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PWM Dc-to-Dc Power Conversion

This introductory chapter presents an overview of the pulsewidth modulated (PWM) dc-to-dc power conversion. We discuss basic principles and unique natures of dc-to-dc power conversion circuits, along with the concept of the PWM technique. This chapter also presents features and issues of dc power distribution systems for modern electronic equipment and systems. Finally, this chapter outlines the contents of forthcoming chapters.

1.1 PWM Dc-to-Dc Power Conversion

The PWM dc-to-dc power conversion is generally described as the process of changing the voltage level of a dc source using the PWM technique. However, a more definitive and precise description is necessary to comprehend natures and features of the PWM dc-to-dc power conversion circuit.

1.1.1 Dc-to-Dc Power Conversion

To formulate an accurate description of the dc-to-dc power conversion, this section presents two different approaches to energizing an electric bulb using a dc voltage sourced from a battery. It is presumed that the electric bulb requires a strict 12 V for operation, while the battery voltage is varied between 18 and 30 V depending on the charging status and operational conditions. Figure 1.1 shows the first approach where a variable resistor and controller are employed between the battery and electric bulb. The controller is assumed to only draw a negligible current.

In Figure 1.1, the controller adjusts the resistance of the variable resistor R_x to meet the following relationship

$$V_O = \frac{R_o}{R_x + R_o} V_B = 12 \text{ V} \tag{1.1}$$

where V_O is the voltage across the electric bulb, R_o denotes the resistance of the bulb, and V_B is the battery voltage that varies between 18 V $< V_B <$ 30 V. Figure 1.1 certainly fulfills the goal of providing a fixed dc voltage from a variable voltage source; however, it has one critical problem that renders this approach impractical.

The variable resistor is accompanied by an ohmic power loss

$$\boxed{P_{loss} = P_{in} - P_{out} = I_O V_B - I_O V_O = I_O (V_B - V_O)} \tag{1.2}$$

where P_{in} is the input power drawn from the battery, P_{out} is the output power delivered to the electric bulb, and I_O is the current flowing from the battery to the electric bulb. The power loss is given by

Pulsewidth Modulated Dc-to-Dc Power Conversion: Circuits, Dynamics, Control, and Dc Power Distribution Systems, Second Edition. Byungcho Choi.

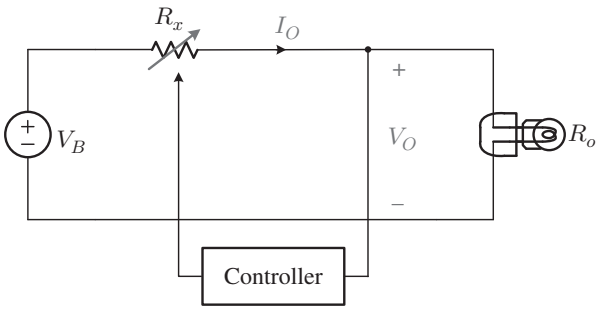

Figure 1.1 Conventional approach to lighting electric bulb.

the product of the load current and the difference between the battery voltage and bulb voltage. This power loss easily becomes significant. For example, when an electric bulb which consumes a 60 W power at 12 V voltage level is connected to a 30 V battery, the power loss is as large as $P_{loss} = (60/12)\ (30 - 12) = 90$ W. This loss is even larger than the power consumed in the bulb, $P_{out} = 60$ W.

The power loss is always transformed into heat and the resulting heat must be removed using an appropriate cooling system. The cooling system usually employs bulky heat sinks and noisy fans, consequently increasing the size and weight of the entire system. Accordingly, Figure 1.1 cannot be used for applications where the dimension and weight should be limited, which is usually the case for most modern electronic equipment and systems.

Figure 1.2 shows an alternative approach where a *switch network* and LC filter are inserted between the battery and electric bulb. The switch network periodically changes its connection.

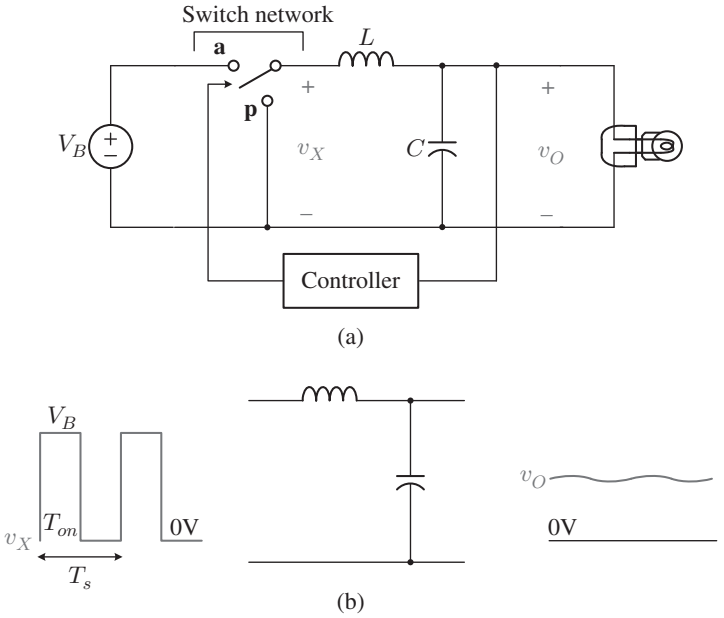

Figure 1.2 Dc-to-dc power conversion applied to power electric bulb. (a) Circuit diagram. (b) Input and output waveforms of LC filter.

Within each switching period T_s, the switch network maintains position **a** for T_{on} and position **p** for the remaining part of the switching period, $T_s - T_{on}$. This switch network is called the *single-pole double-throw* (*SPDT*) *switch* because it contains one pole that is always connected to one of the two contacts, the throw **a** and the throw **p**. With the switching action of the SPDT switch, the battery voltage is transformed into a rectangular waveform at the output of the SPDT switch, v_X in Figure 1.2. The rectangular waveform is then applied to the LC filter. The LC filter alters the rectangular waveform into a smoothly-filtered continuous voltage waveform, v_O in Figure 1.2.

If the LC filter provides sufficient filtering, the output voltage nearly becomes a dc waveform corresponding to the average value of v_X

$$\boxed{v_O(t) \approx V_O = \overline{v}_X(t) = \frac{T_{on}}{T_s} V_B} \tag{1.3}$$

To maintain $V_O = 12$ V at the presence of the battery voltage variation, the controller adjusts the ratio T_{on} to T_s. With a fixed T_s, the controller changes T_{on} to meet the condition

$$\frac{T_{on}}{T_s} V_B = 12 \text{ V} \tag{1.4}$$

For example, with a battery voltage $V_B = 24$ V and switching period $T_s = 10$ μs, the controller generates $T_{on} = 5$ μs to produce $V_O = (5 \times 10^{-6}/10 \times 10^{-6})\ 24 = 12$ V. If the battery voltage is increased to $V_B = 30$ V, the controller reduces T_{on} to 4 μs to regulate V_O at 12 V: $V_O = (4 \times 10^{-6}/10 \times 10^{-6})\ 30 = 12$ V.

Although Figures 1.1 and 1.2 both achieve the same goal, a crucial difference exists between them. Figure 1.2 presumes a lossless operation because the SPDT switch and reactive components in the LC filter do not consume any power. The lossless operation eliminates all the problems associated with the power loss. Because no heat management is required, the circuit could be packaged with a smaller size and lighter weight, thereby making it fully compatible with modern electronic systems.

A more definitive description of the dc-to-dc power conversion is now established as the process of changing the voltage level of a dc source, while eliminating or minimizing power loss. In this perspective, Figure 1.2 is a typical example of the dc-to-dc power conversion circuit, while the conventional circuit illustrated in Figure 1.1 is not classified so.

1.1.2 PWM Technique

The concept of PWM technique could be envisaged from the operation of Figure 1.2, where the ratio T_{on} to T_s of the SPDT switch is adjusted to keep the output voltage constant. By changing the T_{on}/T_s ratio, the pulsewidth of the rectangular voltage waveform is adaptively modulated so that the output voltage remains constant despite the input voltage variation. This control scheme is called the *PWM technique* and the dc-to-dc conversion circuit based on the PWM scheme is known as the *PWM dc-to-dc converter*. The PWM dc-to-dc converter is widely adapted to modern industrial and consumer electronics, thereby becoming the most prevailing dc-to-dc power conversion circuit.

1.2 Standalone Dc-to-Dc Power Conversion System

The basic concept illustrated in Figure 1.2 is generalized into dc-to-dc power conversion systems, whose block diagram representation is shown in Figure 1.3. The system consists of the dc source,

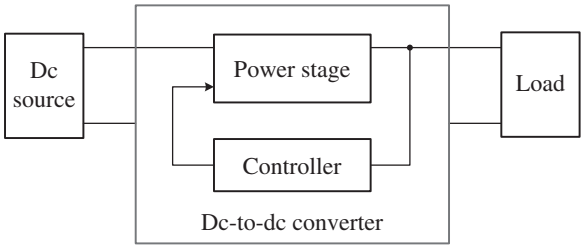

Figure 1.3 Standalone dc-to-dc power conversion system.

dc-to-dc converter, and load. The dc source provides an arbitrary dc voltage to the dc-to-dc converter. The dc-to-dc converter then converts the level of the given dc voltage into the value required by the load and delivers it to the load. The load is an application system that operates with a fixed dc voltage and eventually consumes electrical power. This section presents characteristic features of the dc source, dc-to-dc converter, and load.

1.2.1 Dc Source with Non-ideal Characteristics

The practical dc source falls short of the characteristics of an ideal voltage source in many aspects. First, the voltage level of the dc source could vary with time, as is the case with batteries, fuel cells, and other standalone dc sources. The change in the voltage could occur either gradually or abruptly, depending on the characteristics and conditions of the dc source.

Second, a rectified ac source is often used as a substitute for the dc source. For this case, the rectified ac source usually contains a considerable amount of ac components, known as *ac ripple*. In addition, the output of the rectified ac source could be corrupted with various noises. Accordingly, the dc source represents an arbitrary non-ideal source whose voltage could be varied, polluted with ac ripple and noises, and switched from one value to another.

1.2.2 Dc-to-Dc Converter as Voltage Source

The dc-to-dc converter receives an arbitrary voltage from the non-ideal source and is required to provide a fixed dc voltage for the load. Thus, in addition to altering the voltage level, the dc-to-dc converter should have the capacity of maintaining its output voltage constant at the presence of the variation, ac ripple component, and abrupt change in the input voltage. Ideally, the dc-to-dc converter should function as an *ideal* voltage source, powered from a non-ideal voltage source and programmed to produce the required dc voltage for the load, regardless of the condition of the voltage source.

Although a practical dc-to-dc converter is more complicated in structure and operation than the circuit in Figure 1.2, the converter is still grouped into two functional blocks: the power stage and controller. The power stage alters the level of the input voltage into a desired value using various active and passive circuit components, while the controller provides the necessary signals for the power stage to execute its function.

Dc-to-dc converters come with numerous variations in their power stage configuration and each dc-to-dc converter is named differently after its power stage structure. Despite the wide diversity in structure, all the power stages employ the common electronic components to perform the dc-to-dc power conversion. The power stage utilizes semiconductor devices to implement the function of the SPDT switch, energy storage components to perform filtering, and transformers to change the voltage and current levels of circuit variables while transferring electrical energy with galvanic isolation.

The controller also varies widely in structure and functionality. Even so, all the controllers perform the same role of providing the control signals that are required for the power stage to generate a fixed output voltage, regardless of variations in the input voltage and other operational conditions. In PWM dc-to-dc converters, this important function is executed in a closed-loop fashion using the PWM technique. The closed-loop PWM controller uses various analog and digital ICs, as well as discrete circuit components, to generate the required control signals.

1.2.3 Load as Dynamic Current Sink

The load of a dc-to-dc converter will be an electronic device or system operating with a fixed dc voltage. The load draws the current from the dc-to-dc converter to meet its power requirement. Thus, the load current could fluctuate depending on conditions of the load system. In particular, when high-speed digital systems are connected to a dc-to-dc converter, the current changes could occur frequently and rapidly, including step changes between two different values. Accordingly, the load system presents a dynamic current sink to the dc-to-dc converter, whose current level could change widely and abruptly.

1.3 Features and Issues of PWM Dc-to-Dc Converter

The PWM dc-to-dc converter is a closed-loop controlled circuitry that operates according to the principle of PWM. The PWM dc-to-dc converter is intended to function as an efficient and reliable voltage source, interfacing with the non-ideal dc source and dynamic load system. Accordingly, there are specific features demanded for the dc-to-dc converter and the issues involved with implementing such features in a PWM dc-to-dc converter.

1.3.1 Dc-to-Dc Power Converter Circuits

A dc-to-dc converter is required to accept an arbitrary voltage as the input and to generate a predetermined output voltage. The ratio between the input voltage and output voltage could be either very large or considerably small. Also, a dc-to-dc converter should provide an arbitrary load current, as required by the load. Accordingly, there are demanding requirements for the converter power stage in voltage and current ratings, input-to-output voltage ratio, and power handling capacity. In addition, dc-to-dc converters are frequently required to provide galvanic isolation between the source and load. To meet these demands, numerous power stage configurations have been developed, each with a different complexity and functionality. The power stage configuration occupies a large and important portion of the dc-to-dc power conversion technology.

1.3.2 Dynamic Modeling and Analysis

A dc-to-dc converter should function as a voltage source, which holds its output voltage constant at the desired value, irrespective of any possible changes in the input voltage, load current, and other operational conditions. This vital function is achieved by the closed-loop feedback controller operating under the principle of PWM.

It is well known that a closed-loop controlled system becomes unstable if the system is *not* properly designed. Stability is assessed by investigating the dynamic characteristics of the closed-loop controlled system. There are many analytical methods to judge whether a closed-loop controlled

system is stable or not. However, these methods are mainly intended for linear time-invariant systems. The PWM dc-to-dc converter falls into the category of the nonlinear time-variant system to which the aforementioned stability analysis methods cannot be directly applied.

The dynamic modeling refers to the analytical process of describing the dynamic characteristics of the nonlinear PWM dc-to-dc converter in a special format to which all the classical analysis methods, originally aimed for linear systems only, could be applied. Therefore, the dynamic modeling allows us to investigate the stability and performance of the nonlinear time-variant PWM dc-to-dc converter using the familiar classical control theory. The dynamic modeling and ensuing analysis using the resultant model are collectively referred to as the *dynamic modeling and analysis*. The dynamic modeling and analysis plays an important role in the PWM power conversion technology and deserves rigorous treatments.

1.3.3 Dynamic Performance and Control Design

The performance of a dc-to-dc converter will be grouped into two categories in this book – the static performance and dynamic performance. The *static performance* characterizes the dc-to-dc converter as a static voltage source. The static performance includes the input-to-output voltage conversion ratio, power handling capacity, output voltage ripple, and other steady-state properties. The static performance is solely determined by the power stage and is irrelevant to the feedback controller.

The second category is the *dynamic performance*, which depicts the dc-to-dc converter as a closed-loop controlled dynamic system. Most important dynamic performance is *stability*. The dc-to-dc converter should establish a periodic steady-state operation to produce the desired output voltage. When a certain disturbance is introduced, the converter could temporarily deviate from its steady-state operation. However, the converter should always return to the original periodic operation as the disturbance disappears. This essential feature is possible only when the converter meets the stability criterion.

Another important dynamic performance is the step load response. When a step change occurs in the load current, the output voltage would show a transitional excursion before it returns to its steady-state value. The transitional output voltage response is called the *step load response* in this book. The step load response is of particular concern when digital logic circuits are employed as the load. Modern logic circuits operate with a very tightly-regulated low voltage, for example, 2.1 ± 0.02 V, and draw a large pulsating current. These logic circuits naturally and frequently incur substantial step changes in the load current. For this case, the output voltage excursion should be minimized, in order to avoid the potential failure of digital logic circuits owing to an excessive transitional overshoot or undershoot in the supply voltage.

The dynamic performance is solely determined by the feedback controller. For a given power stage configuration, the controller should be designed for stability and good dynamic performance. While the controller design is primarily based on the dynamic modeling and analysis of PWM converters, it also requires comprehensive knowledge about the control theory, linear system theory, and feedback compensation design.

1.4 Dc Power Distribution Systems

The traditional standalone dc power conversion via one single dc-to-dc converter, illustrated in Figure 1.3, has advanced to multi-stage parallel-module dc power distribution systems, where a

number of dc-to-dc converters and intermediate filter stages are integrated in cascaded and paralleled fashions, in order to power multiple electronic devices efficiently and reliably. The structure of such power distribution systems is very complex and varied. The complexity and variety of the power systems present new challenges to the analysis and design of individual converters and the power system as a whole. This section discusses the issues related with dc power distribution systems.

1.4.1 Structure of Dc Power Distribution Systems

Figure 1.4 depicts a typical dc power distribution system for multiple electronic devices and circuits. The system employs a front-end converter and several load converters in parallel, along with intermediate filter stages. The front-end converter steps down the 48 V source to a regulated 24 V dc link. The 24 V link voltage is distributed to the load converters through the filter stages. The load converters further alter the voltage level to other values, as required by modern analog and digital electronics.

The input current of a PWM converter is either a pulse or triangular waveform, containing substantial amount of harmonic components. If the whole input current of the converter is directly drawn from the voltage source or dc link, large harmonic current components circulate in the system. The current harmonics in turn produce excessive conducted electromagnetic interference (EMI), thereby failing to meet regulatory electromagnetic compatibility (EMC) standards. To avoid such a situation, a filter stage is placed at the input port of the front-end converter and load converters. The filter stage locally bypasses the ac component of the pulsating or triangular input current so that only the smoothly-filtered dc current flows among the voltage source, dc link, and load converters.

The input source of the power system could be any practical standalone dc source or non-ideal dc voltage obtained by rectifying the utility line. Such practical voltage sources have a finite output impedance, $Z_o(s)$ in Figure 1.4. On the other hand, the load converters should support all analog

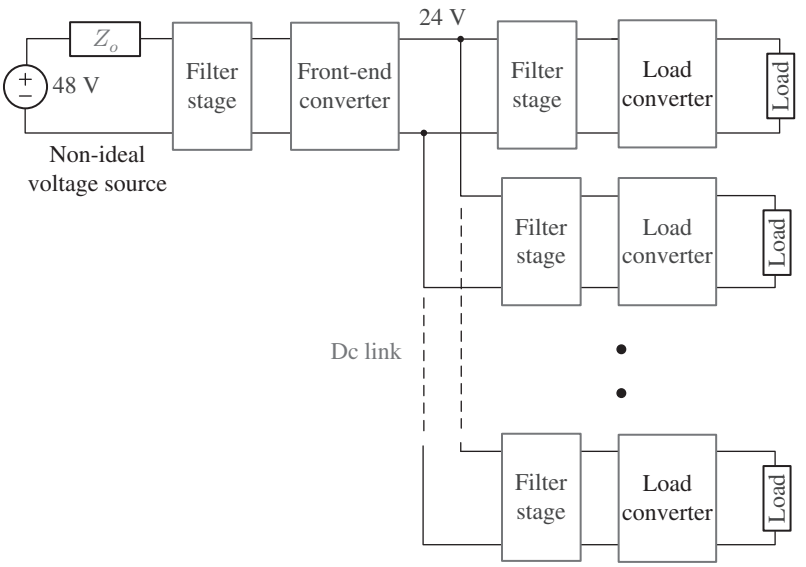

Figure 1.4 Dc power distribution system for electronic devices and circuits.

or digital electronics operating with a fixed dc voltage. These loads are hardly ever resistive and present complex load impedance characteristics. The non-resistive loads and non-ideal voltage source complicate the analysis and design of the individual converters, as well as the entire dc power system.

1.4.2 Issues in Dc Power Distribution System Analysis and Design

The analysis and design of PWM converters have been studied, based on the assumption that the converters are powered from an ideal voltage source and connected to a resistive load. However, neither of these assumptions is valid for PWM converters employed as a functional module in dc power distribution systems. For example, the frond-end converter in Figure 1.4 sees the combination of the non-ideal voltage source and filter stage as the source subsystem. Likewise, the front-end converter has a load subsystem, consisting of all the paralleled filter stages and load converters downstream. Furthermore, the exact structure of the load subsystem is only available after the entire power system is constructed by integrating all the load converters and filter stages. The detailed information about the load subsystem is unknown or undefined in the design and construction stage of the front-end converter. These features and many other aspects bring in new challenges to the analysis and design of both the individual converters and entire power distribution system.

(1) Use of the existing knowledge: Previous textbooks mostly dealt with standalone converters connected with an ideal voltage source and resistive load. We need to refine and extend the previous work for the converters employed in dc power distribution systems, while making the best use of the existing knowledge.
(2) Dynamic analysis and control design of converters: The analysis and control of the converters in the power system soon become intractable when the whole distribution system is considered altogether. As a practical alternative, the task may be broken down into two steps. We first analyze and design individual converters as a separate standalone converter and later incorporate the operational environment in the system, to evaluate the performance of individual converters in real operation. We should establish theoretical frameworks and engineering skills for this two-step approach.
(3) Analysis of subsystem interactions and system stability: The dynamics of each converter will be affected by the other converters and filter stages in power distribution the system. The dynamic interactions among subsystems should be included when analyzing the converter dynamics and system stability, in order to avoid any unexpected and irreversible system failures.
(4) Line filter design for system stability and performance: The intermediate line filter stages, employed for current filtering, exert substantial impacts on the system stability and subsystem interactions. For the system stability and performance, these impacts should be analyzed and incorporated into the line filter design.
(5) Design of dc power distribution systems: The new approach should be employed to methodically design the otherwise intractable dc power distribution systems. The design approach should secure the system stability and subsystem compatibility, without requiring any re-engineering of individual converters.

The true motivation of the current edition is to provide new approaches and techniques to tackle the issues listed earlier. This edition presents the latest research results about the relevant topics.

1.5 Chapter Highlights

The second edition refines the contents of the first edition and broadens them to the analysis and design of multi-stage parallel-module dc power distribution systems. The current edition consists of the four parts.

Part I: Dc-to-Dc converter circuits
Part II: Modeling and dynamics of PWM converters
Part III: Control schemes and converter performance
Part IV: Dc power distribution systems.

From the engineering perspective, this book is grouped into two technical areas. The first area, Parts I through III, covers the standalone PWM converters powered from a single voltage source and supporting a single resistive load. This traditional topic was the subject of the first edition of the book. The contents of the first edition are revised and reinforced to focus on the new topics, relevant to the new area of the second edition.

Part IV is the second area of this edition, dealing with dc power distribution systems for multiple non-resistive loads. Part IV presents four new chapters and constitutes the heart of the second edition. This part explores the challenging task of the analysis and design of multi-stage parallel-module dc power distribution systems. As the final outcome, Part IV presents the design procedures for complex power dc distribution systems.

1.5.1 Part I: Dc-to-Dc Converter Circuits

Part I covers PWM dc-to-dc power converter circuits. The topology and operation of widely-used PWM converters are all discussed. The evolution and diversification of the converter topologies are addressed.

Chapter 2 presents the simplest dc-to-dc power converter circuit, known as the buck converter. Theoretical basics and functional details of the buck converter are presented. This chapter illustrates circuit analysis techniques that are commonly applicable to all other dc-to-dc converters. In addition, Chapter 2 addresses the underlying basics of the PWM technique and closed-loop control of dc-to-dc converters.

Chapter 3 deals with the topology and operation of an important class of PWM dc-to-dc converters. This chapter first introduces two non-isolated converters – the boost converter and buck/boost converter. A number of isolated converters, derived from non-isolated converters by adding a transformer, are later presented. For each converter, the origin of the circuit topology is first illustrated and the steady-state operation is then investigated using the analysis techniques introduced in Chapter 2.

1.5.2 Part II: Modeling and Dynamics of PWM Converters

Part II starts with the modeling of PWM converters and proceeds with the dynamic analysis of the converters studied in Chapters 2 and 3. This part also discusses the closed-loop performance of PWM converters and presents important techniques to evaluate the stability and performance metrics of PWM converters.

Chapter 4 covers the modeling of PWM dc-to-dc converters. This chapter illustrates the procedures of describing nonlinear dynamics of time-variant dc-to-dc converters, using the terms

and formats that have been used for linear time-invariant systems. As the ultimate outcome, this chapter provides a linear circuit model for dc-to-dc converters, which allows us to investigate the nonlinear converter dynamics via conventional linear circuit analyses.

Chapter 5 presents the dynamic analysis of dc-to-dc converters using the linear circuit model developed in Chapter 4. This chapter describes the power stage dynamics of all isolated/non-isolated PWM dc-to-dc converters, thus providing theoretical foundations for the control design and performance evaluation.

In Chapter 6, the performance of the closed-loop controlled dc-to-dc converter is studied. The implication and significance of the performance metrics are demonstrated with examples. The method of stability analysis and performance evaluation are presented using the *s*-domain small-signal models of dc-to-dc converters. The Nyquist stability criterion and Bode plot technique are used for the stability analysis and performance evaluation of PWM converters.

1.5.3 Part III: Control Schemes and Converter Performance

Part III deals with two most prevailing control schemes of PWM converters – voltage mode control and current mode control. The principles, dynamics, and implementation of the two control schemes are presented in a comparative manner. Impacts of the control parameters on the frequency- and time-domain performance are discussed.

Chapter 7 is devoted to the closed-loop performance and feedback compensation of PWM converters with voltage mode control. This chapter first introduces a graphical analysis method, which facilitates the dynamic analysis and compensation design. Using this graphical method, the chapter presents theoretical details of compensation design and performance evaluation. Practical techniques to correlate the compensation parameters with the frequency- and time-domain performance metrics are provided.

Chapter 8 focuses on current mode control, which employs an additional feedback from the inductor current of PWM converters. Current mode control is executed by sampling and holding the error signal produced by the fast-varying inductor current waveform. Due to this sampling and holding mechanism, current mode control exhibits typical characteristics of sampled-data systems. This feature is known as the sampling effect of current mode control. The chapter analyzes the sampling effects, and the results are converted into design equations for current mode control. Examples are given to validate the design equations.

1.5.4 Part IV: Dc Power Distribution Systems

Part IV is dedicated to the dynamics analysis and system design of dc power distribution systems. The results of Parts II and III are combined with specific design/analysis techniques to pursue the dynamic analysis, system design, and performance optimization of multi-stage parallel-module dc power distribution systems.

Chapter 9 first sets up the design strategy for the PWM converters in dc power distribution systems, whose source and load impedances are unknown or undefined at the design stage of the converter and only available after the converters are all fabricated and integrated through the filter stages to create a complete power distribution system. To cope with the uncertainties of the source and load impedances, a design method not requiring the information about the source and load impedances is established.

Upon the system integration, the dynamics and performance of the individual converters are affected by the source and load impedances. Whenever the information about the source and load

impedances is available, we should evaluate the performance of the converters in the real system as precisely as possible. This chapter lays out the procedures to evaluate the converter performance in the presence of the actual source and load impedances. Middlebrook's extra element theorem (EET) is adapted as an instrumental tool for this study.

Chapter 10 explores the impacts of load impedance on the converter dynamics, which are called the loading effects. A typical load impedance of generic dc power distribution systems is used as a reference in studying the loading effects. Middlebrook's EET and graphical analysis method are combined to uncover the converter dynamics under the strong loading effects. The stability and loop gain characteristics of the converters are analyzed. The output impedance, input impedance, and step load transient response are also investigated.

Chapter 11 studies the converter dynamics and performance under influences of the source impedance. A voltage source integrated a filter stage is used to emulate the source subsystem. The output impedance seen from output port of the filter stage is treated as the source impedance. The impacts of the filter stage on the downstream converter dynamics are analyzed. Potential instability, triggered by the unwanted coupling between the resonant peaking of the filter stage and input impedance of the downstream converter, is studied. The conditions to prevent such an instability are provided. This chapter also discusses the requirements to avoid or reduce any adverse effects of the filter stage.

Chapter 12 is devoted to the design of multi-stage parallel-module dc power distribution systems. In the final chapter of the book, the results of Chapters 9 through 11 are all merged together to provide the system design method, which offers stability and predictable/programmable performance metrics for all the converter stages, dc links, and entire power distribution system. The validity of the design method is verified with practical examples.