ticeable impedance resulting from parasitic inductance. As the frequency continues to rise, the impedance of the capacitor begins to be more affected by the inductance. Because inductors resist high-frequency signals by increasing their impedance, the filtering capacitor loses its effect above a certain frequency limit. Figure 12.13 shows the general curve of impedance versus frequency for a capacitor. The curve shows that, above a certain frequency, a capacitor no longer behaves as expected from an ideal perspective. This threshold frequency is different for each type of capacitor and is determined by its physical construction. This is why power filter (e.g., decoupling or bypass) capacitors are ideally chosen based on the expected frequencies of noise that they are expected to attenuate.

As with parasitic inductance, a capacitor's parasitic resistance is a function of its physical construction. The industry-standard term that specifies this attribute is *equivalent series resistance* (ESR). Certain applications for capacitors tend to be more sensitive to ESR than others. ESR is generally not a major concern in high-frequency decoupling applications. However, when power-supply ripple needs to be attenuated, such as in a switching power supply, low-ESR capacitors may be critical to a successful circuit.

Inductors are subject to parasitic properties as well, in the form of series resistance in the wire coil and capacitance between individual coil windings and between the terminals. The nonideal inductor looks very much like the nonideal resistor in Fig. 12.11. Inductors that are used to filter power in a series topology must have a low enough series resistance to handle the current that is passed through them. Inductors are available in a wide variety of sizes, partly because of the need to handle the spectrum of low- and high-power applications.

A major concern in operating inductors at high frequencies is the detrimental effects of their parasitic capacitance. Just as a capacitor's parasitic inductor reduces its effectiveness above a certain frequency, a similar effect is observed in a real inductor as shown in Fig. 12.14. Placing an inductor and capacitor in parallel creates a circuit that resonates at a certain frequency,

$$f_{RES} = \frac{1}{2\pi\sqrt{LC}}$$

A resonant LC circuit can be useful in many applications, including radio tuners. When an engineer specifically wants a circuit to resonate at a particular frequency, such as when trying to pick up radio waves with an antenna, a so-called *LC tank* is desired. However, an LC tank is generally not

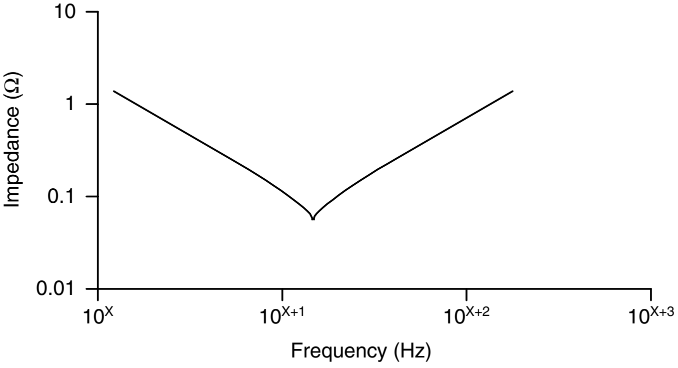

FIGURE 12.13 Nonideal capacitor impedance vs. frequency curve.

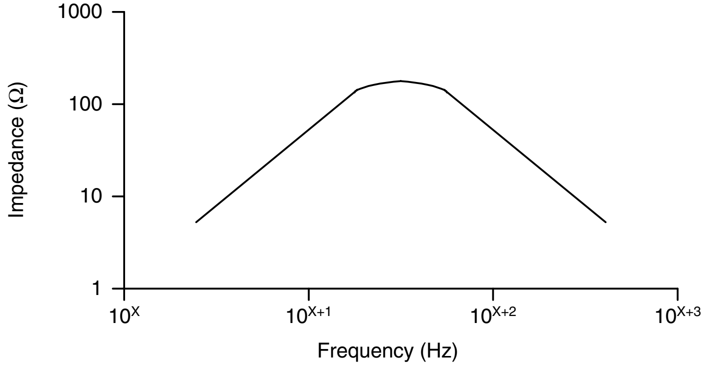

FIGURE 12.14 Nonideal inductor impedance vs. frequency curve.

desired in digital system applications that use inductors. Inductor manufacturers specify an inductor with a certain *self-resonant frequency* (SRF) to characterize the detrimental effects of the parasitic capacitance. Above the SRF, the inductor's impedance declines with increasing frequency. Therefore, if an inductor is operated near its SRF, its parasitic properties should be investigated to ensure that unexpected behavior does not result.

Many filtering applications in digital systems benefit from surface mount *ferrite* beads or chips. Ferrite is a magnetic ceramic material that behaves like an inductor: its impedance rises with frequency. A ferrite bead's parasitic capacitance is lower than that of a standard inductor, because there are no wire coils to capacitively couple with one another. Ferrites are suitable for attenuating high-frequency noise on power supplies and other signals, because they typically have high SRFs. A variety of ferrite materials exist with peak impedances at different frequencies to suit specific applications.

12.8 FREQUENCY DOMAIN ANALYSIS

Electrical signals on a wire can be viewed with an oscilloscope as a plot of voltage (or current) versus time. This is a *time-domain* view of the signals and it provides much useful information for a digital system designer. Using an oscilloscope, an engineer can verify the proper timing of a clock signal and its associated data and control signals. However, time-domain analysis is not very good at determining the frequency content of complex electrical signals. AC components are selected based on their impedances at certain frequencies. Therefore, a method is needed of evaluating a signal's frequency content, thereby knowing the frequencies of interest that the components must handle and enabling selection of suitable values.

Frequency-domain analysis enables an understanding of exactly how an overall AC circuit and its individual components respond to various frequencies that are presented to them. A frequency-domain view of a complex signal allows an engineer to tailor a circuit precisely to the application by relating frequencies and amplitudes rather than time and amplitudes in a conventional time-domain view. Pure sine waves are a convenient representation for signals, because they are easy to manipulate mathematically. While most real-world signals are not sine waves, Joseph Fourier, an eighteenth century French mathematician, demonstrated that an arbitrary signal (e.g., a microprocessor's square wave clock signal) can be expressed as the sum of many sine waves. Frequency-domain analysis is