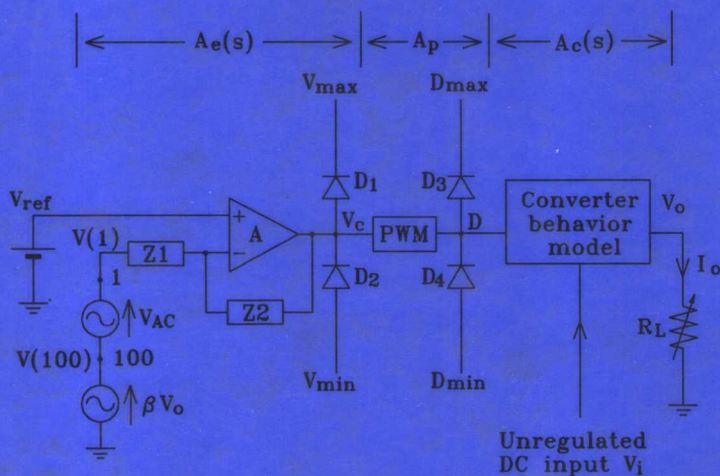


# Computer-Aided Analysis and Design of Switch-Mode Power Supplies



$$A_L(s) = A_e(s) A_p A_c(s) \beta$$

$$D = A_p V_c + D_o \quad \text{for } D_{min} \leq D \leq D_{max}$$

**Yim-Shu Lee**

# **Computer-Aided Analysis and Design of Switch-Mode Power Supplies**

**Yim-Shu Lee**

*Department of Electronic Engineering  
Hong Kong Polytechnic  
Kowloon, Hong Kong*

**Marcel Dekker, Inc.**

**New York • Basel • Hong Kong**

**Library of Congress Cataloging-in-Publication Data**

Lee, Yim-Shu,

Computer-aided analysis and design of switch-mode power supplies/  
Yim-Shu Lee.

p. cm. -- (Electrical engineering and electronics : v. 81)

Includes bibliographical references and index.

ISBN 0-8247-8803-6 (acid-free paper)

1. Switching power supplies—Design—Data processing. 2. Computer-aided design. I. Title. II. Series.

TK7868.P6L43 1993

621.3'17—dc20

92-40316  
CIP

This book is printed on acid-free paper.

Copyright © 1993 by Marcel Dekker, Inc. All Rights Reserved.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage and retrieval system, without permission in writing from the publisher.

Marcel Dekker, Inc.

270 Madison Avenue, New York, New York 10016

Current printing (last digit):

10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

## Preface

---

This book is concerned with the computer-aided analysis and design of the switch-mode power supply (SMPS). The objective is to equip electronics engineers with the necessary background about the SMPS and computer-aided design (CAD) techniques to help them perform analytical and design work efficiently. It is also a suitable text for training courses and undergraduate and graduate programs to prepare the new generation of designers and researchers who can use CAD tools freely to analyze and design power electronic circuits.

The SMPS is actually a class of power supply that makes use of electronic switches to process the electric power. Since ideal switches do not dissipate power, the SMPS can be designed to have, in theory, 100 percent conversion efficiency and infinitely small size. How much an SMPS designer can achieve depends on the quality of the available circuit components and the designer's ability to make the best use of these components. Because of the highly nonlinear nature of the switching circuitry, it is difficult, even for expert designers, to optimize a design in terms of conversion efficiency, size, steady-state/transient regulation characteristics, reliability, and cost. Therefore, most designers rely heavily on trial-and-error work to finalize a design.

CAD tools can be used to enhance a designer's ability to analyze the operation, predict the performance, and optimize the design of an SMPS. However, there are necessary conditions for any successful CAD exercise. They are:

1. The designer must have a good and intuitive understanding, at least qualitatively, of the circuit to be designed.

2. The designer must be able to develop related models of circuits and components for simulation purposes.
3. The designer must be familiar with the available CAD tool and be able to apply it effectively.
4. The CAD tool must be reasonably bug-free and powerful.
5. The simulation speed must be reasonably fast.

With the wide spread of high-speed personal computers such as those using an 80486 processor (or 80386 CPU and 80387 mathematics coprocessor) and powerful simulation programs such as SPICE (or its variants), the conditions specified in points 4 and 5 are actually not difficult to satisfy. It is the intention of this book to help readers create the conditions mentioned in points 1, 2, and 3.

The first five chapters introduce the development, principles of operation, modeling, and manual analysis of the SMPS. The objective of these chapters is to equip the reader with an intuitive and thorough understanding of the fundamental principles. This background is absolutely necessary in order to enable use of CAD tools freely in analyzing and designing the SMPS.

Chapter 6 is concerned with the computer simulation of the switching behaviors of dc-to-dc converters and the modeling of linear and nonlinear circuit components. Such simulations are extremely useful for the design of converters.

Chapter 7 deals with the modeling and simulation of the low-frequency behaviors of converters, including current-controlled converters and converters with multiple outputs. These simulations are essential for the computer-aided design of the feedback and compensation circuits of regulators.

Chapter 8 describes the philosophy, techniques, and precautions of using CAD tools to design converters and regulators. Design examples are given to illustrate the detailed steps involved.

Chapter 9 introduces the principles and design techniques of quasi-resonant and resonant converters.

The practical techniques of design of the SMPS are covered in Chapter 10 as a separate but important topic.

In addition to these ten chapters, this book contains four appendixes designed to help the reader learn the simulation program SPICE.

I wish to thank the Hong Kong Polytechnic for support and the following staff for their contributions: Kelvin So and C. W. Li for their efforts in developing the CAD techniques, preparing the figures, and proofreading; Michael Tse for his advice in reviewing the material; David Cheng, S. C. Wong, Martin Chow, and K. W. Ma for their assistance in developing the simulation techniques; Y. L. Cheng for his experimental work to verify

computer simulations; K. H. Zhang for his advice on SPICE; and Cora Au, Stella Lai, and Rhoda Lam for typing the manuscript.

I also wish to thank Robyn Flemming of Wordswork Ltd. for her editorial advice, and MicroSim Corporation for making complimentary evaluation versions of PSpice available to class instructors. Above all, I loyally give my heartfelt thanks to my truly helpful colleagues at the Polytechnic for their previously unsung support in making the publication of this book possible.

*Yim-Shu Lee*

# Contents

---

<i>Preface</i>	<i>v</i>
<b>1 Switch-Mode Power Supply Fundamentals</b>	<b>1</b>
1.1 The Development of Switch-Mode Power Supplies	2
1.2 The Buck Converter	6
1.3 The Buck-Boost Converter	16
1.4 The Boost Converter	24
1.5 The Ćuk Converter	28
1.6 Electronic Transformers	30
1.7 The Role of CAD Tools in Analysis and Design of the SMPS	35
1.8 Summary and Further Remarks	35
Exercises	36
<b>2 Low-Frequency Behavior Models of Square-Wave Power Converters</b>	<b>37</b>
2.1 Modeling the Low-Frequency Behavior of Switches	37
2.2 Identifying MISSCO and Its Equivalent Circuit	38
2.3 Modeling the Buck Converter	40
2.4 Modeling the Buck-Boost Converter	48
2.5 Modeling the Boost Converter	54
2.6 Modeling Electronic Transformers and the Ćuk Converter	59
2.7 Summary and Further Remarks	62
Exercises	63

<b>3</b>	<b>Analysis of Square-Wave Power Converters</b>	<b>65</b>
3.1	Approximations, Assumptions, and Notations	65
3.2	The Buck Converter in Continuous-Mode Operation	66
3.3	The Buck Converter in Discontinuous-Mode Operation	70
3.4	The Buck-Boost Converter in Continuous-Mode Operation	77
3.5	The Buck-Boost Converter in Discontinuous-Mode Operation	84
3.6	The Boost Converter in Continuous-Mode Operation	88
3.7	The Boost Converter in Discontinuous-Mode Operation	93
3.8	Electronic Transformers and the Ćuk Converter	98
3.9	Comparison of the Various Converters in Different Modes of Operation	105
3.10	Summary and Further Remarks	106
	Exercises	107
<b>4</b>	<b>Power Converters with Transformer Isolation</b>	<b>109</b>
4.1	Forward Converter	110
4.2	Flyback Converter	116
4.3	Ćuk Converter with Transformer Isolation	120
4.4	Electronic Transformers with Transformer Isolation	121
4.5	Transformer-Coupled Push-Pull Converter	122
4.6	Half-Bridge Converter	126
4.7	Full-Bridge Converter	128
4.8	Comparison of the Various Converters	129
4.9	Low-Frequency Behavior Models of Converters with Isolation Transformers	130
4.10	Summary and Further Remarks	130
	Exercises	130
<b>5</b>	<b>Voltage-Mode and Current-Mode-Controlled Switching Regulators</b>	<b>133</b>
5.1	Operation of Voltage-Mode-Controlled Regulators	134
5.2	Operation of Current-Mode-Controlled Regulators	134
5.3	Characteristics of Voltage-Mode-Controlled Regulators and Current-Mode-Controlled Regulators	136
5.4	Operation and Characteristics of Current-Controlled dc-to-dc Converters	137
5.5	Design of Feedback and Compensation Circuits	147



5.6	Special Design Considerations for Current-Mode-Controlled Regulators	151
5.7	Summary and Further Remarks	153
	Exercises	153
<b>6</b>	<b>Cycle-by-Cycle Simulation of Power Converter Circuits</b>	<b>155</b>
6.1	Uses of Cycle-by-Cycle Simulation	156
6.2	Modeling a Near-Ideal Switch	156
6.3	Modeling Semiconductor Devices	159
6.4	Modeling of Linear Capacitors, Inductors, and Transformers	166
6.5	Modeling of Nonlinear Resistors, Inductors, Transformers, and Capacitors	167
6.6	Practical Simulation Problems and Examples	178
6.7	Summary and Further Remarks	184
	Exercises	185
Attachment 6.1	Cycle-by-Cycle Simulation of Forward Converter	186
Attachment 6.2	Cycle-by-Cycle Simulation of Flyback Converter with Nonlinear RCL	191
<b>7</b>	<b>Simulation of Low-Frequency Behaviors of Converters</b>	<b>205</b>
7.1	SPICE Simulation of Mathematical Expressions	206
7.2	Simulating Converters Based on Low-Frequency Behavior Models	212
7.3	Developing a Combined Model for Both Continuous and Discontinuous Modes of Operation	215
7.4	Combined Model for the Ćuk Converter	224
7.5	Modeling Current-Controlled Converters	237
7.6	Modeling Multiple-Output and Push-Pull Converters	240
7.7	Summary and Further Remarks	244
	Exercises	245
Attachment 7.1	Behavior Simulation of Electronic Transformer	246
Attachment 7.2	Behavior Simulation of Buck-Boost Converter	253
Attachment 7.3	Behavior Simulation of Ćuk Converter	260
Attachment 7.4	Behavior Simulation of Current-Controlled Buck Converter	274
Attachment 7.5	Behavior Simulation of Dual-Output Transformer-Coupled Push-Pull Converter	285

<b>8</b>	<b>Computer-Aided Design of Converters and Regulators</b>	<b>295</b>
8.1	Interaction between the Designer and CAD Tools	296
8.2	Computer-Aided Design of Converter Circuits	297
8.3	Computer-Aided Design of Feedback and Compensation Circuits	299
8.4	Converter and Regulator Design Example	312
8.5	Practical Implementation	331
8.6	Summary and Further Remarks	332
	Exercises	333
Attachment 8.1	Simulation of Near-Ideal Half-Bridge Converter	334
Attachment 8.2	Simulation of a More Realistic Half-Bridge Converter	338
Attachment 8.3	Simulation of Final Design of Half-Bridge Converter	345
Attachment 8.4	Simulation of Loop-Gain Characteristic $A_L(s)$	353
Attachment 8.5	Simulation of Steady-State Line and Load Regulation Characteristics	362
Attachment 8.6	Simulation of Loop-Gain Characteristic with 2-Pole 2-Zero Compensation	369
Attachment 8.7	Transient Simulation of Final Design of Regulator	376
<b>9</b>	<b>High-Frequency Quasi-Resonant and Resonant Converters</b>	<b>385</b>
9.1	Problems Encountered in Designing High-Frequency Converters	385
9.2	Minimization of Losses	386
9.3	Quasi-Resonant Converters	389
9.4	Resonant Converters	397
9.5	The Role of CAD Tools in the Design of High-Frequency Converters	410
9.6	Summary and Further Remarks	410
	Exercises	411
<b>10</b>	<b>Practical Techniques of Design of Switch-Mode Power Supplies</b>	<b>413</b>
10.1	Design of the Input Stage	413
10.2	Selection of the Converter Topology	417
10.3	Design of Inductors	418
10.4	Design of Transformers	423

<b>Contents</b>	<b>xiii</b>
10.5 Design of Output Circuits	431
10.6 Design of Controller Circuits	436
10.7 Minimization of Interference	440
10.8 Summary and Further Remarks	442
Exercises	442
<i>APPENDIX A: An Introduction to SPICE</i>	<i>443</i>
<i>APPENDIX B: Summary of Commonly Used SPICE Statements</i>	<i>465</i>
<i>APPENDIX C: Nonconvergence and Related Problems in SPICE</i>	<i>489</i>
<i>APPENDIX D: About PSpice</i>	<i>495</i>
<i>References and Bibliography</i>	<i>499</i>
<i>Symbols</i>	<i>511</i>
<i>Index</i>	<i>517</i>

# 1

## Switch-Mode Power Supply Fundamentals

---

The so-called switch-mode power supply (SMPS) is a class of power supply that makes use of electronic switches to process electric power. Since ideal switches do not dissipate power, the SMPS can be designed to have a high efficiency. When a high switching frequency is used, the size of the transformers and filtering circuits in the SMPS can also be minimized. Because of these overwhelming advantages, the SMPS has today become so common that its linear counterpart is now used only in low-power circuits or in circuits where interference must be kept to an absolute minimum.

As an introduction to the subject of computer-aided analysis and design of the SMPS, the specific aims of this first chapter are:

1. To provide a brief outline of the development of the SMPS
2. To describe the switching behaviors of switches, inductors, and capacitors in the SMPS
3. To identify the role of computer-aided design (CAD) tools

The chapter explains the fundamental principles of dc-to-dc converters, which are the basic power conversion engines used in the SMPS. An understanding of such principles is essential for the modeling, analysis, and CAD work that follows in subsequent chapters.

To help introduce the essential concepts directly, effectively, and without unnecessary complications, the explanation in this chapter is based on idealized circuit elements, such as lossless inductors and capacitors and perfect switches with zero turn-on resistance and zero switching time.

The power converter circuits to be studied in this chapter include the buck converter, buck-boost converter, boost converter, Ćuk converter, and electronic transformers. Converters with transformer isolation will be

covered in Chapter 4, after the modeling and analysis of simple converters in Chapters 2 and 3.

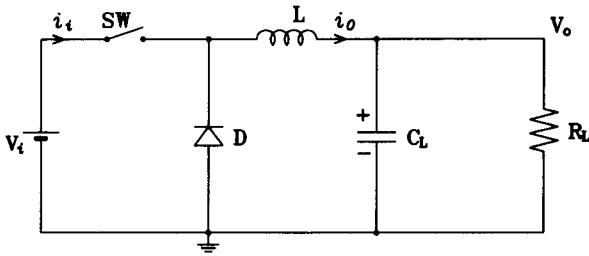
## 1.1 THE DEVELOPMENT OF SWITCH-MODE POWER SUPPLIES

This section contains a brief history of the development of converter circuits, as well as modeling, analysis, and design techniques. The objective is to provide readers with a better perspective of the subject matter and to enable them to trace the important literature related to this field of study. However, readers who are not interested in the history may proceed to Section 1.2.

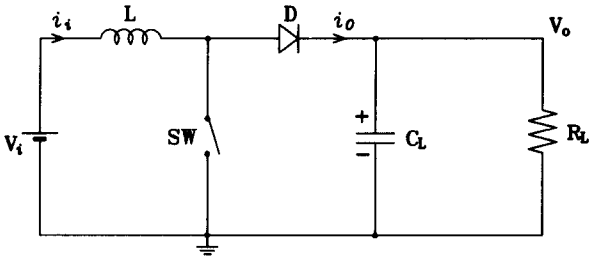
### 1.1.1 The Development of Power Converters

The heart of a SMPS is a dc-to-dc converter, which accepts a dc input and produces a controlled dc output. Semiconductor dc-to-dc converters have appeared in practical use since the 1960s. [10,41,43,44]. The three basic types are the buck converter, the boost converter, and the buck-boost converter, the circuits of which are shown in Fig. 1.1. (Note that a buck converter with an isolation transformer is called a forward converter, and a buck-boost converter with an isolation transformer is known as a flyback converter. The transformer-coupled push-pull converter, half-bridge converter, and full-bridge converter, which will be studied in Chapter 4, are variants of the forward converter.) In each of the converter circuits shown in Fig. 1.1, there is an electronic switch SW that is driven on and off at a high switching frequency (e.g., 5–500 kHz). It is the duty cycle of the electronic switch that controls the dc output voltage  $V_o$ . The output filtering capacitor  $C_L$  in each circuit is used to smooth out the ripple component of the output voltage due to high-frequency switching. By adding a feedback circuit in a converter, the output voltage of the converter can be regulated.

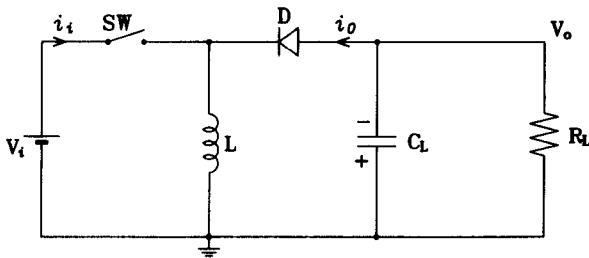
Because of the square/trapezoidal/triangular shape of the current pulses in the switching device, these converters will generally be referred to as square-wave converters or simply converters (as opposed to resonant converters or quasi-resonant converters, which will be studied in Chapter 9). In each of the converter circuits shown in Fig. 1.1, the energy-storage inductance  $L$  can be chosen to be so large that the current in it is substantially smoothed. The buck converter, shown in Fig. 1.1(a), is then characterized by a smoothed output current  $i_o$  but a pulsating input current  $i_i$ . The boost converter, shown in Fig. 1.1(b), is characterized by a smoothed input current but a pulsating output current. The buck-boost converter



(a)



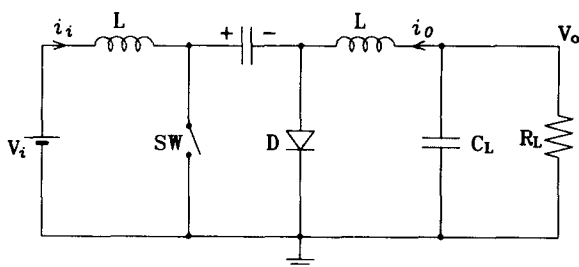
(b)



(c)

**FIGURE 1.1** Basic square-wave converters: (a) buck, (b) boost, (c) buck-boost.

shown in Fig. 1.1(c) has, on the other hand, both pulsating input and output currents. In 1977, Ćuk and Middlebrook introduced a new “optimum topology switching dc-to-dc converter” [22], which is now more commonly referred to as the Ćuk converter. A special feature of the Ćuk converter is that it can be designed to have both smoothed input and output currents, although the current in the switching device remains square/



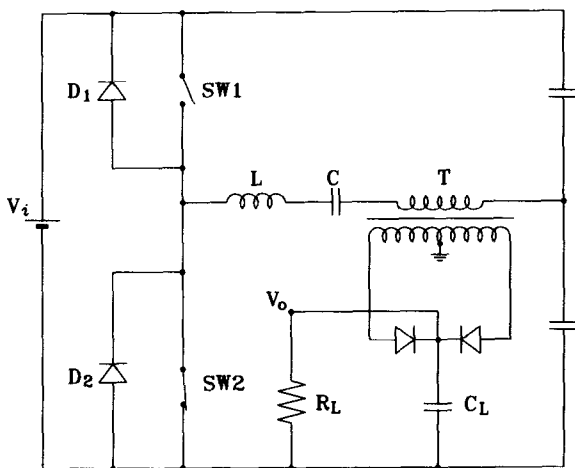
**FIGURE 1.2** Ćuk converter.

trapezoidal/triangular in shape. Figure 1.2 shows the basic circuit of the Ćuk converter, which functionally is a cascaded connection of a boost converter followed by a buck converter. Various topologies of square-wave converters were also studied by Ćuk [24], Landsman [33], and Severns and Bloom [53,124]. Recently, much attention has been focused on the design of high-frequency converters with reduced weight and size [13,28,52,54,101], and the use of fast MOS (metal oxide semiconductor) power transistors as switching elements [55].

Resonant-type dc-to-dc converters using frequency modulation (FM) control were studied and implemented by Schwarz in 1970 [48]. The resonant dc-to-dc converter is characterized by the sinusoidal shape of the resonant currents in the circuit. Figure 1.3 shows the circuit of a typical resonant converter. The potential advantages of resonant converters are:

1. The resonant nature of resonant converters reduces the voltage/current spikes.
2. The leakage inductance of transformers may be absorbed as an integral part of the resonant circuit.
3. For semiconductor switches of a given speed, a higher switching frequency (and therefore a smaller converter size) is possible when used in a resonant converter because the switching time requirements are less stringent.

Some resonant converters, such as those developed by Biess, Inouye, and Shank [12], Schwarz and Klaassens [50], Ranganathan, Ziogas, and Stefanovic [45], Ebginge [25], and Tilgenkamp, de Haan, and Huisman [69], used the SCR (silicon controlled rectifier) as the switching device and operated at a relatively low frequency, typically 5–50 kHz. Transistor resonant converters, which can operate at higher frequencies, were studied by Buchanan and Miller [15,39], Schwarz and Klaassens [51], King and



**FIGURE 1.3** Resonant dc-to-dc converter.

Stuart [31,32], Vorpérian and Ćuk [59], Myers and Peck [42], Steigerwald [58], Robson [47], Witulski and Erickson [62], Redl, Molnár, and Sokal [46,70], and Divan [71]. Many of the designs described in the references were highly successful.

More recently, quasi-resonant converters have been developed and studied by Lee, Liu, Oruganti and Tabisz [73–76], Ngo [77], Vorpérian [78], Weinberg and Ghislanzoni [79], Erickson et al. [80], Barbi et al. [81], and Higashi et al. [82].

### 1.1.2 The Development of Modeling, Analysis, and Design Techniques

In 1970, Middlebrook and his power electronics group at Caltech (California Institute of Technology) began systematic research into the modeling and analysis of switch-mode power supplies [38]. In 1972, Wester and Middlebrook developed, using the averaging technique, a set of low-frequency behavior models for the buck, buck-boost, and boost converters [61]. In 1976, Ćuk and Middlebrook introduced a unified approach to the modeling of dc-to-dc converters using the state-space averaging technique [21,23,35,36], which combines the advantages of both the state-space and the averaging methods. In 1981, a program known as SCAP (Switching Converter Analysis Program) was developed by the Caltech power electronics group to enable small computers to carry out analysis using the state-space averaging technique [9]. This program is capable of performing dc analysis and small-signal analysis at a given dc operating point. The



SCAP was later developed into the SCAMP (Switching Converter Analysis and Measurement Program), which includes additional features to help the designer measure the frequency characteristics of the converter. Large-signal analysis of dc-to-dc converters/regulators was carried out by Edwards and Caughey [26], Lee and Yu [34], Harada and Nabeshima [29], and Erickson, Ćuk, and Middlebrook [27]. Also based on the averaging technique, Chetty proposed in 1981 the use of the CIECA (current injected equivalent circuit approach) to simplify the modeling and analysis of dc-to-dc converters [17–19]. On the other hand, accurate but much more complex approaches to analysis using z-transform and sampled-data methods were studied independently by Capel, Ferrante, and Prajoux [16] and Brown and Middlebrook [14]. Analyses using SPICE [57] were carried out by Bello [11,67], Monteith Jr., and Salcedo [40], Hageman [96], and Kimhi and Ben-Yaakov [102]. Current-controlled converters were investigated by Deisch [92], Redl, Novak, and Sokal [93,94], Holland [95], and Ridley [103]. The use of alternor for the analysis of converters was proposed by Ioinovici [109].

The techniques of modeling and analysis of resonant and quasi-resonant converters have been studied by Schwarz [48,49], King and Stuart [31,32], Vorpérian and Ćuk [59,60,78], Witulski, Erickson, and Hernandez [62,100], Liu, Oruganti, and Lee [64,65,73], Lee and Siri [66], Redl, Molnár, and Sokal [68], Lee and Cheng [3,4,6], Kim and Youn [98], Ninomiya et al. [99], and Kang, Upadhyay, and Stephens [97].

Since power converters and the SMPS are nonlinear circuits, computer-aided analysis and design techniques for such circuits are highly desirable. So far, very little literature in this area has been published. Thus, a major objective of this book is to fill this gap of knowledge. It should be understood, however, that in order to use CAD tools efficiently, the designer must have a good and intuitive understanding of the circuit to be designed. In the following five sections, the principle of operation of the basic square-wave power converters used in the SMPS will be studied. High-frequency resonant and quasi-resonant converters will be discussed in Chapter 9.

## 1.2 THE BUCK CONVERTER

This section describes the operation of the buck converter, which is also known as the step-down converter. The two modes of operation, namely, the continuous mode and the discontinuous mode, will be analyzed in Subsections 1.2.1 and 1.2.2, respectively. The boundary condition between the two modes of operation and the differences in their characteristics will be discussed in Subsections 1.2.3 and 1.2.4.