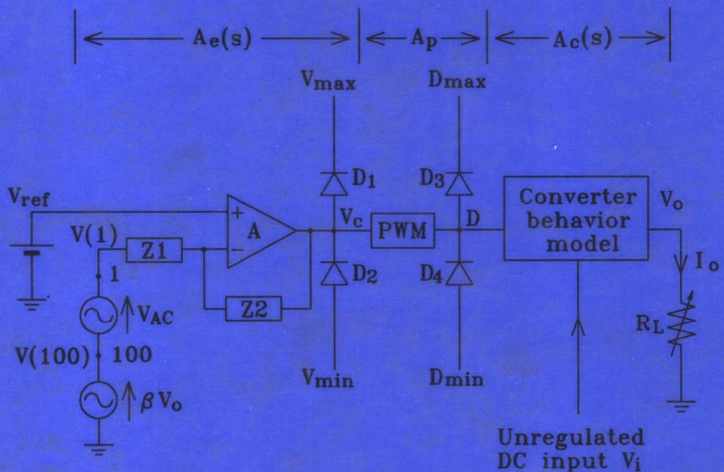
Computer-Aided Analysis and Design of Switch-Mode Power Supplies



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

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

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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

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

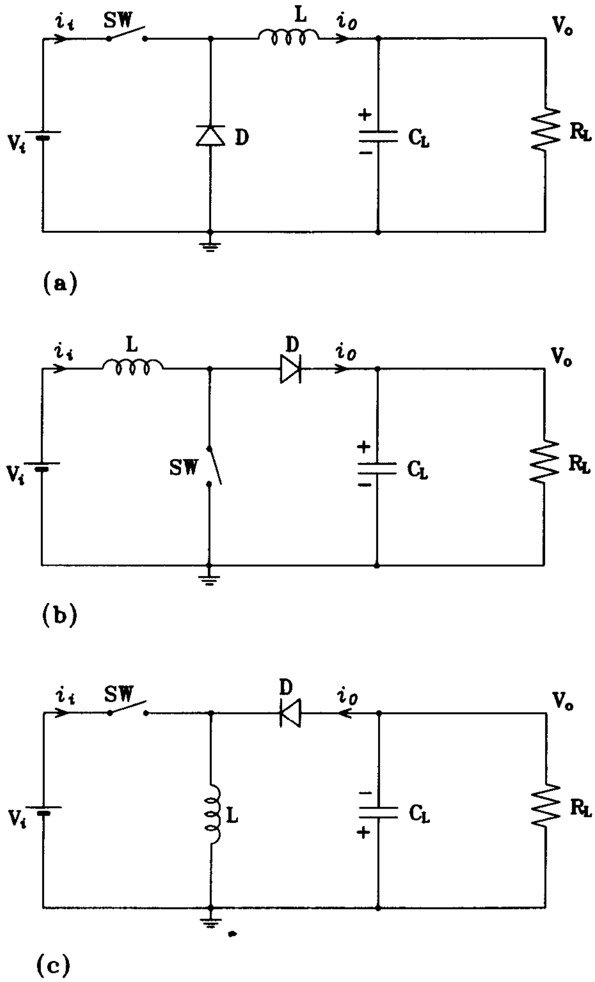

FIGURE 1.1 Basic square-wave converters: (a) buck, (b) boost, (c) buck-boost.

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/

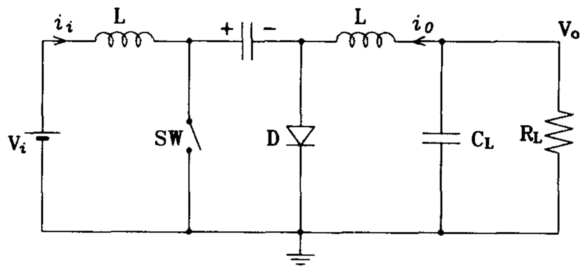

FIGURE 1.2 Ćuk converter.

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], Ebbinge [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

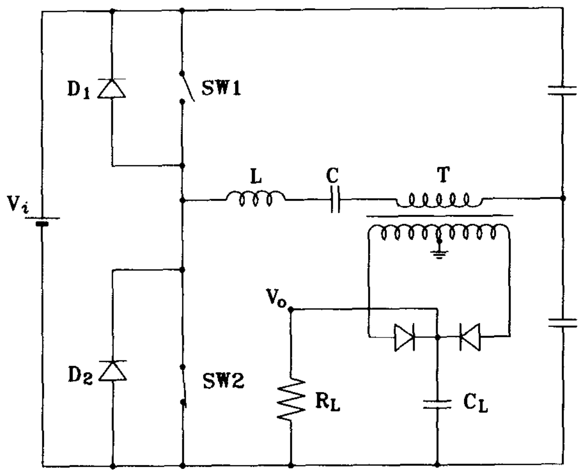

FIGURE 1.3 Resonant dc-to-dc converter.

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.