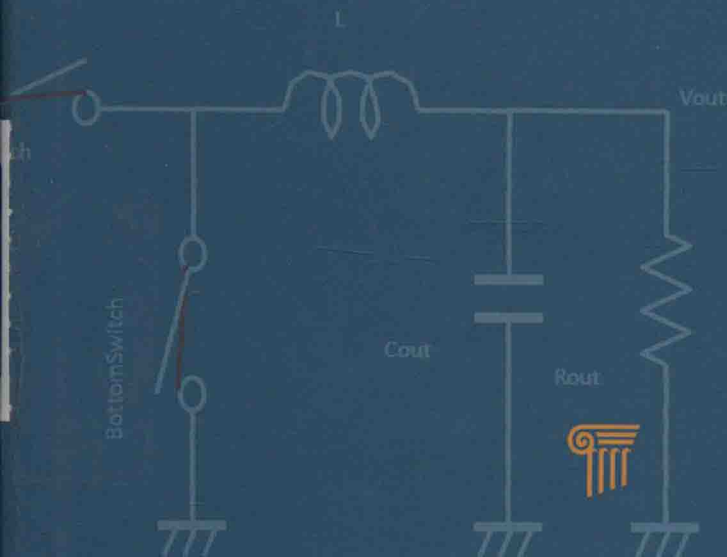


Handbook of Power Management Circuits

edited by

Haruo Kobayashi

Takashi Nabeshima



$$V_{out} = \frac{T_{on}}{T_{on} + T_{off}} V_{in}$$
$$= \frac{T_{on}}{T} V_{in}$$

Handbook of Power Management Circuits

edited by

Haruo Kobayashi
Takashi Nabeshima

Published by

Pan Stanford Publishing Pte. Ltd.
Penthouse Level, Suntec Tower 3
8 Temasek Boulevard
Singapore 038988

Email: editorial@panstanford.com

Web: www.panstanford.com

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Handbook of Power Management Circuits

Copyright © 2016 by Pan Stanford Publishing Pte. Ltd.

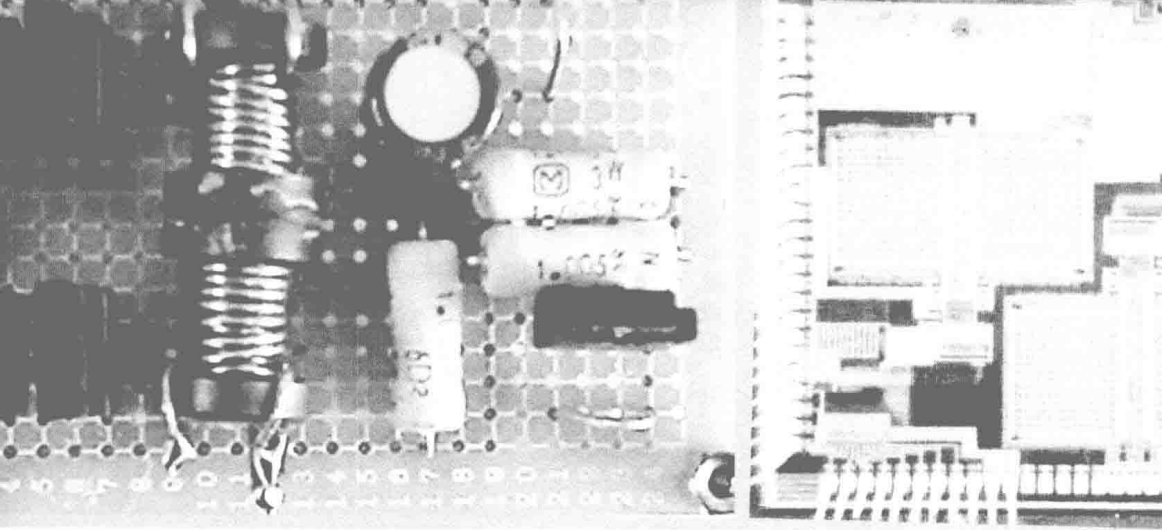
All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

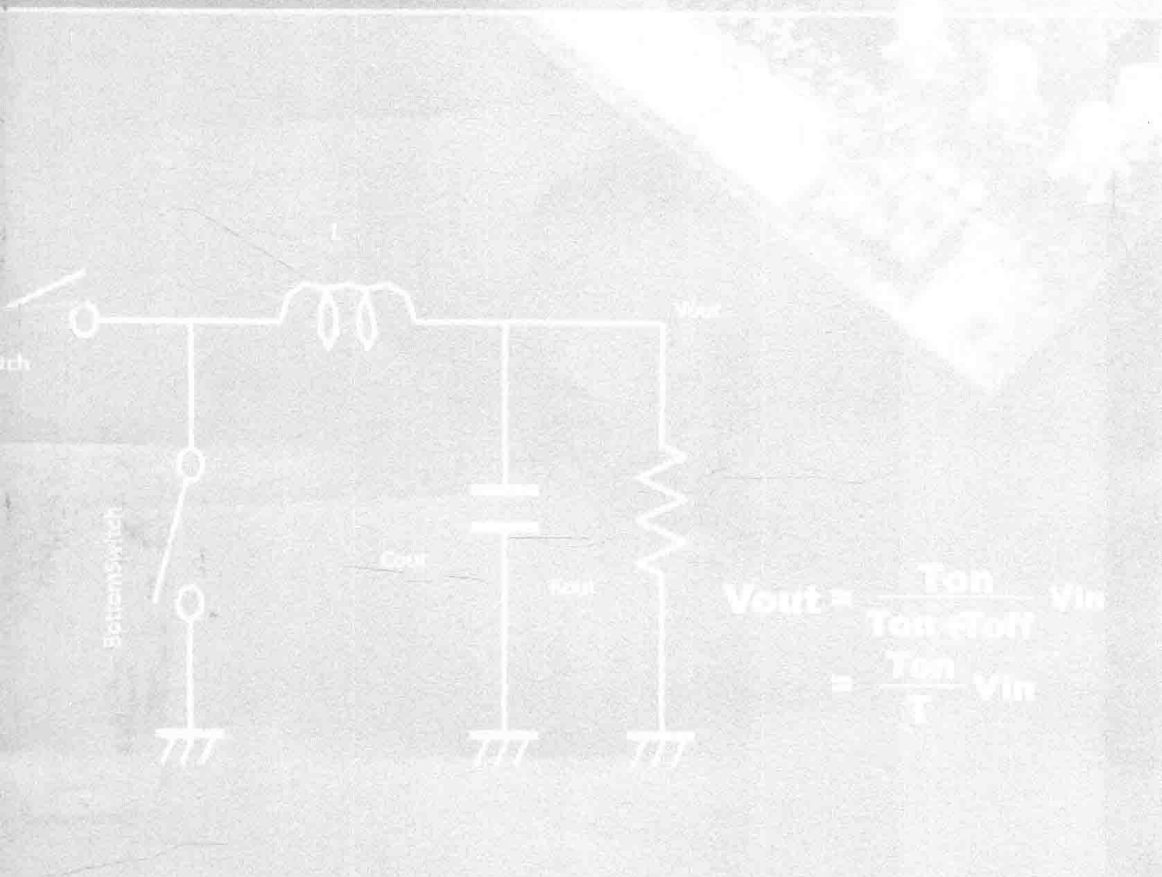
ISBN 978-981-4613-15-6 (Hardcover)

ISBN 978-981-4613-16-3 (eBook)

Printed in the USA



Handbook of Power Management Circuits



Preface

Electronics and electrical engineering may be only one part of physics. However, during the last 100 years, they have advanced rapidly and changed our lives drastically. Their roles can be classified into the following categories: (i) information and signal processing, (ii) information storage, (iii) communication, and (iv) energy and power. In this book, we focus on the fourth category—energy and power, or power electronics—which is becoming more and more important to make the earth green.

The book is intended for tutorials on power supply circuits for engineers and graduate students in circuit design fields as well as power electronics, and it covers a wide range of power supply circuits. The authors of all chapters have been engaged in research and development of their contents, and hence each chapter has its own originality, reflecting the authors' experiences. It is noteworthy that the power supply circuits as well as power amplifier circuits are different from analog, mixed-signal, and RF-integrated circuit design, and even circuit designers who have good background of analog, mixed-signal, and RF circuit design often get puzzled when they start to get involved in power supply circuits. In the 1997 IEEE International Solid-State Circuits Conference, there was a panel discussion session entitled "RF Designers are from Mars, Analog Designers are from Venus." Here I would like to add the following statement "Power Supply Designers are from Mercury and Power Amplifier Designers are from Jupiter."

This handbook is organized in two parts. In Part I, basics of power supply circuit have been reviewed systematically. In Chapter 1, basics of power supply circuit are introduced. The first hurdle to understand the DC–DC converter is the circuit behavior of an inductor. For example, current can be made to flow from lower- to higher-voltage nodes through the inductor, and thanks to the inductor, the DC–DC converter efficiency can theoretically be 100% in ideal conditions.

In Chapter 2, a buck converter—the most important DC–DC converter—for low-voltage applications is described elaborately.

First, buck, boost, and buck–boost DC–DC converters are introduced. Then two operation modes, that are, continuous current mode (CCM) and discontinuous current mode (DCM) are explained. Then their operating principle, circuit analysis with transfer function, closed-loop operation, design consideration such as error amplifier design, are discussed. An example of power supplies in a computer system is also discussed.

In Chapter 3, isolated DC–DC converters with a transformer (isolation of large voltage and current conversion, minimizing voltage and current stresses, multiple outputs, flyback converter, forward converter, push–pull converter, half-bridge converter, full-bridge converter of various types) are explained. These are used for handling relatively large power, and even beginners can understand them by a careful read, although they may find them difficult to understand at first.

Chapter 4 covers modeling and analysis of switching converters, such as state–space average model, averaged device model, and CCM and DCM models as well as transfer function. In Chapter 5, control schemes of switching converters are described, such as a self-oscillating hysteretic PWM control and a current mode control as well as a voltage mode PWM control, including some content based on the authors' research.

Chapter 6 describes passive components (inductor, transformers, and capacitors) and explains the fundamental physics behind inductors and transformers. It then introduces capacitors for switching converters, such as aluminum electrolytic capacitor, tantalum electrolytic capacitor, film capacitor, and ceramic capacitor as well as characteristics and applications of various capacitors.

In Part II, several selected topics are introduced individually. In Chapter 7, on-chip voltage converters are explained for large-scale integration (LSI) designer, such as voltage-reference circuit (bandgap reference circuit, or BGR), voltage-down converters, and voltage-up converters. On-chip voltage converters are very important for low-power operation in large-scale integrations (VLSIs).

Chapter 8 describes applications of DC–DC AC–DC switching converters and some of them are recent research results of the author: non-inverted buck–boost DC–DC converter with dual delta-sigma modulators and non-isolated AC–DC direct converter.

In Chapter 9, single-inductor multi-output DC–DC converters are introduced. The single-inductor multi-output DC–DC converters are

attractive for small size but their control is difficult. Their several configurations and control methods are also described.

Chapter 10 shows a small, low-power boost regulator optimized for energy-harvesting applications. Recently, interests of energy-harvesting applications are booming up and an example of boost-converter design for this purpose is introduced. Chapter 11 introduces wireless power delivery for 3D system integration and for non-contact wafer-level test focusing on the author's experience and interest. Chapter 12 shows high-power GaN–HEMT amplifier for cellular base stations. A lot of attention is now being paid to GaN HEMT, and several power amplifier architecture, design, implementation, and measurement examples with this technology are introduced. Chapter 13 describes power supply circuits with capacitors and switches.

We hope that this book will be helpful for electronics engineers from various fields in understanding these interesting and important areas and the readers will enjoy reading all the chapters.

Finally, we would like to thank Dr. Masashi Ochiai for reviewing the manuscript and providing valuable comments.

Haruo Kobayashi

Takashi Nabeshima

Winter 2015



Contents

<i>Preface</i>		xvii
1. Power Supply Circuit Fundamentals		1
<i>Jun-ichi Matsuda and Haruo Kobayashi</i>		
1.1 Introduction		1
1.1.1 Why Do We Study Power Electronics?		1
1.1.2 Positioning of Power Supplies		3
1.1.2.1 Switching-mode power supplies		3
1.1.2.2 History of switching-mode power supplies		3
1.1.2.3 Applications and products using switching-mode power supplies		3
1.1.2.4 Power supply technological classification		4
1.1.2.5 Electric power flow from generation to consumption and related technologies		4
1.1.3 Power Supply Circuit Basics		5
1.1.3.1 Why are power supply circuits required?		5
1.1.3.2 Importance of power supply technology progress		6
1.1.3.3 Transistor roles		6
1.1.3.4 Basic physics of power circuits		7
1.1.3.5 Control technology		7
1.1.3.6 Modeling		7
1.1.3.7 Inductor L		8
1.1.3.8 Duality of C and L , Voltage and Current		14
1.1.3.9 Why are switching-mode power supplies highly efficient?		15

	1.1.3.10	Intrinsic power loss due to switch on/off transitions and soft switching	17
	1.1.3.11	Switching frequency and circuit technology	20
	1.1.3.12	Difference between analog and power supply circuits	20
	1.1.4	Future Direction	21
1.2	Basics		22
	1.2.1	Inductor Volt-Second (or Magnetic Flux Linkage) Balance and Capacitor Charge Balance in a Buck Converter	22
	1.2.2	Transformer-Equivalent Circuit	26
	1.2.3	General Expression for the Power Factor	29
	1.2.4	Switching Loss	32
	1.2.4.1	MOSFET switching	34
	1.2.4.2	Diode reverse recovery	36
	1.2.4.3	MOSFET output and diode junction capacitances	39
	1.2.4.4	Parasitic series inductances	40
2.	Buck Converter for Low-Voltage Application		43
	<i>Takashi Nabeshima</i>		
2.1	Introduction		43
2.2	Operation and Circuit Analysis		47
	2.2.1	Operation of a Buck Converter	48
	2.2.1.1	S_1 in the on state	48
	2.2.1.2	S_1 in the off state	48
	2.2.2	Circuit Analysis of a Buck Converter	48
	2.2.2.1	Output ripple voltage	50
	2.2.2.2	Transfer function	53
2.3	Closed-Loop Operation		53
	2.3.1	Voltage Regulator	53
	2.3.2	Design Consideration of Feedback Circuit	55
3.	Isolated DC–DC Converters		63
	<i>Kimihiro Nishijima</i>		
3.1	Introduction		63

3.2	Flyback Converter	64
3.3	Forward Converter	68
3.3.1	Single-Switch Forward Converter	68
3.3.2	Two-Switch Forward Converter	73
3.4	Push–Pull Converter	76
3.5	Half-Bridge Converter	81
3.6	Full-Bridge Converter	86
3.6.1	PWM-Controlled Full-Bridge Converter	86
3.6.2	Phase-Shift-Controlled Full-Bridge Converter	92
3.6.3	Full-Bridge Converter with a Current-Doubler Rectifier	94
3.6.4	Full-Bridge Converter with Zero Voltage Switching	95
4.	Modeling and Analysis of Switching Converters	99
	<i>Terukazu Sato</i>	
4.1	Introduction	99
4.2	Switching Converter Analysis Using the Averaged Device Model	101
4.2.1	Kirchhoff's Law for Averaged Voltage and Current	101
4.2.2	The Equivalent Device Model	102
4.2.3	Analysis Procedure Using the Averaged Device Model	104
4.3	Buck Converter in Continuous Conduction Mode	104
4.3.1	Derivation of Waveforms of Currents and Voltages	105
4.3.2	Derivation of the Averaged Device Model	107
4.3.3	Steady-State Characteristics	109
4.3.4	Small-Signal AC Analysis	109
4.3.4.1	Control to the output transfer function	109
4.3.4.2	Input to the output transfer function	111
4.3.4.3	Load to the output transfer function	112

4.4	Buck Converter in Discontinuous Conduction Mode	113
4.4.1	Derivation of Waveforms of Currents and Voltages	115
4.4.2	Derivation of the Averaged Device Model	115
4.4.3	Steady-State Characteristics	117
4.4.4	Small-Signal AC Characteristics	118
4.4.4.1	Control to the output transfer function	118
4.4.4.2	Input to the output transfer function	119
4.4.4.3	Load to the output transfer function	120
4.5	Summary of Steady-State and Dynamic Characteristics of Basic Converters	121
5.	Control Schemes of Switching Converters	125
	<i>Terukazu Sato</i>	
5.1	Introduction	125
5.2	Voltage-Mode PWM Control	125
5.2.1	Transfer Function of an Error Amplifier	126
5.2.2	Transfer Function of a PWM Generator	127
5.3	Self-Oscillating Hysteretic PWM Control	128
5.3.1	Transfer Function of a Hysteretic PWM Generator	129
5.3.2	Constant-Frequency Operation of a Hysteretic PWM Generator	130
5.4	Current-Mode Control	131
5.4.1	Transfer Function of Current-Mode Control	133
5.4.2	Constant-Frequency Operation of a Current-Mode PWM Generator	134
6.	Passive Components	135
	<i>Yuya Tamai and Yoshiyuki Ishihara</i>	
6.1	Inductors and Transformers	135
6.1.1	Inductors	135

	6.1.1.1	Definition of an inductor	135
	6.1.1.2	Construction of inductors	136
6.1.2		Transformers	138
	6.1.2.1	Principles of transformers	138
	6.1.2.2	Structure of transformers	140
	6.1.2.3	Basics of transformer design	141
6.1.3		Materials Used in Inductors and Transformers	142
	6.1.3.1	Magnetic materials	142
	6.1.3.2	Conductors	147
6.1.4		Design Example	149
	6.1.4.1	Inductor design example	149
	6.1.4.2	Design example of a high-frequency transformer	151
6.2		Capacitors	153
	6.2.1	The Position of a Capacitor in Electronic Components	153
	6.2.1.1	The analog AV era	153
	6.2.1.2	The digital era	153
	6.2.1.3	The digital network era	154
6.2.2		Brief Overview of Various Capacitors	155
	6.2.2.1	Aluminum electrolytic capacitor	155
	6.2.2.2	Tantalum electrolytic capacitor	156
	6.2.2.3	Film capacitor	156
	6.2.2.4	Ceramic capacitor	156
6.2.3		Characteristics and Applications of Various Capacitors	157
	6.2.3.1	Aluminum electrolytic capacitor	159
	6.2.3.2	Tantalum electrolytic capacitor	162
	6.2.3.3	Film capacitor	165
	6.2.3.4	Ceramic capacitor	168
6.2.4		Main Roles of a Capacitor in a Power Distribution Network	172
	6.2.4.1	Role of a capacitor in a buck converter (VRM/POL)	172

6.2.4.2	Role of a capacitor in an isolated forward/flyback converter	175
6.2.4.3	Role of a capacitor in an AC/DC rectification circuit and a PFC converter	178
7.	On-Chip Voltage Converters	183
	<i>Masashi Horiguchi</i>	
7.1	Introduction	183
7.2	On-Chip Voltage Conversion	184
7.3	Voltage Reference Circuits	189
7.4	Voltage Down-Converters	198
7.5	Voltage Up-Converters	203
8.	Applications of DC–DC/AC–DC Switching Converters	213
	<i>Yasunori Kobori</i>	
8.1	Noninverted Buck–Boost DC–DC Converter with Dual Delta-Sigma Modulators	213
8.1.1	Introduction	213
8.1.2	Full-Bridge Configuration Buck–Boost Power Source	214
8.1.2.1	Mixed-control method	214
8.1.2.2	Voltage conversion equation in a buck and boost power source	215
8.1.2.3	Voltage conversion equation in the mixed-control method	216
8.1.3	$\Delta\Sigma$ Modulated Mixed-Control Method	216
8.1.4	Dual $\Delta\Sigma$ Modulated Control Method	216
8.1.4.1	Configuration of the dual $\Delta\Sigma$ modulated method	216
8.1.4.2	Characteristics of the $\Delta\Sigma$ modulation control method	217
8.1.5	Dual $\Delta\Sigma$ Buck–Boost Converter (Simulation)	218
8.1.5.1	Normal operation and component waveforms	218

	8.1.5.2	Load fluctuation response and ripple	219
	8.1.5.3	Evaluation of efficiency	220
8.1.6		Confirmation Experiments (Duty Ratio $\Delta\Sigma$ Control Method)	221
	8.1.6.1	Experimental circuit	221
	8.1.6.2	Efficiency improvement in the experimental circuit	222
	8.1.6.3	Measurements of efficiency	222
	8.1.6.4	Voltage ripple versus load current fluctuations	224
8.2		Nonisolated AC–DC Direct Converters	226
	8.2.1	Introduction	226
	8.2.2	Direct Buck–Boost AC–DC Converter with an H Bridge	227
	8.2.2.1	Basic circuit and principle operation	227
	8.2.2.2	Simulation results	229
	8.2.2.3	Voltage conversion ratio	231
	8.2.3	Inverted Direct AC–DC Converter	233
	8.2.3.1	Circuit and operation	233
	8.2.3.1	Simulation results	233
8.3		Power Factor Correction Circuit for a Direct AC–DC Converter	234
	8.3.1	New PFC Circuit in Boundary Conduction Mode	235
	8.3.1.1	Conventional BCM PFC circuit with a diode bridge	235
	8.3.1.2	New BCM PFC in a buck–boost converter with an H bridge	236
	8.3.2	New PFC Circuit in Continuous Conduction Mode	238
	8.3.2.1	Conventional CCM PFC in a boost converter with a diode bridge	238
	8.3.2.2	New CCM PFC in a buck–boost converter with an H bridge	239
8.4		Conclusions	241

9. Single-Inductor Multi-Output DC–DC Converter	245
<i>Nobukazu Takai</i>	
9.1 Introduction	245
9.1.1 Background and Motivation	245
9.1.2 Organization	246
9.2 Basics of a DC–DC Converter	246
9.2.1 Basic Topologies	247
9.2.1.1 Buck converter	247
9.2.1.2 Boost converter	248
9.2.1.3 Buck–boost converter	249
9.2.2 Operation of a DC–DC Converter	249
9.2.2.1 Continuous conduction mode	250
9.2.2.2 Discontinuous conduction mode	250
9.2.2.3 Pseudo-continuous conduction mode	250
9.3 What Is a SIMO DC–DC Converter?	251
9.3.1 Basics of a SIMO Converter	251
9.3.2 Topologies of a SIMO DC–DC Converter	253
9.3.2.1 Buck/buck combination	253
9.3.2.2 Buck/boost combination	254
9.3.2.3 Boost/boost combination	254
9.3.2.4 Buck/positive buck–boost combination	255
9.3.2.5 Boost/positive buck–boost combination	256
9.3.2.6 Buck/negative buck–boost combination	256
9.3.2.7 Boost/negative buck–boost combination	257
9.3.2.8 Positive buck–boost/positive buck–boost combination	258
9.3.2.9 Negative buck–boost/negative buck–boost combination	259