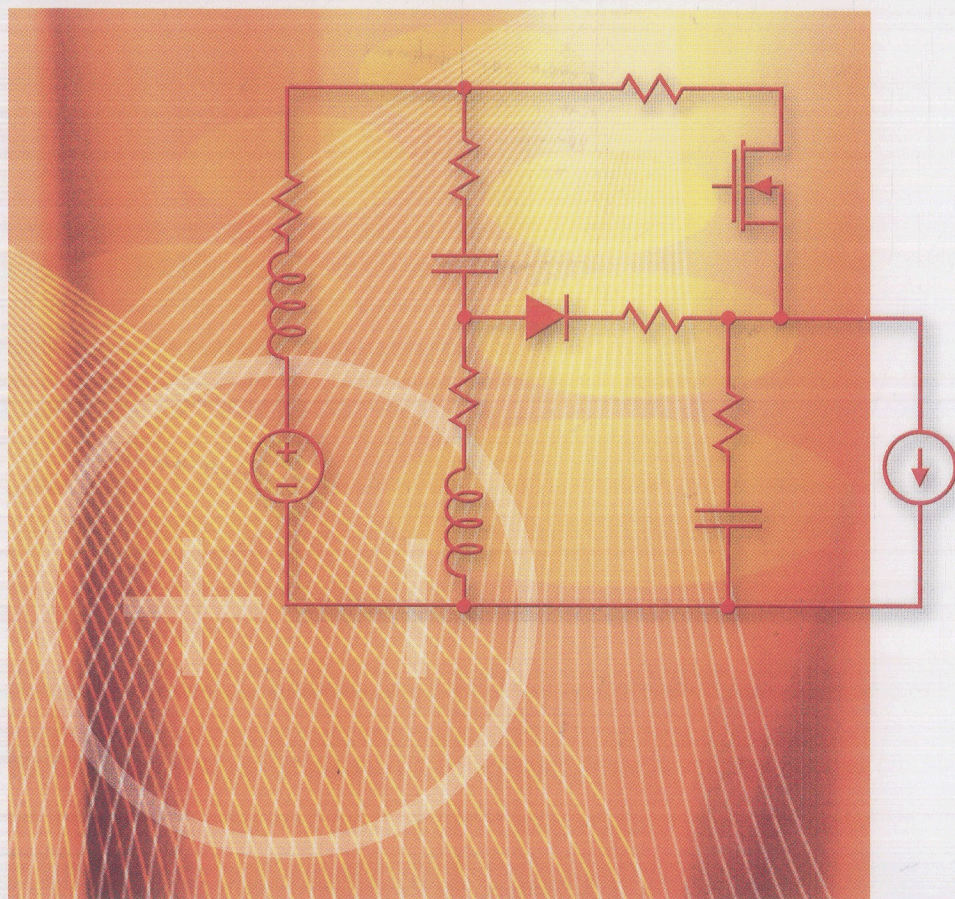


Teuvo Suntio

WILEY-VCH

# Dynamic Profile of Switched-Mode Converter

Modeling, Analysis and Control



# Contents

## Preface XI

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Introduction	1
1.2	Dynamic Modeling of Switched-Mode Converters	4
1.3	Dynamic Analysis of Interconnected Systems	6
1.4	Canonical Equivalent Circuit	8
1.5	Load-Response-Based Dynamic Analysis	9
1.6	Content Review	12
<b>2</b>	<b>Basis for Dynamic Analysis and Control Dynamics</b>	<b>17</b>
2.1	Introduction	17
2.2	Dynamic Representations at Open Loop	17
2.2.1	State Space	19
2.2.2	Two-Port Models	21
2.2.3	Control-Block Diagrams	23
2.3	Dynamic Representations at a Closed Loop	23
2.3.1	Voltage-Output Converter	26
2.3.2	Current-Output Converter	27
2.4	Load and Source Effects	28
2.4.1	Voltage-Output Converter	29
2.4.2	Current-Output Converter	31
2.5	An Example LC Circuit	33
2.5.1	Voltage-Output Circuit	33
2.5.2	Current-Output Circuit	35
2.6	Review of Basic Mathematical Tools	37
2.6.1	Linearization	37
2.6.2	Transfer Functions	38
2.6.2.1	Single Zero	39
2.6.2.2	Single Pole	40
2.6.2.3	Second-Order Transfer Function	40
2.6.2.4	Example	43
2.6.3	Stability and Performance	45

2.6.3.1	Stability	46
2.6.3.2	Loop-Gain-Related Dynamic Indices	48
2.6.3.3	Right-Half-Plane Zero and Pole	50
2.6.4	Matrix Algebra	50
2.6.4.1	Addition of Matrices	53
2.6.4.2	Multiplication by Scalar	53
2.6.4.3	Matrix Multiplication	54
2.6.4.4	Matrix Determinant	54
2.6.4.5	Matrix Inversion	55
2.7	Operational and Control Modes	55

### **3 Average and Small-Signal Modeling of Direct-On-Time Controlled Converters 59**

3.1	Introduction	59
3.2	Direct-on-Time Control	60
3.3	Generalized Modeling Technique	62
3.3.1	Buck Converter	64
3.3.2	Boost Converter	66
3.3.3	Buck–Boost Converter	68
3.4	Fixed-Frequency Operation in CCM	70
3.4.1	Synchronous Buck Converter	71
3.4.2	Dynamic Descriptions of Buck, Boost, and Buck–Boost Converters	76
3.4.2.1	Diode-Switched Buck (Figure 3.6a)	76
3.4.2.2	Diode-Switched Boost (Figure 3.8a)	77
3.4.2.3	Synchronous Boost (Figure 3.8b)	79
3.4.2.4	Diode-Switched Buck–Boost (Figure 3.10a)	80
3.4.2.5	Synchronous Buck–Boost (Figure 3.10b)	81
3.4.3	Steady-State and Small-Signal Equivalent Circuits	82
3.5	Fixed-Frequency Operation in DCM	85
3.5.1	Buck Converter	87
3.5.2	Dynamic Models for Boost and Buck–Boost Converters	92
3.5.2.1	Boost Converter (Figure 3.8a)	92
3.5.2.2	Buck–Boost Converter (Figure 3.10a)	94
3.6	Dynamic Review	95
3.6.1	Buck Converter	96
3.6.1.1	Control-to-Output Transfer Function	96
3.6.1.2	Output Impedance	98
3.6.1.3	Input-to-Output Transfer Function	100
3.6.1.4	Input Admittance	103
3.6.1.5	Ideal Input Admittance	104
3.6.1.6	Short-Circuit Input Admittance	106
3.6.2	Boost Converter	106
3.6.2.1	Control-to-Output Transfer Function	108
3.6.2.2	Output Impedance	109

3.6.2.3	Input-to-Output Transfer Functions	111
3.6.2.4	Input Admittance	112
3.6.2.5	Ideal Input Admittance	114
3.6.2.6	Short-Circuit Input Admittance	116
<b>4</b>	<b>Average and Small-Signal Modeling of Peak-Current-Mode Control</b>	<b>121</b>
4.1	Introduction	121
4.2	PCM-Control Principle	122
4.3	Modeling in CCM	124
4.3.1	Duty-Ratio Constraints for Buck, Boost, and Buck–Boost Converters	126
4.3.1.1	Buck Converter	126
4.3.1.2	Boost Converter	126
4.3.1.3	Buck–Boost	128
4.3.1.4	General CCM Transfer Functions	129
4.3.2	Specific Transfer Functions for the Basic Converters	131
4.3.2.1	Buck Converter	131
4.3.2.2	Boost Converter	133
4.3.2.3	Buck–Boost Converter	134
4.3.3	Origin and Consequences of Mode Limit in CCM	136
4.4	Modeling in DCM	139
4.4.1	Duty-Ratio Constraints for Basic Converters	140
4.4.1.1	Buck Converter	140
4.4.1.2	Boost Converter	142
4.4.1.3	Buck–boost Converter	142
4.4.2	Small-Signal PCMC State Spaces for the Basic Converters	143
4.4.3	Origin and Consequences of Mode Limit in DCM	144
4.5	Dynamic Review	146
4.5.1	Buck Converter	147
4.5.1.1	Control-to-Output Transfer Function	148
4.5.1.2	Output Impedance	151
4.5.1.3	Input-to-Output Transfer Function	152
4.5.1.4	Input Admittance	153
4.5.1.5	Ideal Input Admittance	155
4.5.1.6	Short-Circuit Input Admittance	155
4.5.2	Boost Converter	157
4.5.2.1	Control-to-Output Transfer Function	159
4.5.2.2	Output Impedance	161
4.5.2.3	Input-to-Output Transfer Function	163
4.5.2.4	Input Admittance	164
4.5.2.5	Ideal Input Admittance	165
4.5.2.6	Short-Circuit Input Admittance	166

<b>5</b>	<b>Average and Small-Signal Modeling of Average-Current-Mode Control</b>	<b>169</b>
5.1	Introduction	169
5.2	ACM-Control Principle	169
5.3	Modeling with Full-Ripple-Current Feedback	171
5.4	Dynamic Review	175
5.4.1	Control-to-Output Transfer Function	177
5.4.2	Output Impedance	177
5.4.3	Input-to-Output Transfer Function	179
5.4.4	Input Admittance	183
5.5	Effect of Current-Loop High-Frequency Pole	183
<b>6</b>	<b>Average and Small-Signal Modeling of Self-Oscillation Control</b>	<b>189</b>
6.1	Introduction	189
6.2	Self-Oscillation Modeling	189
6.2.1	Averaged Direct-on-Time Model	190
6.2.2	Small-Signal Direct-on-Time Model	193
6.2.3	Small-Signal PCM Models	194
6.3	Dynamic Review	198
6.3.1	Buck Converter	198
6.3.1.1	Control-to-Output Transfer Function	199
6.3.1.2	Output Impedance	199
6.3.1.3	Input-to-Output Transfer Function	201
6.3.1.4	Input Admittances	201
6.3.2	Flyback Converter	202
6.3.2.1	Control-to-Output Transfer Function	203
6.3.2.2	Output Impedance	206
6.3.2.3	Input-to-Output Transfer Function	206
6.3.2.4	Input Admittance	207
6.3.2.5	Ideal and Short-Circuit Admittances	208
<b>7</b>	<b>Dynamic Modeling and Analysis of Current-Output Converters</b>	<b>211</b>
7.1	Introduction	211
7.2	Dynamic Models for Current-Output Converter	212
7.2.1	Modified-State-Space-Averaging Technique	213
7.2.2	General Dynamic Models	215
7.3	Load and Supply Interactions	216
7.4	Cascaded Voltage-Current Loops	218
7.5	Dynamic Review	219
<b>8</b>	<b>Interconnected Systems</b>	<b>225</b>
8.1	Introduction	225
8.2	Theoretical Interaction Formulation	226
8.2.1	Load and Supply Interactions	227

8.2.2	Internal and Input–Output Stabilities	230
8.2.3	Output Voltage Remote Sensing	234
8.2.4	Input EMI Filter	236
8.3	Review of Methods to Reduce the Interactions	238
8.3.1	Input-Voltage Feedforward	238
8.3.2	Output-Current Feedforward	240
8.4	Experimental Dynamic Review	241
8.4.1	Load and Supply Interactions	243
8.4.2	Remote Sensing	251
8.4.3	System Stability	255
<b>9</b>	<b>Control Design Issues</b>	<b>261</b>
9.1	Introduction	261
9.2	Feedback-Loop-Design Constraints	265
9.2.1	Phase and Gain Margins	266
9.2.2	RHP Zeros and Poles	268
9.2.3	Minimum and Maximum Loop Crossover Frequencies	268
9.2.4	Internal Gain of an Operational Amplifier	270
9.3	Controller Implementations	271
9.4	Optocoupler Isolation	272
9.5	Shunt-Regulator-Based Control Systems	274
9.5.1	Dynamic Model	274
9.5.2	Two-Loop Control System	281
9.6	Simple Control-Design Method	284
9.6.1	Control Design Example: VMC Buck Converter	285
9.6.2	Control Design Example: PCMC Buck Converter	290
9.6.3	Control Design Example: VMC Boost Converter	295
9.6.4	Control Design Example: PCMC Boost Converter	298
9.7	Conclusions	302
<b>10</b>	<b>The Fourth-Order Converter – Superbuck</b>	<b>307</b>
10.1	Introduction	307
10.2	Basic Dynamics	309
10.2.1	Averaged Models	311
10.2.1.1	Averaged State Space	311
10.2.1.2	Steady-State Operating Point	311
10.2.1.3	Boundary Conduction Mode	312
10.2.2	Small-Signal Models	312
10.2.2.1	Small-Signal State Space	312
10.2.2.2	Transfer Functions	313
10.2.3	RHP Poles	315
10.2.4	Design Considerations	317
10.3	Coupled-Inductor Superbuck	318
10.3.1	Small-Signal Models	319

10.3.2	RHP Poles	322
10.3.3	Input-Current-Ripple Reduction	322
10.3.4	Design Considerations	325
10.4	PCM-Controlled Superbuck	325
10.4.1	Small-Signal Models	326
10.4.2	Design Considerations	330
10.4.2.1	Inductor-Current-Feedback Compensation	330
10.4.2.2	Avoiding RHP Poles	330
10.5	Coupled-Inductor PCM-Controlled Superbuck	331
10.5.1	Small-Signal Models	331
10.5.2	Design Considerations	336
10.6	Dynamic Review	337
10.6.1	Superbuck I: 15–20 V/10 V/2.5 A	337
10.6.2	Superbuck II: 6–9 V/3.4 V/12 A	345
10.7	Summary	348