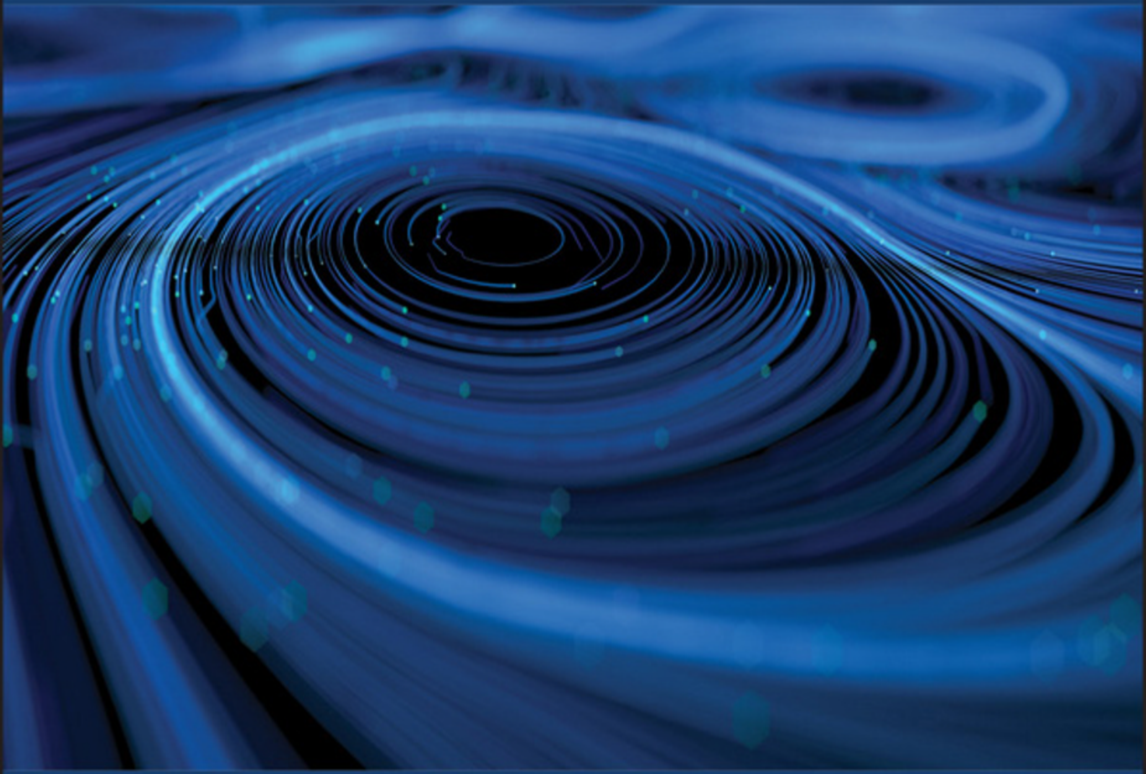
TSAI-FU WU | YU-KAI CHEN

ORIGIN OF POWER CONVERTERS

DECODING, SYNTHESIZING, AND MODELING



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WILEY

This edition first published 2020

Registered Office
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

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Library of Congress Cataloging-in-Publication data applied for
ISBN: 9781119632986

Cover design by Wiley
Cover image: © zf L/Getty Images

Set in 9.5/12.5pt STIXTwoText by SPi Global, Pondicherry, India

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

To Our Families
Ching-Ying, Charles and Jerry
Yun-Wen and Allen

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Preface

This book is divided into two parts. Part I presents evolution and development of power converters from the original converter. Hundreds of power converter topologies have been developed over past one century by many researchers. However, there is no single systematic approach to developing the converters. Inspired by Charles Darwin who published the book entitled *The Origin of Species* and based on the principle of resonance, we identify the original converter, on which we develop the mechanisms of evolution, decoding, and synthesizing processes, to derive PWM power converters systematically. With the decoding process, the input-to-output transfer codes (ratios) are decoded into code configurations in terms of the transfer codes derived from the original converter. With the synthesizing process, we have developed the graft and layer schemes, which are used in growing plants, along with circuit fundamentals to synthesize the code configurations into converters. With these two processes, illustrations of the existing and newly developed hard-switching and soft-switching PWM converters, including the well-known z-source converters, Vienna converters, modular multilevel converters, switched-inductor/switched-capacitor converters, *etc.*, are presented in detail. Additionally, determination of converters' switch-voltage stresses based on their transfer codes is addressed. Moreover, based on the principle of resonance, the well-known six PWM converters are reconfigured, and analogy of PWM converters to DNA is presented, from which mutation and replication of PWM converters are discussed.

Part II presents modeling and applications of power converters based on the original converter and the developed graft and layer schemes. The six PWM converters can be modeled into families represented in two-port networks. Therefore, relationships among the converters can be identified and the modeling processes can be simplified. In addition, single-stage converters to fulfill multiple functions are derived and modeled, on which two application examples are presented and verified with experimental results.

Since Charles Darwin in 1859 initiated an evolution principle, through around one hundred years and many researchers' study, Gregor J. Mendel developed the laws of inheritance in 1866, Boveri-Sutton developed chromosome theory in 1902, and James D. Watson discovered the double-helix structure of DNA in 1953, affecting significantly the followed genetic engineering innovations. Like Charles Darwin, we initiate an evolution of power converters, and we do expect other researchers can follow this stepstone to go further. This does not conclude the work, but just gets started.

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Acknowledgments

This book collects most of our work in converter development and modeling over past 25 years. We are grateful to our former PhD and Master students who have contributed to this book, especially Dr Te-Hung Yu and Dr Frank Liang. We are also thankful to the Ministry of Science and Technology, Taiwan, for constantly funding our research work. Our special appreciation goes to Cecilia Wang and Ya-Fen Cheng who edit the book prudently to meet the requirements from Wiley Publisher.

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Yu-Kai Chen

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Yu-Kai Chen is a professor in the Department of Aeronautical Engineering, National Formosa University, Taiwan, ROC where he is the director of Innovative Design and Energy Application Lab. (IDEAL). In 2015, he received the outstanding industry collaboration award from National Formosa University. His research interests include modeling and control of power converters, design of solar panel-supplied inverters for grid connection, and DSP- and microprocessor-based application systems with fuzzy and robust controls.

Part I

Decoding and Synthesizing

1

Introduction

Electrical energy has been widely applied, and its growth rate has been increasing dramatically over the past two decades. In particular, renewable energy coming to play has driven electricity utilization and processing needs to reach another growth peak. Additionally, machine electrification and factory automation have also increased the demand of electricity. With increasing use of sophisticated equipment and instruments, high power quality becomes just essential. To supply sufficient, of high quality, and stable electrical power in desired voltage or current forms, power processing systems are indispensable. Meanwhile, they also play an important role in supporting continuous growth of human beings' civilization, environmental conservation, and energy harvesting. In designing a power processing system, the first step needs to select a power converter topology since the converter topology mainly governs the fundamental properties, such as step-up, step-down, bipolar operation, component stresses, etc. Converters come out with very diversified configurations. How to derive or develop them systematically without trial and error is an interesting topic. Thus, many researchers have devoted in developing power converter topologies for various types of applications.

In this chapter, configuration of a power processing system is first addressed. Fundamental two types of power converter classifications, general pulse-width modulated (PWM) converters and non-PWM ones, are presented. Then, the well-known PWM converters are introduced for later comparison and illustration. In literature, there are many approaches to developing power converters, and their fundamental principles will be described briefly. In addition, an evolution concept is presented for illustrating later converter derivation. A section introducing the overall organization of this book will be included in the end of this chapter.

Origin of Power Converters: Decoding, Synthesizing, and Modeling, First Edition.
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1.1 Power Processing Systems

Configuration of a power processing system can be illustrated in Figure 1.1, which mainly includes input filter, power converter, feedback/feedforward circuits, controller, gate driver, and protection circuit. The input source can be obtained from utility outlet/grid or renewable energy generators, such as photovoltaic panel, wind turbine, geothermal heat pump, etc. Its voltages and currents can be any form, and their amplitudes might vary with time or fluctuate frequently. At the output side, the load may require various voltage and current forms, too. Thus, a proper power converter topology along with a promising controller is usually required to realize a power processing system.

Conventionally, the conceptual block diagram of a power processing system shown in Figure 1.1 can be realized by the circuit shown in Figure 1.2, which, as an example, is a linear regulator. In the circuit, semiconductor switch Q_N is operated in linear region to act as a variable resistor, which can absorb the voltage difference between input voltage V_i and output voltage V_o and in turn regulate V_o under load variation. The primary merits of a linear regulator include low output voltage ripple and low noise interference. However, it has many drawbacks, such

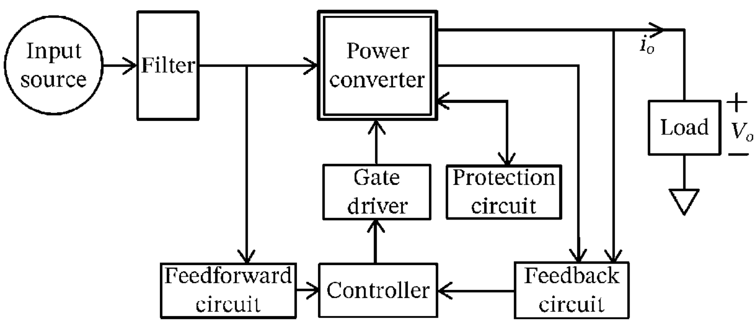

Figure 1.1 Configuration of a power processing system.

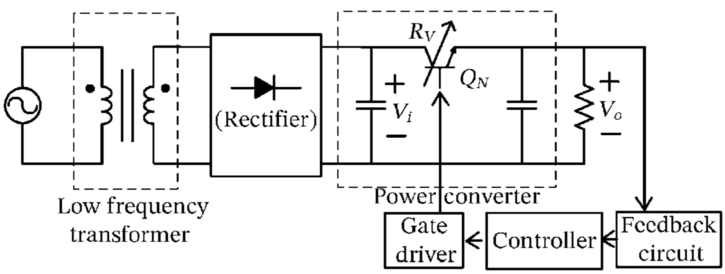

Figure 1.2 Block diagram of a linear regulator.

as the transformer with low operating frequency results in bulky size and heavy weight, semiconductor Q_N operating in linear region results in high power loss and low efficiency, and the low efficiency requires a large, heavy heat sink and even needs forced ventilation. These drawbacks have limited its wide applications to compact electronic products, renewable power generators, and energy harvesters, where efficiency and size are the essential concerns.

To improve efficiency and release the aforementioned limitations, switching power regulators were developed. A typical configuration of the switching regulators is shown in Figure 1.3, where in the power converter, switch M_1 is operated in saturation region (if using BJT as a switch) or in ohmic region (if using MOSFET as a switch), reducing conduction loss dramatically. At the input side, the corner frequency of the filter is close to switching frequency, and its size and weight can be also reduced significantly. If isolation is required, high frequency transformer will be introduced to the converter, and its size and weight are relatively small as compared with a low-frequency one (operating at 50/60 Hz). In general, a switching regulator has the merits of high power density, small volume, low weight, improved efficiency, and cost and component reduction. There still exist several limitations, such as resulting in high switching noise, increasing analysis and design complexity, and requiring sophisticated control. Although switching regulators have the limitations, thanks to recent advances in high efficiency and high frequency component development, nanoscale integrated circuit (IC) fabrication technique, and analysis tool, they have been widely applied to electronic products, energy harvesting, and power quality improvement. For further discussion, we will focus on switching regulators only.

For a switching regulator or a more general term, switching power converter, the input source can be either AC or DC form, and the output load can be also supplied by either AC or DC form. Thus, there are four types of combinational forms in classifying power converter topologies, which are AC to DC, AC to AC, DC to AC, and DC to DC. In Figure 1.3, the *rectifier* converts AC to DC, and the *power converter* converts DC to DC. Typically, a power processing system may

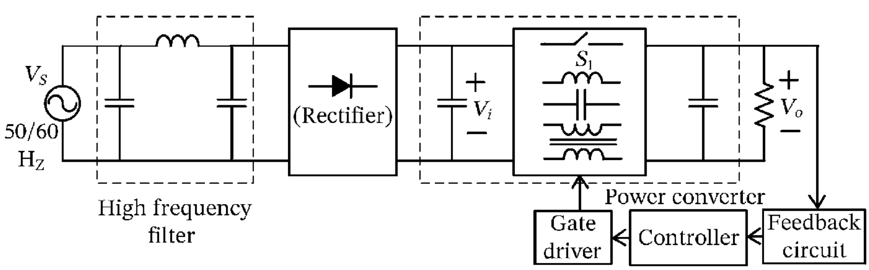

Figure 1.3 Block diagram of a switching regulator.

need multiple power converters to collaborate each other, but they might be integrated into a single power stage for certain applications, such as a notebook adapter consisting of a rectifier (AC to DC), a power factor corrector (DC to DC), and an isolated regulator (DC to DC), which can be integrated into a bridgeless isolated regulator. A power converter requires at least a control gear or switch to control power flow between source and load, and it might need some buffers or filters to smooth and hold up voltage and current, which can be illustrated in Figure 1.4. The switch can be realized with BJT, MOSFET, IGBT, GTO, etc. along with freewheeling diodes. It is worth noting that recent advances in wide-band-gap switching device development, such as SiC and GaN, have merited to switching power converters because their switching losses have been reduced significantly. The buffer or filter is realized with capacitor alone or capacitor–inductor pair. If it requires galvanic isolation, a transformer is introduced into the converter. Additionally, the transformer provides another degree of freedom in tuning input-to-output voltage ratio and can implement multiple outputs readily. To fulfill multiple functions or increase power capacity, converters can be connected in series or parallel, which will complicate analysis, design, and control.

As shown in Figure 1.4, connecting switch(es) and capacitors/inductors to form a power converter sounds simple. However, how to configure a power converter to achieve step-up, step-down, and step-up/step-down DC output, AC output, PWM control, variable frequency control, etc. is not an easy task. Even with the same step-up/step-down transfer ratio, there exist different converter topologies, and they might have different dynamic performances and different component stresses. Among the four types of power converter topologies is the DC to DC, simplified to DC/DC, converter type relatively popular. In the following, we will first present how to figure out the derivation of DC/DC converter topologies, on which the rest of converter types will be discussed. Exploring systematic approaches to developing power converter topologies is the unique feature of this book.

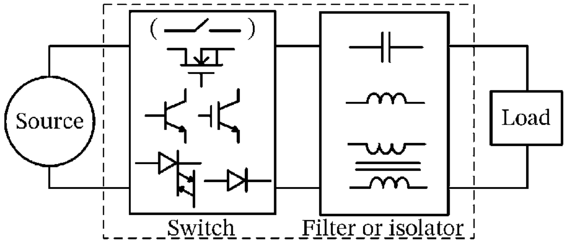

Figure 1.4 Possible components in a power converter.

1.2 Non-PWM Converters Versus PWM Converters

In power converters, when switch turns on with infinite current through or infinite voltage across components, this is because there is no current-limiting or voltage-blocking components in the conduction path, resulting in severe electromagnetic interference (EMI) problems. This type of power converter cannot be controlled with PWM and is called a non-PWM converter. On the contrary, there exist current-limiting and voltage-blocking components in the conduction path of a power converter, and it can be controlled with PWM, which is called a PWM converter. This claim will be presented and illustrated with some power converter examples, as follows.

1.2.1 Non-PWM Converters

The major concern of a power converter is its input–output conversion efficiency. In practice, there is no resistor allowed in a converter configuration. A qualified converter includes only ideal switch(es) and capacitor(s)/inductor(s). However, even with these components only, there might still exist loss during power transfer, such as the converters shown in Figure 1.5a and b. Figure 1.5a shows power transfer between two capacitors, and it is controlled by switch S_1. Assuming capacitor C_1 is associated with an initial voltage of V_o and C_2 is with zero voltage, and capacitance $C_1 = C_2$, it can be shown that there is an electrical energy loss, $(1/4)C_1V_o^2$, which is half the initially stored energy in C_1. Moreover, when switch S_1 is turned on, an inrush current flows from C_1 to C_2 and through S_1 in almost no time, which may damage the components and cause EMI problems. For this type of circuit configuration, the only current limiter is the equivalent inductance and resistance of the components and the circuit path. It can be said that there is no control on the capacitor currents and voltages, and the voltages of both capacitors C_1 and C_2 will be always balanced at $(1/2)V_o$. This type of power converter configuration is classified as a non-PWM converter.

Similarly, the conceptual inductor–inductor–switch configuration shown in Figure 1.5b has the same limitations. If, initially, inductor L_1 carries a current of I_o

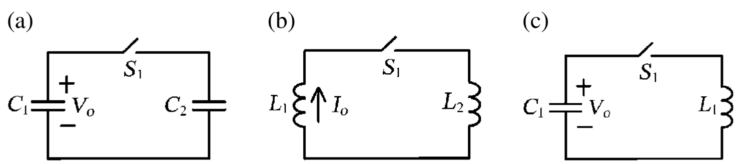

Figure 1.5 (a) Capacitor–capacitor–switch, (b) inductor–inductor–switch, and (c) capacitor–inductor–switch networks.

but there is no current in L_2, after turning on switch S_1, there will be an extremely high impulse voltage across the inductors and the switch, causing EMI problems and damage to the components. Again, there is half electrical energy loss $(1/4)L_1I_o^2$ if $L_1 = L_2$, and there is no control on the inductor voltages and currents at all. It is also a non-PWM converter.

In summary, non-PWM converters come out high inrush current or high impulse voltage, resulting in high EMI, as well as high component stress, and they could yield low conversion efficiency even with ideal components. In particular, under large initial voltage difference, the maximum electrical energy loss can be as high as 50%.

Other examples adopting the configuration shown in Figure 1.5a are shown in Figure 1.6. Figure 1.6a shows a two-lift converter. When switches S_1 and S_2 are turned on, capacitor C_1 will charge C_2 directly. On the other hand, when switch S_3 and S_4 are turned on, capacitors C_1 and C_2 are connected in series to charge capacitor C_3 and lift the output voltage V_o to be twice the input voltage V_i. It can be seen

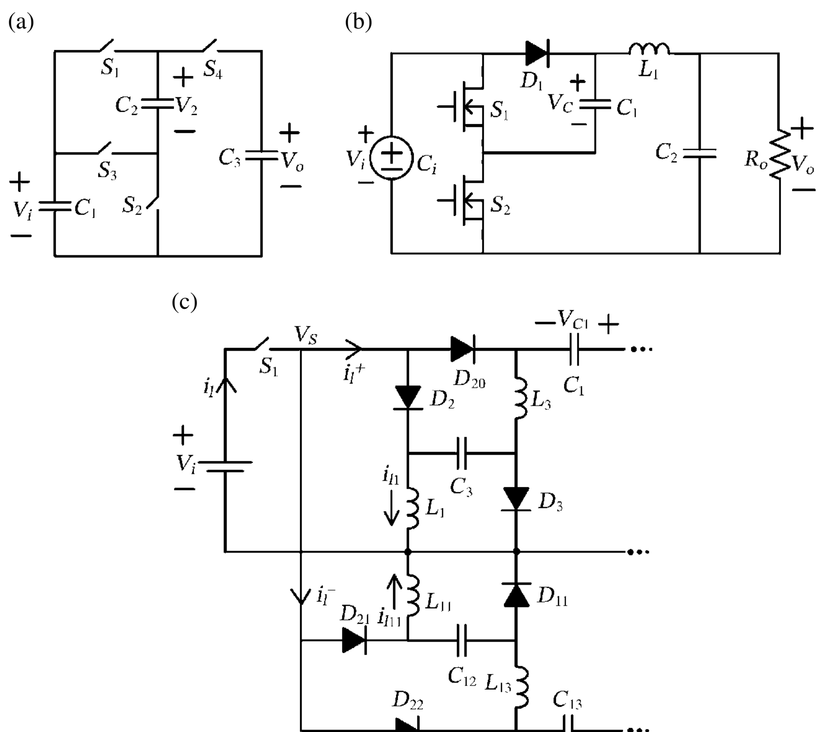

Figure 1.6 Non-PWM converters: (a) two lift, (b) KY, and (c) re-lift circuit.

that during capacitor charging, there is no current limiter, resulting in high inrush current. Figure 1.6b shows the KY converter. When switch S_2 is turned on, input voltage V_i will charge capacitor C_1 through diode D_1 but again without current limiter. When switch S_2 is turned off and S_1 is turned on, input voltage V_i together with capacitor voltage V_C will magnetize inductor L_1 through the output path. This path of power flow is with the current limiter of inductor L_1. Figure 1.6c shows a re-lift converter. When switch S_1 is turned on, there are two capacitor charging paths without current limiter, V_i-S_1-D_2-C_3-D_3-V_i and V_i-S_1-D_{21}-C_{12}-D_{11}-V_i. When switch S_1 is turned off, the energy stored in capacitors C_3 and C_{12} will be released to the output through the inductors and capacitors, which are the current limiters.

With a non-PWM converter, the processed power level is usually pretty low because of high inrush current or high pulse voltage. It can be used for supplying integrated circuits, which require low power consumption, of which the low current rating switches have high conduction resistance and act as current limiters. For high power processing, we need PWM power converters.

1.2.2 PWM Power Converters

Power transfer between a capacitor and an inductor can be modulated by a switch, as shown in Figure 1.5c, and their total electrical energy is always conserved to their initially stored energy. In the network, capacitor C_1 limits the slew rate of voltage variation, inductor L_1 limits that of current variation, and switch S_1 controls the time interval of power transfer, i.e., pulse-width modulation. Thus, component stresses can be properly controlled, and high conversion efficiency can be insured. Additionally, EMI level can be also reduced significantly. Power converter configurations based on this type of network are called PWM power converters. Note that it requires an additional freewheeling path when switch S_1 is turned off, which will be discussed in later section. For simplicity while without confusion in power electronics area, the short-form PWM converters or converters will be used to represent the PWM power converters. They have been widely applied to various types of power conversion for their controllable power transfer, theoretically no loss, and finite component stresses.

The minimum-order network of a PWM converter is a second-order *LC* network, and it must at least include a switch to control power flow. The order of network can be increased to third, fourth, and even higher. For a valid PWM converter, the network must be always in resonant manner at either switch turn-on or turn-off.

Over the past century, PWM converters have been well developed and have diversified configurations, such as buck, boost, buck-boost, Ćuk, sepic, Zeta, flyback, forward, push-pull, half-bridge, full-bridge, Z-source, neutral-point clamped (NPC), modular multilevel, quasi-resonant, and *LLC* resonant converters. They can be classified into non-isolated and isolated configurations. Typically, the isolated versions can be derived from the non-isolated ones by inserting a DC transformer or an AC transformer to a proper location of the converter. Thus, we will first introduce non-isolated converters, which can lay out a firm foundation for later discussions on isolated converters.

1.3 Well-Known PWM Converters

Almost all people entering power electronics field know about buck, boost, and buck-boost converters, as shown in Figure 1.7. To my best knowledge, it is unknown that who invented the buck converter and when it was invented. Since electricity started to be used frequently between the late nineteenth century and the early twentieth century, the invention of the buck converter was designated as year 1900. The boost converter was invented during World War II, which was used to boost voltage for transmitting radio signals across Atlantic Ocean. The buck-boost converter was invented around 1950.

Analyzing their operational principles will realize that the buck, boost, and buck-boost converters can achieve step-down, step-up, and step-down/step-up input-to-output voltage conversions, respectively. They all have a second-order *LC* network and a pair of active–passive switches but have different circuit configurations.

If we explore further, there are another three famous converters, and each of which has a fourth-order *LC* network and a pair of active–passive switches, as shown in Figure 1.8, in which they have different circuit configurations, but they all can fulfill the same step-down/step-up voltage conversion. Ćuk converter was

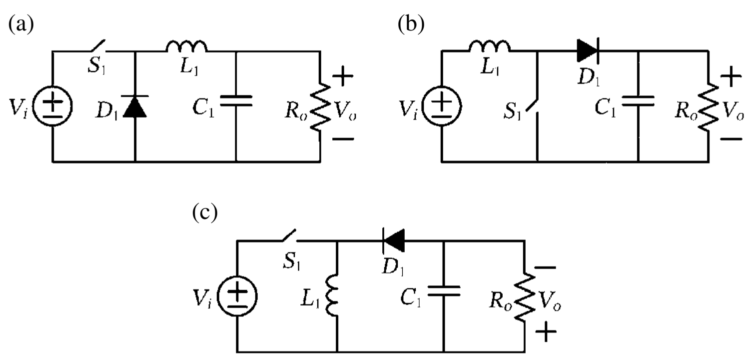

Figure 1.7 Power converters with a second-order *LC* network and a pair of active–passive switches: (a) buck converter, (b) boost converter, and (c) buck-boost converter.