Technology Brief 4: EM Cancer Zappers

From laser eye surgery to 3-D X-ray imaging, EM sources and sensors have been used as medical diagnostic and treatment tools for many decades. Future advances in information processing and other relevant technologies will undoubtedly lead to greater performance and utility of EM devices, as well as to the introduction of entirely new types of devices. This Technology Brief introduces two recent EM technologies that are still in their infancy, but are fast developing into serious techniques for the surgical treatment of cancer tumors.

Microwave Ablation

In medicine, ***ablation*** is defined as the "surgical removal of body tissue," usually through the direct application of chemical or thermal therapies.

► Microwave ablation applies the same heat-conversion process used in a microwave oven (see TB3), but instead of using microwave energy to cook food, it is used instead to destroy cancerous tumors by exposing them to a focused beam of microwaves. ◄

The technique can be used ***percutaneously*** (through the skin), ***laparoscopically*** (via an incision), or ***intraoperatively*** (open surgical access). Guided by an imaging system, such as a CT scanner or an ultrasound imager, the surgeon can localize the tumor and then insert a thin coaxial transmission line (~ 1.5 mm in diameter) directly through the body to position the tip of the transmission line (a probe-like antenna) inside the tumor (**Fig. TF4-1**). The transmission line is connected to a generator capable of delivering 60 W of power at 915 MHz (**Fig. TF4-2**). The rise in temperature of the tumor is related to the amount of microwave energy it receives, which is equal to the product of the generator's power level and the duration of the ablation treatment. Microwave ablation is a promising new technique for the treatment of liver, lung, and adrenal tumors.

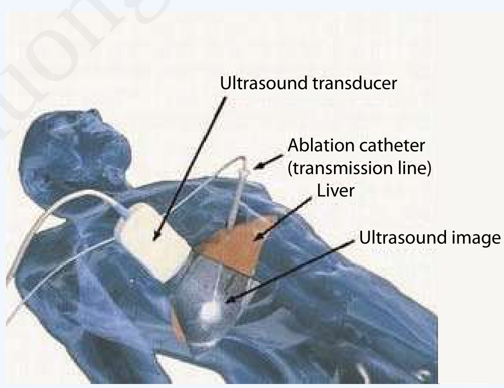


Figure TF4-1 Microwave ablation for liver cancer treatment.

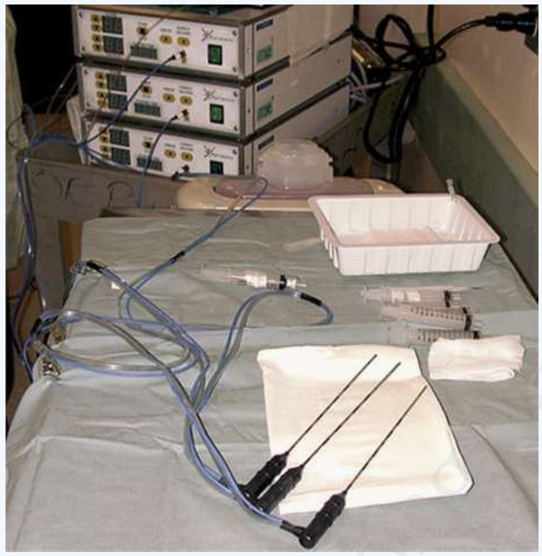


Figure TF4-2 Photograph of the setup for a percutaneous microwave ablation procedure in which three single microwave applicators are connected to three microwave generators.

High-Power Nanosecond Pulses

Bioelectrics is an emerging field focused on the study of how electric fields behave in biological systems. Of particular recent interest is the desire to understand how living cells might respond to the application of extremely short pulses (on the order of nanoseconds (10^{-9} s), and even as short as picoseconds (10^{-12} s)) with exceptionally high voltage and current amplitudes.

► The motivation is to treat cancerous cells by ***zapping*** them with high-power pulses. The pulse power is delivered to the cell via a transmission line, as illustrated by the example in **Fig. TF4-3**. ◄

Note that the pulse is about 200 ns long, and its voltage and current amplitudes are approximately 3,000 V and 60 A, respectively. Thus, the peak power level is about 180,000 W! However, the total energy carried by the pulse is only $(1.8 \times 10^5) \times (2 \times 10^{-7}) = 0.0036$ Joules. Despite the low energy content, the very high voltage appears to be very effective in destroying malignant tumors (in mice, so far), with no regrowth.

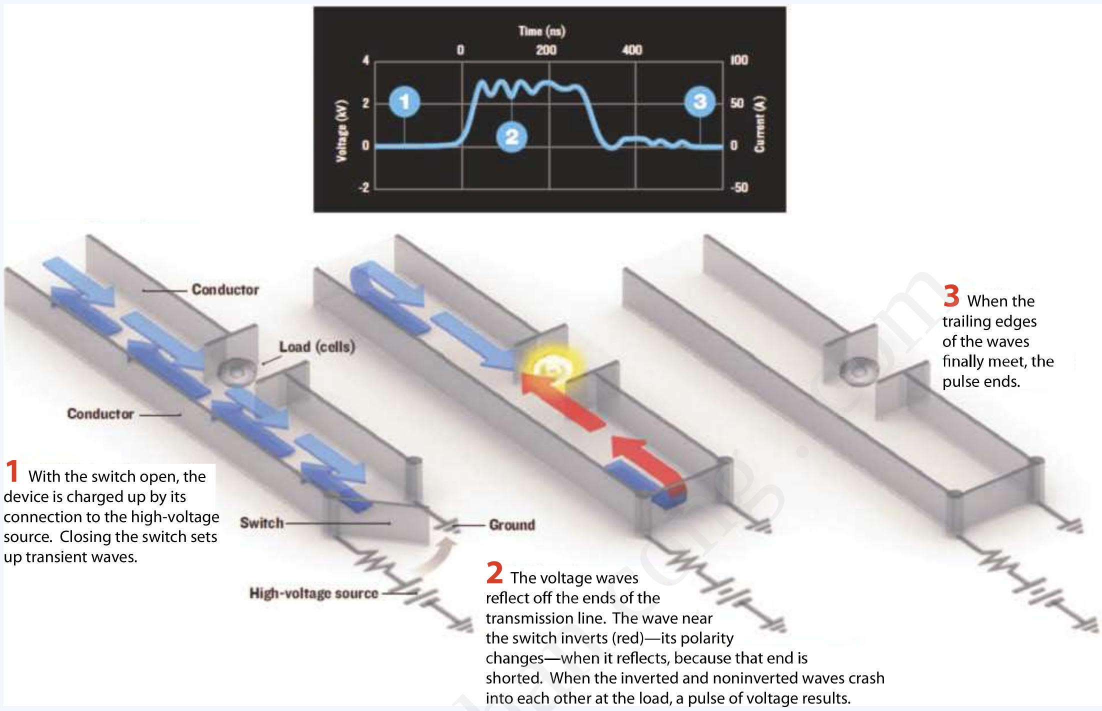


Figure TF4-3 High-voltage nanosecond pulse delivered to tumor cells via a transmission line. The cells to be shocked by the pulse sit in a break in one of the transmission-line conductors.

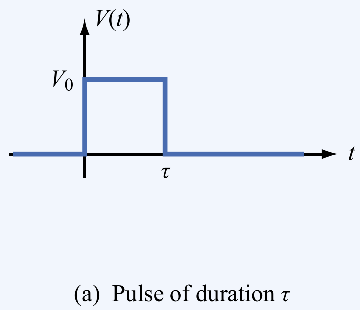


Figure 2-39 A rectangular pulse $V(t)$ of duration τ can be represented as the sum of two step functions of opposite polarities displaced by τ relative to each other.

can be described mathematically as the sum of two unit step functions:

$$V(t) = V_1(t) + V_2(t) = V_0\,u(t) - V_0\,u(t-\tau), \qquad (2.147)$$

where the unit step function $u(x)$ is

$$u(x) = \begin{cases} 1 & \text{for } x > 0, \\ 0 & \text{for } x < 0. \end{cases} \qquad (2.148)$$

The first component, $V_1(t) = V_0\,u(t)$, represents a dc voltage of amplitude V_0 that is switched on at $t = 0$ and retains that value indefinitely, and the second component, $V_2(t) = -V_0\,u(t-\tau)$, represents a dc voltage of amplitude $-V_0$ that is switched on at $t = \tau$ and remains that way indefinitely. As can be seen from **Fig. 2-39(b)**, the sum $V_1(t) + V_2(t)$ is equal to V_0 for $0 < t < \tau$ and equal to zero for $t < 0$ and $t > \tau$. This representation of a pulse in terms of two step functions allows us to analyze the transient behavior of the pulse on a transmission line as the superposition of two dc signals. Hence, if we can develop basic tools for describing the transient behavior of a single step function, we can apply the same tools for each of the two components of the pulse and then add the results to obtain the response to $V(t)$.

2-12.1 Transient Response to a Step Function

The circuit shown in **Fig. 2-40(a)** (page 115) consists of a generator, composed of a dc voltage source V_g and a series resistance R_g, connected to a lossless transmission line of length l and characteristic impedance Z_0. The line is terminated in a purely resistive load R_L at $z = l$.

▶ Note that whereas in previous sections, $z = 0$ was defined as the location of the load, now it is more convenient to define it as the location of the source. ◀

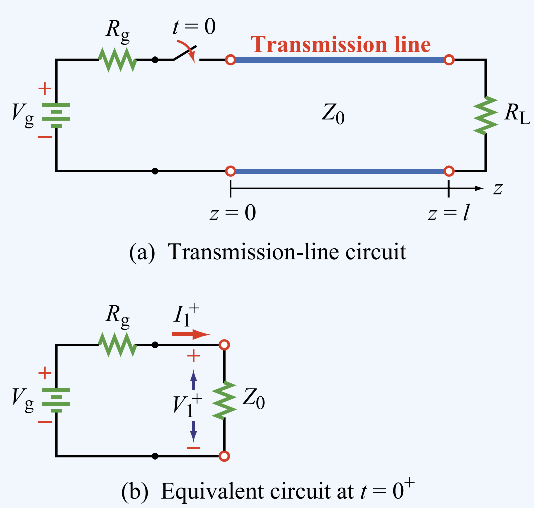


Figure 2-40 At $t = 0^+$, immediately after closing the switch in the circuit in (a), the circuit can be represented by the equivalent circuit in (b).

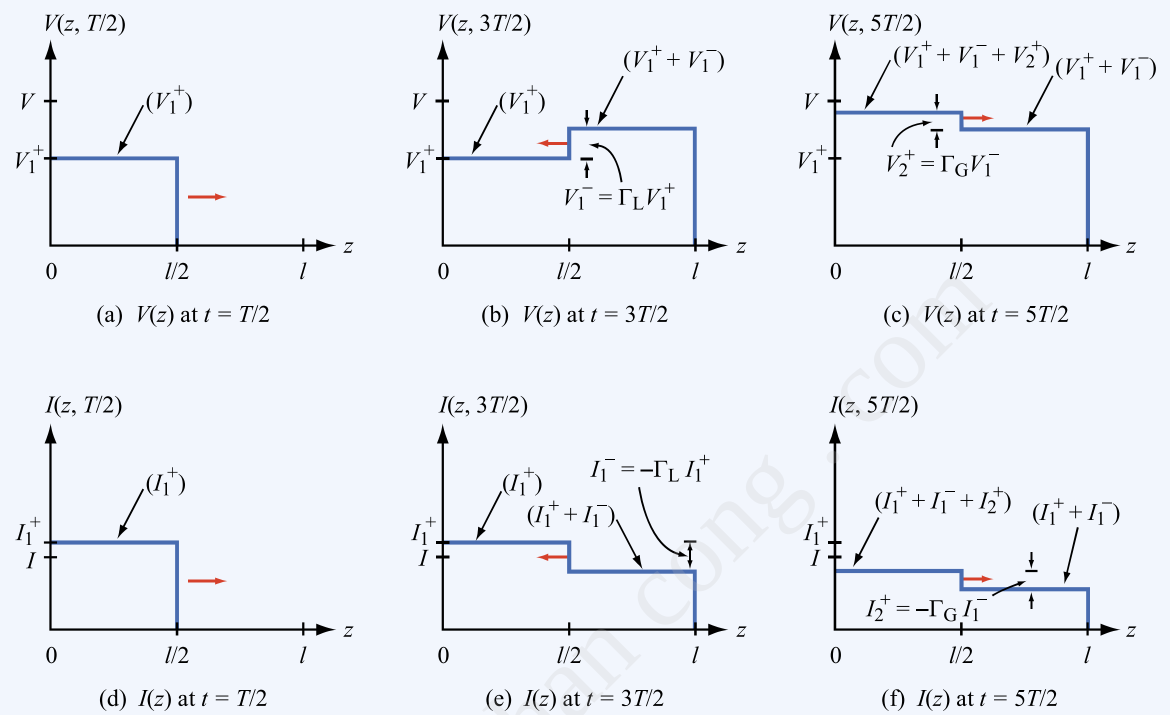


Figure 2-41 Voltage and current distributions on a lossless transmission line at $t = T/2$, $t = 3T/2$, and $t = 5T/2$, due to a unit step voltage applied to a circuit with $R_g = 4Z_0$ and $R_L = 2Z_0$. The corresponding reflection coefficients are $\Gamma_L = 1/3$ and $\Gamma_g = 3/5$.

The switch between the generator circuit and the transmission line is closed at $t = 0$. The instant the switch is closed, the transmission line appears to the generator circuit as a load with impedance Z_0. This is because, in the absence of a signal on the line, the input impedance of the line is unaffected by the load impedance R_L. The circuit representing the ***initial condition*** is shown in **Fig. 2-40(b)**. The ***initial current*** I_1^+ and corresponding ***initial voltage*** V_1^+ at the sending end of the transmission line are given by

$$I_1^+ = \frac{V_g}{R_g + Z_0}\ , \qquad (2.149a)$$

$$V_1^+ = I_1^+ Z_0 = \frac{V_g Z_0}{R_g + Z_0}\ . \qquad (2.149b)$$

The combination of V_1^+ and I_1^+ constitutes a wave that travels along the line with velocity $u_p = 1/\sqrt{\mu\epsilon}$, immediately after the switch is closed. The plus-sign superscript denotes the fact that the wave is traveling in the $+z$ direction. The transient response of the wave is shown in **Fig. 2-41** at each of three instances in time for a circuit with $R_g = 4Z_0$ and $R_L = 2Z_0$. The first response is at time $t_1 = T/2$, where $T = l/u_p$ is the time it takes the wave to travel the full length of the line. By time t_1, the wave has traveled halfway down the line; consequently, the voltage on the first half of the line is equal to V_1^+, while the voltage on the second half is still zero [**Fig. 2-41(a)**]. At $t = T$, the wave reaches the load at $z = l$, and because $R_L \neq Z_0$, the mismatch generates a reflected wave with amplitude

$$V_1^- = \Gamma_L V_1^+, \qquad (2.150)$$

where

$$\Gamma_L = \frac{R_L - Z_0}{R_L + Z_0} \qquad (2.151)$$

is the reflection coefficient of the load. For the specific case illustrated in Fig. 2-41, $R_L = 2Z_0$, which leads to $\Gamma_L = 1/3$. After this first reflection, the voltage on the line consists of the sum of two waves: the initial wave V_1^+ and the reflected wave V_1^-. The voltage on the transmission line at $t_2 = 3T/2$ is shown in Fig. 2-41(b); $V(z, 3T/2)$ equals V_1^+ on the first half of the line $(0 \le z < l/2)$, and $(V_1^+ + V_1^-)$ on the second half $(l/2 \le z \le l)$.

At $t = 2T$, the reflected wave V_1^- arrives at the sending end of the line. If $R_g \ne Z_0$, the mismatch at the sending end generates a reflection at $z = 0$ in the form of a wave with voltage amplitude V_2^+ given by

$$V_2^+ = \Gamma_g V_1^- = \Gamma_g \Gamma_L V_1^+, \tag{2.152}$$

where

$$\Gamma_g = \frac{R_g - Z_0}{R_g + Z_0} \tag{2.153}$$

is the reflection coefficient of the generator resistance R_g. For $R_g = 4Z_0$, we have $\Gamma_g = 0.6$. As time progresses after $t = 2T$, the wave V_2^+ travels down the line toward the load and adds to the previously established voltage on the line. Hence, at $t = 5T/2$, the total voltage on the first half of the line is

$$V(z, 5T/2) = V_1^+ + V_1^- + V_2^+ = (1 + \Gamma_L + \Gamma_L\Gamma_g)V_1^+ \qquad (0 \le z < l/2), \tag{2.154}$$

while on the second half of the line the voltage is only

$$V(z, 5T/2) = V_1^+ + V_1^- = (1 + \Gamma_L)V_1^+ \qquad (l/2 \le z \le l). \tag{2.155}$$

The voltage distribution is shown in Fig. 2-41(c).

So far, we have examined the transient response of the voltage wave $V(z, t)$. The associated transient response of the current $I(z, t)$ is shown in Figs. 2-41(d)–(f). The current behaves similarly to the voltage $V(z, t)$, except for one important difference. Whereas at either end of the line the reflected voltage is related to the incident voltage by the reflection coefficient at that end, the reflected current is related to the incident current by the negative of the reflection coefficient. This property of wave reflection is expressed by Eq. (2.61). Accordingly,

$$I_1^- = -\Gamma_L I_1^+, \tag{2.156a}$$

$$I_2^+ = -\Gamma_g I_1^- = \Gamma_g \Gamma_L I_1^+, \tag{2.156b}$$

and so on.

▶ The multiple-reflection process continues indefinitely, and the ultimate value that $V(z, t)$ reaches as t approaches $+\infty$ is the same at all locations on the transmission line. ◀

It is given by

$$\begin{aligned} V_\infty &= V_1^+ + V_1^- + V_2^+ + V_2^- + V_3^+ + V_3^- + \cdots \\ &= V_1^+[1 + \Gamma_L + \Gamma_L\Gamma_g + \Gamma_L^2\Gamma_g + \Gamma_L^2\Gamma_g^2 + \Gamma_L^3\Gamma_g^2 + \cdots] \\ &= V_1^+[(1 + \Gamma_L)(1 + \Gamma_L\Gamma_g + \Gamma_L^2\Gamma_g^2 + \cdots)] \\ &= V_1^+(1 + \Gamma_L)[1 + x + x^2 + \cdots], \end{aligned} \tag{2.157}$$

where $x = \Gamma_L\Gamma_g$. The series inside the square bracket is the geometric series of the function

$$\frac{1}{1 - x} = 1 + x + x^2 + \cdots \qquad \text{for } |x| < 1. \tag{2.158}$$

Hence, Eq. (2.157) can be rewritten in the compact form

$$V_\infty = V_1^+ \frac{1 + \Gamma_L}{1 - \Gamma_L\Gamma_g}. \tag{2.159}$$

Upon replacing V_1^+, Γ_L, and Γ_g with Eqs. (2.149b), (2.151), and (2.153), and simplifying the resulting expression, we obtain

$$V_\infty = \frac{V_g R_L}{R_g + R_L}. \tag{2.160}$$

The voltage V_∞ is called the ***steady-state voltage*** on the line, and its expression is exactly what we should expect on the basis of dc analysis of the circuit in Fig. 2-40(a), wherein we treat the transmission line as simply a connecting wire between the generator circuit and the load. The corresponding ***steady-state current*** is

$$I_\infty = \frac{V_\infty}{R_L} = \frac{V_g}{R_g + R_L}. \tag{2.161}$$

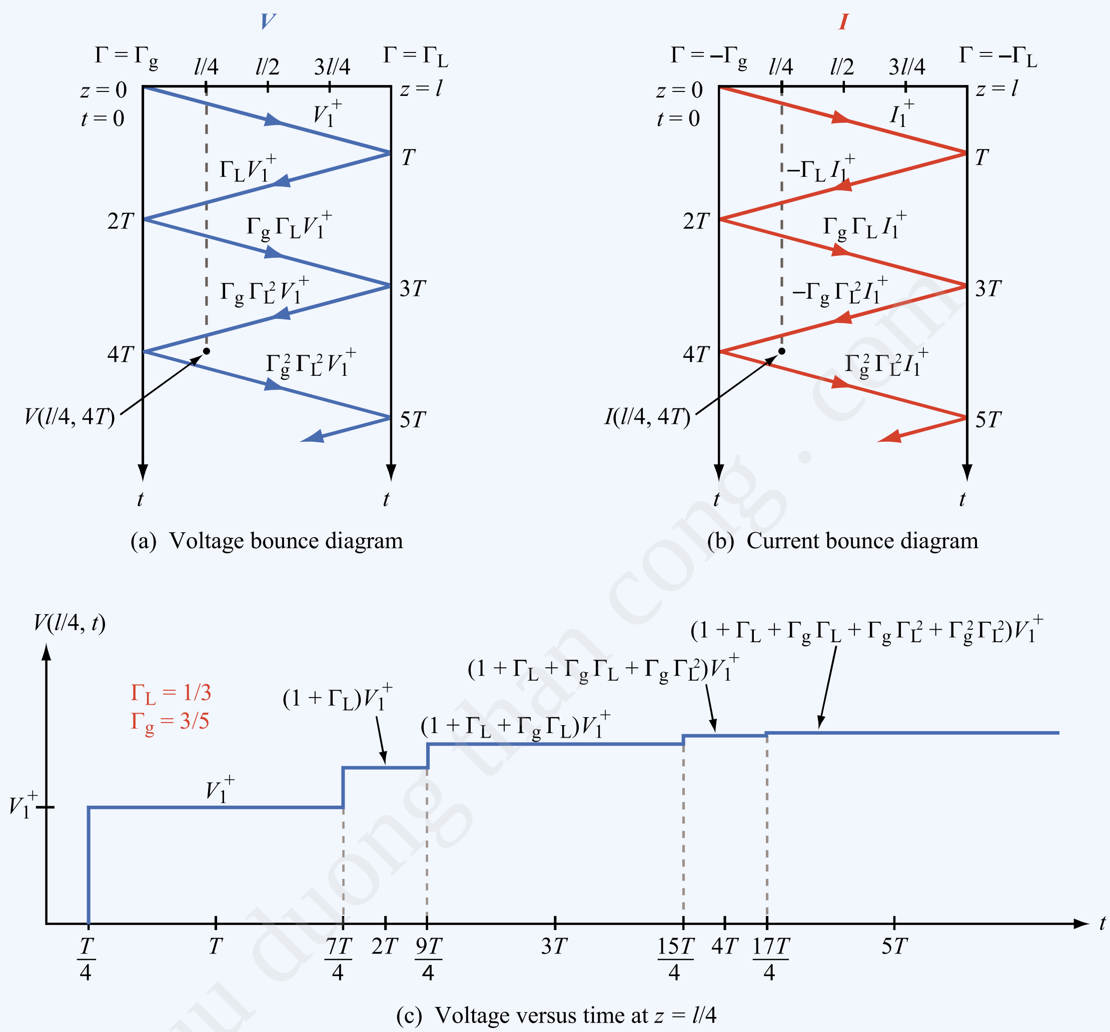


Figure 2-42 Bounce diagrams for (a) voltage and (b) current. In (c), the voltage variation with time at $z = l/4$ for a circuit with $\Gamma_g = 3/5$ and $\Gamma_L = 1/3$ is deduced from the vertical dashed line at $l/4$ in (a).

2-12.2 Bounce Diagrams

Keeping track of the voltage and current waves as they bounce back and forth on the line is a rather tedious process. The ***bounce diagram*** is a graphical presentation that allows us to accomplish the same goal, but with relative ease. The horizontal axes in **Figs. 2-42(a)** and **(b)** represent position along the transmission line, while the vertical axes denote time. **Figures 2-42(a)** and **(b)** pertain to $V(z, t)$ and $I(z, t)$, respectively. The bounce diagram in **Fig. 2-42(a)** consists of a zigzag line indicating the progress of the voltage wave on the line. The incident wave V_1^+ starts at $z = t = 0$ and travels in the $+z$ direction until it reaches the load at $z = l$ at time $t = T$. At the very top of the bounce diagram, the reflection coefficients are indicated by $\Gamma = \Gamma_g$ at the generator end and by $\Gamma = \Gamma_L$ at the load end. At the end of the first straight-line segment of the zigzag line, a second line is drawn to represent the reflected voltage wave $V_1^- = \Gamma_L V_1^+$. The amplitude of each new straight-line segment equals the product of the amplitude of the preceding straight-line segment and the reflection coefficient at that end of the line. The bounce diagram for the current $I(z, t)$ in **Fig. 2-42(b)** adheres to the same principle except for the reversal of the signs of Γ_L and Γ_g at the top of the bounce diagram.

Using the bounce diagram, the total voltage (or current) at any point z_1 and time t_1 can be determined by drawing a vertical line through point z_1, then adding the voltages (or currents) of all the zigzag segments intersected by that line between $t = 0$ and $t = t_1$. To find the voltage at $z = l/4$ and $T = 4T$, for example, we draw a dashed vertical line in **Fig. 2-42(a)** through $z = l/4$ and we extend it from $t = 0$ to $t = 4T$. The dashed line intersects four line segments. The total voltage at $z = l/4$ and $t = 4T$ therefore is

$$V(l/4, 4T) = V_1^+ + \Gamma_L V_1^+ + \Gamma_g \Gamma_L V_1^+ + \Gamma_g \Gamma_L^2 V_1^+$$
$$= V_1^+ (1 + \Gamma_L + \Gamma_g \Gamma_L + \Gamma_g \Gamma_L^2).$$

The time variation of $V(z, t)$ at a specific location z can be obtained by plotting the values of $V(z, t)$ along the (dashed) vertical line passing through z. **Figure 2-42(c)** shows the variation of V as a function of time at $z = l/4$ for a circuit with $\Gamma_g = 3/5$ and $\Gamma_L = 1/3$.

Example 2-15: Pulse Propagation

The transmission-line circuit of **Fig. 2-43(a)** is excited by a rectangular pulse of duration $\tau = 1$ ns that starts at $t = 0$. Establish the waveform of the voltage response at the load, given that the pulse amplitude is 5 V, the phase velocity is c, and the length of the line is 0.6 m.

Solution: The one-way propagation time is

$$T = \frac{l}{c} = \frac{0.6}{3 \times 10^8} = 2 \text{ ns}.$$

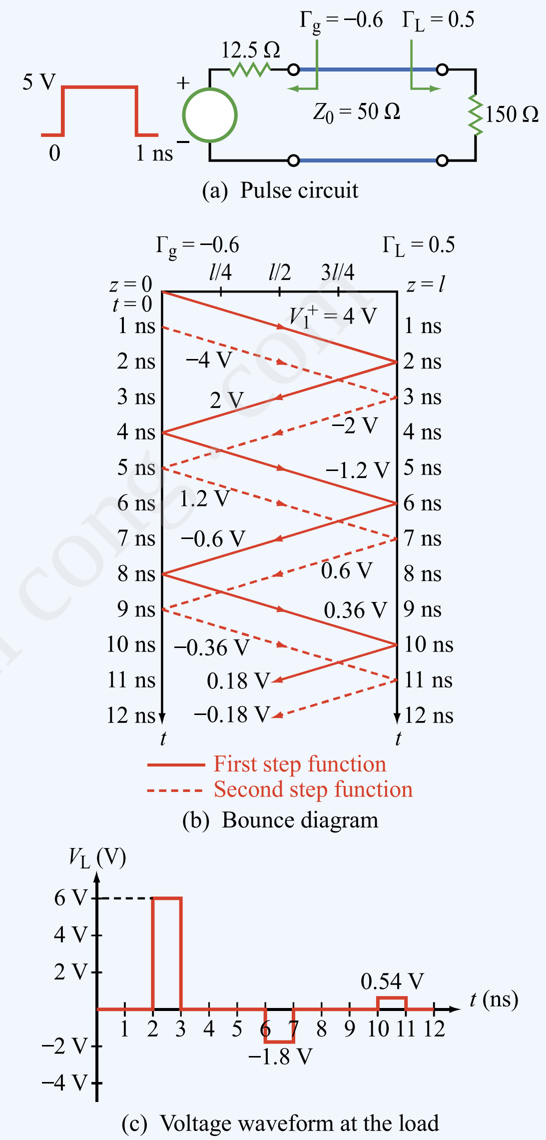


Figure 2-43 Example 2-15.

The reflection coefficients at the load and the sending end are

$$\Gamma_L = \frac{R_L - Z_0}{R_L + Z_0} = \frac{150 - 50}{150 + 50} = 0.5,$$

$$\Gamma_g = \frac{R_g - Z_0}{R_g + Z_0} = \frac{12.5 - 50}{12.5 + 50} = -0.6.$$

By Eq. (2.147), the pulse is treated as the sum of two step functions, one that starts at $t = 0$ with an amplitude $V_{10} = 5$ V and a second one that starts at $t = 1$ ns with an amplitude $V_{20} = -5$ V. Except for the time delay of 1 ns and the sign reversal of all voltage values, the two step functions generate identical bounce diagrams, as shown in **Fig. 2-43(b)**. For the first step function, the initial voltage is given by

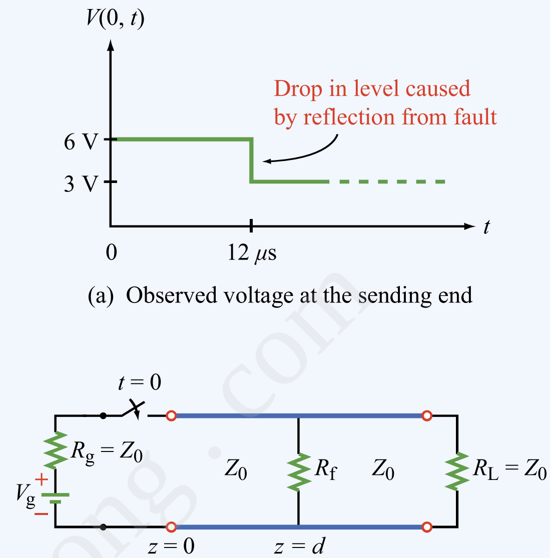
$$V_1^+ = \frac{V_{01} Z_0}{R_g + Z_0} = \frac{5 \times 50}{12.5 + 50} = 4 \text{ V}.$$

Using the information displayed in the bounce diagram, it is straightforward to generate the voltage response shown in **Fig. 2-43(c)**.

Example 2-16: Time-Domain Reflectometer

A time-domain reflectometer (TDR) is an instrument used to locate faults on a transmission line. Consider, for example, a long underground or undersea cable that gets damaged at some distance d from the sending end of the line. The damage may alter the electrical properties or the shape of the cable, causing it to exhibit at the fault location an impedance R_{Lf}. A TDR sends a step voltage down the line, and by observing the voltage at the sending end as a function of time, it is possible to determine the location of the fault and its severity.

If the voltage waveform shown in **Fig. 2-44(a)** is seen on an oscilloscope connected to the input of a 75 Ω matched transmission line, determine (a) the generator voltage, (b) the location of the fault, and (c) the fault shunt resistance. The line's insulating material is Teflon with $\epsilon_r = 2.1$.



(a) Observed voltage at the sending end

(b) The fault at $z = d$ is represented by a fault resistance R_f

Figure 2-44 Time-domain reflectometer of Example 2-16.

Solution: **(a)** Since the line is properly matched, $R_g = R_L = Z_0$. In **Fig. 2-44(b)**, the fault located a distance d from the sending end is represented by a shunt resistance R_f. For a matched line, Eq. (2.149b) gives

$$V_1^+ = \frac{V_g Z_0}{R_g + Z_0} = \frac{V_g Z_0}{2Z_0} = \frac{V_g}{2}.$$

According to **Fig. 2-44(a)**, $V_1^+ = 6$ V. Hence,

$$V_g = 2V_1^+ = 12 \text{ V}.$$

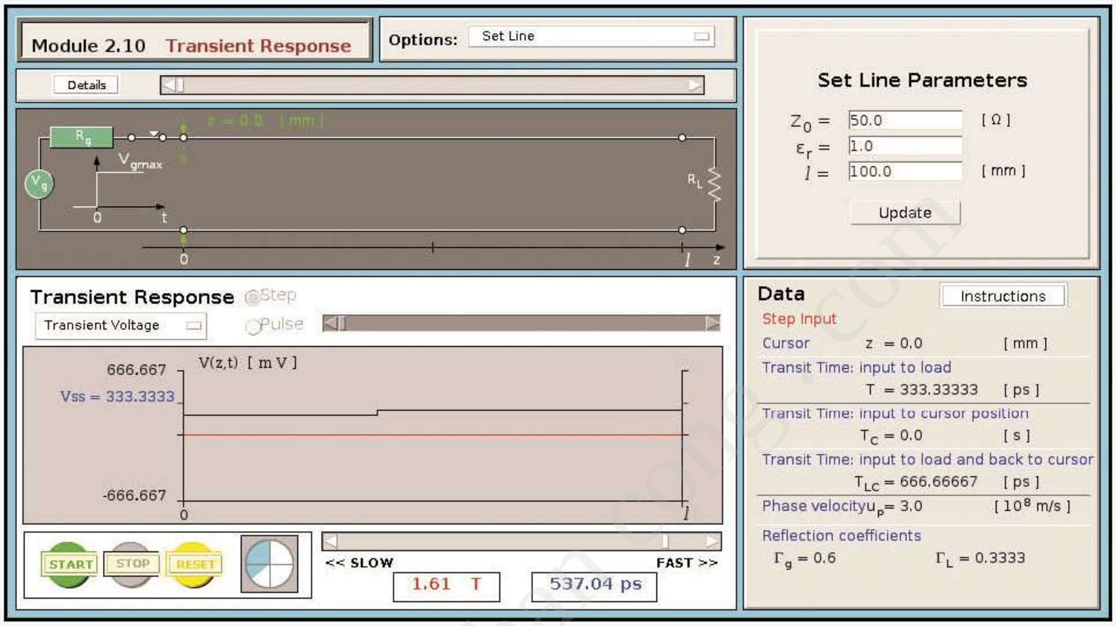
(b) The propagation velocity on the line is

$$u_p = \frac{c}{\sqrt{\epsilon_r}} = \frac{3 \times 10^8}{\sqrt{2.1}} = 2.07 \times 10^8 \text{ m/s}.$$

For a fault at a distance d, the round-trip time delay of the echo is

$$\Delta t = \frac{2d}{u_p}.$$

Module 2.10 Transient Response For a lossless line terminated in a resistive load, the module simulates the dynamic response, at any location on the line, to either a step or pulse waveform sent by the generator.



From **Fig. 2-44(a)**, $\Delta t = 12\ \mu$s. Hence,

$$d = \frac{\Delta t}{2}\, u_{\text{p}} = \frac{12 \times 10^{-6}}{2} \times 2.07 \times 10^{8} = 1,242 \text{ m}.$$

(c) The change in level of $V(0,t)$ shown in **Fig. 2-44(a)** represents V_1^-. Thus,

$$V_1^- = \Gamma_{\text{f}} V_1^+ = -3 \text{ V},$$

or

$$\Gamma_{\text{f}} = \frac{-3}{6} = -0.5,$$

where Γ_{f} is the reflection coefficient due to the fault load R_{Lf} that appears at $z = d$.

From Eq. (2.59),

$$\Gamma_{\text{f}} = \frac{R_{\text{Lf}} - Z_0}{R_{\text{Lf}} + Z_0},$$

which leads to $R_{\text{Lf}} = 25\ \Omega$. This fault load is composed of the fault shunt resistance R_{f} and the characteristic impedance Z_0 of the line to the right of the fault:

$$\frac{1}{R_{\text{Lf}}} = \frac{1}{R_{\text{f}}} + \frac{1}{Z_0},$$

so the shunt resistance must be 37.5 Ω.

Concept Question 2-27: What is transient analysis used for?

Concept Question 2-28: The transient analysis presented in this section was for a step voltage. How does one use it for analyzing the response to a pulse?

Concept Question 2-29: What is the difference between the bounce diagram for voltage and the bounce diagram for current?