The cutoff frequency is determined as was done previously for the first-order filter, for which the magnitude of the transfer function's denominator is the square root of 2. To meet this criterion, $2\pi f = 1/\sqrt{LC}$. The additional AC element in the filter introduces a frequency-squared term that doubles the slope of the gain curve beyond f_C. Therefore, this second-order lowpass filter declines at 40 dB per decade instead of just 20 dB per decade.

Higher-order filters can be created by adding LC segments to the basic second-order circuit to achieve steeper gain curves as shown in Fig. 12.22. These basic topologies are commonly referred to as *T* and *pi* due to their graphical resemblance to the two characters.

Lowpass filters are probably the most common class of filters used in purely digital systems for purposes of noise reduction. However, when analog circuits are mixed in, typically for interface applications including audio and radio frequencies, other types of filters become useful. The inverse of a lowpass filter is a *highpass* filter, which attenuates lower frequencies and passes higher frequencies. A first-order RC highpass filter is very similar to the lowpass version except that the topology is reversed as shown in Fig. 12.23. Here, the capacitor blocks lower frequency signals but allows higher frequencies to pass as its impedance drops with increasing frequency.

As done previously, the transfer function can be calculated by combining the impedances of each element into a single expression:

$$A = \frac{Z_R}{Z_R + Z_C} = \frac{R}{R + \dfrac{1}{2\pi fC}} = \frac{2\pi fRC}{2\pi fRC + 1}$$

It can be observed from the transfer function that, as the frequency approaches DC, the filter's gain approaches 0. At higher frequencies, the filter's gain approaches 1, or 0 dB. First- and second-order highpass filters have gain slopes of 20 and 40 dB per decade, respectively, as mirror images of the lowpass filter frequency response. A second-order highpass filter can be created by substituting an appropriate inductor in place of the shunt resistor. The inductor appears as a short circuit to the negative voltage rail at low frequencies and gradually increases its impedance as the frequency rises. At high frequencies, the inductor's impedance is sufficiently high that it is shunting almost no current to the negative voltage rail.

Just as for lowpass filters, higher-order highpass filters can be created by adding LC segments in T and pi topologies, albeit with the locations of the inductors and capacitors swapped to achieve the highpass transfer function.

12.10   BANDPASS AND BAND-REJECT FILTERS

Some signal manipulation applications require the passing or rejection of a selective range of frequencies that do not begin at DC (a lowpass filter) nor end at an upper limit that is conceptually in-
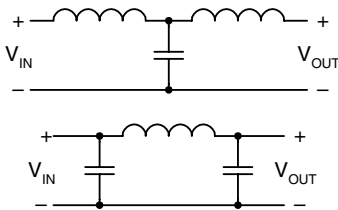
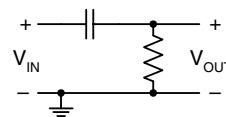**FIGURE 12.22**   Third-order LC lowpass filters.

FIGURE 12.23   First-order RC highpass filter.

finity (a highpass filter). When a radio or television is tuned to a certain channel, a *bandpass* filter selects a certain narrow range of frequencies to pass while attenuating frequencies above and below that range. Bandpass filters may have limited utility in a typical digital system, but certain interface circuitry may require bandpass filtering to attenuate low-frequency and DC content while also reducing high frequency noise.

Bandpass filter design can get fairly complex, depending on the required AC specifications. Design issues include the width of the passband and the slope of the gain curve on either side of the passband. Two basic bandpass topologies are shown in Fig. 12.24. These are second-order circuits that pair an inductor and capacitor together in either a series or shunt configuration. The series topology operates by blocking the high-frequency stopband with the inductor and the low-frequency stopband with the capacitor. In the middle is a range of frequencies that are passed by both elements. The shunt topology operates by diverting the high-frequency stopband to ground with the capacitor and the low-frequency stopband with the inductor. This topology takes special advantage of the parallel LC resonant circuit mentioned previously.

Each of these topologies can be designed with passbands of arbitrary width. The bandwidth of the filter has a direct impact on the shape of its transfer function. However, for a second-order bandpass filter, each AC element contributes a –20 dB per decade roll-off on either side of the center frequency. Therefore, a narrow ideal second-order bandpass filter has the transfer function shown in Fig. 12.25, and its center frequency is
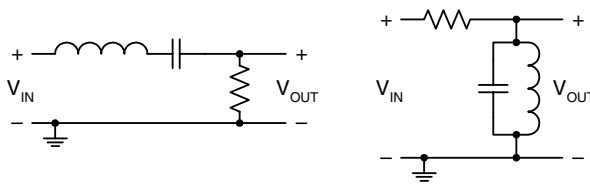
$$f_C = \frac{1}{2\pi\sqrt{LC}}$$

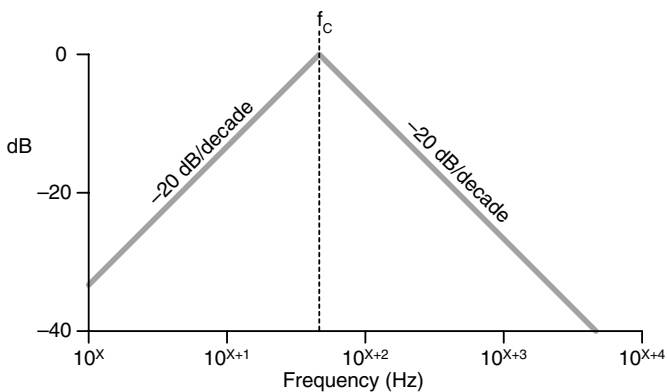**FIGURE 12.24**   Second-order bandpass filter topologies.

FIGURE 12.25   Idealized bandpass filter frequency response.