1
Introduction

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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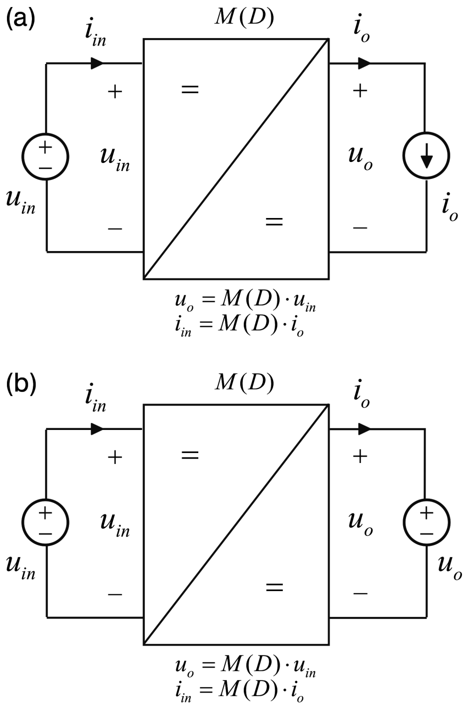

Figure 1.1 Voltage-sourced converter (a) at voltage-output mode and (b) at current-output mode.

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

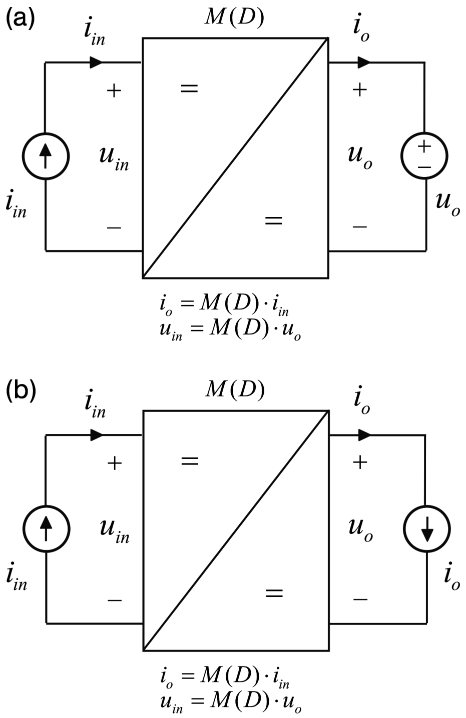

Figure 1.2 Current-sourced converter (a) at current-output mode and (b) at voltage-output mode.

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

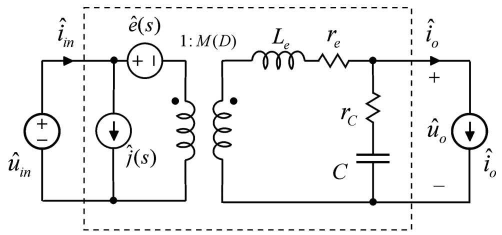

Figure 1.3 Small-signal canonical equivalent circuit for a two-memory-element converter.

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].

1.3
Dynamic Analysis of Interconnected Systems

The first system-level analysis was actually applied to a system comprising of an EMI (electromagnetic interference) filter and a regulated converter in the mid-1970s [40]. The analysis yielded the design rules for the EMI-filter design. The equivalent circuit of Figure 1.3 was effectively utilized. It was noticed that the EMI filter would influence the converter dynamics through its output impedance if certain impedance overlaps take place. The developed design rules were straightforward: avoid impedance overlap with a substantial margin. It was also stated that the stability of the converter can be deduced based on the ratio of the filter output impedance and the closed-loop input impedance of the converter by applying the *Nyquist* stability criterion. The impedance ratio is commonly known as minor-loop gain according to [40].

The analyses of interconnected regulated systems [41] have been based on the minor-loop-gain concept. It was concluded that the design rules given in [40] are too conservative and they may lead to unnecessary costs if applied as such. Typically, the design rules are given as a certain forbidden region in a complex plane out of which the minor-loop gain should stay to avoid instability and performance degradation. The shaded area in Figure 1.4 is the minimum area out of which the minor-loop gain should stay for stability to exist. This criterion is known as ESAC criterion [41]. The design rules of [40] would define the forbidden region as the area outside the circle having a radius of 1/GM, where GM stands for gain margin related to the minor-loop gain.

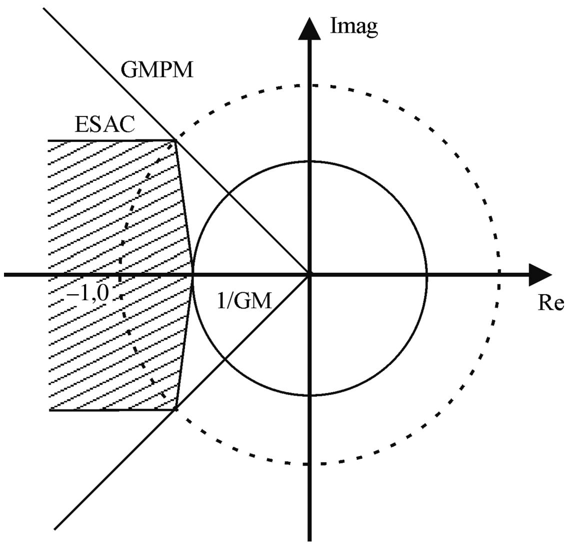

Figure 1.4 Forbidden regions.

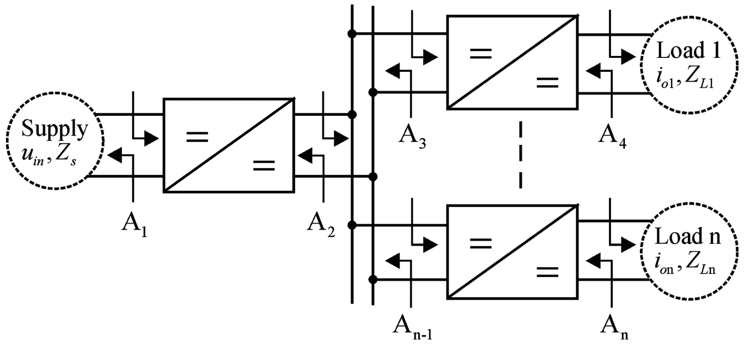

Figure 1.5 Different system interfaces.

It has turned out that avoiding the stated forbidden regions does not actually ensure that the transient performance of the converter would stay intact but more detailed considerations should be carried out [42, 43]: The practical power systems consist of several interfaces at which the minor-loop gain can be defined as depicted in Figure 1.5 (i.e., $A_1 - A_N$) containing also different information on the dynamics of the overall system. The interfaces that exist at the direct input or output of the power stage of the converter would contain the most useful information as actually has been demonstrated in [40]. The existence of stability can be concluded equally based on any of the defined minor-loop gains within the system [44]. The existence of stability even with a good margin (i.e., no impedance overlap) does not necessarily ensure that the transient performance of the associated converters is acceptable [42, 43].

Typically the converters are equipped with EMI filters or capacitors at the input side further complicating the performance analysis based on the measurable information at system level (Figure 1.6) due to hiding effects of those components [43]. The converter modules may be also provided with output-voltage remote sensing [45]. The application of the remote sensing may profoundly change the dynamics of the associated converter depending on what kind of external passive circuit elements are connected inside the converter (Figure 1.6) as demonstrated in [46].

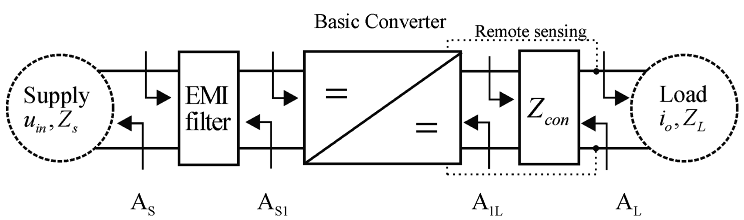

Figure 1.6 Internal system interfaces inside a converter.

As a summary we can state that the stability analysis of an interconnected-regulated system would be deterministic but to conclude whether the transient performance of the system is satisfactory or not is a more complicated issue and perfect information on it is difficult to obtain. Therefore, the methods by means of which the interactions can be reduced or totally eliminated are of great importance and worth to be considered as explained and demonstrated in [47–50].

1.4 Canonical Equivalent Circuit

The equivalent circuit introduced in Figure 1.3 as a canonical circuit is not a true canonical equivalent circuit, because it can only represent the dynamics of a two-memory-element VMC converter operating in CCM. A two-port model (Figure 1.7), where the input port is a Norton equivalent circuit and the output port a Thevenin equivalent circuit, would provide a real canonical representation of the dynamics associated with a voltage-input–voltage-output converter [11, 51]: The input and output-port parameters constitute of a set known as G-parameters, which can be proved to exist always and thus they can be defined for any voltage-input-voltage-output electrical system [14]. In practice, the set composes of the well-known transfer functions typically used to characterize switched-mode converters. It is essential that the transfer functions are defined in such a way that the source and load effects are removed in order to represent the real internal dynamics. Such transfer functions are commonly known as unterminated transfer functions [51].

In addition, the dynamic representation of the current-output converter can be derived from the two-port model of the voltage-output converter by transforming its Thevenin output port to an equivalent Norton representation shown in Figure 1.8 [52, 53]. The parameters of the current-output model (i.e., admittance or Y-parameters) can be derived as a function of the well-known voltage-output transfer functions (i.e., the G-parameters).

It is known that the source and load impedances, Figure 1.9, may affect the dynamics of a converter [11]. Mathematical formulation describing analytically the effects can be solved by using either circuit theory [15] or by applying the extra element theorem (EET) described in [16]. The EET method would provide useful formulation but may be difficult to apply.

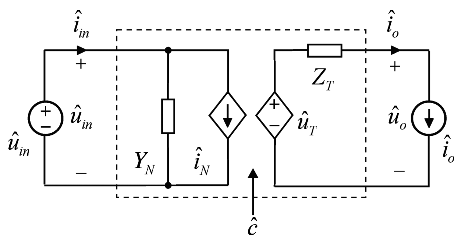

Figure 1.7 Canonical equivalent circuit of voltage-output converter.

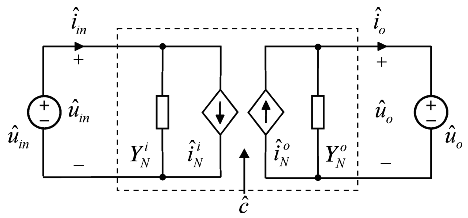

Figure 1.8 Canonical equivalent circuit for current-output converter.

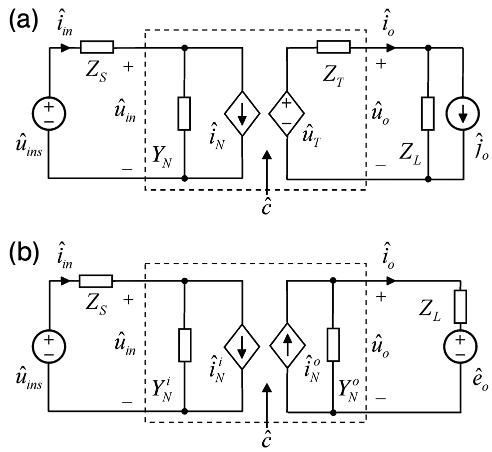

Figure 1.9 Nonideal source and load: (a) voltage-output converter and (b) current-output converter.

1.5 Load-Response-Based Dynamic Analysis

The frequency response of the voltage or current loop can be measured injecting an excitation signal into the corresponding loop, which has to be disconnected in such a way that only the DC signal can pass through it. This means that the internal circuitry of the converter has to be manipulated. Therefore, the methods not requiring the tear-down approach would be desirable such as the load-transient analysis [54–56]. The transient-based-analysis technique is commonly used in the control engineering textbooks such as [54]. It should, however, be noticed that the control engineering textbooks usually discuss on the transients resulting from applying excitations into the reference input, which is usually not available in the power electronic converters. The transients resulting from applying excitations into the disturbance inputs (i.e., input voltage or load current) also contain the effect of the corresponding open-loop transfer function in addition with the loop behavior. Those effects usually dominate and they would hide the information from the loop behavior. An illustrative example of such a phenomenon is shown in Figure 1.10 [16], where a certain converter under three different control principles is subjected to a constant-current-type load change. Some similarities and differences are clearly observable:

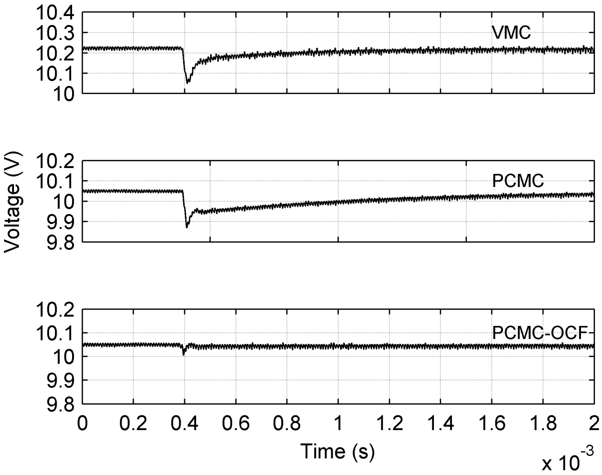

Figure 1.10 Output-voltage responses of a buck converter under VMC, PCM, and PCM with output-current-feedforward (OCF) control to an output- current change.

The setup time of the PCM converter seems to be very long compared to the VMC converter interpreted easily as a substantial difference in the voltage-loop crossover frequencies if following the information given for example in [56]. The output transient of the PCMC-OCF converter is extremely small and recovers quickly. This could be interpreted as a sign of very high control bandwidth. The output-voltage loop gains of the converters are, however, designed in a comparable manner as shown in Figure 1.11. Therefore, Figure 1.10 clearly demonstrates that the time-domain transients

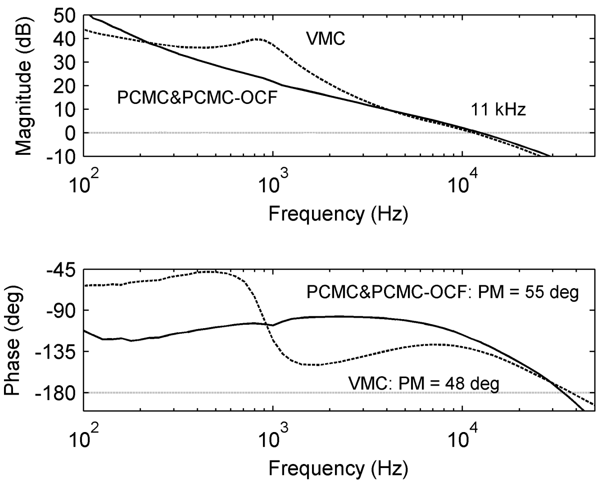

Figure 1.11 Measured voltage-loop gains (PM = phase margin).

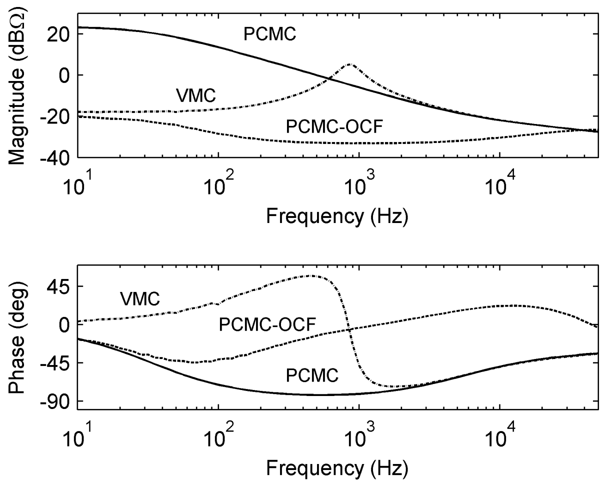

Figure 1.12 Measured open-loop output impedances.

do not provide the desired information on the voltage-loop properties because of the dominating effect of the disturbance input.

The measured open-loop output impedances of the converters are shown in Figure 1.12 and the corresponding closed-loop output impedances in Figure 1.13, where the voltage-loop-gain effect is observable. The closed-loop impedances provides the explanations for the observed load transients as explained in detail in [57–59], but basically the origin of the observed differences is the internal open-loop output impedances (Figure 1.12).

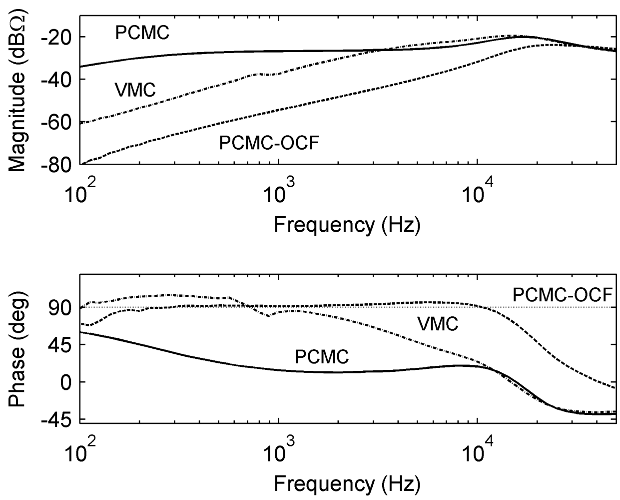

Figure 1.13 Measured closed-loop output impedances.

The internal open- and closed-loop output impedances are important sources of information, because they can be used to predict the dynamic behavior of the converter in different load environment and eventually to choose a best type of converter for the specific application [12].

1.6 Content Review

The content of the subsequent chapters is briefly reviewed in order to clarify the message each chapter contains:

The conceptual and theoretical basis of the book is provided in Chapter 2 in a simple and practical manner without using difficult mathematical treatments. The same theoretical formulas are repeated in the associate chapters if deemed to be necessary for understanding the message. The definition of different stability concepts, the influence of zeros and poles in the transfer functions, and the definition of the open-loop condition in a converter are especially important to be fully understood in order to understand the messages the book will provide.

The unified dynamic modeling of the direct-on-time control is provided in Chapter 3. The method is applied more in detail to the basic converters (i.e., buck, boost, and buck–boost) in the fixed-frequency mode of operation both in continuous (CCM) and discontinuous conduction modes (DCM). The variable-frequency operation is treated separately in Chapter 6. Extensive dynamic review is provided at the end of the chapter based both on experimental and theoretical evidence. The emphasis is in introducing the dynamical changes the operation in CCM and DCM would provide. The modeling of the direct-on-time control is important, because the dynamical models of the other control modes would be mainly derived based on it. The presented methods are also easily applicable to modeling of higher order converters.

The dynamic modeling of peak-current-mode control (PCMC) is provided in Chapter 4 and applied to the same converters as in Chapter 3. The origin of the peculiar phenomena observed in the operation of the PCM-controlled converters is fully explained. Extensive dynamic review is provided at the end of the chapter based both on experimental and theoretical evidence. The dynamic differences of the VM- and PCM-controlled buck and boost converters in CCM are compared. The PCM control is widely applied in controlling the switched-mode converters due to providing advantageous features but its modeling is the subject of intensive discussions. Unanimously accepted modeling method does not exist. The method presented in the book is based on the natural processes taking place in the converter without any kind of curve fitting or similar approaches. Therefore, the resulting dynamic models naturally represent the dynamics of the converter well and also provide the scientifically sound explanations for the phenomena observed in a PCM-controlled converter.

The dynamic modeling of average-current-mode control (ACMC) is provided in Chapter 5 and applied to a buck converter in CCM. The ACM control has naturally similarities to the PCM control, because both of the control methods use the inductor current for producing the duty ratio. Therefore, the presented modeling method applies the PCMC modeling presented in Chapter 4. The full ripple-feedback case is treated in detail. The effect of the high-frequency pole in the inductor-current-loop amplifier is discussed more in detail. The comparisons between VM, PCM, and ACM control in a buck converter are provided in order to highlight the dynamic changes and features the ACM control would provide.

The dynamic modeling of self-oscillation control (i.e., variable-frequency operation) is provided in Chapter 6 and applied to the basic converters. The dynamic review is provided for buck and buck–boost or flyback converters. The self-oscillation control is usually a form of PCM control requiring similar modeling steps as the fixed-frequency PCM control introduced in Chapter 4.

The dynamics associated with the current-output converters is treated in Chapter 7. The dynamic review is provided for a buck converter under VM and PCM controls based on the experimental and theoretical evidence. The observed peculiar dynamical behavior is fully explained. The chapter concentrates on the single-feedback-loop case but the method to solve the dynamic modeling of cascaded cases is also provided.

The dynamic issues related to the interconnected systems are treated in Chapter 8. The theoretical interaction formalism is briefly reviewed. The concepts of intermediate and input–output stabilities are consistently defined by applying system theory and shown to be related to the impedance ratio known as minor-loop gain. The analysis of the output-voltage remote-sensing and EMI-filter effects are briefly discussed and the theoretical formulation to treat them is provided. Practical evidence is provided to support the theoretical findings.

The control-related issues such as different controller implementations, factors affecting the transient, responses and limiting the maximum loop crossover frequency are discussed in Chapter 9. In addition, the dynamic constraints related to the simple control systems based on the adjustable shunt regulator TL431 are treated. Finally, a consistent method to shape the loop gain in order to achieve the desired loop dynamics is proposed and verified experimentally.

Dynamic modeling and analysis of a fourth-order converter known as two-inductor buck, current-sourced buck, and superbuck converter is provided in Chapter 10 as an example of the higher order converters and the possible dynamic anomalies involved in them. The superbuck converter has similar features as the conventional buck converter but its input and output currents are continuous. The input-current ripple can be further reduced by coupling the inductors. Consistent and easy-to-apply analysis methods for the coupled-inductor technique are given and applied to the VM- and PCM-controlled converter. Practical evidence on the dynamics of the PCM-controlled superbuck converter is provided.

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