tic, total capacitance is increased when multiple capacitors are placed in parallel and decreased when placed in series. Consider the following calculation for two equal values capacitors in parallel:

$$Z_{TOTAL} = \frac{1}{\sum \frac{1}{Z_N}} = \frac{1}{2\pi fC + 2\pi fC} = \frac{1}{2\pi f(2C)}$$

The resulting impedance is what would be obtained with a capacitor twice as large as each individual capacitor. Similarly, capacitance is reduced as follows when two capacitors are in series:

$$Z_{TOTAL} = \sum Z_N = \frac{1}{2\pi fC} + \frac{1}{2\pi fC} = \frac{2}{2\pi fC} = \frac{1}{2\pi f(0.5C)}$$

The series impedance is what would be obtained with a capacitor half the size of each individual capacitor.

12.6 INDUCTORS

An *inductor*, also called a *choke* or *coil*, is the other basic circuit element whose impedance changes as a function of frequency. An inductor is a coil of wire that stores energy as a magnetic field. The strength of a magnetic field in a coil is proportional to the current flowing through the coil. If the current flowing through an inductor changes suddenly, the existing magnetic field tends to resist that change. Therefore, inductors present low impedances at low frequencies and high impedances at higher frequencies, the opposite the behavior of a capacitor. Inductance (L) is measured in *henries*. Most inductors encountered in digital systems are measured in microhenries (μH) or nanohenries (nH).

The impedance of an ideal inductor is expressed as $Z_L = 2\pi fL$, clearly showing the proportional relationship of frequency and impedance. In digital systems, inductance is used mainly for filtering purposes and for analyzing the (usually unwanted) inductance of other components. All conductors exhibit some inductance, because a magnetic field naturally develops in proportion to current flow. A straight wire may have much less inductance than a coil, but its inductance is not zero. Such attributes become very important at high frequencies because of the relationship between frequency and impedance.

Just as a capacitor can be used as a parallel element to shunt high-frequency noise, an inductor can be used as a series element to block that noise. Because of their varying impedance, DC signals such as power are passed without attenuation, whereas high frequencies are met with a large impedance. Effective noise filters are made with both series (inductance) and shunt (capacitance) elements as shown in Fig. 12.10. The inductance and capacitance values are chosen to be effective at the desired noise frequency, resulting in a large series resistance followed by a very small shunt resistance. This creates a basic voltage divider arrangement, effective only at high frequencies as intended.

Because of their proportional impedance versus frequency characteristic, inductance combines in the same way as resistance: decreasing with parallel inductors and increasing with series inductors.

12.7 NONIDEAL RLC MODELS

Having presented the three basic passive circuit elements in idealized form, the ways in which resistance, capacitance, and inductance combine in real-world components can be discussed. All conduc-

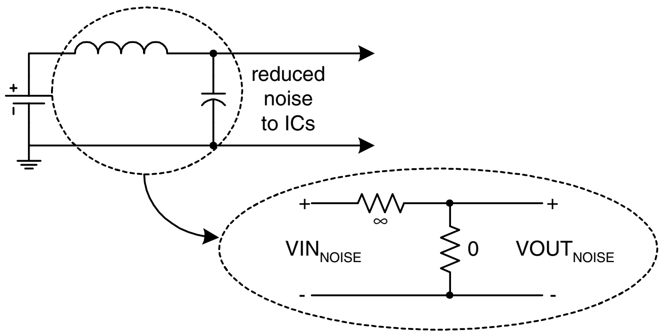

FIGURE 12.10 Noise filtering with LC network.

tors exhibit some series resistance and inductance, and all nearby pairs of conductors exhibit some mutual capacitance. A resistor consists of a resistive element encapsulated in some packaging material with a relatively small conductor at each end to connect the resistive element to an external circuit. Depending on the type of resistor, the conductors may be wires (leaded resistor) or small pieces of metal foil (surface mount). The resistive element itself will vary in size according to its power rating, material, and desired resistance. The finite lengths of the connecting leads and the resistive element each contribute a small quantity of inductance. There is also a small capacitance between the resistor's leads. These unwanted extras are called *parasitic* properties, because they usually detract from the performance of a system rather than improving it. A resistor's function is to provide a certain resistance value in a circuit, but its physical construction results in finite parasitic inductance and capacitance. Figure 12.11 shows a model of a nonideal resistor that enables analysis of its parasitic properties.

Each type of resistor exhibits different magnitudes of parasitic properties. Applications at lower frequencies often ignore these properties, because the parasitic inductance and capacitance is negligible as a result of the frequency/impedance relationships of inductors and capacitors. As the frequencies involved increase, series inductance is generally the first problem that is encountered. Inductance is minimized in resistors that have small leads or, better yet, no leads at all, as is the case with surface mount resistors. Inter-lead capacitance does not become a problem until frequencies get significantly higher.

Similarly, a capacitor exhibits parasitic resistance and inductance. The conductors that form the capacitor have finite resistance and inductance associated with them. A nonideal model of a capacitor is shown in Fig. 12.12. Inductance figures into a capacitor in much the same way that it does a resistor. Smaller leads and components result in reduced parasitic inductance.

At high frequencies, however, the capacitor's parasitic inductance has noticeable effects. The earlier example of using a capacitor to filter high-frequency noise showed that the capacitor removed most of the noise, but not all of it. As the frequency rises, the capacitor's impedance steadily decreases as expected. At a certain point, however, the frequency becomes high enough to cause no-

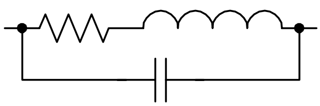

FIGURE 12.11 Nonideal resistor model.

FIGURE 12.12 Nonideal capacitor model.