Converter systems invariably require feedback. For example, in a typical dc–dc converter application, the output voltage \( v(t) \) must be kept constant, regardless of changes in the input voltage \( v_g(t) \) or in the effective load resistance \( R \). This is accomplished by building a circuit that varies the converter control input [i.e., the duty cycle \( d(t) \)] in such a way that the output voltage \( v(t) \) is regulated to be equal to a desired reference value \( v_{\text{ref}} \). In inverter systems, a feedback loop causes the output voltage to follow a sinusoidal reference voltage. In modern low-harmonic rectifier systems, a control system causes the converter input current to be proportional to the input voltage, such that the input port presents a resistive load to the ac source. So feedback is commonly employed.

A typical dc–dc system incorporating a buck converter and feedback loop block diagram is illustrated in Fig. 7.1. It is desired to design this feedback system in such a way that the output voltage is accurately regulated, and is insensitive to disturbances in \( v_g(t) \) or in the load current. In addition, the feedback system should be stable, and properties such as transient overshoot, settling time, and steady-state regulation should meet specifications. The ac modeling and design of converters and their control systems such as Fig. 7.1 is the subject of Part II of this book.

To design the system of Fig. 7.1, we need a dynamic model of the switching converter. How do variations in the power input voltage, the load current, or the duty cycle affect the output voltage? What are the small-signal transfer functions? To answer these questions, we will extend the steady-state models developed in Chapters 2 and 3 to include the dynamics introduced by the inductors and capacitors of the converter. Dynamics of converters operating in the continuous conduction mode can be modeled using techniques quite similar to those of Chapters 2 and 3; the resulting ac equivalent circuits bear a strong resemblance to the dc equivalent circuits derived in Chapter 3.

Modeling is the representation of physical phenomena by mathematical means. In engineering,
it is desired to model the important dominant behavior of a system, while neglecting other insignificant phenomena. Simplified terminal equations of the component elements are used, and many aspects of the system response are neglected altogether, that is, they are “unmodeled.” The resulting simplified model yields physical insight into the system behavior, which aids the engineer in designing the system to operate in a given specified manner. Thus, the modeling process involves use of approximations to neglect small but complicating phenomena, in an attempt to understand what is most important. Once this basic insight is gained, it may be desirable to carefully refine the model, by accounting for some of the previously ignored phenomena. It is a fact of life that real, physical systems are complex, and their detailed analysis can easily lead to an intractable and useless mathematical mess. Approximate models are an important tool for gaining understanding and physical insight.

As discussed in Chapter 2, the switching ripple is small in a well-designed converter operating in continuous conduction mode (CCM). Hence, we should ignore the switching ripple, and model only the underlying ac variations in the converter waveforms. For example, suppose that some ac variation is introduced into the converter duty cycle \( d(t) \), such that

\[
d(t) = D + D_m \cos \omega_m t
\]  

(7.1)

where \( D \) and \( D_m \) are constants, \( |D_m| \ll D \), and the modulation frequency \( \omega_m \) is much smaller than the converter switching frequency \( \omega_s = 2\pi f_s \). The resulting transistor gate drive signal is illustrated in Fig. 7.2(a), and a typical converter output voltage waveform \( v(t) \) is illustrated in Fig. 7.2(b). The spectrum of \( v(t) \) is illustrated in Fig. 7.3. This spectrum contains components at the switching frequency as well as its harmonics and sidebands; these components are small in magnitude if the switching ripple is small. In addition, the spectrum contains a low-frequency component at the modulation frequency \( \omega_m \). The magnitude and phase of this component depend not only on the duty cycle variation, but also on the frequency response of the converter. If we neglect the switching ripple, then this low-frequency compo-