Pulse Waveforms and the R-C Response

Objectives

- Become familiar with the specific terms that define a pulse waveform and how to calculate various parameters such as the pulse width, rise and fall times, and tilt.

- Be able to calculate the pulse repetition rate and the duty cycle of any pulse waveform.

- Become aware of the parameters that define the response of an R-C network to a square-wave input.

- Understand how a compensator probe of an oscilloscope is used to improve the appearance of an output pulse waveform.

24.1 INTRODUCTION

Our analysis thus far has been limited to alternating waveforms that vary in a sinusoidal manner. This chapter introduces the basic terminology associated with the pulse waveform and examines the response of an *R-C* circuit to a square-wave input. The importance of the pulse waveform to the electrical/electronics industry cannot be overstated. A vast array of instrumentation, communication systems, computers, radar systems, and so on, all use pulse signals to control operation, transmit data, and display information in a variety of formats.

The response to a pulse signal of the networks described thus far is quite different from that obtained for sinusoidal signals. In fact, we must refer to the dc chapter on capacitors (Chapter 10) for a few fundamental concepts and equations that will help us in the analysis to follow. This chapter is just an introduction, designed to provide the fundamentals that will be helpful when the pulse waveform is encountered in specific areas of application.

24.2 IDEAL VERSUS ACTUAL

The **ideal pulse** in Fig. 24.1 has vertical sides, sharp corners, and a flat peak characteristic; it starts instantaneously at t_1 and ends just as abruptly at t_2.
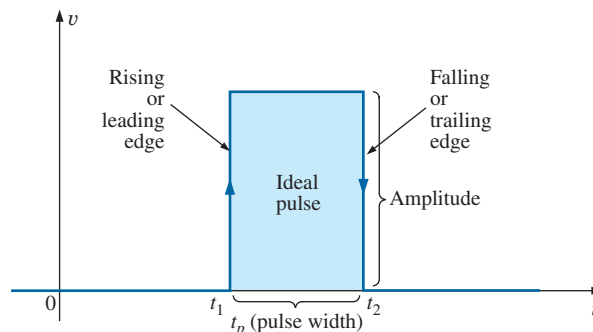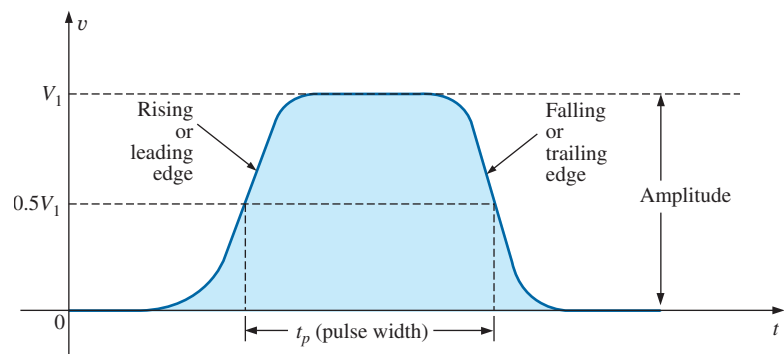

FIG. 24.1
Ideal pulse waveform.

The waveform in Fig. 24.1 is applied in the analysis in this chapter and probably in the initial investigation of areas of application beyond the scope of this text. Once the fundamental operation of a device, package, or system is clearly understood using ideal characteristics, the effect of an **actual** (or **true** or **practical**) **pulse** must be considered. If an attempt were made to introduce all the differences between an ideal and actual pulse in a single figure, the result would probably be complex and confusing. A number of waveforms are therefore used to define the critical parameters.

The reactive elements of a network, in their effort to prevent instantaneous changes in voltage (capacitor) and current (inductor), establish a slope to both edges of the pulse waveform, as shown in Fig. 24.2. The *rising edge* of the waveform in Fig. 24.2 is defined as the edge that increases from a lower to a higher level.

FIG. 24.2
Actual pulse waveform.

The falling edge is defined by the region or edge where the waveform decreases from a higher to a lower level. Since the rising edge is the first to be encountered (closest to t = 0 s), it is also called the leading edge. The falling edge always follows the leading edge and is therefore often called the trailing edge.

Both regions are defined in Figs. 24.1 and 24.2.

Amplitude

For most applications, the **amplitude of a pulse waveform** is defined as the peak-to-peak value. Of course, if the waveforms all start and return to the zero-volt level, then the peak and peak-to-peak values are synonymous.

For the purposes of this text, the amplitude of a pulse waveform is the peak-to-peak value, as illustrated in Figs. 24.1 and 24.2.

Pulse Width

The pulse width (t_p), or pulse duration, is defined by a pulse level equal to 50% of the peak value.

For the ideal pulse in Fig. 24.1, the pulse width is the same at any level, whereas t_p for the waveform in Fig. 24.2 is a very specific value.

Base-Line Voltage

The base-line voltage (V_b) is the voltage level from which the pulse is initiated.

The waveforms in Figs. 24.1 and 24.2 both have a 0 V base-line voltage. In Fig. 24.3(a) the base-line voltage is 1 V, whereas in Fig. 24.3(b) the base-line voltage is -4 V.
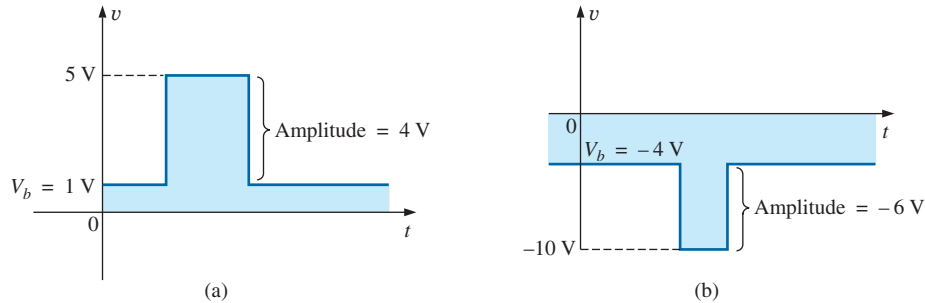
FIG. 24.3
Defining the base-line voltage.

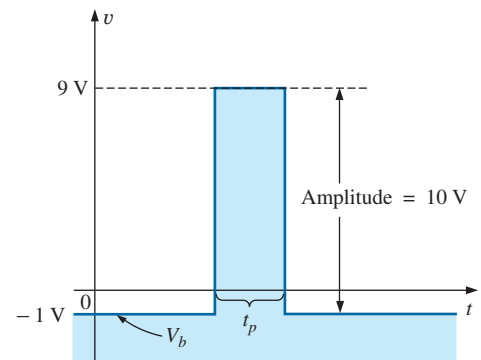## Positive-Going and Negative-Going Pulses

A positive-going pulse increases positively from the base-line voltage, whereas a negative-going pulse increases in the negative direction from the base-line voltage.

The waveform in Fig. 24.3(a) is a positive-going pulse, whereas the waveform in Fig. 24.3(b) is a negative-going pulse.

Even though the base-line voltage in Fig. 24.4 is negative, the waveform is positive-going (with an amplitude of 10 V) since the voltage increased in the positive direction from the base-line voltage.

Rise Time (t_r) and Fall Time (t_f)

The time required for the pulse to shift from one level to another is of particular importance. The *rounding* (defined in Fig. 24.5) that occurs at the beginning and end of each transition makes it difficult to define the exact point at which the rise time should be initiated and terminated. For this reason,

FIG. 24.4
Positive-going pulse.
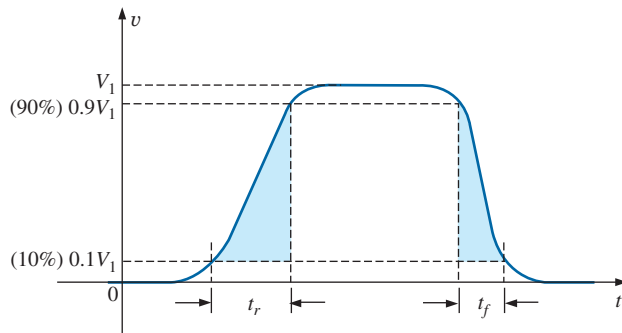
FIG. 24.5
Defining t_r and t_f.

the rise time and the fall time are defined by the 10% and 90% levels, as indicated in Fig. 24.5.

Note that there is no requirement that t_r equal t_f.

Tilt

Fig. 24.6 illustrates an undesirable but common distortion normally occurring due to a poor low-frequency response characteristic of the system through which a pulse has passed. The drop in peak value is called **tilt, droop,** or **sag.** The percentage tilt is defined by
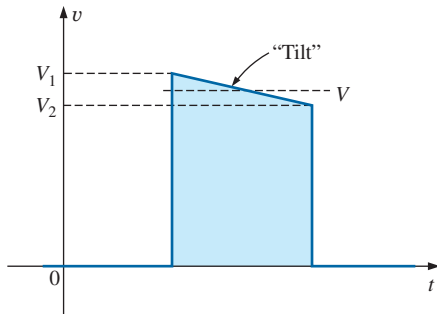
$$\% \text{ tilt} = \frac{V_1 - V_2}{V} \times 100\% \qquad (24.1)$$

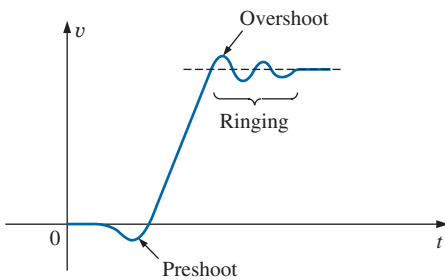where V is the average value of the peak amplitude as determined by

$$V = \frac{V_1 + V_2}{2} \qquad (24.2)$$

Naturally, the less the percentage tilt or sag, the more ideal the pulse. Due to rounding, it may be difficult to define the values of V_1 and V_2. It is then necessary to approximate the sloping region by a straight-line approximation and use the resulting values of V_1 and V_2.

Other distortions include the *preshoot* and *overshoot* appearing in Fig. 24.7, normally due to pronounced high-frequency effects of a system, and *ringing,* due to the interaction between the capacitive and inductive elements of a network at their natural or resonant frequency.
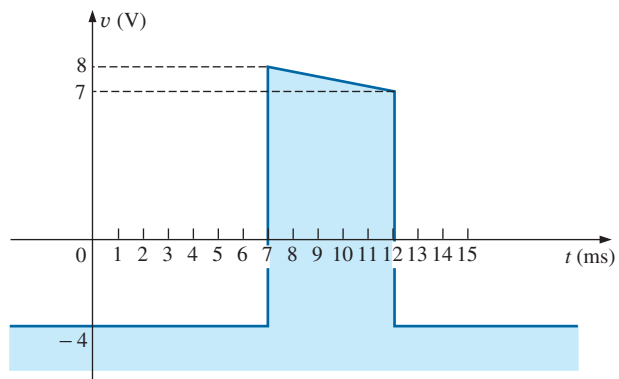
EXAMPLE 24.1 Determine the following for the pulse waveform in Fig. 24.8:

  a. positive- or negative-going?
  b. base-line voltage
  c. pulse width
  d. maximum amplitude
  e. tilt

FIG. 24.6
Defining tilt.

FIG. 24.7
Defining preshoot, overshoot, and ringing.

FIG. 24.8
Example 24.1.

Solutions:

a. **positive-going**
b. $V_b = -4$ **V**
c. $t_p = (12 - 7)$ ms = **5 ms**
d. $V_{max} = 8$ V + 4 V = **12 V**
e. $V = \dfrac{V_1 + V_2}{2} = \dfrac{12 \text{ V} + 11 \text{ V}}{2} = \dfrac{23 \text{ V}}{2} = 11.5$ V

$\% \text{ tilt} = \dfrac{V_1 - V_2}{V} \times 100\% = \dfrac{12 \text{ V} - 11 \text{ V}}{11.5 \text{ V}} \times 100\% = \textbf{8.7\%}$
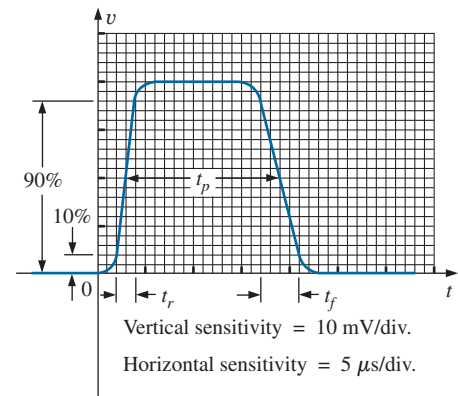
(Remember, V is defined by the average value of the peak amplitude.)

EXAMPLE 24.2 Determine the following for the pulse waveform in Fig. 24.9:

a. positive- or negative-going?
b. base-line voltage
c. tilt
d. amplitude
e. t_p
f. t_r and t_f

Solutions:

a. **positive-going**
b. $V_b = $ **0 V**
c. $\%$ tilt = **0%**
d. amplitude = (4 div.)(10 mV/div.) = **40 mV**
e. t_p = (3.2 div.)(5 μs/div.) = **16 μs**
f. t_r = (0.4 div.)(5 μs/div.) = **2 μs**
   t_f = (0.8 div.)(5 μs/div.) = **4 μs**

Vertical sensitivity = 10 mV/div.
Horizontal sensitivity = 5 μs/div.

FIG. 24.9
*Example 24.2.*

24.3 PULSE REPETITION RATE AND DUTY CYCLE

A series of pulses such as those appearing in Fig. 24.10 is called a **pulse train.** The varying widths and heights may contain information that can be decoded at the receiving end.

If the pattern repeats itself in a periodic manner as shown in Fig. 24.11(a) and (b), the result is called a **periodic pulse train.**

The *period (T)* of the pulse train is defined as the time differential between any two similar points on the pulse train, as shown in Figs. 24.11(a) and (b).
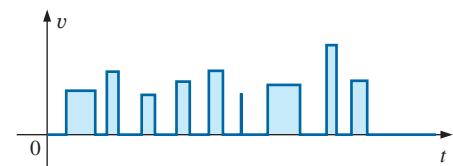
FIG. 24.10
Pulse train.

(a)

(b)
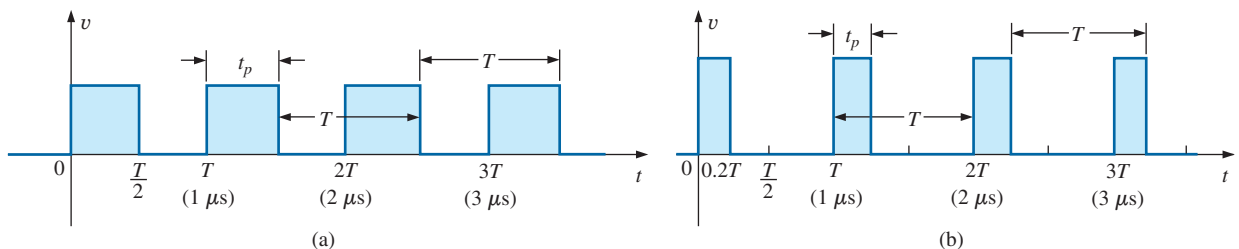
FIG. 24.11
Periodic pulse trains.

The **pulse repetition frequency** (prf), or **pulse repetition rate** (prr), is defined by

$$\boxed{\text{prf (or prr)} = \frac{1}{T}} \qquad \text{Hz or pulses/s} \qquad \textbf{(24.3)}$$

Applying Eq. (24.3) to each waveform in Fig. 24.11 results in the same pulse repetition frequency since the periods are the same. The result clearly reveals that

the shape of the periodic pulse does not affect the determination of the pulse repetition frequency.

The pulse repetition frequency is determined solely by the period of the repeating pulse. The factor that reveals how much of the period is encompassed by the pulse is called the **duty cycle,** defined as follows:

$$\text{Duty cycle} = \frac{\text{pulse width}}{\text{period}} \times 100\%$$

or

$$\boxed{\text{Duty cycle} = \frac{t_p}{T} \times 100\%} \qquad \textbf{(24.4)}$$

For Fig. 24.11(a) (a square-wave pattern),

$$\text{Duty cycle} = \frac{0.5T}{T} \times 100\% = \textbf{50\%}$$
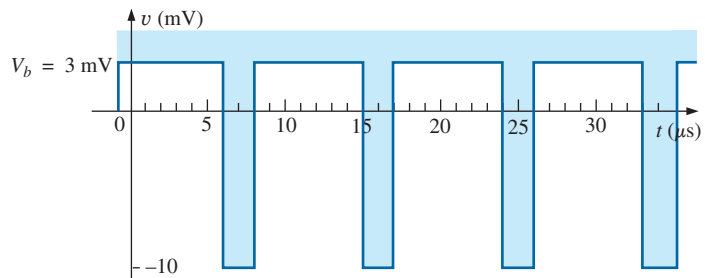
and for Fig. 24.11(b),

$$\text{Duty cycle} = \frac{0.2T}{T} \times 100\% = \textbf{20\%}$$

The above results clearly reveal that

the duty cycle provides a percentage indication of the portion of the total period encompassed by the pulse waveform.

EXAMPLE 24.3 Determine the pulse repetition frequency and the duty cycle for the periodic pulse waveform in Fig. 24.12.
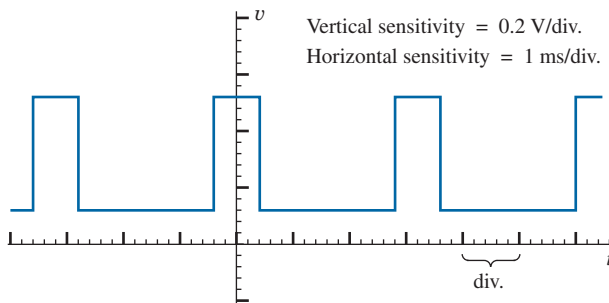

FIG. 24.12
Example 24.3.

Solution:

$$T = (15 - 6) \ \mu s = 9 \ \mu s$$

$$\text{prf} = \frac{1}{T} = \frac{1}{9 \ \mu s} \cong \textbf{111.11 kHz}$$

$$\text{Duty cycle} = \frac{t_p}{T} \times 100\% = \frac{(8 - 6) \ \mu s}{9 \ \mu s} \times 100\%$$

$$= \frac{2}{9} \times 100\% \cong \textbf{22.22\%}$$

EXAMPLE 24.4 Determine the pulse repetition frequency and the duty cycle for the oscilloscope pattern in Fig. 24.13 having the indicated sensitivities.

Vertical sensitivity = 0.2 V/div.
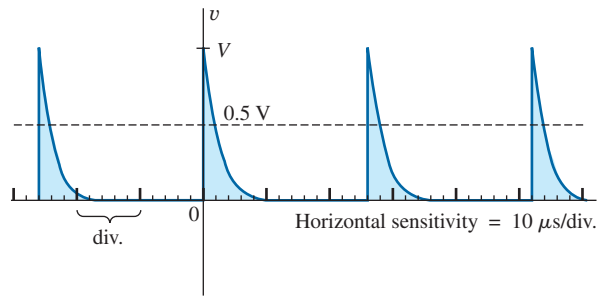Horizontal sensitivity = 1 ms/div.

div.

FIG. 24.13
Example 24.4.

Solution:

$$T = (3.2 \ \text{div.})(1 \ \text{ms/div.}) = 3.2 \ \text{ms}$$
$$t_p = (0.8 \ \text{div.})(1 \ \text{ms/div.}) = 0.8 \ \text{ms}$$
$$\text{prf} = \frac{1}{T} = \frac{1}{3.2 \ \text{ms}} = \textbf{312.5 Hz}$$
$$\text{Duty cycle} = \frac{t_p}{T} \times 100\% = \frac{0.8 \ \text{ms}}{3.2 \ \text{ms}} \times 100\% = \textbf{25\%}$$

EXAMPLE 24.5 Determine the pulse repetition rate and duty cycle for the trigger waveform in Fig. 24.14.

Solution:

$$T = (2.6 \ \text{div.})(10 \ \mu s/\text{div.}) = 26 \ \mu s$$
$$\text{prf} = \frac{1}{T} = \frac{1}{26 \ \mu s} = \textbf{38,462 kHz}$$
$$t_p \cong (0.2 \ \text{div.})(10 \ \mu s/\text{div.}) = 2 \ \mu s$$
$$\text{Duty cycle} = \frac{t_p}{T} \times 100\% = \frac{2 \ \mu s}{26 \ \mu s} \times 100\% = \textbf{7.69\%}$$
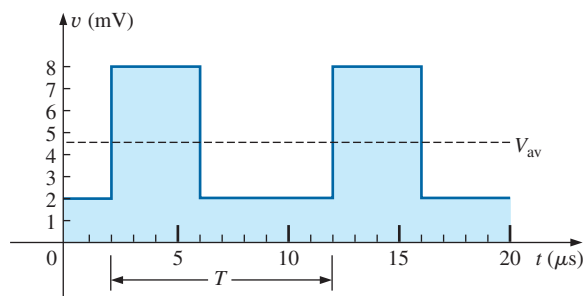
FIG. 24.14
Example 24.5.

24.4 AVERAGE VALUE

The average value of a pulse waveform can be determined using one of two methods. The first is the procedure outlined in Section 13.7, which can be applied to any alternating waveform. The second can be applied only to pulse waveforms since it utilizes terms specifically related to pulse waveforms; that is,

$$V_{av} = (\text{duty cycle})(\text{peak value}) + (1 - \text{duty cycle})(V_b) \qquad \textbf{(24.5)}$$

In Eq. (24.5), the peak value is the maximum deviation from the reference or zero-volt level, and the duty cycle is in decimal form. Eq. (24.5) does not include the effect of any tilt pulse waveforms with sloping sides.

EXAMPLE 24.6 Determine the average value for the periodic pulse waveform in Fig. 24.15.

FIG. 24.15
Example 24.6.

Solution: By the method in Section 13.7,

$$G = \frac{\text{area under curve}}{T}$$

$$T = (12 - 2)\ \mu s = 10\ \mu s$$

$$G = \frac{(8\ \text{mV})(4\ \mu s) + (2\ \text{mV})(6\ \mu s)}{10\ \mu s} = \frac{32 \times 10^{-9} + 22 \times 10^{-9}}{10 \times 10^{-6}}$$

$$= \frac{44 \times 10^{-9}}{10 \times 10^{-6}} = \textbf{4.4 mV}$$

By Eq. (24.5),

$$V_b = +2 \text{ mV}$$

$$\text{Duty cycle} = \frac{t_p}{T} = \frac{(6 - 2) \ \mu\text{s}}{10 \ \mu\text{s}} = \frac{4}{10} = 0.4 \text{ (decimal form)}$$

$$\text{Peak value (from 0 V reference)} = 8 \text{ mV}$$

$$V_{av} = (\text{duty cycle})(\text{peak value}) + (1 - \text{duty cycle})(V_b)$$
$$= (0.4)(8 \text{ mV}) + (1 - 0.4)(2 \text{ mV})$$
$$= 3.2 \text{ mV} + 1.2 \text{ mV} = \mathbf{4.4 \ mV}$$

as obtained above.

EXAMPLE 24.7 Given a periodic pulse waveform with a duty cycle of 28%, a peak value of 7 V, and a base-line voltage of −3 V:

a. Determine the average value.
b. Sketch the waveform.
c. Verify the result of part (a) using the method of Section 13.7.

Solutions:

a. By Eq. (24.5),

$$V_{av} = (\text{duty cycle}) (\text{peak value}) + (1 - \text{duty cycle}) (V_b)$$
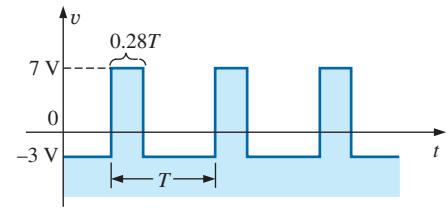$$= (0.28)(7 \text{ V}) + (1 - 0.28)(-3 \text{ V}) = 1.96 \text{ V} + (-2.16 \text{ V})$$
$$= \mathbf{-0.2 \ V}$$

b. See Fig. 24.16.

c. $$G = \frac{(7 \text{ V})(0.28T) - (3 \text{ V})(0.72T)}{T} = 1.96 \text{ V} - 2.16 \text{ V}$$

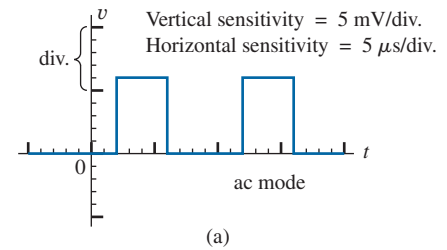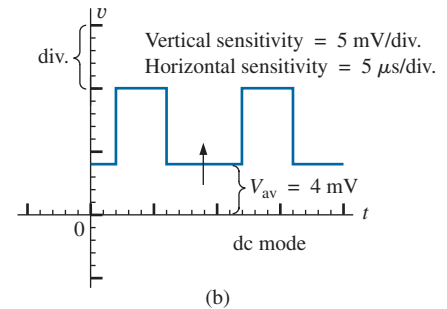$$= \mathbf{-0.2 \ V}$$

as obtained above.

FIG. 24.16
*Solution to part (b) of Example 24.7.*

(a)

Instrumentation

The average value (dc value) of any waveform can be easily determined using the oscilloscope. If the mode switch of the scope is set in the ac position, the average or dc component of the applied waveform is blocked by an internal capacitor from reaching the screen. The pattern can be adjusted to establish the display in Fig. 24.17(a). If the mode switch is then placed in the dc position, the vertical shift (positive or negative) reveals the average or dc level of the input signal, as shown in Fig. 24.17(b).

(b)

FIG. 24.17
Determining the average value of a pulse waveform using an oscilloscope.

24.5 TRANSIENT *R-C* NETWORKS

In Chapter 10, the general solution for the transient behavior of an *R-C* network with or without initial values was developed. The resulting equation for the voltage across a capacitor is repeated below for convenience.

$$v_C = V_f + (V_i - V_f)e^{-t/RC} \qquad \textbf{(24.6)}$$

Recall that V_i is the initial voltage across the capacitor when the transient phase is initiated as shown in Fig. 24.18. The voltage V_f is the steady-state (resting) value of the voltage across the capacitor when the transient phase has ended. The transient period is approximated as 5τ, where τ is the time constant of the network and is equal to the product RC.
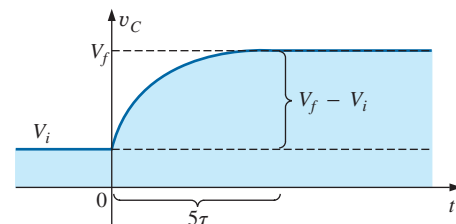
FIG. 24.18
Defining the parameters of Eq. (24.6).
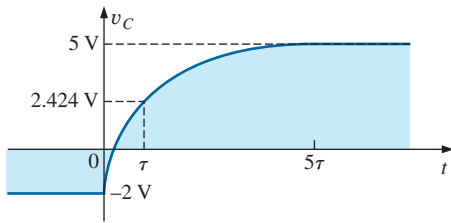
FIG. 24.19
Example of the use of Eq. (24.6).

For the situation where the initial voltage is zero volts, the equation reduces to the following familiar form, where V_f is often the applied voltage:

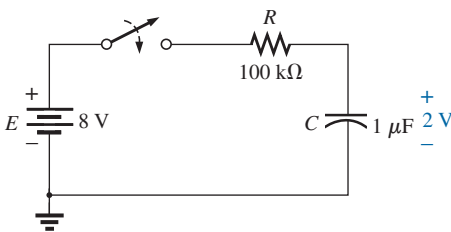$$\boxed{v_C = V_f(1 - e^{-t/RC})} \quad\bigg|_{V_i = 0\,\text{V}} \qquad\qquad \textbf{(24.7)}$$

For the case in Fig. 24.19, $V_i = -2$ V, $V_f = +5$ V, and

$$v_C = V_i + (V_f - V_i)(1 - e^{-t/RC})$$
$$= -2\,\text{V} + [5\,\text{V} - (-2\,\text{V})](1 - e^{-t/RC})$$
$$v_C = -2\,\text{V} + 7\,\text{V}(1 - e^{-t/RC})$$

For the case where $t = \tau = RC$,

$$v_C = -2\,\text{V} + 7\,\text{V}\,(1 - e^{-t/\tau}) = -2\,\text{V} + 7\,\text{V}\,(1 - e^{-1})$$
$$= -2\,\text{V} + 7\,\text{V}\,(1 - 0.368) = -2\,\text{V} + 7\,\text{V}\,(0.632)$$
$$v_C = 2.424\,\text{V}$$

as verified by Fig. 24.19.

FIG. 24.20
Example 24.8.

FIG. 24.21
v_C and i_C for the network in Fig. 24.20.

EXAMPLE 24.8 The capacitor in Fig. 24.20 is initially charged to 2 V before the switch is closed. The switch is then closed.

a. Determine the mathematical expression for v_C.
b. Determine the mathematical expression for i_C.
c. Sketch the waveforms of v_C and i_C.

Solutions:
a. $V_i = 2$ V
V_f (after 5τ) $= E = 8$ V
$\tau = RC = (100\text{ k}\Omega)(1\ \mu\text{F}) = 100$ ms

By Eq. (24.6),

$$v_C = V_f + (V_i - V_f)e^{-t/RC}$$
$$= 8\,\text{V} + (2\,\text{V} - 8\,\text{V})e^{-t/\tau}$$

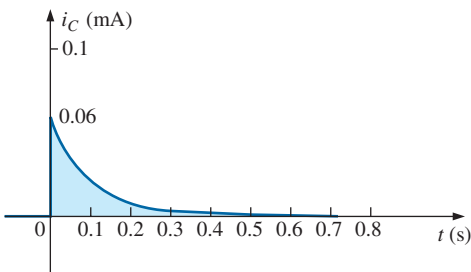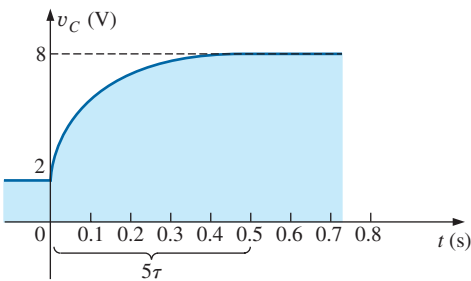and $\qquad\qquad\qquad vc = \mathbf{8\,V - 6\,V}\,e^{-t/\tau}$

b. When the switch is first closed, the voltage across the capacitor cannot change instantaneously, and $V_R = E - V_i = 8\,\text{V} - 2\,\text{V} = 6$ V. The current therefore jumps to a level determined by Ohm's law:

$$I_{R_{max}} = \frac{V_R}{R} = \frac{6\,\text{V}}{100\text{ k}\Omega} = 0.06\text{ mA}$$

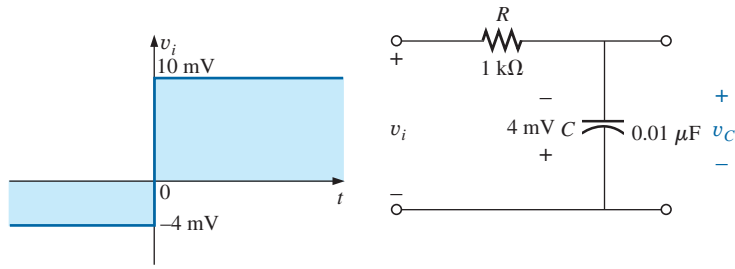The current then decays to zero amperes with the same time constant calculated in part (a), and

$$i_C = \mathbf{0.06\ mA}e^{-t/\tau}$$

c. See Fig. 24.21.

EXAMPLE 24.9 Sketch v_C for the step input shown in Fig. 24.22. Assume that the -4 mV has been present for a period of time in excess of five time constants of the network. Then determine when $v_C = 0$ V if the step changes levels at $t = 0$ s.

FIG. 24.22
Example 24.9.

Solution:

$$V_i = -4 \text{ mV} \qquad V_f = 10 \text{ mV}$$
$$\tau = RC = (1 \text{ k}\Omega)(0.01 \ \mu\text{F}) = 10 \ \mu\text{s}$$

By Eq. (24.6),

$$v_C = V_f + (V_i - V_f)e^{-t/RC}$$
$$= 10 \text{ mV} + (-4\text{mV} - 10 \text{ mV})e^{-t/10\mu s}$$

and $\qquad\qquad v_C = \mathbf{10 \text{ mV} - 14 \text{ mV} } \ e^{-t/10\mu s}$

The waveform appears in Fig. 24.23.
Substituting $v_C = 0$ V into the above equation yields

$$v_C = 0 \text{ V} = 10 \text{ mV} - 14 \text{ mV} \ e^{-t/10\mu s}$$

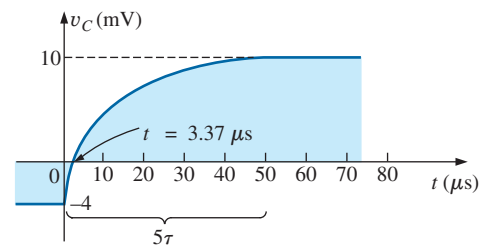and $\qquad\qquad \dfrac{10 \text{ mV}}{14 \text{ mV}} = e^{-t/10\mu s}$

or $\qquad\qquad 0.714 = e^{-t/10\mu s}$

but $\qquad\qquad \log_e 0.714 = \log_e(e^{-t/10\mu s}) = \dfrac{-t}{10 \ \mu s}$

and $\quad t = -(10 \ \mu s)\log_e 0.714 = -(10 \ \mu s)(-0.377) = \mathbf{3.37 \ \mu s}$
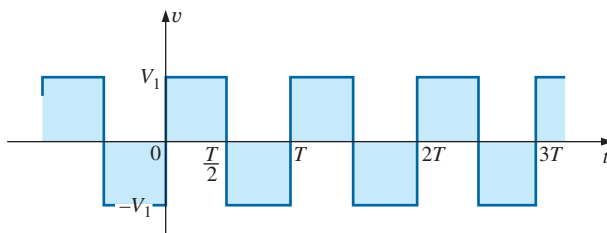
as indicated in Fig. 24.23.

FIG. 24.23
v_C for the network in Fig. 24.22.

24.6 *R-C* RESPONSE TO SQUARE-WAVE INPUTS

The **square wave** in Fig. 24.24 is a particular form of pulse waveform.
It has a duty cycle of 50% and an average value of zero volts, as calculated below:

FIG. 24.24
Periodic square wave.

$$\text{Duty cycle} = \frac{t_p}{T} \times 100\% = \frac{T/2}{T} \times 100\% = \mathbf{50\%}$$

$$V_{av} = \frac{(V_1)(T/2) + (-V_1)(T/2)}{T} = \frac{0}{T} = \mathbf{0\ V}$$

The application of a dc voltage V_1 in series with the square wave in Fig. 24.24 can raise the base-line voltage from $-V_1$ to zero volts and the average value to V_1 volts.

If a square wave such as developed in Fig. 24.25 is applied to an *R-C* circuit as shown in Fig. 24.26, the period of the square wave can have a pronounced effect on the resulting waveform for v_C.

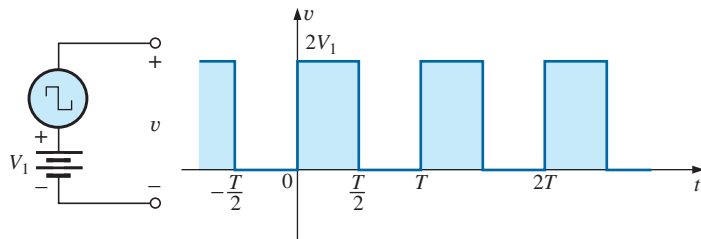**FIG. 24.25**

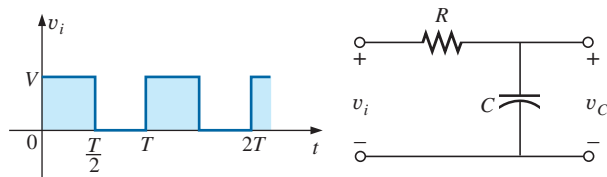*Raising the base-line voltage of a square wave to zero volts.*

FIG. 24.26

Applying a periodic square-wave pulse train to an R-C network.

For the analysis to follow, we will assume that steady-state conditions will be established after a period of five time constants has passed. The types of waveforms developed across the capacitor can then be separated into three fundamental types: $T/2 > 5\tau$, $T/2 = 5\tau$, and $T/2 < 5\tau$.

$T/2 > 5\tau$

The condition $T/2 > 5\tau$ or $T > 10\tau$, establishes a situation where the capacitor can charge to its steady-state value in advance of $t = T/2$. The resulting waveforms for v_C and i_C appear as shown in Fig. 24.27. Note how
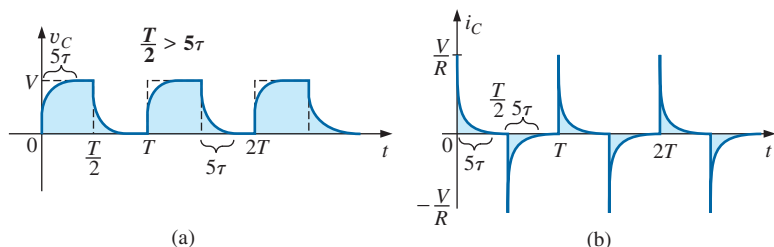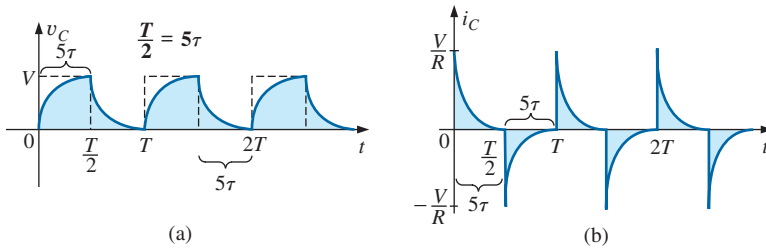

FIG. 24.27

v_C *and* i_C *for* $T/2 > 5\tau$.

closely the voltage v_C shadows the applied waveform and how i_C is nothing more than a series of very sharp spikes. Note also that the change of V_i from V to zero volts during the trailing edge results in a rapid discharge of v_C to zero volts. In essence, when $V_i = 0$, the capacitor and resistor are in parallel and the capacitor discharges through R with a time constant equal to that encountered during the charging phase but with a direction of charge flow (current) opposite to that established during the charging phase.

$T/2 = 5\tau$

If the frequency of the square wave is chosen such that $T/2 = 5\tau$ or $T = 10\tau$, the voltage v_C reaches its final value just before beginning its discharge phase, as shown in Fig. 24.28. The voltage v_C no longer resembles the square-wave input and, in fact, has some of the characteristics of a triangular waveform. The increased time constant has resulted in a more rounded v_C, and i_C has increased substantially in width to reveal the longer charging period.


FIG. 24.28
v_C and i_C for $T/2 = 5\tau$.

$T/2 < 5\tau$

If $T/2 < 5\tau$ or $T < 10\tau$, the voltage v_C will not reach its final value during the first pulse (Fig. 24.29), and the discharge cycle will not return to zero volts. In fact, the initial value for each succeeding pulse changes until steady-state conditions are reached. In most instances, it is a good approximation to assume that steady-state conditions have been established in five cycles of the applied waveform.
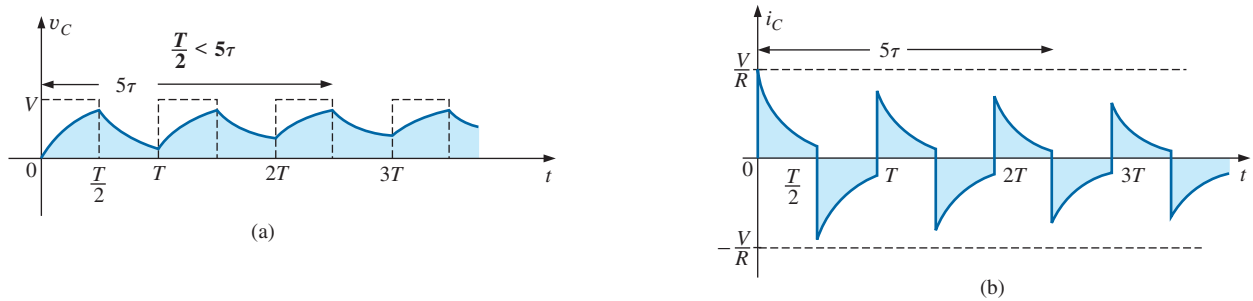
FIG. 24.29
v_C and i_C for $T/2 < 5\tau$.

As the frequency increases and the period decreases, there will be a flattening of the response for v_C until a pattern like that in Fig. 24.30 results. Fig. 24.30 begins to reveal an important conclusion regarding the response curve for v_C:
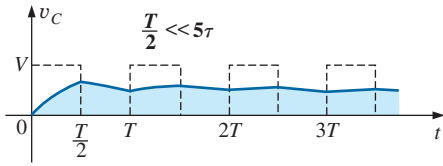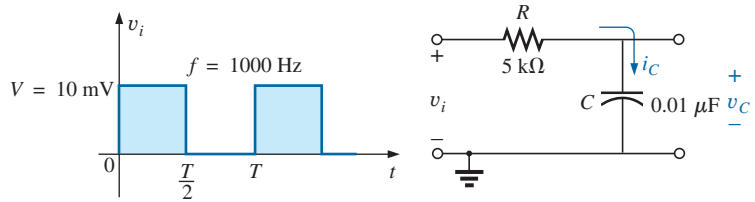
FIG. 24.30

v_C for $T/2 \ll 5\tau$ or $T \ll 10\tau$.

Under steady-state conditions, the average value of v_C will equal the average value of the applied square wave.

Note in Figs. 24.29 and 24.30 that the waveform for v_C approaches an average value of $V/2$.

EXAMPLE 24.10 The 1000 Hz square wave in Fig. 24.31 is applied to the *R-C* circuit of the same figure.

a. Compare the pulse width of the square wave to the time constant of the circuit.
b. Sketch v_C.
c. Sketch i_C.

FIG. 24.31

Example 24.10.

Solutions:

a. $\quad T = \dfrac{1}{f} = \dfrac{1}{1000} = 1$ ms

$\quad t_p = \dfrac{T}{2} = 0.5$ ms

$\quad \tau = RC = (5 \times 10^3 \ \Omega)(0.01 \times 10^{-6} \ F) = 0.05$ ms

$\quad \dfrac{t_p}{\tau} = \dfrac{0.5 \text{ ms}}{0.05 \text{ ms}} = 10$ and

$\quad t_p = \mathbf{10\tau} = \dfrac{T}{2}$

The result reveals that v_C charges to its final value in half the pulse width.

b. For the charging phase, $V_i = 0$ V and $V_f = 10$ mV, and

$$v_C = V_f + (V_i - V_f)e^{-t/RC}$$
$$= 10 \text{ mV} + (0 - 10 \text{ mV})e^{-t/\tau}$$

and $\quad\quad\quad v_C = \mathbf{10\ mV(1 - e^{-t/\tau})}$

For the discharge phase, $V_i = 10$ mV and $V_f = 0$ V, and

$$v_C = V_f + (V_i - V_f)e^{-t/\tau}$$
$$= 0 \text{ V} + (10 \text{ mV} - 0 \text{ V})e^{-t/\tau}$$

and $\quad\quad\quad v_C = \mathbf{10\ mV}e^{-t/\tau}$

The waveform for v_C appears in Fig. 24.32.

c. For the charging phase at $t = 0$ s, $V_R = V$ and $I_{R_{max}} = V/R = 10$ mV/5 k$\Omega = 2 \ \mu$A and

$$i_C = I_{max}e^{-t/\tau} = \mathbf{2\ \mu A}e^{-t/\tau}$$
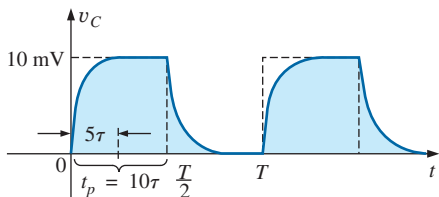
FIG. 24.32

v_C for the R-C network in Fig. 24.31.

For the discharge phase, the current will have the same mathematical formulation but the opposite direction, as shown in Fig. 24.33.

EXAMPLE 24.11 Repeat Example 24.10 for $f = 10$ kHz.

Solution:

$$T = \frac{1}{f} = \frac{1}{10 \text{ kHz}} = 0.1 \text{ ms}$$

and

$$\frac{T}{2} = 0.05 \text{ ms}$$

with

$$\tau = t_p = \frac{T}{2} = 0.05 \text{ ms}$$

FIG. 24.33
i_C for the R-C network in Fig. 24.31.

In other words, the pulse width is exactly equal to the time constant of the network. The voltage v_C will not reach the final value before the first pulse of the square-wave input returns to zero volts.

For t in the range $t = 0$ to $T/2$, $V_i = 0$ V and $V_f = 10$ mV, and

$$v_C = 10 \text{ mV}(1 - e^{-t/\tau})$$

Recall from Chapter 10 that at $t = \tau$, $v_C = 63.2\%$ of the final value. Substituting $t = \tau$ into the equation above yields

$$v_C = (10 \text{ mV})(1 - e^{-1}) = (10 \text{ mV})(1 - 0.368)$$
$$= (10 \text{ mV})(0.632) = 6.32 \text{ mV}$$

as shown in Fig. 24.34.

FIG. 24.34
v_C response for $t_p = \tau = T/2$.

For the discharge phase between $t = T/2$ and T, $V_i = 6.32$ mV and $V_f = 0$ V, and
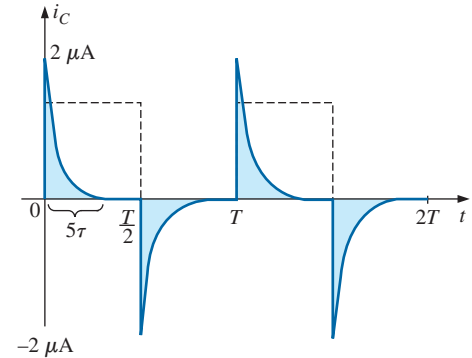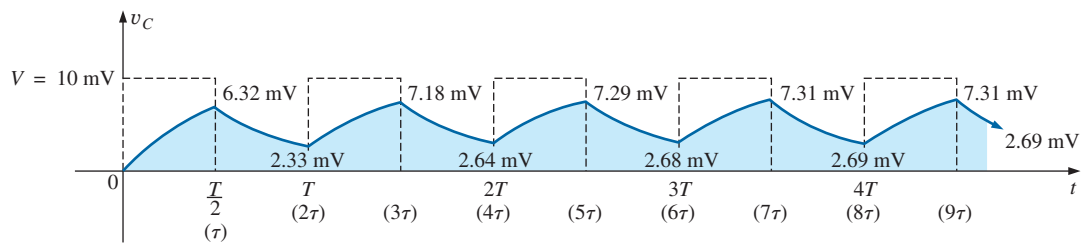
$$v_C = V_f + (V_i - V_f)e^{-t/\tau}$$
$$= 0 \text{ V} + (6.32 \text{ mV} - 0 \text{ V})e^{-t/\tau}$$
$$v_C = 6.32 \text{ mV}e^{-t/\tau}$$

with t now being measured from $t = T/2$ in Fig. 24.34. In other words, for each interval in Fig. 24.34, the beginning of the transient waveform is defined as $t = 0$ s. The value of v_C at $t = T$ is therefore determined by substituting $t = \tau$ into the above equation, and not 2τ as defined by Fig. 24.34.

Substituting $t = \tau$,

$$v_C = (6.32 \text{ mV})(e^{-1}) = (6.32 \text{ mV})(0.368)$$
$$= 2.33 \text{ mV}$$

as shown in Fig. 24.34.

For the next interval, $V_i = 2.33$ mV and $V_f = 10$ mV, and

$$v_C = V_f + (V_i - V_f)e^{-t/\tau}$$
$$= 10 \text{ mV} + (2.33 \text{ mV} - 10 \text{ mV})e^{-t/\tau}$$
$$v_C = 10 \text{ mV} - 7.67 \text{ mV}e^{-t/\tau}$$

At $t = \tau$ (since $t = T = 2\tau$ is now $t = 0$ s for this interval),

$$v_C = 10 \text{ mV} - 7.67 \text{ mV}e^{-1}$$
$$= 10 \text{ mV} - 2.82 \text{ mV}$$
$$v_C = 7.18 \text{ mV}$$

as shown in Fig. 24.34.

For the discharge interval, $V_i = 7.18$ mV and $V_f = 0$ V, and

$$v_C = V_f + (V_i - V_f)e^{-t/\tau}$$
$$= 0 \text{ V} + (7.18 \text{ mV} - 0)e^{-t/\tau}$$
$$v_C = 7.18 \text{ mV}e^{-t/\tau}$$

At $t = \tau$ (measured from 3τ in Fig. 24.34),

$$v_C = (7.18 \text{ mV})(e^{-1}) = (7.18 \text{ mV})(0.368)$$
$$= 2.64 \text{ mV}$$

as shown in Fig. 24.34.

Continuing in the same manner, the remaining waveform for v_C is generated as depicted in Fig. 24.34. Note that repetition occurs after $t = 8\tau$, and the waveform has essentially reached steady-state conditions in a period of time less than 10τ, or five cycles of the applied square wave.

A closer look reveals that both the peak and the lower levels continued to increase until steady-state conditions were established. Since the exponential waveforms between $t = 4T$ and $t = 5T$ have the same time constant, the average value of v_C can be determined from the steady-state 7.31 mV and 2.69 mV levels as follows:

$$V_{av} = \frac{7.31 \text{ mV} + 2.69 \text{ mV}}{2} = \frac{10 \text{ mV}}{2} = 5 \text{ mV}$$

which equals the average value of the applied signal as stated earlier in this section.

We can use the results in Fig. 24.34 to plot i_C. At any instant of time,

$$v_i = v_R + v_C \quad \text{or} \quad v_R = v_i - v_C$$

and

$$i_R = i_C = \frac{v_i - v_C}{R}$$

At $t = 0^+$, $v_C = 0$ V, and

$$i_R = \frac{v_i - v_C}{R} = \frac{10 \text{ mV} - 0}{5 \text{ k}\Omega} = 2 \ \mu\text{A}$$

as shown in Fig. 24.35.

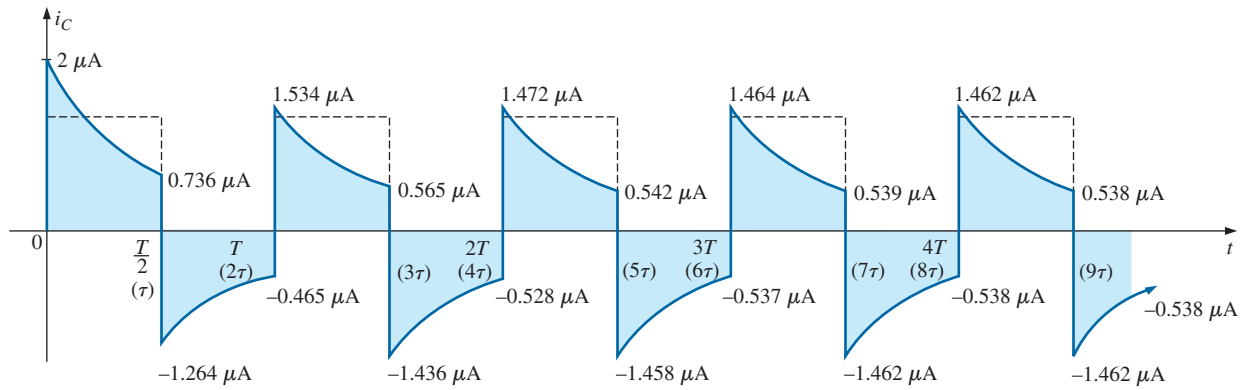As the charging process proceeds, the current i_C decays at a rate determined by

$$i_C = 2 \ \mu\text{A}e^{-t/\tau}$$

At $t = \tau$,

$$i_C = (2 \ \mu\text{A})(e^{-\tau/\tau}) = (2 \ \mu\text{A})(e^{-1}) = (2 \ \mu\text{A})(0.368)$$
$$= 0.736 \ \mu\text{A}$$

as shown in Fig. 24.35.

FIG. 24.35

i_C response for $t_p = \tau = T/2$.

For the trailing edge of the first pulse, the voltage across the capacitor cannot change instantaneously, resulting in the following when v_i drops to zero volts:

$$i_C = i_R = \frac{v_i - v_C}{R} = \frac{0 - 6.32 \text{ mV}}{5 \text{ k}\Omega} = -1.264 \ \mu\text{A}$$

as illustrated in Fig. 24.35. The current then decays as determined by

$$i_C = -1.264 \ \mu\text{A}e^{-t/\tau}$$

and at $t = \tau$ (actually $t = 2\tau$ in Fig. 24.35),

$$i_C = (-1.264 \ \mu\text{A})(e^{-\tau/\tau}) = (-1.264 \ \mu\text{A})(e^{-1})$$
$$= (-1.264 \ \mu\text{A})(0.368) = -0.465 \ \mu\text{A}$$

as shown in Fig. 24.35.

At $t = T$ ($t = 2\tau$), $v_C = 2.33$ mV, and v_i returns to 10 mV, resulting in

$$i_C = i_R = \frac{v_i - v_C}{R} = \frac{10 \text{ mV} - 2.33 \text{ mV}}{5 \text{ k}\Omega} = 1.534 \ \mu\text{A}$$

The equation for the decaying current is now

$$i_C = 1.534 \ \mu\text{A}e^{-t/\tau}$$

and at $t = \tau$ (actually $t = 3\tau$ in Fig. 24.35),

$$i_C = (1.534 \ \mu\text{A})(0.368) = 0.565 \ \mu\text{A}$$

The process continues until steady-state conditions are reached at the same time they were attained for v_C. Note in Fig. 24.35 that the positive peak current decreased toward steady-state conditions while the negative peak became more negative. Note that the current waveform becomes symmetrical about the axis when steady-state conditions are established. The result is that the net average current over one cycle is zero, as it should be in a series *R-C* circuit. Recall from Chapter 10 that the capacitor under dc steady-state conditions can be replaced by an open-circuit equivalent, resulting in $I_C = 0$ A.

Although both examples provided above started with an uncharged capacitor, the same approach can be used effectively for initial conditions. Simply substitute the initial voltage on the capacitor as V_i in Eq. (24.6) and proceed as above.

24.7 OSCILLOSCOPE ATTENUATOR AND COMPENSATING PROBE

The ×10 **attenuator probe** used with oscilloscopes is designed to reduce the magnitude of the input voltage by a factor of 10. If the input impedance to a scope is 1 MΩ, the ×10 attenuator probe will have an internal resistance of 9 MΩ, as shown in Fig. 24.36.
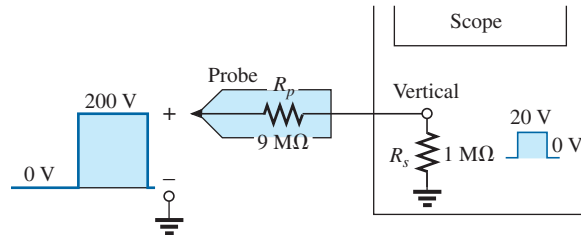
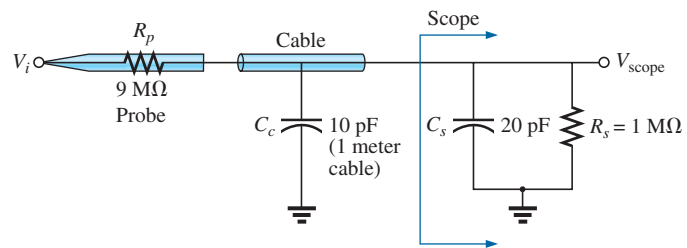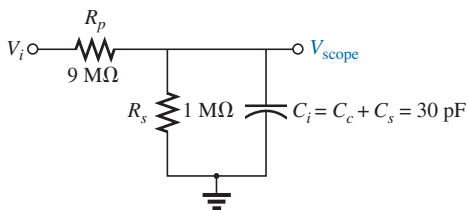**FIG. 24.36**
×10 attenuator probe.

Applying the voltage divider rule,

$$V_{\text{scope}} = \frac{(1 \text{ M}\Omega)(V_i)}{1 \text{ M}\Omega + 9 \text{ M}\Omega} = \frac{1}{10}V_i$$
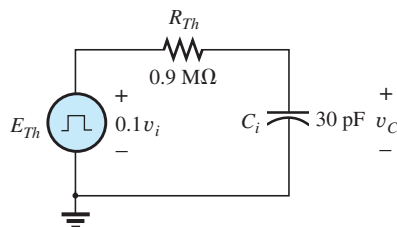
In addition to the input resistance, oscilloscopes have some internal input capacitance, and the probe adds an additional capacitance in parallel with the oscilloscope capacitance, as shown in Fig. 24.37. The probe

FIG. 24.37
Capacitive elements present in an attenuator probe arrangement.

FIG. 24.38
Equivalent network in Fig. 24.37.

capacitance is typically about 10 pF for a 1 m (3.3 ft) cable, reaching about 15 pF for a 3 m (9.9 ft) cable. The total input capacitance is therefore the sum of the two capacitive elements, resulting in the equivalent network in Fig. 24.38.

For the analysis to follow, let us determine the Thévenin equivalent circuit for the capacitor C_i:

$$E_{Th} = \frac{(1 \text{ M}\Omega)(V_i)}{1 \text{ M}\Omega + 9 \text{ M}\Omega} = \frac{1}{10}V_i$$

and $$R_{Th} = 9 \text{ M}\Omega \parallel 1 \text{ M}\Omega = 0.9 \text{ M}\Omega$$

The Thévenin network is shown in Fig. 24.39.

For $v_i = 200$ V (peak),

$$E_{Th} = 0.1v_i = 20 \text{ V (peak)}$$

and for v_C, $V_f = 20$ V and $V_i = 0$ V, with

FIG. 24.39
Thévenin equivalent for C_i in Fig. 24.38.

$$\tau = RC = (0.9 \times 10^6 \ \Omega)(30 \times 10^{-12} \ F) = 27 \ \mu s$$

For an applied frequency of 5 kHz,

$$T = \frac{1}{f} = 0.2 \ ms \quad \text{and} \quad \frac{T}{2} = 0.1 \ ms = 100 \ \mu s$$

with $5\tau = 135 \ \mu s > 100 \ \mu s$, as shown in Fig. 24.40, clearly producing a severe rounding distortion of the square wave and a poor representation of the applied signal.

To improve matters, a variable capacitor is often added in parallel with the resistance of the attenuator, resulting in a **compensated attenuator probe** such as the one shown in Fig. 24.41. In Chapter 22, it was demonstrated that a square wave can be generated by a summation of sinusoidal signals of particular frequency and amplitude. If we therefore design a network such as the one shown in Fig. 24.42 that ensures that V_{scope} is $0.1v_i$ for any frequency, then the rounding distortion is removed, and V_{scope} has the same appearance as v_i.

Applying the voltage divider rule to the network in Fig. 24.42,

$$\boxed{V_{\text{scope}} = \frac{Z_s V_i}{Z_s + Z_p}} \quad \text{(24.8)}$$

If the parameters are chosen or adjusted such that

$$\boxed{R_p C_p = R_s C_s} \quad \text{(24.9)}$$

the phase angle of Z_s and Z_p will be the same, and Eq. (24.8) will reduce to

$$\boxed{V_{\text{scope}} = \frac{R_s V_i}{R_s + R_p}} \quad \text{(24.10)}$$

which is insensitive to frequency since the capacitive elements have dropped out of the relationship.

In the laboratory, simply adjust the probe capacitance using a standard or known square-wave signal until the desired sharp corners of the square wave are obtained. If you avoid the calibration step, you may make a rounded signal look square since you assumed a square wave at the point of measurement.

Too much capacitance results in an overshoot effect, whereas too little continues to show the rounding effect.

24.8 APPLICATION

TV Remote

The TV remote works in many ways like a garage door opener or car alarm transmitter. There is no visible connection between the transmitter and the receiver, and each transmitter is linked to its receiver with a special code. The only major difference is that the TV remote uses an infrared frequency while the other two use a much lower radio frequency.

The TV remote in Fig. 24.43(a) has been opened to reveal the internal construction of its keypad and face in Fig. 24.43(b). The three components in Fig. 24.43(b) are lined up to show how the holes in the cover
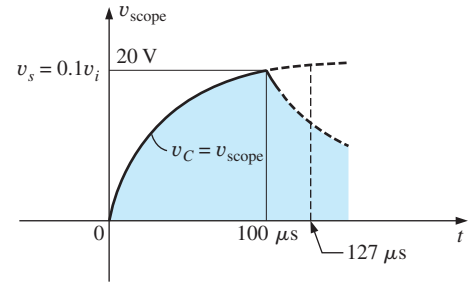

FIG. 24.40

The scope pattern for the conditions in Fig. 24.38 with $v_i = 200 \ V$ peak.

FIG. 24.41

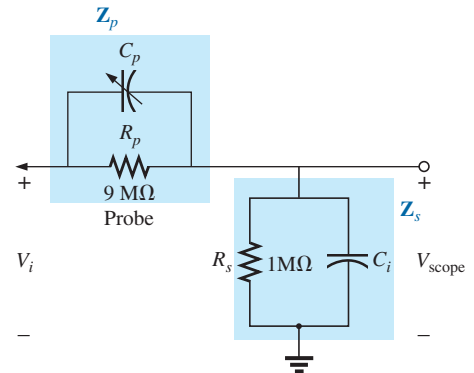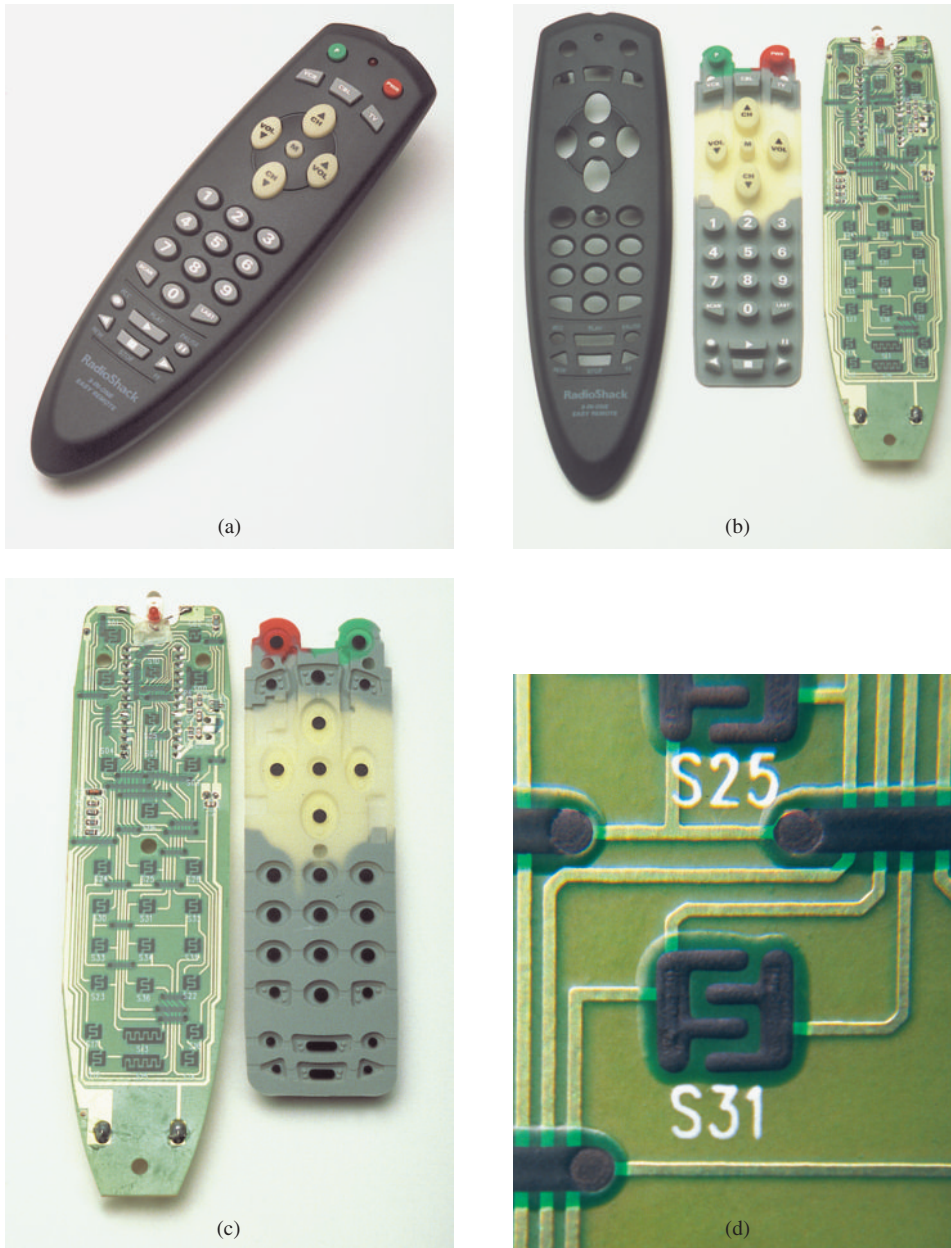*Commercial compensated 10 : 1 attenuator probe. (Courtesy of Tektronix, Inc.)*

FIG. 24.42

Compensated attenuator and input impedance to a scope, including the cable capacitance.

FIG. 24.43

TV remote: (a) external appearance; (b) internal construction; (c) carbon keypads; (d) enlarged view of S31 keypad.

match the actual keys in the switch membrane and where each button on the keypad hits on the face of the printed circuit board. Note on the printed circuit board that there is a black pad to match each key on the membrane. The back side of the switch membrane in Fig. 24.43(c) shows the soft carbon contacts that make contact with the carbon contacts on the printed board when the buttons are depressed. An enlarged view of one of the contacts (S31) in Fig. 24.43(c) is shown in Fig. 24.43(d) to illustrate the separation between circuits and the pattern used to ensure continuity when the solid round carbon pad at the bottom of the key is put in place.

All the connections established when a key is pressed are passed on to a relatively large switch-matrix-encoder IC chip appearing on the back side

of the printed circuit board as shown in Fig. 24.44. For the pad (S31) in Fig. 24.43(d), three wires of the matrix appearing in Fig. 24.43(b) are connected when the corresponding key (number 5) is pressed. The encoder then reacts to this combination and sends out the appropriate signal as an infrared (IR) signal from the IR LED appearing at the end of the remote control, as shown in Fig. 24.43(b) and Fig. 24.44. The second smaller LED (red on actual unit) appearing at the top of Fig. 24.43(b) blinks during transmission. Once the batteries are inserted, the CMOS electronic circuitry that controls the operation of the remote is *always on.* This is possible only because of the very low power drain of CMOS circuitry. The power (PWR) button is used only to turn the TV on and activate the receiver.

The signal sent out by the majority of remotes is one of the two types appearing in Fig. 24.45. In each case there is a *key pulse* to initiate the signal sequence and to inform the receiver that the coded signal is about to arrive. In Fig. 24.45(a), a 4-bit binary-coded signal is transmitted using pulses in specific locations to represent the "ones" and using the absence of a pulse to represent the "zeros." That coded signal can then be interpreted by the receiver unit and the proper operation performed. In Fig. 24.45(b), the signal is frequency controlled. Each key has a different frequency associated with it. The result is that each key has a specific transmission frequency. Since each TV receiver responds to a different pulse train, a remote must be coded for the TV under control. There are *fixed program* remotes that can be used with only one TV. Then there are *smart* remotes that are preprogrammed internally with a number of remote control codes. You have to set up remotes of this type according to the TV you have, using a three-digit coding system accessed through the TV setup screen. *Learning* remotes are those that can use the old remote to learn the code and then store it for future use. In this case, one remote is set directly in front of the other, and the information is transferred from one to the other when both are energized. Remotes are also available that are a combination of the last two.

The remote in Fig. 24.43 uses four AAA batteries in series for a total of 6 V. It has its own local crystal oscillator separate from the IC as shown by the discrete elements to the top right and midleft of the printed circuit
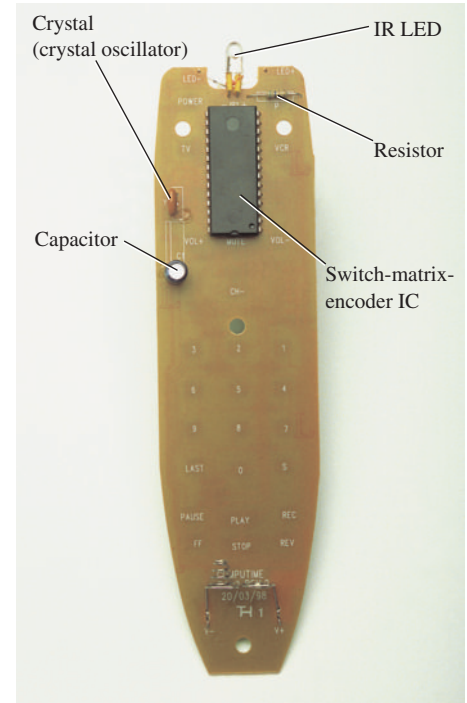
FIG. 24.44
Back side of TV remote in Fig. 24.43.
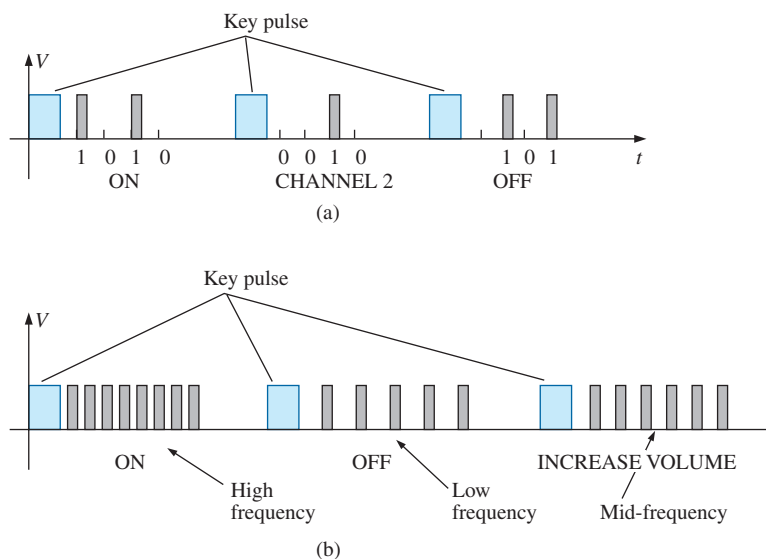
FIG. 24.45
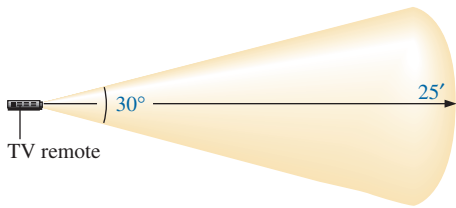*Signal transmission: (a) pulse train; (b) variation.*

FIG. 24.46

Range and coverage arc for TV remote in Fig. 24.43.

board in Fig. 24.43(c). The crystal itself, which is relatively large compared to the other elements, appears on the other side of the board just above the electrolytic capacitor in Fig. 24.44. The oscillator generates the pulse signal required for proper IC operation. Note how flush most of the discrete elements are in Fig. 24.43(b) and the rather large electrolytic capacitor on the back of the printed circuit board in Fig. 24.44. The specifications on the unit give it a range control of 25 ft with a 30° coverage arc as shown in Fig. 24.46. The arc coverage of your unit can easily be tested by pointing it directly at the TV and then moving it in any direction until it no longer controls the TV.

24.9 COMPUTER ANALYSIS

PSpice

***R-C* Response**   Our analysis begins with a verification of the results of Example 24.10 which examined the response of the series *R-C* circuit appearing on the schematic in Fig. 24.47. The source is one used in
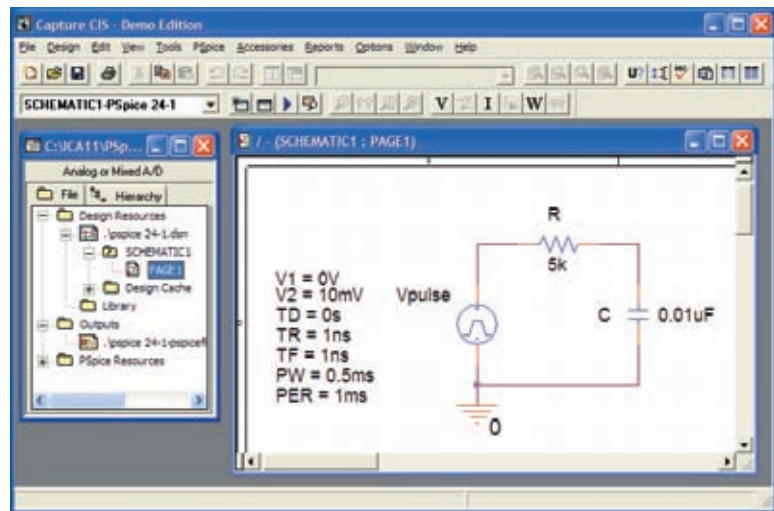

FIG. 24.47
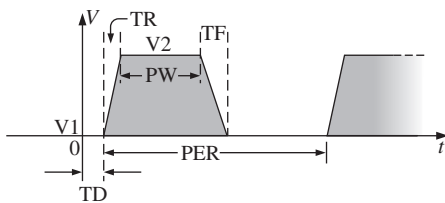
*Using PSpice to verify the results of Example 24.10.*

FIG. 24.48

*Defining the PSpice **Vpulse** parameters.*

Chapters 10 and 11 to replicate the action of a switch in series with a dc source. The defining attributes for the pulse waveform are repeated for convenience in Fig. 24.48. Recall that the **PW** was made long enough so that the full transient period could be examined. In this analysis, the pulse width is adjusted to permit viewing the transient behavior of an *R-C* network between changing levels of the applied pulse. Initially the **PW** is set at 10 times the time constant of the network so that the full transient response can occur between changes in voltage level. The time constant of the network is $\tau = RC = (5\text{ k}\Omega)(0.01\text{ }\mu\text{F}) = 0.05$ ms, resulting in a **PW** of 0.5 ms in Fig. 24.47. To establish a square-wave appearance, the period was chosen as twice the pulse width or 1 ms as shown in the **VPulse** listing.

In the **Simulation Settings** dialog box, select **Time Domain(Transient)** to get a response versus time. Select the **Run to time** at 2 ms so that two full cycles result. Leave the **Start saving data after** on the default value of 0 s, and set the **Maximum step size** at 2 ms/1000 = 2 μs. After simulation, **Trace-Add Trace-I(C)-OK,** the bottom plot in Fig. 24.49 is the result. Note that the maximum current is 2 μA as determined by

$I_{C_{max}} = 10$ mV/5 kΩ, and the full transient response appears within each pulse. Note also that the current dropped below the axis to reveal a change in direction when the applied voltage dropped from the 10 mV level to 0 V. Through **Plot-Add Plot to Window-Trace-Add Trace-V(Vpulse:+)-OK-Trace-Add Trace-V(C:1)-OK,** the plots of the applied voltage and the voltage across the capacitor can be displayed in the upper graph in Fig. 24.49. First, select the upper graph in Fig. 24.49 so that you can move the **SEL>>,** and then select the **Toggle cursor** key. Now left-click on **V(C:1)** at the bottom right of the graph and left-click again to set a cursor on the graph. Setting the cursor at five time constants reveals that the transient voltage has reached 9.935 mV. Setting the right-click cursor at ten time constants reveals that V_C has essentially reached the 10 mV level.
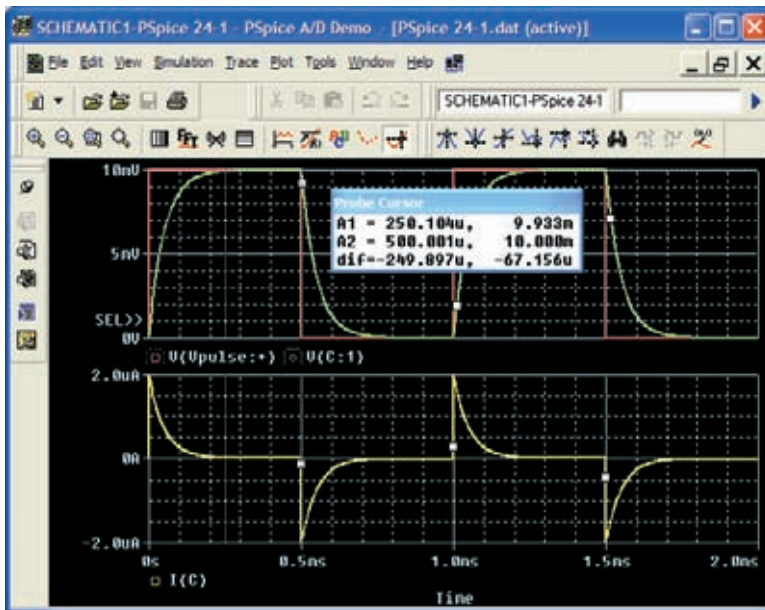
FIG. 24.49
Plot of v_{pulse}, v_C, and i_C for the circuit in Fig. 24.47.

Setting $t_p = \tau = T/2$ The parameters of the source will now be modified by changing the frequency of the pulse waveform to 10 kHz with a period of 0.1 ms and a pulse width of 0.05 ms. For **Vpulse,** the changes are **PW** = 0.05 ms and **PER** = 0.1 ms. The time constant of the network remains the same at 0.05 ms, so the pulse width equals the time constant of the circuit. The result is that it will take a number of pulses before the voltage across the capacitor reaches its final value of 10 mV. Under the **Simulation Settings,** change the **Run to time** to 0.5 ms = 500 μs or five cycles of the applied voltage. Change the **Maximum step size** to 500 μs/1000 = 500 ns = 0.5 μs. Under the **SCHEMATIC1** window, select **Trace-Add Trace-V(C:1)-OK** to obtain the transient voltage across the capacitor. Select **Trace-Add Trace-V(Vpulse:+)-OK** to place the applied voltage on the same screen. Note in the resulting plots in Fig. 24.50 that the voltage builds up from 0 V until it appears to reach a fairly steady state after 400 μs. At 400 μs, use a left cursor **(A1)** to find the minimum point with 2.71 mV resulting—a close match with the longhand calculation of Example 24.11 at 2.69 mV. At 450 μs, the right-click cursor **(A2)** provides a level of 7.29 mV which is again a close match with the calculated level of 7.31 mV.
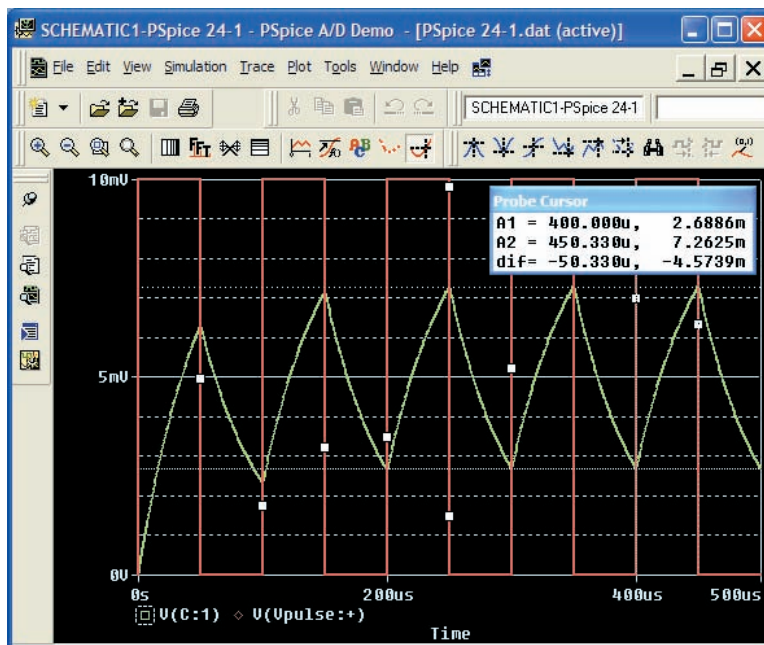
FIG. 24.50

Plot of v_C for the circuit in Fig. 24.47 with $t_p = \tau = T/2$.

PROBLEMS

SECTION 24.2 Ideal versus Actual

1. Determine the following for the pulse waveform in Fig. 24.51:
   a. positive- or negative-going?
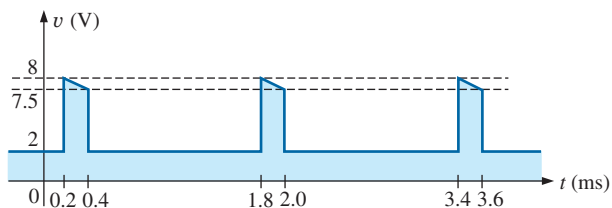   b. base-line voltage
   c. pulse width
   d. amplitude
   e. % tilt

FIG. 24.51

Problems 1, 8, and 12.

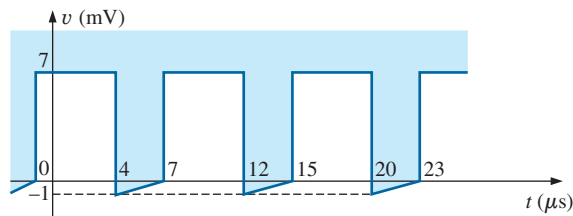2. Repeat Problem 1 for the pulse waveform in Fig. 24.52.

FIG. 24.52

Problems 2 and 9.

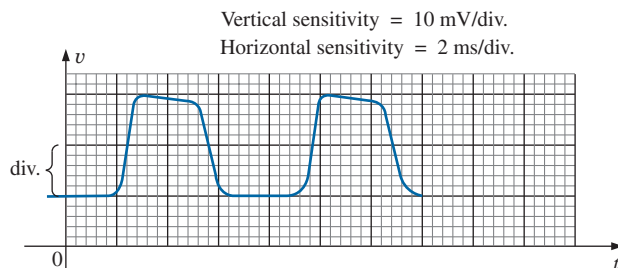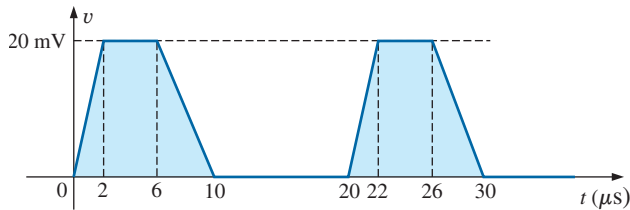3. Repeat Problem 1 for the pulse waveform in Fig. 24.53.

Vertical sensitivity = 10 mV/div.
Horizontal sensitivity = 2 ms/div.

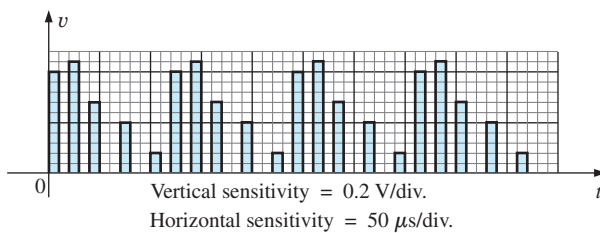**FIG. 24.53**

Problems 3, 4, 10, and 13.

4. Determine the rise and fall times for the waveform in Fig. 24.53.

5. Sketch a pulse waveform that has a base-line voltage of -5 mV, a pulse width of 2 μs, an amplitude of 15 mV, a 10% tilt, a period of 10 μs, and vertical sides, and that is positive-going.

6. For the waveform in Fig. 24.54, established by straight-line approximations of the original waveform:
   a. Determine the rise time.
   b. Find the fall time.
   c. Find the pulse width.
   d. Calculate the frequency.

FIG. 24.54
Problems 6 and 14.

7. For the waveform in Fig. 24.55:
   a. Determine the period.
   b. Find the frequency.
   c. Find the maximum and minimum amplitudes.

Vertical sensitivity = 0.2 V/div.
Horizontal sensitivity = 50 μs/div.
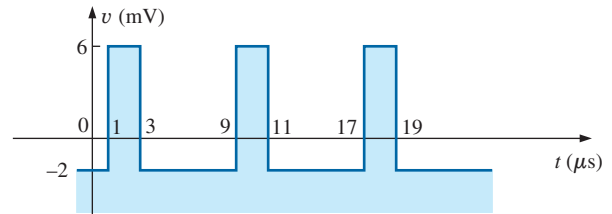
FIG. 24.55
Problems 7 and 15.

SECTION 24.3   Pulse Repetition Rate and Duty Cycle

8. Determine the pulse repetition frequency and duty cycle for the waveform in Fig. 24.51.

9. Determine the pulse repetition frequency and duty cycle for the waveform in Fig. 24.52.

10. Determine the pulse repetition frequency and duty cycle for the waveform in Fig. 24.53.

SECTION 24.4   Average Value

11. For the waveform in Fig. 24.56, determine the
   a. period.
   b. pulse width.
   c. pulse repetition frequency.
   **d.** average value.
   e. effective value.

FIG. 24.56
Problem 11.

12. Determine the average value of the periodic pulse waveform in Fig. 24.51.

13. To the best accuracy possible, determine the average value of the waveform in Fig. 24.53.

14. Determine the average value of the waveform in Fig. 24.54.

15. Determine the average value of the periodic pulse train in Fig. 24.55.

SECTION 24.5   Transient *R-C* Networks

16. The capacitor in Fig. 24.57 is initially charged to 5 V, with the polarity indicated in the figure. The switch is then closed at $t = 0$ s.
   a. What is the mathematical expression for the voltage v_C?
   b. Sketch v_C versus t.
   c. What is the mathematical expression for the current i_C?
   d. Sketch i_C versus t.
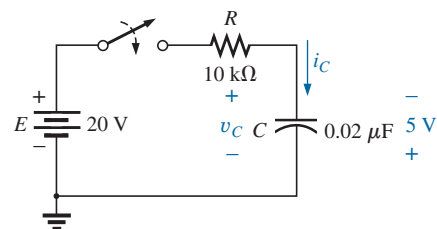
FIG. 24.57
Problem 16.

17. For the input voltage v_i appearing in Fig. 24.58, sketch the waveform for v_o. Assume that steady-state conditions were established with $v_i = 8$ V.
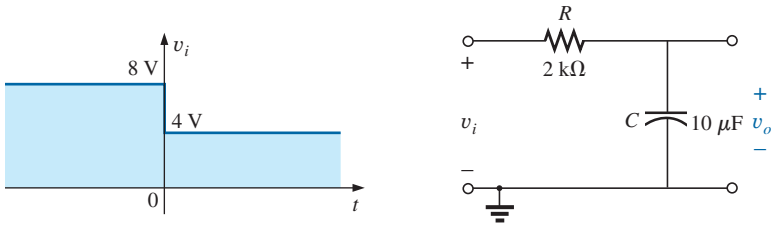

FIG. 24.58
Problem 17.

18. The switch in Fig. 24.59 is in position 1 until steady-state conditions are established. Then the switch is moved (at $t = 0$ s) to position 2. Sketch the waveform for the voltage v_C.
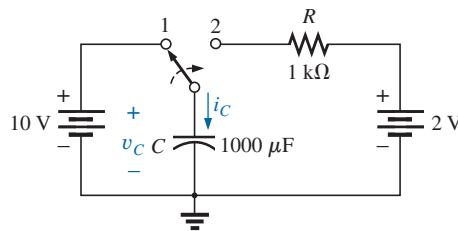

FIG. 24.59
Problems 18 and 19.

19. Sketch the waveform for i_C for Problem 18.

SECTION 24.6   *R-C* Response to Square-Wave Inputs

20. Sketch the voltage v_C for the network in Fig. 24.60 due to the square-wave input of the same figure with a frequency of
   a. 500 Hz.
   b. 100 Hz.
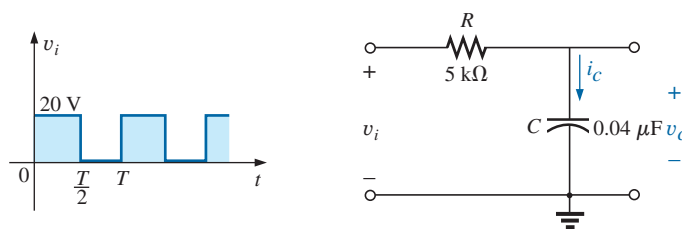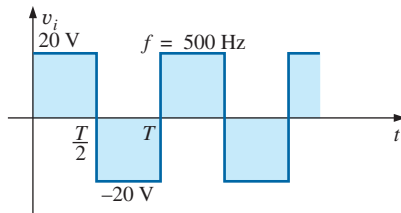   **c.** 5000 Hz.

FIG. 24.60
Problems 20, 21, 23, 24, 27, and 28.

21. Sketch the current i_C for each frequency in Problem 20.

22. Sketch the response v_C of the network in Fig. 24.60 to the square-wave input in Fig. 24.61.

FIG. 24.61
Problem 22.

23. If the capacitor in Fig. 24.60 is initially charged to 20 V, sketch the response v_C to the same input signal (in Fig. 24.60) at a frequency of 500 Hz.

24. Repeat Problem 23 if the capacitor is initially charged to -10 V.

SECTION 24.7 Oscilloscope Attenuator and Compensating Probe

25. Given the network in Fig. 24.42 with $R_p = 9$ MΩ and $R_s = 1$ MΩ, find $\mathbf{V}_{scope}$ in polar form if $C_p = 3$ pF, $C_s = 18$ pF, $C_c = 9$ pF, and $v_i = \sqrt{2}$ (100) sin $2\pi10,000t$. That is, determine $\mathbf{Z}_s$ and $\mathbf{Z}_p$, substitute into Eq. (24.8), and compare the results obtained with Eq. (24.10). Is it verified that the phase angle of $\mathbf{Z}_s$ and $\mathbf{Z}_p$ is the same under the condition $R_pC_p = R_sC_s$?

26. Repeat Problem 25 at $\omega = 10^5$ rad/s.

SECTION 24.9 Computer Analysis

PSpice

27. Using schematics, obtain the waveforms for v_C and i_C for the network in Fig. 24.60 for a frequency of 1 kHz.

*28. Using schematics, place the waveforms of v_i, v_C, and i_C on the same printout for the network in Fig. 24.60 at a frequency of 2 kHz.

*29. Using schematics, obtain the waveform appearing on the scope in Fig. 24.37 with a 20 V pulse input at a frequency of 5 kHz.

*30. Place a capacitor in parallel with R_p in Fig. 24.37 that will establish an in-phase relationship between v_{scope} and v_i. Using schematics, obtain the waveform appearing on the scope in Fig. 24.37 with a 20 V pulse input at a frequency of 5 kHz.

GLOSSARY

Actual (true, practical) pulse A pulse waveform having a leading edge and a trailing edge that are not vertical, along with other distortion effects such as tilt, ringing, or overshoot.

Amplitude of a pulse waveform The peak-to-peak value of a pulse waveform.

Attenuator probe A scope probe that will reduce the strength of the signal applied to the vertical channel of a scope.

Base-line voltage The voltage level from which a pulse is initiated.

Compensated attenuator probe A scope probe that can reduce the applied signal and balance the effects of the input capacitance of a scope on the signal to be displayed.

Duty cycle Factor that reveals how much of a period is encompassed by the pulse waveform.

Fall time (t_f) The time required for the trailing edge of a pulse waveform to drop from the 90% to the 10% level.

Ideal pulse A pulse waveform characterized as having vertical sides, sharp corners, and a flat peak response.

Negative-going pulse A pulse that increases in the negative direction from the base-line voltage.

Periodic pulse train A sequence of pulses that repeats itself after a specific period of time.

Positive-going pulse A pulse that increases in the positive direction from the base-line voltage.

Pulse repetition frequency (pulse repetition rate) The frequency of a periodic pulse train.

Pulse train A series of pulses that may have varying heights and widths.

Pulse width (t_p) The pulse width defined by the 50% voltage level.

Rise time (t_r) The time required for the leading edge of a pulse waveform to travel from the 10% to the 90% level.

Square wave A periodic pulse waveform with a 50% duty cycle.

Tilt (droop, sag) The drop in peak value across the pulse width of a pulse waveform.