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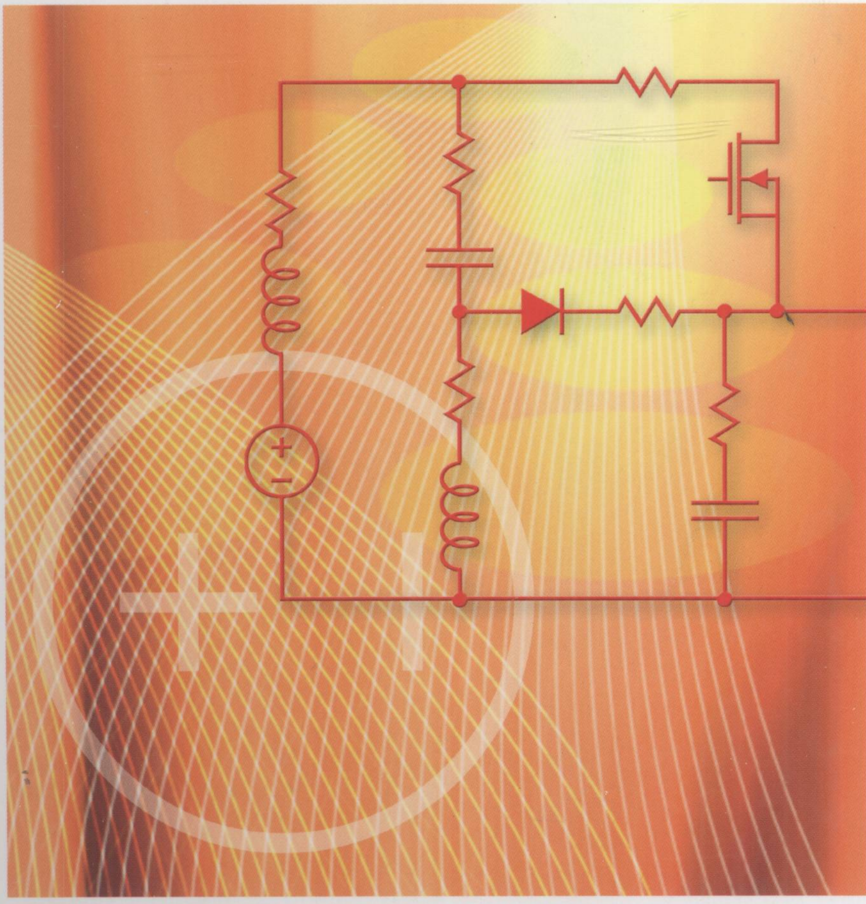
Dynamic Profile of Switched-Mode Converter

Modeling, Analysis and Control



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Preface

Twenty-five years in industry engaged in the practical design of switched-mode converters and the systems based on them and especially the multitude of problems we faced convinced me that there has to be something we do not really understand. After joining the academy, I decided to find out what are the reasons for the problems we were confronted with almost daily. After ten years in academy, I understand many of the problems but there still seems to be a lot to solve. The biggest challenge is to convince the other designers and academics that the electrical circuits have an internal dynamic sole which dictates the way the circuits behave and contribute to the behavior of the systems composed of them. The plain sole has to be known for being able to understand and predict the behavior and especially to avoid the undesired consequences such as instability and deteriorated transient performance. The book is intended to introduce the dynamic features the different converter topologies may incorporate and the changes the different control methods and operation modes may create in them in addition to the introduction of the methods to model analytically the dynamic behavior and to design the controllers.

Many individuals have helped me to create the book and especially to understand the extent of the problems and to find the solutions for them: Professor Dr. D. R. Vij as the consultant editor and the staff of Wiley-VCH have provided me the opportunity to publish the book and patient guidance during the process. Dr. Kai Zenger has guided me into the secrets of control engineering but a lot of work is still left. My former doctorate students Dr. Idris Gadoura, Dr. Ander Tenno, Dr. Mikko Hankaniemi, Dr. Ali Altowati, and Dr. Matti Karppanen have contributed substantially to the solutions presented in the book and especially to their experimental validation. I am very grateful to my wife Sirpa for her love and patience during the process.

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1.1
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The switched-mode converters can be divided into two main classes such as voltage- (Figure 1.1) and current-sourced (Figure 1.2) converters [1], where either the output voltage (Figures 1.1a and 1.2b) or output current (Figures 1.1b and 1.2a) is kept constant [2]. As a consequence, there are four different main types of converters namely voltage-to-voltage, voltage-to-current, current-to-current, and current-to-voltage converters having different dynamic features. The most usual converter is the voltage-to-voltage converter (Figure 1.1a) because most of the energy sources are voltage sources and the loads current sinks [3]. Sometimes storage batteries are connected at the output of the voltage-sourced converter, which requires to limiting the maximum output current for preventing the converters from damage due to the extremely low internal impedance of a storage battery [4–8]. The operation at current-limiting mode changes the voltage-to-voltage converter to voltage-to-current converter (Figure 1.1b). Current-sourced converters can be used to interface solar arrays and magnetic energy storage systems due to the current-output nature of those energy sources [9, 10]. Such a basic converter is naturally the current-to-current converter (Figure 1.2a). If the maximum-output voltage limiting is used, the current-to-current converter changes to a current-to-voltage converter (Figure 1.2b).

Every switched-mode converter has a unique dynamic profile or internal dynamics, which would determine the obtainable transient dynamics and robustness of stability as well as the converter's sensitivity to the external source and load impedances [11–13]. The dynamic profile can be changed by means of certain internal feedback or feedforward arrangements but not much in practice by means of the feedback-loop control design. The internal dynamics can be characterized by means of a certain set of open-loop transfer functions constituting the circuit theoretical two-port parameters known as G (Figure 1.1a), Y (Figure 1.1b), H (Figure 1.2a), or Z (Figure 1.2b) depending on the input source and the type of the converter output [11–15]. The different sets do characterize only one main type of a converter and are not interchangeable

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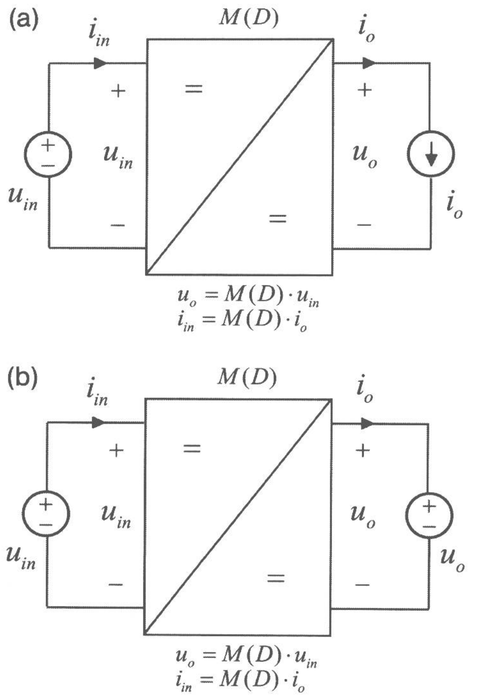

Figure 1.1 Voltage-sourced converter (a) at voltage-output mode and (b) at current-output mode.

but the parameters within the main converter class (i.e., G and Y, H and Z) can be computed from each other. In addition with the open-loop transfer functions, certain admittance or impedance parameters have to be defined for obtaining the full picture of the internal dynamic profile [11].

The term internal means that the transfer functions constituting the sets are to be such that all the effects of the source and load impedances are removed from them. The analytical models can be easily derived to be such, when knowing the correct load yielding the internal models (Figures 1.1. and 1.2). The dynamic parameter sets for the voltage-to-voltage and current-to-current converters can also be usually measured by means of frequency response analyzers but certain internal control modes may change the open-loop converter such that it cannot operate at the defined load or the required ideal load is not available. In such cases, a resistive load has to be used and the internal models have to be solved computationally [11, 16, 17]. It is, however, extremely important to obtain those internal models because they only characterize the converter not the source- or load-affected models.

A large number of power electronics text books are available such as [18–26], which tend to give a comprehensive picture of all the issues related to the design of switched-mode converters both in AC and DC applications. Therefore, it is understandable that the dynamic issues are typically not treated adequately. The exceptions are [27] and [28], which mainly concentrates on the dynamic

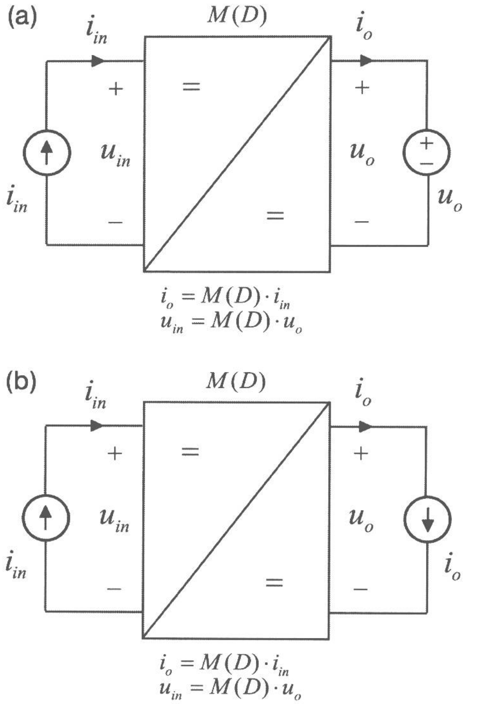

Figure 1.2 Current-sourced converter (a) at current-output mode and (b) at voltage-output mode.

issues. The main deficiency of the dynamic analyses in the aforementioned text books is the inclusion of the load usually as a resistor in the presented dynamic models, which may effectively hide the true dynamics and thereby made the output of the system-level interaction analyses useless. A describing example of the misunderstanding such a treatment can cause is the prevailing understanding that the damping of the resonant behavior in a converter would decrease, when the resistive load is decreased [29]. The phenomenon is naturally true from the external point of view but the internal dynamics does not, however, change if the operating point is maintained. Therefore, it may be a big surprise when the converter behaves nicely in the laboratory but dynamic problems arise when connected into a real application. Such an experience might be very common among the industrial switched-mode-converter designers leading easily to frustration and blaming the customer of abusing the converter.

The main goal of the book is to provide the reader with the tools by means of which the challenging dynamics of the systems comprising of switched-mode converters can be made more understandable and the design of them more deterministic. It is natural that the key element is the building block of such a system – the switched-mode converter. The most fundamental issue behind the ideas provided in the book is the observation that each electrical device or circuit has its unique internal dynamic profile similar to the psychological profile of a human being [11]: the profile determines how the device or circuit would behave as a part of the system under different external interactions and how it would affect the other subsystems within the overall system. The internal profile cannot be basically changed by applying external feedback control but only by providing internal feedback or feedforward from the input, output and/or state variables constituting the dynamic constellation of the device. An illustrative example is the application of inductor current to produce the duty ratio in a peak-current-mode-controlled (PCMC) converter [30], which changes profoundly the converter dynamics compared to the corresponding direct-duty-ratio or voltage-mode-controlled (VMC) converter, where the duty ratio is produced using a constant ramp voltage: The resonant nature of the VMC converter disappears, the input-noise attenuation may be substantially increased, the internal open-loop output impedance is increased but the nonminimum nature if existing in the VMC converter would not be removed. A multitude of similar examples can be given, which actually proves the existence of such a profile.

During the time of writing the book, the analog control is still dominating but digital control with all the opportunities involved in it is evidently coming and may dominate the future converter applications. The fact is, however, that the power stage does not change and, therefore, the basic dynamic profile related to the power stage does not change. The digital control with the physical resolution and time limitations may cause more dynamic problems or equally also improvements, which can be revealed and analyzed using the methods and information based on the corresponding continuous-time processes treated in this book.

The issues related to the dynamic profiles are briefly discussed and clarified in the subsequent subsections in order to make the reader familiar with the issues treated in the subsequent chapters. Even if we discussed on the current-sourced converters in the beginning of the chapter, we will limit our discussions on the voltage-sourced converters within the rest of the book.

1.2 Dynamic Modeling of Switched-Mode Converters

The dynamic analysis of the voltage-output switched-mode converters dates back to the early 1970s [31], when the foundation for the state-space-averaging (SSA) method [32] was laid down. It was observed that the dynamics associated with the direct-duty-ratio or VMC converter in continuous conduction mode (CCM) could be quite accurately captured up to half the switching frequency by averaging the converter variables within a switching cycle and computing the small-signal models from the corresponding averaged state space by means of linearization. The dynamic behavior of a converter was represented by means of the canonical equivalent circuit shown in Figure 1.3 for the

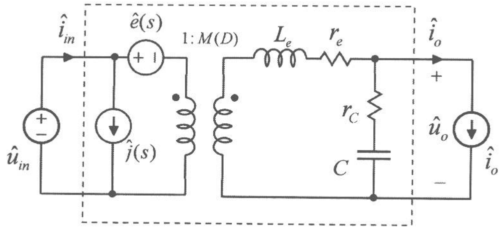

Figure 1.3 Small-signal canonical equivalent circuit for a two-memory-element converter.

two-memory-element converters, where the different circuit elements are defined according to a specific converter. It may be obvious that the equivalent circuit in Figure 1.3 provides real physical insight into the dynamic processes inside the converter and has, therefore, promoted the acceptance of the theoretical method providing the model. Similar equivalent circuit to Figure 1.3 can also be naturally constructed for the higher order converters.

The first attempt to model the dynamics associated with a VMC converter operating in discontinuous mode (DCM) is presented in [33] but it failed to capture the true full-order dynamics due to the lack of proper understanding of the dynamical processes inside a converter. The accurate small-signal models for the DCM operation were developed in the late 1990s [34]. A unified method based on the SSA method was finally developed in the early 2000s providing consistent modeling tools for fixed and variable-frequency operation both in DCM, CCM, and even in the combination of them [35]. The pulsewidth modulation (PWM) process would not produce linear responses but only at rather low frequencies (i.e., ~1/10 of switching frequency) for sinus excitations [36–38]. Therefore, the responses measured through the PWM input (i.e., control-to-input and control-to-output) may have more phase lag than the models derived using the SSA method would predict. Further studies on the topic are needed in order to find the correct dynamic behavior of the converter also at the frequencies approaching half the switching frequency. This is important because the desired loop crossover frequencies tend to approach ever higher frequencies beyond those typically used in the past.

The small-signal models of the VMC operation are important because the other control modes would usually only change the dynamics associated with the duty-ratio generation and, therefore, the corresponding dynamic models can be derived from the VMC state-space representation by substituting the perturbed duty ratio with the developed relation between the new control variable and the duty ratio known as duty-ratio constraints [22].

In reality, the controlled variable is usually the length of the on-time of the main switch [35]. Under fixed-frequency operation, the dynamical information incorporated into the on-time is equal to that of the duty ratio because of constant cycle time. Under variable-frequency operation, the duty ratio is nonlinear and, therefore, the on-time has to be used as the control variable under the VMC mode of operation. A comprehensive survey of the modeling issues can be found from [39].