In reality, the inverter does not switch sharply as the input voltage slowly passes out of the valid logic-0 and logic-1 voltage thresholds. This creates a separate switching threshold when going from low to high versus high to low. The voltage difference between these thresholds depends on temperature, the operating voltage, and the individual chip's characteristics. Therefore, a simple inverter-based oscillator does not provide a very stable oscillation period over time without additional circuitry. The waveform in Fig. 12.7 shows how this RC oscillator behaves.

This waveform shows the nonlinear charging characteristics of an RC circuit. The frequency at which this oscillator runs depends on the differential between the two switching thresholds, the input current of the inverter, and the RC values. The ideal RC charge/discharge curve is modified by the inverter's input current. When the capacitor is at logic-1, the positive input (sink) current of the inverter works with the resistor to more rapidly discharge the capacitor. Similarly, when the capacitor is at logic-0, the negative input (source) current of the inverter works with the resistor to more rapidly charge the capacitor. These source and sink currents are unequal in a bipolar logic IC; therefore, the charge/discharge effects of the inverter will be unequal as well.

## 12.5 CAPACITORS AS AC ELEMENTS

Capacitors have a far broader range of applications than just RC oscillators. The circuits presented up to this point are *direct current* (DC) circuits. In our context, DC refers to steady-state signals with no frequency content being applied to a circuit. While the RC oscillator example certainly varies its voltages, it is a piecewise DC circuit that flips its applied charging voltage at regular intervals. The world is not static, however, and signals are characterized by direct and *alternating current* (AC) components. AC circuits deal with the time-varying properties of signals, their frequency content.

Just as resistors exhibit resistance, capacitors exhibit *reactance*. Both measures are expressed in ohms, but resistance is constant across frequency, whereas reactance (X) varies with frequency. The two terms are combined into a single *impedance* expression, $Z = R + jX$. Impedance is the overall resistance of an element that includes both DC and AC components. The imaginary (AC) component, a function of frequency, is marked by the constant $j$, the imaginary number $\sqrt{-1}$ .

AC circuit analysis expresses frequencies in radians per second rather than in hertz and uses the lower-case Greek letter omega, ω, to denote radian frequency. There are 2π radians in a 360° circle,

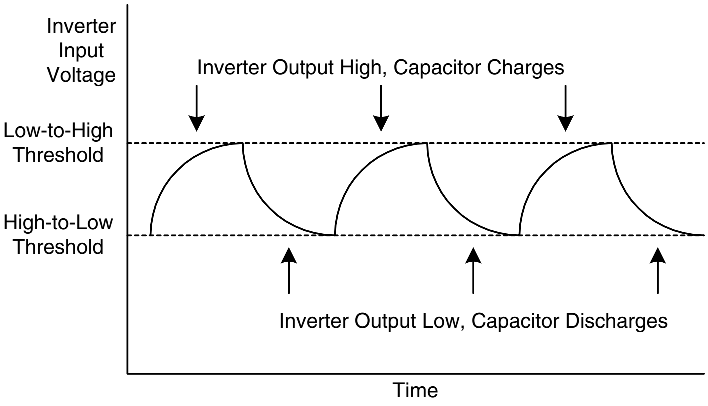

**FIGURE 12.7** RC oscillator waveform.

or cycle. Therefore, there are 2π radians per hertz, or ω = 2πf. The 2πf equivalent is primarily used in this book to illustrate how various circuits interact with digital systems running at arbitrary frequencies.

The impedance of an ideal capacitor is inversely related to the frequency applied to it and is expressed as

$$Z_C = \frac{1}{2\pi fC}$$

At low frequencies, the capacitor exhibits very high impedance and appears essentially as an open circuit. Considering a basic RC circuit, once the capacitor fully charges, the circuit transitions to a steady-state DC circuit without any AC component. Therefore, no more current flows through the circuit, because the capacitor has achieved the same voltage as the battery, and there is no voltage drop across the charging resistor. In AC analysis terms, the frequency of the circuit is zero, and the impedance of the capacitor is infinite. Conversely, a capacitor's impedance asymptotically approaches zero at very high frequencies and becomes a short circuit.

A capacitor can be used to reduce noise in a system, because its impedance is a function of frequency. *Decoupling*, or *bypass*, capacitors are arranged in shunt (parallel) configurations across power supplies that may contain noise, as shown in Fig. 12.8. Power distribution wires can have noise injected back into them by the high-speed on/off switching of a digital circuit. Each time a logic gate or flop transitions, a small surge of current is created to establish the new voltage level. When hundreds or thousands of signals within and external to an IC switch on and off, noise can become a substantial problem.

Decoupling capacitors can be chosen to present a low impedance at the noise frequencies of interest in a digital system. Lower-frequency systems often use 0.1-μF capacitors that exhibit impedance of under 1 Ω at over 1 MHz. Higher-frequency systems may use 0.01-μF or 0.001-μF capacitors for the same purpose. The capacitor functions as a selective resistor that only kicks in at certain frequencies of interest and leaves the DC signal, in this case power, undisturbed. Figure 12.9 illustrates the effect of a decoupling capacitor in shunting the majority of the high-frequency AC component (noise) to ground. Most of the noise is removed, but some remains, as will be explained later.

Multiple capacitors arranged together follow the same series and parallel impedance calculation rule as resistors. However, because of the capacitor's inversely proportional impedance characteris-

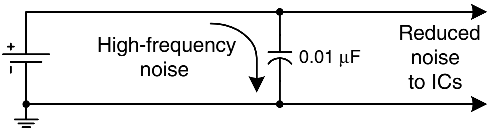

**FIGURE 12.8** Noise filtering with shunt capacitance.

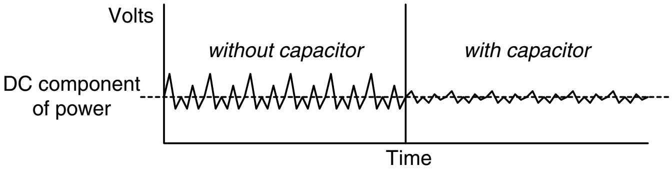

**FIGURE 12.9** AC noise removed from DC power.