CHAPTER ONE

ELECTRONIC SYSTEMS: A CENTURY OF PROGRESS

Our daily lives are shaped by electronic systems. In the home we have a myriad of electronic accessories: radios, TVs, VCRs, hi-fis, camcorders, cassette and CD players, telephone answering machines, microwave ovens, and personal computers. Not so obvious but just as much a part of our lives are sophisticated electronic controls such as the microprocessor engine control of our car. We utilize a telephone system that functions with electronic devices to amplify and transfer telephone signals. Our conversations are carried around the world using a combination of microwave or fiber-optic links and satellites. Electronic radar systems are relied on for a safe flight from one airport to the next, and electronic sensors and computers "fly" a modern jet airplane. Modern medical practice depends on extremely complex diagnostic and monitoring electronic systems. Moreover, the commercial and industrial sectors could no longer function without electronic communications and information processing systems. The video monitor is a pervasive reminder of the new electronic world.

For better and at times for worse, electronics has changed our lives. Although we are in constant touch with what is happening around the world, we are also at the peril of weapons of unimaginable destructive power that rely on electronic developments. An understanding of electronics is imperative not only for designing and using electronic systems but for directing the evolution of electronic systems so that they serve to improve the human condition.

It has been stated that to move forward we must know where we have been. The 20th century is the era of electronics – it was only after 1900 that the devices we now describe as electronic appeared. The use of the term *electronics* in the current sense did not occur until 1930 (Süsskind 1966). This introductory chapter starts with a very brief overview of electronic devices and is followed by a discussion of wireless systems: radio. The first application of electronic devices, the vacuum tube diode invented in 1904 and the triode invented in 1906, was for radio receivers. Radio communications was not only nearly a decade old at the time the tube was invented, but most of the systems of the first decade of the 1900s did not use tubes. The vacuum tube, without

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exaggeration, can be described as having revolutionized radio communications, resulting in the generation of coherent transmitting signals and highly sensitive and selective receivers. The vacuum tube, following its first telephone use in 1913, also became an important component of telephone systems. With vacuum tube amplifiers and multiplexing circuits, long-distance telephone service greatly expanded. With the development of digital systems made possible by the transistor and integrated circuits in the latter half of the 20th century, telephone switching and transmission systems were again significantly improved.

The development of electronic devices, on the one hand, depended on a knowledge of basic physical principles: the behavior of electrons in a vacuum and the interaction of electrons with matter. On the other hand, electron devices were frequently developed to fulfill perceived needs. The characteristics of electronic devices dictated those applications that could be realized. Television, discussed in Section 1.4, illustrates the interrelatedness of the development of electronic devices and circuits with a particular application. An analog television system was developed in the 1930s and was commercially introduced in the late 1940s. Over the rest of the 20th century, television was based on this analog system, and the only enhancement was the introduction of a subcarrier for color information. At the close of the 20th century, a digital system, totally different, and therefore incompatible with the analog system, was developed. Although this digital system, from a transmission perspective, is considerably more efficient, the signal processing required is very complex. Without the development of very-large-scale integrated (VLSI) circuits during the 1980s that could do the encoding and decoding, digital TV would not have been possible.

The electromagnetic spectrum (Section 1.5) is used for a variety of radio, TV, and other communications services. Although early radar systems can be traced back to the 1930s, it was the impetus of World War II that resulted in a rapid development of this technology. New electronic devices capable of transmitting and detecting extremely high-frequency signals ($f > 1000$ MHz) were invented. Communications satellites, first launched in the 1960s, also relied on these extremely high-frequency (microwave) devices.

Digital electronic circuits have revolutionized computing. Early computers, until about the mid-1960s, relied on vacuum tube circuits. These computers, from today's perspective, not only had minuscule processing capabilities, but, owing to the limited reliability of vacuum tubes, were frequently down. Solid-state devices resulted not only in a tremendous improvement in reliability but made possible machines with much greater computing capabilities. With ultra-large-scale integrated circuits, desktop computers emerged with a computing capability that a decade earlier was available only in large mainframe machines.

Needless to say, electronic devices and circuits have become common for many applications in addition to those discussed. Power electronics is dependent on electronic switching devices and circuits. Frequency and voltage transformations, as well as alternating-to-direct-current and direct-to-alternating-current conversions can often be efficiently achieved using electronic systems. In medical electronics, a variety of electronic sensing circuits have been developed along with computer systems to process and display the data. Furthermore, electronic systems, such as heart pacemakers, have been perfected to augment body functions. Electronic sensing and control systems dependent on simple microprocessors are now used in applications ranging from programmable thermostats to automobile ignition and fuel systems. More complex sensing and control systems involving large computing capabilities are used for automated manufacturing systems. Although it is beyond this introductory chapter to discuss these and other applications, it should be recognized that similar electronic devices and circuits are often used by these different systems. A knowledge of basic concepts, the subject of this text, is a prerequisite for understanding both the simplest and the most esoteric of electronic systems.

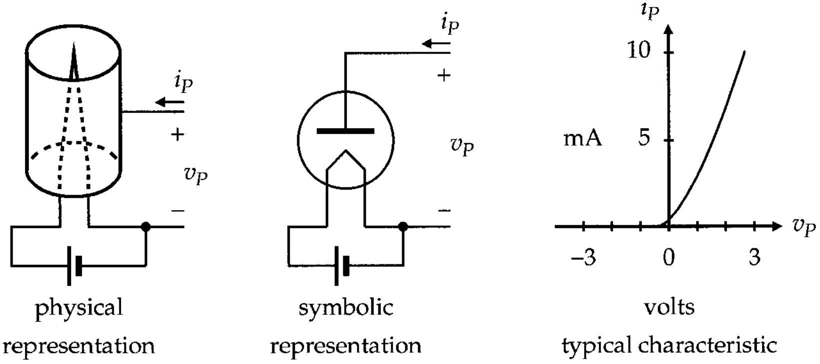
1.1 ELECTRONIC DEVICES: AN OVERVIEW

The thermionic valve or vacuum tube was developed in Great Britain by Sir John Ambrose Fleming (Pierce 1950; Shiers 1969). This tube relied on what is known as the *Edison effect*, a current being produced by the hot filament of a light bulb. Fleming, through a series of experiments with bulbs having an electrode near the hot filament, deduced that this current was due to negative electric charges. We now understand the current to be due to electrons emitted by the hot filament that are collected by the electrode. To the extent that only electrons are responsible for this current, the current to the electrode is only in one direction; in a high-vacuum tube, a current corresponding to the movement of positive charges does not occur.

THE DIODE

Fleming's valve consisted of a hot filament (corresponding to the incandescent filament of a light bulb) heated by a current produced by an external battery. The emitted electrons were then collected by a plate surrounding the filament (Figure 1.1). Even though the physical current is that due to electrons traveling from the filament to the plate, the plate current i_P, is, by convention, a positive quantity because a current is defined in terms of the movement of hypothetical positive charges. A positive plate voltage v_P attracts electrons, thus increasing the current, whereas a negative plate voltage repels electrons, yielding either

Figure 1.1: Vacuum tube diode and typical characteristic.



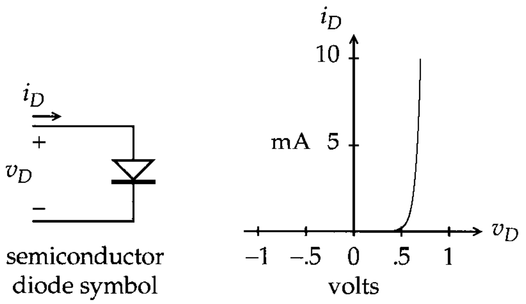


Figure 1.2: Semiconductor diode and a typical characteristic.

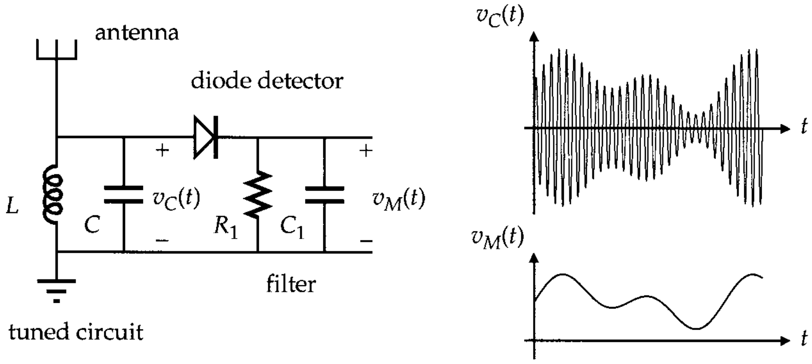
a very small or zero current. This nonlinear effect results in a current in only one direction ($i_P \geq 0$). For significant negative voltages, the current of a well-evacuated tube is essentially zero.

At about the same time that Fleming introduced his vacuum tube, Greenleaf W. Pickard was experimenting with a point-contact semiconductor detector (Douglas 1981). This device may be considered the precursor of modern solid-state devices. In addition to the detector using silicon developed by Pickard, a similar detector using Carborundum was developed by Henry H. C. Dunwoody in 1906. Point-contact diodes were extensively used until the junction semiconductor diode was introduced in the 1950s.

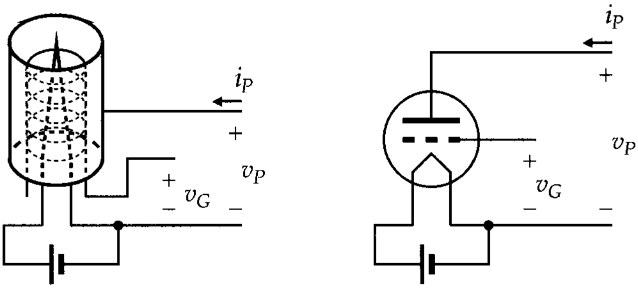
A semiconductor diode has a nonlinear characteristic, as does the vacuum tube (Figure 1.2). The current of the diode i_D increases very rapidly with diode voltage v_D (for an ideal semiconductor diode it may be shown that the current has an exponential dependence on the diode voltage). The rectification property of a diode, which allows a current in only one direction, was first used for the detection of radio signals. The detection problem provided the impetus for the development of vacuum tube and semiconductor diodes. Represented in Figure 1.3 is a basic radio receiver with a typical amplitude-modulated carrier signal. Although carrier frequencies of 50 to 100 kHz were common for early communications systems, the present radio broadcast band consists of signals with carrier frequencies of 540 to 1600 kHz. For an *on–off* system (continuous wave or CW), the carrier is simply keyed on and off to form a pattern of dots and dashes. However, for amplitude modulation (AM), the amplitude of the carrier signal is varied in accordance with the modulating signal; for example, that of a voice signal produced with a microphone.

It should be noted that the period corresponding to the carrier frequency is generally much smaller than that associated with the time scale over which appreciable variations in the modulating signal occur. In a radio receiver, the

Figure 1.3: An elementary diode radio detector.



energy received by the antenna is coupled to the tuned circuit which, ideally, excludes all other signals with different carrier frequencies. A diode rectifier is then used to convert the carrier signal $v_C(t)$ to a signal with a single polarity. For the circuit shown, the capacitor C_1 tends to smooth the detected signal. Without the capacitor, a signal similar to the top half of $v_C(t)$ would result.



physical representation symbolic representation

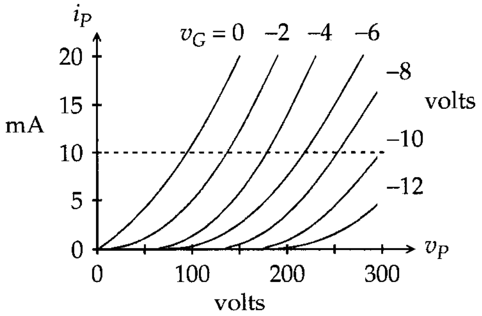
Figure 1.4: A triode vacuum tube.

THE VACUUM TRIODE

The next significant development that, in effect, ushered in the electronics age, was Lee De Forest's addition of a control electrode or grid to Fleming's vacuum diode. This resulted in the triode vacuum tube. A sketch of the physical device, which is referred to as a triode because it has three elements, is presented in Figure 1.4. The third element, the grid, is a cagelike wire structure surrounding the filament of the tube. An externally applied grid potential regulates the plate current of the tube.

For normal operation, the grid is at a negative potential (relative to that of the filament), which tends to repel electrons emitted by the hot filament. The more negative the grid potential v_G, the smaller the plate current i_P for a given plate voltage v_P (Figure 1.5). Because electrons are repelled by a negative grid potential, the grid current is essentially zero. (The exceedingly small grid current that does occur is due to positive ions produced by ionizing electron collisions with the air molecules of the imperfect vacuum. Although the grid current of De Forest's early tube may have been significant, those of later tubes with good vacuums were truly negligible.) As a result of this essentially zero grid current, the power utilized by the grid circuit is extremely close to zero. Herein lies the worth of the triode vacuum tube. Its plate current and voltage are not only controlled by the grid voltage, but essentially zero power is required to do the controlling. It is not a perpetual-motion device (a power source is required for the plate circuit) but, for many applications, it is the next best thing!

Figure 1.5: The plate characteristic of a typical triode vacuum tube.



To illustrate the utility of a vacuum tube triode, consider the typical characteristic of Figure 1.5 and suppose that a constant current source of 10 mA is connected between the filament and plate of the tube ($i_P = 10$ mA). For a particular value of grid voltage, the resultant plate voltage corresponds to the intersection of the curve corresponding to that grid voltage with the 10-mA coordinate (shown as a

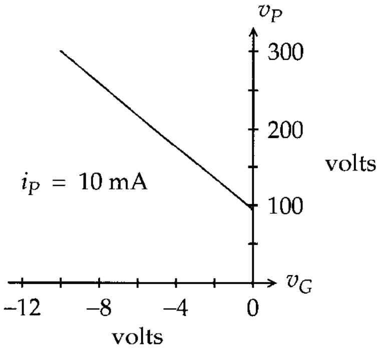


Figure 1.6: The transfer characteristic of the triode of Figure 1.5.

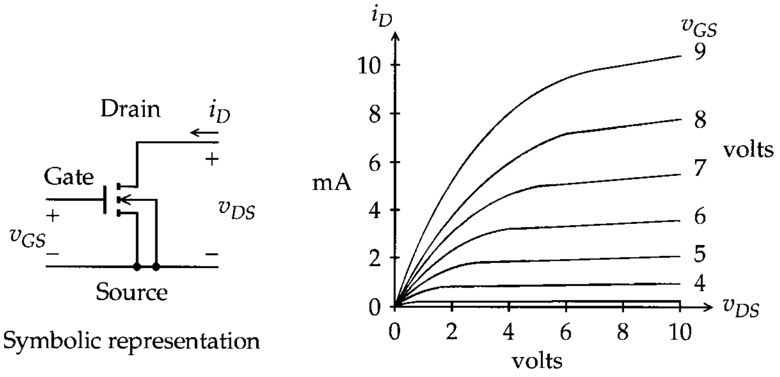
dashed line in Figure 1.5). A grid voltage of −4 V, for example, results in a plate voltage of 180 V; a grid voltage of −6 V in a plate voltage of 220 V, and so forth. The transfer characteristic of Figure 1.6 is thus obtained. Of particular importance is that a relatively small change in grid voltage results in a fairly large change in plate voltage. The slope of the characteristic of Figure 1.6 is approximately −20. This implies that a 1-V change in v_G results in a change of −20 V in v_P. The minus sign signifies that an increase in v_G results in a decrease in v_P. This circuit therefore has a voltage gain with a magnitude of approximately 20.

The first triode vacuum tube of De Forest was used to detect radio signals (in place of the diode of Figure 1.3); it was initially described as an oscillation valve. However, because vacuum tube triodes have the ability to amplify as well as to detect radio signals, tubes were soon used for a multitude of applications, including the generation of high-frequency radio signals.

THE TRANSISTOR AND INTEGRATED CIRCUITS

Solid-state devices, transistors, have replaced vacuum tubes for most, but not all, electronic applications. The symbolic representation and typical characteristic of a modern metal-oxide semiconductor field-effect transistor (MOSFET) are given in Figure 1.7. For the device shown, free electrons from the source of the MOSFET semiconductor device flow to its drain. In a manner analogous to that of the grid of the vacuum tube, the free-electron current is controlled by the gate potential of the MOSFET device. The gate current, like the grid current of a triode, is essentially zero. The free electrons, however, are produced by a doped semiconductor rather than by a hot filament, thus resulting in a much more efficient device. Furthermore, the voltage levels required for a typical MOSFET application are considerably smaller than those of a typical triode vacuum tube circuit.

Figure 1.7: The metal-oxide semiconductor field-effect transistor (MOSFET).



Symbolic representation

In addition to MOSFET devices, the bipolar junction transistor (BJT) is also extensively used in modern electronic circuits. Germanium bipolar junction transistors were developed shortly after the invention of the point-contact transistor in 1948. With the development of silicon processing techniques during the 1950s, germanium and silicon transistors tended to replace vacuum tubes for most applications by the 1960s. It was, however, the introduction of the integrated circuit, a single semiconductor wafer initially limited to a few tens of transistors, that has had the most profound effect on electronic systems. This effect has been characterized by some as revolutionary (Noyce 1977).

Vacuum tubes generally consisted of only one, two, or possibly three electronic devices enclosed by a single glass envelope. These tube circuits were generally mounted on a metal chassis that had sockets relying on spring contacts to hold the vacuum tubes. This permitted vacuum tubes to be readily replaced – an all-too-frequent need. Connections between the sockets and other components were achieved through hand-soldered wires. Small components, such as resistors and capacitors, were often supported directly by their leads while forming connections between components.

Even the earliest commercially produced transistors, introduced during the 1950s, were considerably more reliable than the vacuum tubes they replaced. Hence, transistors could be wired directly into a circuit, thereby eliminating the need for sockets. This led to the printed circuit board utilizing copper foil conductors bonded to a phenolic base. Transistors, as well as other components, were mounted directly on the printed circuit board, and a dip-type soldering process was used for electrical connections to the copper foil. Because transistors are much smaller than vacuum tubes and tend to dissipate considerably less power, a much higher density of components was possible.

A batch process was soon developed in which several transistors were simultaneously fabricated on a single semiconductor wafer. The wafer was then cut to obtain individual transistors, leads were attached, and the transistors were encapsulated in a package suitable for their application. During the assembly process, individual transistors were tested, and faulty ones were discarded. With the improvement of processing techniques, the yield of well-functioning devices greatly increased.

In retrospect, it now seems obvious to question why the individual transistors of a semiconductor wafer were separated. Why not develop a process for electrically isolating the devices from each other to replace the isolation that had been achieved by cutting them apart? The devices could then be interconnected on the semiconductor wafer to form what we now refer to as an integrated circuit. At the end of the 1950s, this idea was realized (Meindl 1977). As is often the case, several individuals working independently were involved in developing the earliest integrated circuits. However, Jack Kilby is frequently credited with having "invented" the integrated circuit (Kilby 1976). In 1958, he demonstrated a hand-fabricated phase-shift oscillator and a flip-flop using germanium transistors. Resistors consisted of appropriately doped semiconductors, whereas capacitors utilized reverse-biased semiconductor junctions. These demonstration circuits established the feasibility of a concept that was rapidly exploited.

1.2 WIRELESS COMMUNICATION: A NEW ERA

The first use of the triode vacuum tube was for wireless communication. Lee De Forest, its inventor, described the tube as an oscillation valve – that is a device for detecting wireless or radio signals. (As an aside, it should be noted that Lee De Forest's autobiography has the subtitle of *Father of Radio*. This parentage is not widely accepted.) A close relationship of electronic devices to radio characterized the first half of the 20th century. The related professional organization in the United States was the Institute of Radio Engineers founded in 1912. It was not until 1963 that the designation "radio" was dropped when this organization merged with the Institute of Electrical Engineers to form the Institute of Electrical and Electronic Engineers (IEEE).

Maxwell's equations, the kernel of electromagnetic theory, provide the basis on which wireless communication, that is radio, is based. James Clerk Maxwell built on the work of Coulomb, Oersted, Ampère, Henry, Faraday, and Gauss in formulating these now well-known equations. Through a series of experimental observations and theoretical deductions, Heinrich Rudolf Hertz demonstrated the validity of Maxwell's equations. Hertz published the first text on electrodynamics in 1892 *Untersuchungen über die Ausbreitung der elektrischen Kraft* (*Electric Waves*, the title of an English translation by D. E. Jones). Following the death of Hertz in 1894, the lectures on the studies of Hertz by Oliver Joseph Lodge laid the groundwork for a much wider understanding of electromagnetic principles. Lodge and Ferdinand Braun were responsible for developing the concept of resonant tuning and demonstrating the importance of having the transmitter and receiver of a system tuned to the same frequency (Aitken 1976, Jolly 1975, Kurylo and Süsskind 1981, McNicol 1946). Concurrently, Oliver Heaviside is credited with putting Maxwell's equations into their presently utilized form (Nahin 1988, 1990).

A difficulty encountered in performing early electromagnetic experiments was that of obtaining a suitable detector of high-frequency signals. An early detector was the coherer, basically a small glass tube filled with loosely packed metal filings. The operation of this device relied on the nonlinear nature of the resistance of the filings. For small currents the filings had a high resistance, whereas for larger currents the filings tended to cohere, resulting in a small resistance. A mechanical tapping of the coherer was necessary to restore the high resistance after the termination of a large current. For a receiver, the alternating current produced by an electromagnetic signal caused the filings to cohere. This effect was detected by a low-voltage direct-current circuit connected to the coherer. Edouard Branly developed several different coherers and appears to have been the first to use the term radio (in this context) by proposing the name *radioconductor* for the coherer.

It was Guglielmo Marconi who in 1895 refined and assembled the appropriate apparatus and demonstrated that it could be used for signaling (Jolly 1972, Masini 1995). Not being successful in interesting his Italian government in this new means of communication, he traveled to England, where the British post office was receptive. Recognizing the commercial importance of wireless

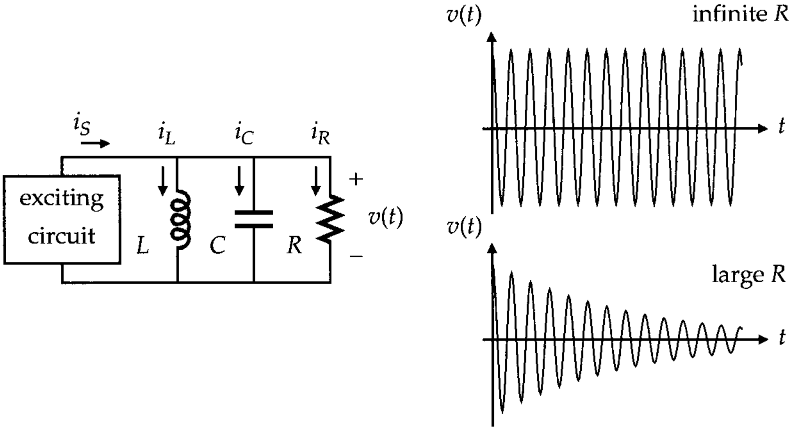


Figure 1.8: A resonant circuit.

telegraphy, he took out patents and formed the Marconi Wireless Signal Company. Progress was rapid: in 1901 he succeeded in sending a wireless signal across the Atlantic.

ELECTRICAL TUNING

An important aspect of radio communication is that of tuning; that is, to utilize a circuit that has an optimal response at a particular signal frequency. This is generally achieved with an inductor–capacitor circuit such as that of the parallel circuit of Figure 1.8. The resistance R is included to account for circuit losses (the resistance of the inductor) and energy that might be radiated as a result of an antenna connected to the circuit. Early wireless transmitters used a current impulse i_S produced by a spark gap to initiate the voltage oscillations of the circuit. Consider the case for which the circuit has previously been excited and the current i_S is zero. This implies that the sum of the currents of the individual elements must be zero, as given by the following:

$$\begin{aligned} &i_S(t) = i_L + i_C + i_R = 0 \\ &i_L = \frac{1}{L}\int v\,dt, \qquad i_C = C\frac{dv}{dt}, \qquad i_R = \frac{v}{R} \end{aligned} \tag{1.1}$$

These two equations may be combined and then differentiated to produce a single second-order differential equation:

$$\begin{aligned} &\frac{1}{L}\int v\,dt + C\frac{dv}{dt} + \frac{v}{R} = 0 \\ &\frac{d^2v}{dt^2} + \frac{1}{RC}\frac{dv}{dt} + \frac{v}{LC} = 0 \end{aligned} \tag{1.2}$$

For an ideal circuit with no loss ($R \to \infty$), a constant-amplitude oscillating voltage is a valid solution of the differential equation as follows:

$$v(t) = V_m \cos\omega_0 t, \qquad \omega_0 = \frac{1}{\sqrt{LC}} \tag{1.3}$$

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Hence, once this lossless circuit is excited by an external current, its voltage will continue to oscillate indefinitely.

For a circuit with loss (finite R), damped sinusoidal oscillations occur given by

$$v(t) = V_m\, e^{-\alpha t} \cos \omega_0 t$$
$$\alpha = \frac{1}{2RC}, \qquad \omega_0 = \sqrt{\frac{1}{LC} + \left(\frac{1}{2RC}\right)^2} \tag{1.4}$$

The current impulse of a spark was used for the earliest wireless transmitters. Modern transmitters (radio and TV stations, citizens band transceivers, cellular telephones, etc.) rely on essentially the same principle except that an electronic exciting circuit is utilized that generally provides a current impulse for each oscillating cycle.

How does this circuit manage to continue to oscillate when the exciting current no longer exists? To answer this question, we must recall that inductors and capacitors store electrical energy. Let e_C and e_L be the instantaneous stored energies of the capacitor and inductor, respectively.

$$e_C = \frac{1}{2}Cv^2, \qquad e_L = \frac{1}{2}Li^2 \tag{1.5}$$

Consider the idealized case ($R \to \infty$) for which the amplitude of the voltage is constant (Eq. (1.3)).

$$i_L = \frac{1}{L}\int v\, dt = \frac{V_m}{\omega_0 L} \sin \omega_0 t$$
$$e_L = \frac{1}{2}\frac{V_m^2}{\omega_0^2 L} \sin^2 \omega_0 t = \frac{1}{2} C V_m^2 \sin^2 \omega_0 t \quad \text{because} \quad \frac{1}{\omega_0^2} = LC \tag{1.6}$$

The total energy $e_C + e_L$ is constant for this circuit:

$$e_C + e_L = \frac{1}{2} C V_m^2 = \frac{1}{2}\frac{V_m^2}{\omega_0^2 L} \tag{1.7}$$

It will be noted that when the stored energy of the capacitor is a maximum, that of the inductor is zero and vice versa (Figure 1.9).

In effect, there is an interchange of energy between the capacitor and the inductor of the circuit. For a circuit with a finite resistance, the electrical energy is gradually dissipated by the resistor; that is, the electrical energy is converted to thermal energy (or radiated if the resistor represents the effect of an antenna).

VACUUM TUBE CIRCUITS

Following its invention, the vacuum tube triode was extensively improved, and numerous electronic circuits were developed that greatly increased the tube's utility. Armstrong's invention of regeneration in 1912, the use of positive feedback to increase the gain of a circuit, increased the sensitivity of receivers. For example, using Armstrong's regeneration principle, it is possible to build a shortwave receiver with but a single vacuum tube (or transistor) that is capable of receiving signals from all over the world. A modification of this circuit was also used