Signal Model	568			
		11.2.2	Modulator Gain F_m^*	570			
		11.2.3	$H_e(s)$: s-Domain Representation of Sampling Effects	571			
		11.2.4	Feedforward Gains	580			
	11.3	New Co	ontrol Design Procedures for Current Mode Control	584			
		11.3.1	New Power Stage Model	584			
		11.3.2	Control-to-Output Transfer Function with Current				
			Loop Closed	586			
		11.3.3	Control Design Procedures	592			
		11.3.4	Correlation between New and Classical Design				
			Procedures	606			
	11.4	Off-Lin	e Flyback Converter with Optocoupler-Isolated Current				
		Mode (Control	612			
		11.4.1	Off-Line Power Supplies	612			
		11.4.2	Current Mode Control for Flyback Converter with				
			Optocoupler-Isolated Feedback	613			
	11.5	Summa		628			
		Referer	•	629			
		Probler	ns	629			
Inde	x			633			