integrating each side of the equation. The variables in Eq. [1] are i and t, and it is apparent that the equation may be multiplied by dt, divided by i, and arranged with the variables separated:

$$\frac{di}{i} = -\frac{R}{L}\,dt \qquad [2]$$

Since the current is I_0 at $t = 0$ and $i(t)$ at time t, we may equate the two definite integrals which are obtained by integrating each side between the corresponding limits:

$$\int_{I_0}^{i(t)} \frac{di'}{i'} = \int_0^t -\frac{R}{L}\,dt'$$

Performing the indicated integration,

$$\ln i'\Big|_{I_0}^{i} = -\frac{R}{L}t'\Big|_0^t$$

which results in

$$\ln i - \ln I_0 = -\frac{R}{L}(t - 0)$$

After a little manipulation, we find that the current $i(t)$ is given by

$$i(t) = I_0 e^{-Rt/L} \qquad [3]$$

We check our solution by first showing that substitution of Eq. [3] in Eq. [1] yields the identity $0 = 0$, and then showing that substitution of $t = 0$ in Eq. [3] produces $i(0) = I_0$. Both steps are necessary; the solution must satisfy the differential equation which characterizes the circuit, and it must also satisfy the initial condition.

EXAMPLE 8.1

If the inductor of Fig. 8.2 has a current $i_L = 2$ A at $t = 0$, find an expression for $i_L(t)$ valid for $t > 0$, and its value at $t = 200\ \mu$s.

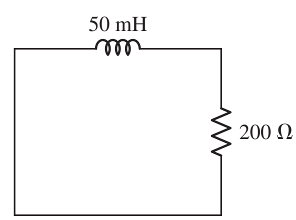
This is the identical type of circuit just considered, so we expect an inductor current of the form

$$i_L = I_0 e^{-Rt/L}$$

where $R = 200\ \Omega$, $L = 50$ mH and I_0 is the initial current flowing through the inductor at $t = 0$. Thus,

$$i_L(t) = 2e^{-4000t}$$

Substituting $t = 200 \times 10^{-6}$ s, we find that $i_L(t) = 898.7$ mA, less than half the initial value.

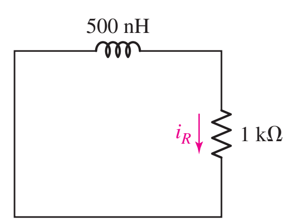


■ FIGURE 8.2 A simple *RL* circuit in which energy is stored in the inductor at $t = 0$.

PRACTICE

8.1 Determine the current i_R through the resistor of Fig. 8.3 at $t = 1$ ns if $i_R(0) = 6$ A.

Ans: 812 mA.



■ FIGURE 8.3 Circuit for Practice Problem 8.1.

Solving, we find that $s = -10$, so

$$v(t) = Ae^{-10t} \qquad [10]$$

(which, upon substitution into the left-hand side of Eq. [9], results in

$$-10Ae^{-10t} + 10Ae^{-10t} = 0$$

as expected.)

We find A by setting $t = 0$ in Eq. [10] and employing the fact that $v(0) = -96$ V. Thus,

$$v(t) = -96e^{-10t} \qquad [11]$$

and so $v(0.2) = -12.99$ V, down from a maximum of -96 V.

▶ ***Verify the solution. Is it reasonable or expected?***

Instead of writing a differential equation in v, we could have written our differential equation in terms of i_L:

$$40i_L + 10i_L + 5\frac{di_L}{dt} = 0$$

or

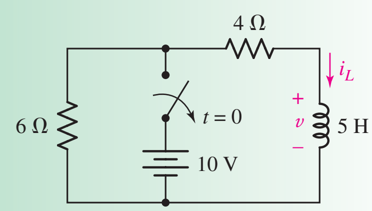
$$\frac{di_L}{dt} + 10i_L = 0$$

which has the solution $i_L = Be^{-10t}$. With $i_L(0) = 2.4$, we find that $i_L(t) = 2.4e^{-10t}$. Since $v = -40i_L$, we once again obtain Eq. [11]. We should note: it is **no coincidence** that the inductor current and the resistor voltage have the same exponential dependence!

PRACTICE

8.2 Determine the inductor voltage v in the circuit of Fig. 8.6 for $t > 0$.

Ans: $-25e^{-2t}$ V.



■ FIGURE 8.6 Circuit for Practice Problem 8.2.

Accounting for the Energy

Before we turn our attention to the interpretation of the response, let us return to the circuit of Fig. 8.1, and check the power and energy relationships. The power being dissipated in the resistor is

$$p_R = i^2R = I_0^2Re^{-2Rt/L}$$

and the total energy turned into heat in the resistor is found by integrating the instantaneous power from zero time to infinite time:

$$w_R = \int_0^\infty p_R\,dt = I_0^2R\int_0^\infty e^{-2Rt/L}\,dt$$
$$= I_0^2R\left(\frac{-L}{2R}\right)e^{-2Rt/L}\Big|_0^\infty = \frac{1}{2}L\,I_0^2$$

This is the result we expect, because the total energy stored initially in the inductor is $\frac{1}{2}LI_0^2$, and there is no longer any energy stored in the inductor at infinite time since its current eventually drops to zero. All the initial energy therefore is accounted for by dissipation in the resistor.

negligible fraction of its former self. Thus, if we are asked, "*How long does it take for the current to decay to zero?*" our answer might be, "*About five time constants*." At that point, the current is less than 1 percent of its original value!

PRACTICE

8.3 In a source-free series *RL* circuit, find the numerical value of the ratio: (*a*) $i(2\tau)/i(\tau)$; (*b*) $i(0.5\tau)/i(0)$; (*c*) t/τ if $i(t)/i(0) = 0.2$; (*d*) t/τ if $i(0) - i(t) = i(0)\ln 2$.

Ans: 0.368; 0.607; 1.609; 1.181.

COMPUTER-AIDED ANALYSIS

The transient analysis capability of PSpice is very useful when considering the response of source-free circuits. In this example, we make use of a special feature that allows us to vary a component parameter, similar to the way we varied the dc voltage in other simulations. We do this by adding the component **PARAM** to our schematic; it may be placed anywhere, as we will not wire it into the circuit. Our complete *RL* circuit is shown in Fig. 8.10, which includes an initial inductor current of 1 mA.

In order to relate our resistor value to the proposed parameter sweep, we must perform three tasks. First, we provide a name for our parameter, which we choose to call Resistance for the sake of simplicity. This is accomplished by double-clicking on the **PARAMETERS:** label in the schematic, which opens the Property Editor for this pseudo-component. Clicking on **New Column** results in the dialog box shown in Fig. 8.11*a*, in which we enter *Resistance* under **Name** and a placeholder value of 1 under **Value.** Our second task consists of linking the

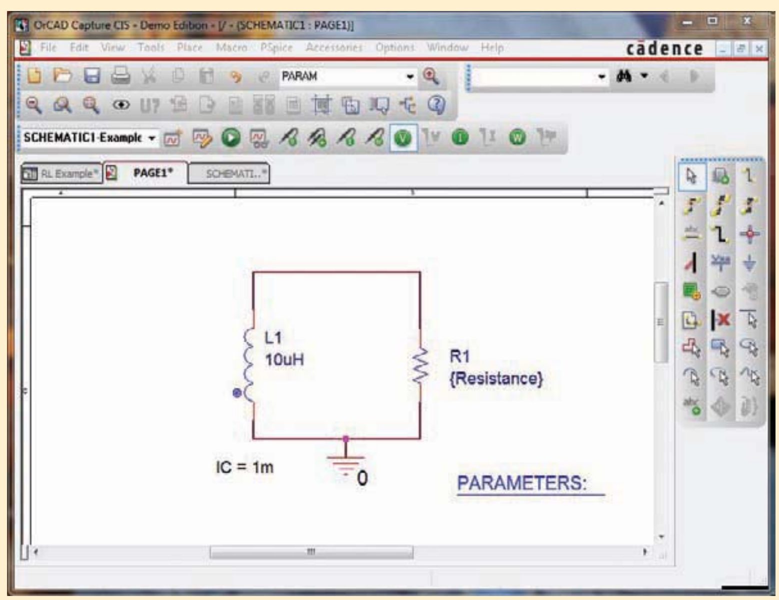
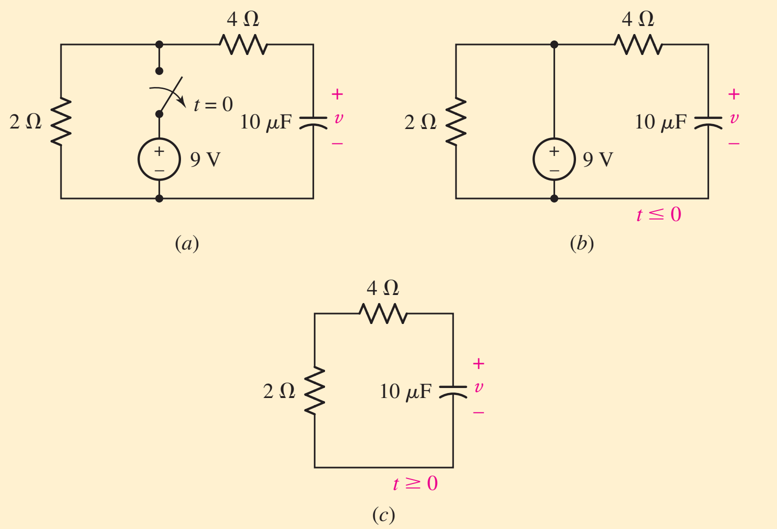


FIGURE 8.10 Simple *RL* circuit drawn using the schematic capture tool.



■ FIGURE 8.17 (*a*) A simple *RC* circuit with a switch thrown at time $t = 0$. (*b*) The circuit as it exists prior to $t = 0$. (*c*) The circuit after the switch is thrown, and the 9 V source is removed.

The capacitor voltage must be the same in both circuits at $t = 0$; no such restriction is placed on any other voltage or current. Substituting Eq. [17] into Eq. [18],

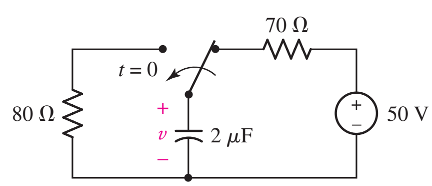
$$v(t) = 9e^{-t/60\times10^{-6}} \text{ V}$$

so that $v(200 \times 10^{-6}) = 321.1$ mV (less than 4 percent of its maximum value).

PRACTICE

8.4 Noting carefully how the circuit changes once the switch in the circuit of Fig. 8.18 is thrown, determine $v(t)$ at $t = 0$ and at $t = 160\ \mu$s.

Ans: 50 V, 18.39 V.



■ FIGURE 8.18

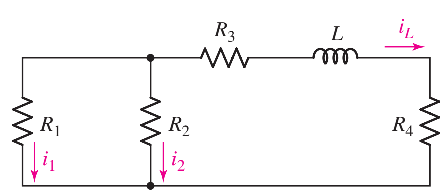
8.4 A MORE GENERAL PERSPECTIVE

As seen indirectly from Examples 8.2 and 8.3, regardless of how many resistors we have in the circuit, we obtain a single time constant (either $\tau = L/R$ or $\tau = RC$) when only one energy storage element is present. We can formalize this by realizing that the value needed for R is in fact the Thévenin equivalent resistance seen by our energy storage element. (*Strange as it may seem, it is even possible to compute a time constant for a circuit containing dependent sources!*)

General *RL* Circuits

As an example, consider the circuit shown in Fig. 8.19. The equivalent resistance the inductor faces is

$$R_{\text{eq}} = R_3 + R_4 + \frac{R_1 R_2}{R_1 + R_2}$$



■ FIGURE 8.19 A source-free circuit containing one inductor and several resistors is analyzed by determining the time constant $\tau = L/R_{\text{eq}}$.

and the time constant,

$$\tau = \frac{L_{\text{eq}}}{R_{\text{eq}}} = \frac{2.2 \times 10^{-3}}{110} = 20\ \mu\text{s}$$

Thus, the form of the natural response is $Ke^{-50{,}000t}$, where K is an unknown constant. Considering the circuit just prior to the switch opening ($t = 0^-$), $i_L = 18/50$ A. Since $i_L(0^+) = i_L(0^-)$, we know that $i_L = 18/50$ A or 360 mA at $t = 0^+$ and so

$$i_L = \begin{cases} 360 \text{ mA} & t < 0 \\ 360e^{-50{,}000t} \text{ mA} & t \geq 0 \end{cases}$$

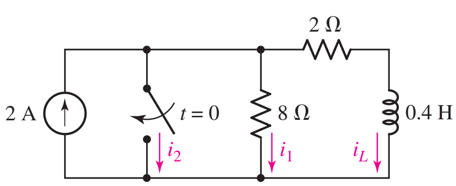
There is no restriction on i_1 changing instantaneously at $t = 0$, so its value at $t = 0^-$ (18/90 A or 200 mA) is not relevant to finding i_1 for $t > 0$. Instead, we must find $i_1(0^+)$ through our knowledge of $i_L(0^+)$. Using current division,

$$i_1(0^+) = -i_L(0^+)\frac{120 + 60}{120 + 60 + 90} = -240 \text{ mA}$$

Hence,

$$i_1 = \begin{cases} 200 \text{ mA} & t < 0 \\ -240e^{-50{,}000t} \text{ mA} & t \geq 0 \end{cases}$$

We can verify our analysis using PSpice and the switch model **Sw_tOpen,** although it should be remembered that this part is actually just two resistance values: one corresponding to before the switch opens at the specified time (the default value is 10 mΩ), and one for after the switch opens (the default value is 1 MΩ). If the equivalent resistance of the remainder of the circuit is comparable to either value, the values should be edited by double-clicking on the switch symbol in the circuit schematic. Note that there is also a switch model that closes at a specified time: **Sw_tClose.**



■ FIGURE 8.21

PRACTICE

8.5 At $t = 0.15$ s in the circuit of Fig. 8.21, find the value of (*a*) i_L; (*b*) i_1; (*c*) i_2.

Ans: 0.756 A; 0; 1.244 A.

We have now considered the task of finding the natural response of any circuit which can be represented by an equivalent inductor in series with an equivalent resistor. *A circuit containing several resistors and several inductors does not always possess a form which allows either the resistors or the inductors to be combined into single equivalent elements*. In such instances, there is no single negative exponential term or single time constant associated with the circuit. Rather, there will, in general, be several negative where

$$v(0^+) = v(0^-) = V_0 \qquad \text{and} \qquad R_{\text{eq}} = R_2 + \frac{R_1 R_3}{R_1 + R_3}$$

Every current and voltage in the resistive portion of the network must have the form $Ae^{-t/R_{\text{eq}}C}$, where A is the initial value of that current or voltage. Thus, the current in R_1, for example, may be expressed as

$$i_1 = i_1(0^+)e^{-t/\tau}$$

where

$$\tau = \left(R_2 + \frac{R_1 R_3}{R_1 + R_3}\right) C$$

and $i_1(0^+)$ remains to be determined from the initial condition. Any current flowing in the circuit at $t = 0^+$ must come from the capacitor. Therefore, since v cannot change instantaneously, $v(0^+) = v(0^-) = V_0$ and

$$i_1(0^+) = \frac{V_0}{R_2 + R_1 R_3/(R_1 + R_3)} \frac{R_3}{R_1 + R_3}$$

PRACTICE

8.6 Find values of v_C and v_o in the circuit of Fig. 8.23 at t equal to (*a*) 0^-; (*b*) 0^+; (*c*) 1.3 ms.

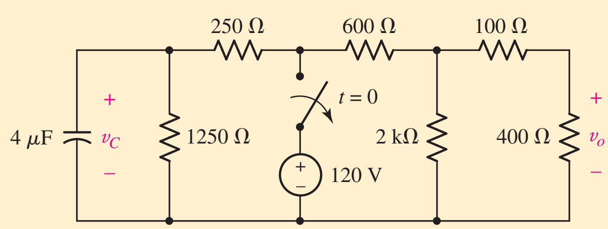


FIGURE 8.23

Ans: 100 V, 38.4 V; 100 V, 25.6 V; 59.5 V, 15.22 V.

Our method can be applied to circuits with one energy storage element and one or more dependent sources as well. In such instances, we may write an appropriate KCL or KVL equation along with any necessary supporting equations, distill this down into a single differential equation, and extract the characteristic equation to find the time constant. Alternatively, we may begin by finding the Thévenin equivalent resistance of the network connected to the capacitor or inductor, and use this in calculating the appropriate *RL* or *RC* time constant—unless the dependent source is controlled by a voltage or current associated with the energy storage element, in which case the Thévenin approach cannot be used.

Substituting Eq. [23] into Eq. [22] and performing some algebra, we obtain

$$\frac{dv_C}{dt} - \frac{1}{60 \times 10^{-6}} v_C = 0$$

which has the characteristic equation

$$s - \frac{1}{60 \times 10^{-6}} = 0$$

Thus,

$$s = \frac{1}{60 \times 10^{-6}}$$

and so

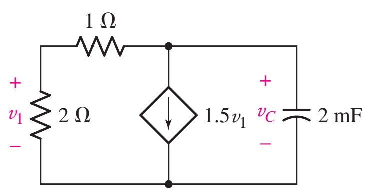
$$v_C(t) = Ae^{t/60\times10^{-6}} \qquad \text{V}$$

as we found before. Substitution of $A = v_C(0^+) = 2$ results in Eq. [21], our expression for the capacitor voltage for $t > 0$.

PRACTICE

8.7 (*a*) Regarding the circuit of Fig. 8.25, determine the voltage $v_C(t)$ for $t > 0$ if $v_C(0^-) = 11$ V. (*b*) Is the circuit "stable"?

Ans: (*a*) $v_C(t) = 11e^{-2\times10^3 t/3}$ V, $t > 0$. (*b*) Yes; it decays (exponentially) rather than grows with time.



■ FIGURE 8.25 Circuit for Practice Problem 8.7.

Some circuits containing a number of both resistors and capacitors may be replaced by an equivalent circuit containing only one resistor and one capacitor; it is necessary that the original circuit be one which can be broken into two parts, one containing all resistors and the other containing all capacitors, such that the two parts are connected by only two ideal conductors. Otherwise, multiple time constants and multiple exponential terms will be required to describe the behavior of the circuit (one time constant for each energy storage element remaining in the circuit after it is reduced as much as possible).

As a parting comment, we should be wary of certain situations involving only ideal elements which are suddenly connected together. For example, we may imagine connecting two ideal capacitors in series having unequal voltages prior to $t = 0$. This poses a problem using our mathematical model of an ideal capacitor; however, real capacitors have resistances associated with them through which energy can be dissipated.

8.5 THE UNIT-STEP FUNCTION

We have been studying the response of *RL* and *RC* circuits when no sources or forcing functions were present. We termed this response the *natural response,* because its form depends only on the nature of the circuit. The reason that any response at all is obtained arises from the presence of initial

PRACTICE

8.9 The voltage source $60 - 40u(t)$ V is in series with a 10 Ω resistor and a 50 mH inductor. Find the magnitudes of the inductor current and voltage at t equal to (a) 0^-; (b) 0^+; (c) ∞; (d) 3 ms.

Ans: 6 A, 0 V; 6 A, 40 V; 2 A, 0 V; 4.20 A, 22.0 V.

Developing an Intuitive Understanding

The reason for the two responses, forced and natural, may be seen from physical arguments. We know that our circuit will eventually assume the forced response. However, at the instant the switches are thrown, the initial inductor currents (or, in *RC* circuits, the voltages across the capacitors) will have values that depend only on the energy stored in these elements. These currents or voltages cannot be expected to be the same as the currents and voltages demanded by the forced response. Hence, there must be a transient period during which the currents and voltages change from their given initial values to their required final values. The portion of the response that provides the transition from initial to final values is the natural response (often called the *transient* response, as we found earlier). If we describe the response of the simple source-free *RL* circuit in these terms, then we should say that the forced response is zero and that the natural response serves to connect the initial response dictated by the stored energy with the zero value of the forced response.

This description is appropriate only for those circuits in which the natural response eventually dies out. This always occurs in physical circuits where some resistance is associated with every element, but there are a number of "pathologic" circuits in which the natural response is nonvanishing as time becomes infinite. Those circuits in which trapped currents circulate around inductive loops, or voltages are trapped in series strings of capacitors, are examples.

8.7 NATURAL AND FORCED RESPONSE

There is also an excellent mathematical reason for considering the complete response to be composed of two parts—the forced response and the natural response. The reason is based on the fact that the solution of any linear differential equation may be expressed as the sum of two parts: the *complementary solution* (natural response) and the *particular solution* (forced response). Without delving into the general theory of differential equations, let us consider a general equation of the type met in the previous section:

$$\frac{di}{dt} + Pi = Q$$

or

$$di + Pi\,dt = Q\,dt \qquad [28]$$

We may identify Q as a forcing function and express it as $Q(t)$ to emphasize its general time dependence. Let us simplify the discussion by and recall that

$$i = i_f + i_n$$

The natural response is therefore a negative exponential as before:

$$i_n = Ke^{-t/2} \qquad \text{A} \qquad t > 0$$

Since the forcing function is a dc source, the forced response will be a constant current. The inductor acts like a short circuit to dc, so that

$$i_f = \tfrac{100}{2} = 50 \text{ A}$$

Thus,

$$i = 50 + Ke^{-0.5t} \qquad \text{A} \qquad t > 0$$

In order to evaluate K, we must establish the initial value of the inductor current. Prior to $t = 0$, this current is 25 A, and it cannot change instantaneously. Thus,

$$25 = 50 + K$$

or

$$K = -25$$

Hence,

$$i = 50 - 25e^{-0.5t} \qquad \text{A} \qquad t > 0$$

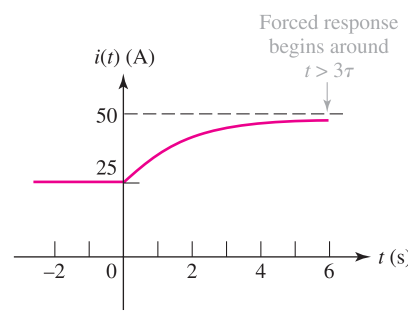
We complete the solution by also stating

$$i = 25 \text{ A} \qquad t < 0$$

or by writing a single expression valid for all t,

$$i = 25 + 25(1 - e^{-0.5t})u(t) \qquad \text{A}$$

The complete response is sketched in Fig. 8.38. Note how the natural response serves to connect the response for $t < 0$ with the constant forced response.



■ FIGURE 8.38 The response $i(t)$ of the circuit shown in Fig. 8.37 is sketched for values of times less and greater than zero.

PRACTICE

8.10 A voltage source, $v_s = 20u(t)$ V, is in series with a 200 Ω resistor and a 4 H inductor. Find the magnitude of the inductor current at t equal to (a) 0^-; (b) 0^+; (c) 8 ms; (d) 15 ms.

Ans: 0; 0; 33.0 mA; 52.8 mA.

As a final example of this method by which the complete response of any circuit subjected to a transient may be written down *almost by inspection,* let us again consider the simple RL series circuit, but subjected to a voltage pulse.

The left curve is drawn for the case where the time constant is only one-half as large as the length of the applied pulse; the rising portion of the exponential has therefore almost reached V_0/R before the decaying exponential begins. The opposite situation is shown to the right; there, the time constant is twice t_0 and the response never has a chance to reach the larger amplitudes.

The procedure we have been using to find the response of an *RL* circuit after dc sources have been switched on or off (or in or out of the circuit) at some instant of time is summarized in the following. We assume that the circuit is reducible to a single equivalent resistance R_{eq} in series with a single equivalent inductance L_{eq} when all independent sources are set equal to zero. The response we seek is represented by $f(t)$.

1. With all independent sources zeroed out, simplify the circuit to determine R_{eq}, L_{eq}, and the time constant $\tau = L_{eq}/R_{eq}$.
2. Viewing L_{eq} as a short circuit, use dc analysis methods to find $i_L(0^-)$, the inductor current just prior to the discontinuity.
3. Again viewing L_{eq} as a short circuit, use dc analysis methods to find the forced response. This is the value approached by $f(t)$ as $t \to \infty$; we represent it by $f(\infty)$.
4. Write the total response as the sum of the forced and natural responses: $f(t) = f(\infty) + Ae^{-t/\tau}$.
5. Find $f(0^+)$ by using the condition that $i_L(0^+) = i_L(0^-)$. If desired, L_{eq} may be replaced by a current source $i_L(0^+)$ [an open circuit if $i_L(0^+) = 0$] for this calculation. With the exception of inductor currents (and capacitor voltages), other currents and voltages in the circuit may change abruptly.
6. $f(0^+) = f(\infty) + A$ and $f(t) = f(\infty) + [f(0^+) - f(\infty)]\, e^{-t/\tau}$, or total response = final value + (initial value − final value) $e^{-t/\tau}$.

PRACTICE

8.11 The circuit shown in Fig. 8.41 has been in the form shown for a very long time. The switch opens at $t = 0$. Find i_R at t equal to (*a*) 0^-; (*b*) 0^+; (*c*) ∞; (*d*) 1.5 ms.

Ans: 0; 10 mA; 4 mA; 5.34 mA.

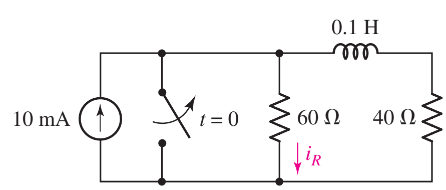


FIGURE 8.41

8.8 DRIVEN *RC* CIRCUITS

The complete response of any *RC* circuit may also be obtained as the sum of the natural and the forced response. Since the procedure is virtually identical to what we have already discussed in detail for *RL* circuits, the best approach at this stage is to illustrate it by working a relevant example completely, where the goal is not just a capacitor-related quantity but the current associated with a resistor as well.

To evaluate A, we need to know $i(0^+)$. This is found by fixing our attention on the energy-storage element (the capacitor). The fact that v_C must remain 100 V during the switching interval is the governing condition which establishes the other currents and voltages at $t = 0^+$. Since $v_C(0^+) = 100$ V, and since the capacitor is in parallel with the 200 Ω resistor, we find $i(0^+) = 0.5$ ampere, $A = 0.4$ ampere, and thus

$$i(t) = 0.1923 \text{ ampere} \qquad t < 0$$

$$i(t) = 0.1 + 0.4e^{-t/1.2} \qquad \text{ampere} \qquad t > 0$$

or

$$i(t) = 0.1923 + (-0.0923 + 0.4e^{-t/1.2})u(t) \qquad \text{amperes}$$

where the last expression is correct for all t.

The complete response for all t may also be written concisely by using $u(-t)$, which is unity for $t < 0$ and 0 for $t > 0$. Thus,

$$i(t) = 0.1923u(-t) + (0.1 + 0.4e^{-t/1.2})u(t) \qquad \text{amperes}$$

This response is sketched in Fig. 8.43*b*. Note that only four numbers are needed to write the functional form of the response for this single-energy-storage-element circuit, or to prepare the sketch: the constant value prior to switching (0.1923 ampere), the instantaneous value just after switching (0.5 ampere), the constant forced response (0.1 ampere), and the time constant (1.2 s). The appropriate negative exponential function is then easily written or drawn.

PRACTICE

8.12 For the circuit of Fig. 8.44, find $v_C(t)$ at t equal to (*a*) 0^-; (*b*) 0^+; (*c*) ∞; (*d*) 0.08 s.

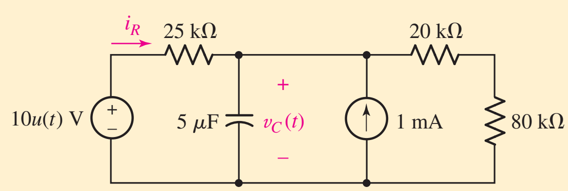


FIGURE 8.44

Ans: 20 V; 20 V; 28 V; 24.4 V.

We conclude by listing the duals of the statements given at the end of Sec. 8.7.

The procedure we have been using to find the response of an *RC* circuit after dc sources have been switched on or off, or in or out of the circuit, at some instant of time, say $t = 0$, is summarized in the following. We assume that the circuit is reducible to a single equivalent resistance R_{eq} in parallel with a single equivalent capacitance C_{eq} when all independent sources are set equal to zero. The response we seek is represented by $f(t)$.

A little rearranging results in

$$\frac{dv}{dt} + 3.092 \times 10^3 v = 72.67 \times 10^3\, e^{-2000t}$$

which, upon comparison with Eqs. [28] and [30], allows us to write the complete response as

$$v(t) = e^{-Pt} \int Qe^{Pt} dt + Ae^{-Pt}$$

where in our case $P = 1/\tau = 3.092 \times 10^3$ and $Q(t) = 72.67 \times 10^3 e^{-2000t}$. We therefore find that

$$v(t) = e^{-3092t} \int 72.67 \times 10^3 e^{-2000t} e^{3092t} dt + Ae^{-3092t} \qquad \text{V}$$

Performing the indicated integration,

$$v(t) = 66.55e^{-2000t} + Ae^{-3092t} \qquad \text{V} \qquad [38]$$

Our only source is controlled by a step function with zero value for $t < 0$, so we know that $v(0^-) = 0$. Since v is a capacitor voltage, $v(0^+) = v(0^-)$, and we therefore find our initial condition $v(0) = 0$ easily enough. Substituting this into Eq. [38], we find $A = -66.55$ V and so

$$v(t) = 66.55(e^{-2000t} - e^{-3092t}) \text{ V} \qquad t > 0$$

PRACTICE

8.13 Determine the capacitor voltage v in the circuit of Fig. 8.46 for $t > 0$.

Ans: $23.5 \cos 3t + 22.8 \times 10^{-3} \sin 3t - 23.5e^{-3092t}$ V.

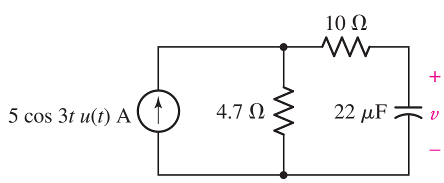


FIGURE 8.46 A simple *RC* circuit driven by a sinusoidal forcing function.

8.9 PREDICTING THE RESPONSE OF SEQUENTIALLY SWITCHED CIRCUITS

In Example 8.9 we briefly considered the response of an *RL* circuit to a pulse waveform, in which a source was effectively switched into and subsequently switched out of the circuit. This type of situation is common in practice, as few circuits are designed to be energized only once (passenger vehicle airbag triggering circuits, for example). In predicting the response of simple *RL* and *RC* circuits subjected to pulses and series of pulses—sometimes referred to as ***sequentially switched circuits***—the key is the relative size of the circuit time constant to the various times that define the pulse sequence. The underlying principle behind the analysis will be whether the energy storage element has time to fully charge before the pulse ends, and whether it has time to fully discharge before the next pulse begins.

Consider the circuit shown in Fig. 8.47*a*, which is connected to a pulsed voltage source described by seven separate parameters defined in Fig. 8.47*b*. The waveform is bounded by two values, **V1** and **V2.** The time t_r required to change from **V1** to **V2** is called the ***rise time (TR),*** and the time t_f required to change from **V2** to **V1** is called the ***fall time (TF).*** The duration W_p of the pulse is referred to as the ***pulse width (PW),*** and the ***period*** T of the waveform **(PER)** is the time it takes for the pulse to repeat. Note also that SPICE allows a time delay **(TD)** before the pulse train