1

Introduction

1.1 General Remarks

Power electronics converters are widely utilized in almost every aspect of todays' modernized world including computers, smart home systems, electric vehicles (EVs), trains, marine, aircrafts, microgrids, robots, renewable energy conversion and integration, and many industrial applications. The main function of a power converter is to convert the electrical power from one form to the other [1]. In general, there are four different categories of power converters: DC–DC, AC–DC, DC–AC, and AC–AC. In each category, various converter topologies have been developed to meet the desired conversion and application objectives. For instance, when the photovoltaic (PV) energy is to be converted and injected into the grid, a DC–DC boost converter is connected between the PV panel and DC–AC inverter to ensure a constant inverter input voltage and to possibly track the panel's maximum power point. The necessity of DC–DC boost converter in such application arises due to the buck operation of the inverter (i.e. DC input voltage is greater than the amplitude of its AC voltage). On the other hand, an AC–DC converter (usually referred to as rectifier) is used in an electric vehicle (EV) charging system to convert the grid's AC voltage to DC such that the battery can be charged. Another example is the use of series active filter (usually referred to as dynamic voltage restorer) in the protection of sensitive loads (i.e. medical equipment in the hospitals, data centers, and so on) against voltage sags, and voltage swells in the grid voltage. When such voltage variations occur in the grid, the series active filter, which is built using a DC–AC inverter, generates and injects the required compensation voltage to the point of common coupling such that the sensitive load

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voltage is always kept at the desired value. Similar examples can be given for the other converter categories.

Thus, considering the importance of today's energy demand and the need for clean and reliable resources, the use of power electronics has increased tremendously. As such, the performance of the power converters used in these applications has gained utmost importance. In most of the power electronics-related applications, closed-loop control is essential to keep the voltage or current at reference values under various conditions, which include load changes, grid voltage deterioration (voltage sags, voltage swells, and distorted grid voltages), and parameter variations, which occur because of aging and operating conditions. More importantly, the stability of closed-loop system should not be jeopardized under these situations. For this reason, the design of a closed-loop system that responds to these challenges is an essential and difficult task. First of all, it should be noted that the design of closed-loop control for power electronics converters requires a deep knowledge in many areas such as circuit analysis, advanced mathematics, modeling, control systems, and power electronics. In this regard, this chapter starts with the introduction of simplest closed-loop control for power converters. Then, mathematical modeling, basic control objectives, and performance evaluation are explained briefly. Hence, the reader is urged to refresh or gain further basic information in the areas of control theory and power electronics converters from the literature.

This book is primarily concerned with advanced nonlinear control of power converters. A closed-loop control is referred to as nonlinear control if it contains at least one nonlinear component. Nonlinear control of power converters received attention of many researchers in the last two decades. The main reason of this popularity comes from the advantages over linear control methods, which lack guaranteed stability in large operation range of the converters; facing hard nonlinearities (saturation, dead-zone, backlash, and hysteresis), which cannot be approximated linearly; and having model uncertainties, which are assumed to be known when designing the linear controller. Whereas the nonlinear control is able to cope with the problems mentioned above. In this book, sliding mode control, Lyapunov function-based control, and model predictive control methodologies are explained for power converters. Although these nonlinear control methods are not new, their application in power converter control was limited in the past due to the required extensive computations. Since last decade, the advent of fast implementation platforms such as digital signal processors and field programmable gate arrays (FPGAs) relieved the computation burden issue. Therefore, compiling the design and application of the nonlinear control methods mentioned above in a single book is very beneficial for the interested readers.

1.2 Basic Closed-Loop Control for Power Converters

A basic single input single output (SISO) closed-loop power converter control system is illustrated in Figure 1.1. Here, the main aim is to control the power converter in order to accomplish specific desired control objectives (see Section 1.4). Clearly, the output signal (i.e. voltage or current) is measured and compared with the reference one to produce an error signal. This error signal is applied to the controller. Then, the controller generates modulation signal from which the pulse width modulation (PWM) signals are generated. These signals are applied to the gates of switching devices (i.e. insulated gate bipolar transistors [IGBTs], metal oxide semiconductor field effect transistors [MOSFETs], etc.) in the power converter. Upon the application of PWM signals, the switching devices are turned on and off. The value of voltage (or current) in the converter is changed by these switching actions. If the controller is well designed, the error signal is

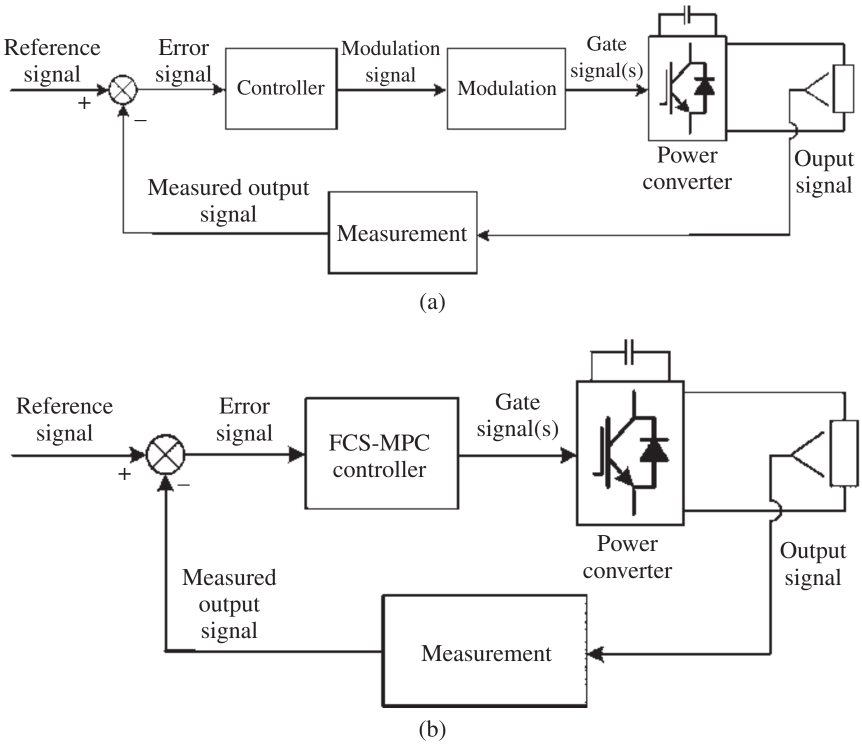

Figure 1.1 Basic closed-loop power converter control system. (a) With modulation, (b) without modulation.

continually reduced until the output signal tracks the reference signal in the steady state. On the other hand, the number of loops in a control system may be more than one depending on the converter topology and the application area.

Numerous control approaches have been developed for the power converters. Each control approach has its own advantages and disadvantages concerning with the controller complexity and cost, dynamic response, steady-state error, robustness to parameter variations, and closed-loop stability. It is worth to mention that the discussion in this book is based on the introduction, design and application of sliding mode control, Lyapunov function-based control, and model predictive control methods used in various power converters. While the sliding mode control and Lyapunov function-based control methods require a modulation block as shown in Figure 1.1a, the finite control set model predictive control (FCS-MPC) method does not require a modulation as shown in Figure 1.1b. The design of sliding mode control, Lyapunov function-based control, and model predictive control are explained in Chapters 3, 4, and 5, respectively. The following sections intend to present background information regarding the steps that should be taken into consideration when designing a controller. Even though these steps are well known in the modern control systems area, the readers, who are not fully familiar with these, will gain a knowledge before learning each of these control methods.

1.3 Mathematical Modeling of Power Converters

Usually, an accurate mathematical model of the converter is necessary when there is a need to design its controller. As it will be discussed in Chapter 3, the sliding mode control does not require mathematical modeling of the converter. Whereas the Lyapunov function-based control and model predictive control approaches rely on the mathematical model of the power converter as will be explained in Chapters 4 and 5, respectively. However, a perfect mathematical model, which represents all dynamics of the converter, is not possible in practice due to the certain noises (i.e. measurement noise) and possible failure conditions. There are two types of mathematical models in the continuous time: linear models and nonlinear models. The behavior of a linear converter system is usually described by linear differential equations written in the state-space form as follows:

$$\begin{aligned} \frac{d\mathbf{x}}{dt} &= A\mathbf{x} + Bu \\ y &= C\mathbf{x} + Du \end{aligned} \tag{1.1}$$

where $\mathbf{x}$ represents the state vector, u represents the input vector, y represents the output vector, and A, B, C, and D represent the matrices with appropriate dimension. Such models are suitable to be used with the root-locus method, state-space method, and frequency domain design methods such as Bode plot and Nyquist method. As will be discussed in Chapter 4, the Lyapunov function-based control method uses the linear converter system model in (1.1). On the other hand, the model predictive control method (see Chapters 5 and 9) uses discrete-time version of the continuous-time model in (1.1) as given below:

$$\begin{aligned} \mathbf{x}(k+1) &= A_d\mathbf{x}(k) + B_d u(k) \\ y(k) &= C_d\mathbf{x}(k) + D_d u(k), \qquad k = 0, 1, 2, 3, \ldots \end{aligned} \tag{1.2}$$

where A_d, B_d, C_d, and D_d are discretized matrices of A, B, C, and D, respectively. The sampling instants are represented by k and $k+1$. It is worth to mention that the sampling period T_s is omitted in (1.2) for brevity. In general, the discretization of (1.1) can be based on the integral approximation method or Euler's method. In the case of integral approximation method, the input is assumed to be constant between sampling instants k and $k+1$ (i.e. $u(t) = u(kT_s)$, $kT_s \le t \le (k+1)T_s$), which results in following discrete-time state equation:

$$\mathbf{x}((k+1)T_s) = e^{AT_s}\mathbf{x}(kT_s) + \int_{kT_s}^{(k+1)T_s} e^{A((k+1)T_s-\tau)}Bu(kT_s)d\tau \tag{1.3}$$

Note that (1.3) is same as first equation of (1.2) if T_s is omitted. Comparing (1.2) and (1.3), it can be seen that

$$\begin{aligned} A_d &= e^{AT_s} \\ B_d &= e^{AT_s} + \int_{kT_s}^{(k+1)T_s} e^{A((k+1)T_s-\tau)}d\tau B \end{aligned} \tag{1.4}$$

The discrete-time output equation can be derived in the same way. In the case of Euler's method, the first derivative of state equation at $t = kT_s$ is approximated as follows:

$$\frac{d\mathbf{x}(\mathrm{t})}{dt} \approx \frac{\mathbf{x}((k+1)) - \mathbf{x}(k)}{T_s} \tag{1.5}$$

Equation (1.5) is referred to as Euler's forward approximation in literature [2], [3]. Applying (1.5) to the first equation of (1.1), one can obtain:

$$\mathbf{x}((k+1)T_s) \approx (I + T_sA)\mathrm{x}(kT_s) + T_sBu(kT_s) \tag{1.6}$$

where I is the identity matrix. When first equation of (1.2) and (1.6) are compared, the following relations are obtained easily:

$$A_d = I + T_sA, \quad B_d = T_sB \tag{1.7}$$

On the other hand, the behavior of a nonlinear converter can be described by using a nonlinear mathematical model of the form:

$$\begin{aligned}\frac{d\mathbf{x}}{dt} &= f(\mathbf{x}, u) \\ y &= g(\mathbf{x}, u)\end{aligned} \tag{1.8}$$

where $f(\mathbf{x}, u)$ and $g(\mathbf{x}, u)$ are the nonlinear functions of $\mathbf{x}$ and u. It is worth noting that the behavior of some converters can also be defined by using the following nonlinear mathematical model:

$$\frac{d\mathbf{x}}{dt} = f(\mathbf{x}) + g(\mathbf{x})u \tag{1.9}$$

where $f(\mathbf{x})$ and $g(\mathbf{x})$ are the nonlinear functions of $\mathbf{x}$. The nonlinear functions in (1.8) and (1.9) are usually unknown. For this reason, robust control method such as the sliding mode control is emerged to obtain the desired performance.

1.4 Basic Control Objectives

Controller design is usually based on satisfying some closed-loop specifications, which can be referred to as the control objectives. These control objectives can be described as follows.

1.4.1 Closed-Loop Stability

In the control design, the closed-loop stability analysis of a converter to be controlled is the first step. The closed-loop stability of linear systems can be tested either in s-domain [4] or in z-domain [5]. When the controller is designed in continuous-time, the stability check is performed in Laplace domain. In this case, the closed-loop converter system is stable if all the roots of its characteristic equation are located in the left half of s-plane (complex plane). It should be noted that the roots of characteristic equation are the poles of closed-loop system. If any root is located in the right half of s-plane, the closed-loop converter system is unstable. The effects of the root locations on the dynamic response of the closed-loop system are depicted in Figure 1.2. Clearly, while complex conjugate roots with negative real parts cause a decreasingly oscillatory response, a root with negative real part leads to a converging smooth response. On the other hand, complex conjugate roots with positive real parts cause an increasingly oscillatory response while a root with positive real part leads to a diverging smooth response. Hence, an idea about the speed of the transient response can be obtained from the root locations. For instance, real roots located near the imaginary axis cause slow transient

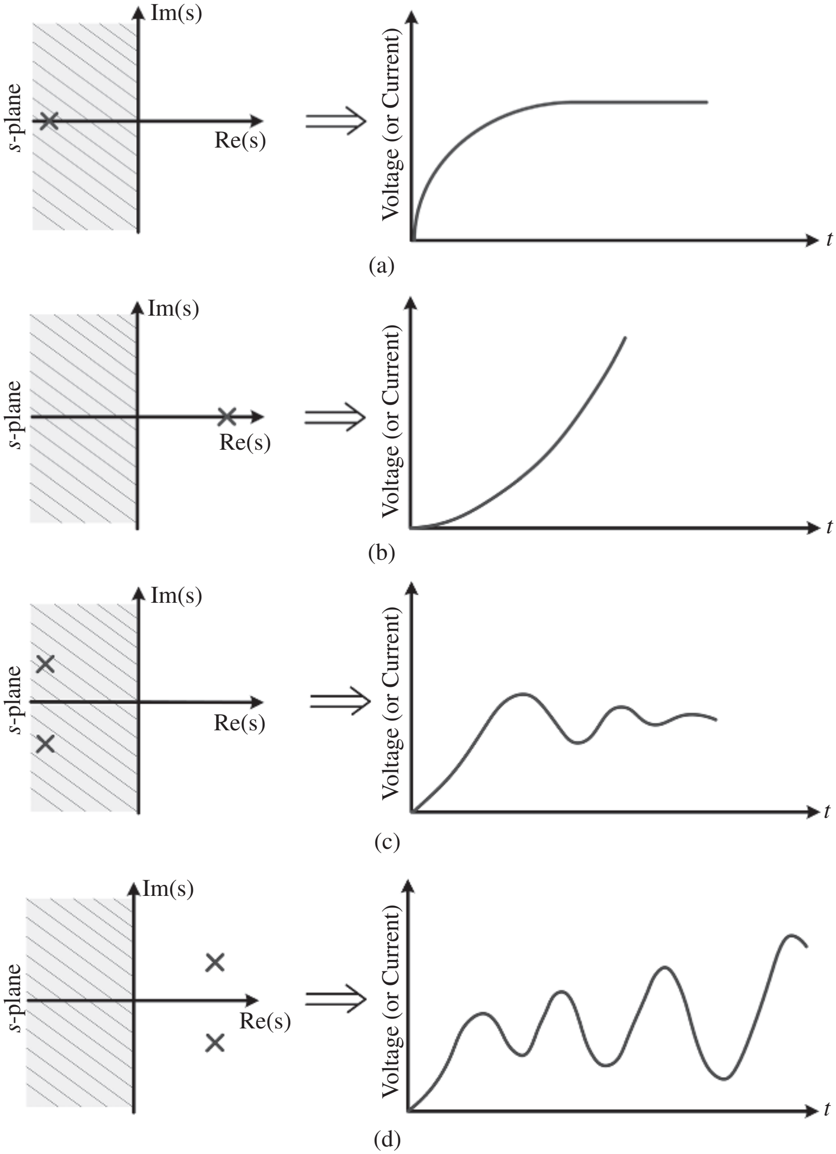

Figure 1.2 Effects of the root locations on the dynamic response of the closed-loop system. (a) Negative real root, (b) positive real root, (c) complex conjugate root with negative real parts, (d) complex conjugate root with positive real parts.

response due to the fact that $\tau_1 = 1/p_1$ where τ_1 is the closed-loop time constant and p_1 is the real root. Similarly, complex roots located close to the imaginary axis slow down the transient response.

When the order of characteristic equation is higher four, then the determining closed-loop stability is not easy due to the difficulty in solving the roots analytically. In this case, Routh–Hurwitz stability criterion can be used to determine the stability of a linear system [4]. Consider the following characteristic equation:

$$F(s) = a_n s^n + a_{n-1} s^{n-1} + a_{n-2} s^{n-2} + \dots + a_1 s + a_0 = 0 \tag{1.10}$$

The Routh–Hurwitz stability criterion relies on ordering the coefficients of the characteristic equation in the form of an array shown below [4]:

$$\begin{array}{c|ccc} s^n & a_n & a_{n-2} & a_{n-4} \\ s^{n-1} & a_{n-1} & a_{n-3} & a_{n-5} \\ s^{n-2} & b_{n-1} & b_{n-3} & b_{n-5} \\ . & c_{n-1} & c_{n-3} & c_{n-5} \\ . & . & . & . \\ . & . & . & . \\ s & . & . & . \\ s^0 & h_{n-1} & . & . \end{array} \tag{1.11}$$

where $b_{n-1} = \frac{-1}{a_{n-1}} \det \begin{bmatrix} a_n & a_{n-2} \\ a_{n-1} & a_{n-3} \end{bmatrix}$, $b_{n-3} = \frac{-1}{a_{n-1}} \det \begin{bmatrix} a_n & a_{n-4} \\ a_{n-1} & a_{n-5} \end{bmatrix}$, $c_{n-1} = \frac{-1}{b_{n-1}} \det \begin{bmatrix} a_{n-1} & a_{n-3} \\ b_{n-1} & b_{n-3} \end{bmatrix}$, and so on. According to the Routh–Hurwitz stability criterion, all roots of a characteristic equation are located in the left half of s-plane if and only if all first-column elements of the array in (1.11) have the same sign. However, it should be noted that the Routh–Hurwitz criterion is useful for only continuous-time linear systems and, hence, cannot be considered to test the stability of discrete-time systems.

On the other hand, when the controller is designed in discrete-time, the left-half of s-plane is mapped to the interior of a unit circle as illustrated in Figure 1.3. This implies that the closed-loop converter system is stable if all the roots of its characteristic equation are located within the unit circle (i.e. $|z| < 1$). It is worthy noting that while the entire imaginary axis in the s-plane is mapped onto the unit circle ($|z| = 1$), the right-half of s-plane is mapped to the outside of the unit circle. Thus, the closed-loop system becomes unstable when the roots are outside of the unit circle (i.e. $|z| > 1$).

In the case of difficulty in solving the roots analytically in discrete time, the Jury stability criterion can be used to test the stability of the linear system [5]. The Jury stability criterion involves determinant operations as in the Routh–Hurwitz

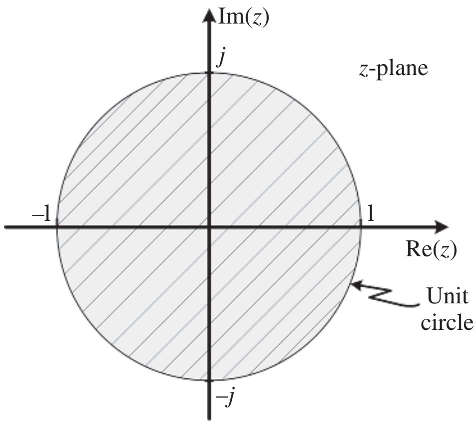

Figure 1.3 Stable region of the closed-loop system in discrete time.

stability criterion. However, determining the closed-loop stability is more time consuming. Consider the following characteristic equation [6]:

$$F(z) = a_n z^n + a_{n-1} z^{n-1} + a_{n-2} z^{n-2} + \dots + a_1 z + a_0 = 0 \tag{1.12}$$

Then, Table 1.1 can be constructed as follows.

The entries of table can be computed as follows:

$$b_k = \det\begin{bmatrix} a_0 & a_{n-k} \\ a_n & a_k \end{bmatrix}, \quad k = 0, 1, \dots, n-1 \tag{1.13}$$

Table 1.1 Jury's table.

Row	z^0	z^1	z^2	...	z^{n-k}	...	z^{n-1}	z^n
1	a_0	a_1	a_2	...	a_{n-k}	...	a_{n-1}	a_n
2	a_n	a_{n-1}	a_{n-2}	...	a_k	...	a_1	a_0
3	b_0	b_1	b_2	...	b_{n-k}	...	b_{n-1}	
4	b_{n-1}	b_{n-2}	b_{n-3}	...	b_k	...	b_0	
5	c_0	c_1	c_2	...	...	c_{n-2}		
6	c_{n-2}	c_{n-3}	c_{n-4}	...	...	c_0		
.	.	.	.	...	...			
.	.	.	.	...	...			
$2n-5$	p_0	p_1	p_2	p_3				
$2n-4$	p_3	p_2	p_1	p_0				
$2n-3$	q_0	q_1	q_2					

$$c_k = \det\begin{bmatrix} b_0 & b_{n-k} \\ b_n & b_k \end{bmatrix}, \quad k = 0, 1, \ldots, n-2 \tag{1.14}$$

$$q_0 = \det\begin{bmatrix} p_0 & p_3 \\ p_3 & p_0 \end{bmatrix}, \quad q_1 = \det\begin{bmatrix} p_0 & p_2 \\ p_3 & p_1 \end{bmatrix}, \quad q_2 = \det\begin{bmatrix} p_0 & p_1 \\ p_3 & p_2 \end{bmatrix} \tag{1.15}$$

According to the Jury stability criterion, the roots of $F(z)$ are inside the unit circle if and only if the following conditions are held,

1. $F(1) > 0$
2. $(-1)^n F(-1) > 0$
3. $|a_0| < a_n$
4. $|b_0| > |b_{n-1}|$
5. $|c_0| > |c_{n-2}|$

. .

. .

$n+1$ $|q_0| > |q_2|$

The stability analysis of Lyapunov function-based control and model predictive control methods, which will be described in Chapters 8 and 9 of this book, can be determined by using the methods described above. It is worth noting that the stability analysis of sliding mode control is based on special conditions as explained in Chapters 2 and 3. On the other hand, the stability analysis of nonlinear converter systems can be based on Lyapunov functions, which are also discussed in Chapter 2.

1.4.2 Settling Time

In the power converter control problem, the settling time is described as the time taken by a voltage (or a current) from a step variation to reach its final value and remain within a predefined tolerance band as shown in Figure 1.4. In other words, the settling time can be described as the dynamic response time of the control method. In some applications, the controller is highly desired to have a fast dynamic response (i.e. short settling time) against load variations, reference voltage (or current), and input voltage variations. In some control methods, the settling time can be adjusted to meet the desired speed by tuning the control gains. For example, the proportional gain in a proportional-integral (PI) controller has the effect on the settling time. Similarly, the sliding coefficient in the sliding mode control method plays an important role to make the settling time faster or slower. The Lyapunov function-based control and model predictive control methods have control parameters that directly affect the settling time.

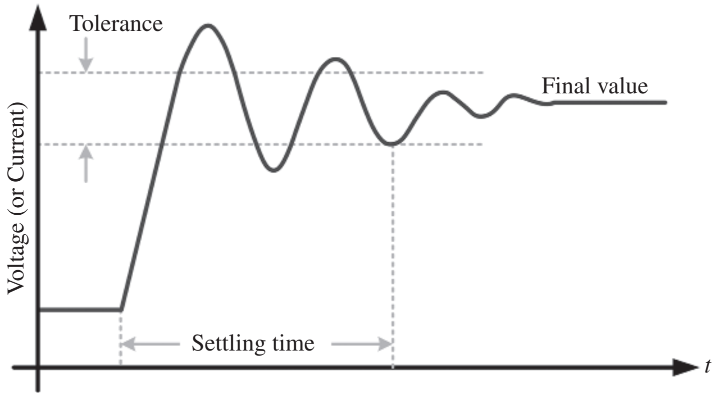

Figure 1.4 Settling time.

1.4.3 Steady-State Error

In the power converter control problem, the steady-state error is described as the difference between the actual value and reference value of a voltage (or a current) when the converter reaches steady state. Figure 1.5 shows the steady-state error graphically where the actual output is not equal to the desired output value during the steady state. When a steady-state error exists, it implies that the converter operates slightly away from its desired operating point. In such a case, the efficiency of the converter is reduced. For this reason, achievement of almost zero steady-state error is very important. For example, the integral term in the PI controller has the ability to achieve zero steady-state error. The integral gain determines how fast

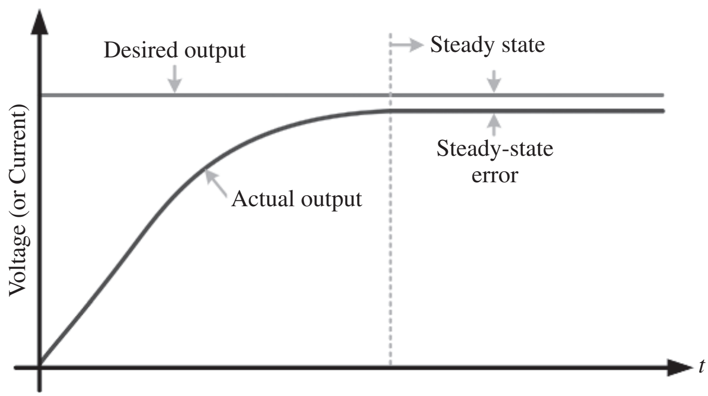

Figure 1.5 Steady-state error.

the error becomes zero in the steady state. In the case of sliding mode control, zero steady-state error can be achieved at the expense of high switching frequency. Similarly, the Lyapunov function-based control and model predictive control methods may yield zero steady-state error provided that the control parameters are selected appropriately.

1.4.4 Robustness to Parameter Variations and Disturbances

Robustness is defined as the ability of a closed-loop converter system to compensate the parameter variations and disturbances in the converter, and to maintain the stability and control objectives. The values of circuit parameters such as resistors, inductors, and capacitors vary due to aging and operating conditions. Also, the disturbances such as abrupt voltage (or current) variations may result in adverse effects in the performance and stability of the closed-loop system. For this reason, the effects of parameter variations as well as disturbances should be investigated. Among the control methods that are discussed in this book, only the sliding mode control is robust to the parameter variations and disturbances. This property is not surprising since the sliding mode control is not based on the mathematical model of the converter. As such, this property makes the sliding mode control very attractive in the applications where the robustness is important. On the other hand, the Lyapunov function-based control and model predictive control methods highly depend on the system parameters. Hence, the effect of parameter variations and disturbances on the performance of the designed controller should be investigated. In some cases, the parameters variations may endanger the closed-loop stability and result in an unstable system.

1.5 Performance Evaluation

The performance of the designed controller should be tested to see whether the desired control objectives are satisfied or not. In general, there are two methods to verify that the designed controller works properly.

1.5.1 Simulation-Based Method

In this method, a simulation model of the closed-loop converter control system is built and used to investigate the satisfaction of the control objectives. The most popular simulation platforms for power converter control are MATLAB®\Simulink, PSIM®, PLECS®, and POWERSIM®. An accurate simulation model that includes the effects of practical implementation can also be developed. Hence, the simulation-based method is very useful in enhancing the confidence that the predefined control objectives of the designed closed-loop system are achieved.

1.5.2 Experimental Method

In this method, the designed closed-loop system for the converter is implemented and tested under various operating conditions. Contrary to the simulation-based method, experimental method requires significant resources such as AC/DC power supplies, voltage/current sensors, AC/DC loads, passive components (resistors, inductors, capacitors, transformers), and measuring devices (oscilloscope, power quality analyzer, voltmeter, ammeter). More importantly, a platform is needed to realize the designed control method in real time. Digital signal processors (DSPs), field programmable gate arrays (FPGAs), and real-time simulators (e.g. OPAL-RT, Typhoon, and dSpace) are widely used in converter control problems. It is worth noting that the fixed-point DSPs are widely used in industrial applications due to their low cost. On the other hand, the computational power that is measured in terms of millions of instructions per second (MIPS) of DSPs is improved by time. Today, there exist very powerful DSPs in the market, which can handle the heavy computations needed in most of the control algorithms.

1.6 Contents of the Book

This book is organized as nine chapters. Chapter 1 presents brief information about the design of basic closed-loop controller for power converters, mathematical modeling, basic control objectives, and performance evaluation. Chapter 2 introduces the basics of advanced control methods such as sliding mode control (SMC), Lyapunov function-based control, and model predictive control (MPC). The introduction of these advanced control methods constitutes a bridge between theory and application.

Chapter 3 highlights the design of SMC for power converters in detail. For the sake of simplicity, two well-known DC–DC converters (Buck and Cuk) are selected. The simulation of these converters is presented and discussed. Thereafter, the SMC design procedure that includes sliding surface function selection, control input design, chattering mitigation techniques, and modulation techniques is presented. Finally, other types of SMC are also discussed briefly.

Chapter 4 highlights the design of Lyapunov function-based control for power converters in detail. The idea behind the selection of Lyapunov function for various converters is explained. For the sake of simplicity, two well-known DC–DC converters (Buck and Boost) are selected. The simulation of these converters is presented and discussed.

Chapter 5 highlights the design of MPC for power converters in detail. This includes the discussions about predictive control methods, finite control set MPC, continuous control set MPC, and design and implementation issues.

Chapter 6 presents MATLAB/Simulink tutorial on physical modeling and experimental setup. It includes discussions about building simulation models for power converters, modeling of sliding mode controlled single-phase grid-connected inverter, modeling of Lyapunov function-based control for three-phase rectifier, modeling of MPC-controlled quasi-Z-source three-phase four-leg inverter, modeling of distributed generations in islanded AC microgrid, real-time modeling of single-phase T-type rectifier, and building rapid control prototyping for single-phase T-type rectifier.

Chapter 7 presents the SMC of various power converters in detail with simulation as well as experimental results. The discussion starts with a single-phase grid-connected inverter with LCL filter. It includes mathematical modeling, SMC design, PWM signal generation using single- and double-band hysteresis modulations, switching frequency computation of both hysteresis modulation methods, selection of control gains, simulation and experimental results. Then, a three-phase grid-connected inverter with LCL filter is considered. The discussion includes model equations, design of SMC, stability analysis, experimental results, and computational load and performance of SMC. Then, a three-phase rectifier is considered. The discussion includes nonlinear model of the rectifier, problem formulation, axis-decoupling based on an estimator, design of SMC, and experimental results. A three-phase transformerless dynamic voltage restorer is also considered. After modeling of the system, the SMC design is presented. Then, the time-varying switching frequency equation is derived. Thereafter, constant switching frequency with boundary-layer-based SMC design is discussed. Simulation and experimental results are presented to verify the theoretical considerations. Finally, a three-phase shunt active power filter is considered. The discussion starts with the shunt active filter model and continues with problem formulation, SMC design, and experimental results.

Chapter 8 presents the Lyapunov function-based control of various power converters in detail with simulation as well as experimental results. The discussion starts with a single-phase grid-connected inverter with LCL filter. It includes mathematical modeling, controller design with capacitor voltage feedback, inverter current generation using proportional-resonant controller, grid current transfer function, harmonic impedance, simulation, and experimental results. Then, a single-phase quasi-Z-source grid-connected inverter with LCL filter is considered. The discussion includes quasi-Z-source modeling, grid-connected inverter modeling, control design of quasi-Z-source network, control design for grid-connected inverter, reference generation using cascaded proportional-resonant controller, and simulations results.

Chapter 9 presents continuous control set MPC for three-phase grid-connected voltage source inverter, MPC of single-phase three-level shunt active filter, MPC of quasi-Z-source three-phase four-leg inverter, weighting factorless MPC of DC-DC SEPIC converter, MPC droop control of distributed generation inverters in islanded AC microgrid, finite control set MPC of three-phase shunt active power filter, finite control set MPC of single-phase T-type rectifier, predictive torque control of brushless doubly fed induction generator fed by a matrix converter, and an enhanced finite control set MPC method with self-balancing capacitor voltages of three-level T-type rectifier.

References

1 M. P. Kazmierkowski, R. Krishnan, and F. Blaabjerg, *Control in Power Electronics: Selected Problems*. USA: Academic, 2002.

2 N. Guler, S. Biricik, S. Bayhan, and H. Komurcugil, "Model predictive control of DC–DC SEPIC converters with auto-tuning weighting factor," *IEEE Trans. Ind. Electron.*, vol. 68, no. 10, pp. 9433–9443, Oct. 2021.

3 N. Guler and H. Komurcugil, "Energy function based finite control set predictive control strategy for single-phase split source inverters," *IEEE Trans. Ind. Electron.*, vol. 69, no. 6, pp. 5669–5679, Jun. 2022.

4 N. S. Nise, *Control Systems Engineering*. USA: Wiley, 2004.

5 S. Buso and P. Mattavelli, *Digital Control in Power Electronics*. Switzerland: Springer-Verlag, 2015.

6 M. S. Fadali and A. Visioli, *Digital Control Engineering: Analysis and Design*. USA: Academic, 2009.