Semiconductor Pulse and Switching Circuits

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Preface

Although several well-known books on pulse circuits are already in print, each with some strong points and some weak points, an author always strives to perfect the depth (contents), order of topics, and presentation (language) of the subject matter, even when using existing texts. It was with this thought in mind that this book was written.

In addition, the reader will find the following features that distinguish this book from its predecessors:

1. The topics discussed are only those that are pertinent to pulse circuits. The discussion is kept to the point. No redundant or "nice-to-know" material is included.
2. The underlying idea throughout the book is that the reader should be able to follow the material presented without any outside help. As an aid to understanding, many examples are given at every step along the way.
3. The content, and the depth to which it is discussed, is ideally suited for an introductory course in pulse circuits especially, for the training of technicians and technologists.
4. Wherever possible, mathematics, rather than elaborate descriptive prose, is used as a tool to explain circuit behavior.
5. Calculus is sometimes used to show the derivation of a useful equation. However, the reader does *not* need knowledge of calculus to follow the presentation or to solve problems.
6. For the most part, the operation of a circuit is described in *reduced-type* print and in orderly steps. This is done to spotlight it amid the rest of the presentation in that section.
7. Within the presentation, important terms and phrases are printed in *italic* script to emphasize their importance.
8. Self-Evaluation Questions, Summaries, and Glossaries of important terms serve to display the contents of the chapter. These sections indicate the important topics, or the "meat" of the chapter.
9. The text is outlined so that the material presented in one chapter follows that of the preceding chapter in the most logical

manner. For the most part, however, a chapter is an entity by itself. This makes it easier for the reader to arrange his/her own order of reading or to read only the necessary chapters.

10. The operation of circuits containing discrete components is explained first, and then the corresponding TTL IC circuits are discussed. This is done to show the direct link that exists between circuits having discrete components and the newer ICs.
11. Chapters 1 and 2 review the important topics in basic electrical circuit theory. It is assumed that the reader is already familiar with these and does not need to spend any appreciable amount of time on them. However, it is important that the reader understands them well enough to follow their use in other pulse circuits.
12. Chapter 11 is devoted to logic fundamentals and their use in pulse and switching circuits. Details are provided for the design of combinational switching networks, starting with the word problem and ending with the required logic gate circuit. Common IC families and their important characteristics also are discussed in this chapter.
13. The experiment provided at the end of each chapter is an integral part of the chapter. It is designed to complement the important material presented in the chapter. Each experiment has been laboratory- (student-) tested. An average student takes about three hours to perform the experiment and write a brief report on it. A slower student may have to do some calculations in advance in order to finish it in three hours. Sometimes it will take more than three hours of laboratory time to cover all the important topics presented in a chapter. In such cases, the experiment is divided into parts such that each part will take three hours of laboratory time. The equipment prescribed for each experiment consists of standard-value and readily-available components. The test equipment consists of a dual-beam (or dual-trace) oscilloscope, a multimeter, a multifunction generator, and a dual power supply—standard equipment in an electronics laboratory.

Chapters 1 and 2 review the important concepts of electric circuit theory. These are used to explain the operation of pulse circuits discussed in other chapters. It is assumed that the reader is already familiar with these and, if necessary, will use them as reference material.

The response of an RC circuit to a step input (pulse) is discussed in detail in Ch. 3. The role of an inductor as a waveshaping device is downplayed, because it is seldom used in practical circuits. The damping characteristics of an RLC circuit are discussed to explain the oscillations that are sometimes encountered in pulse circuits. The proper way to compensate an attenuator is also shown.

The basic characteristics of semiconductor devices such as diodes, bipolar junction transistors, and field effect transistors (FET) are reviewed in Chs. 4 and 5. Attention is focused on their use as a switch. Factors that control their turn-ON time and turn-OFF time are discussed in detail. The 7404 TTL IC hex-inverter is used to show the switching action of diodes and transistors, as well as the direct link that exists between ICs and circuits having discrete components.

Multivibrators are discussed in Chs. 6 and 7. In each case an analysis of a circuit using discrete components is followed by a discussion on the operation of the corresponding TTL IC. The use of F/Fs in binary registers and counters is also explained.

Voltage-sweep and current-sweep principles, as well as corresponding circuits, are discussed in Ch. 8. Methods of producing linear voltage sweep are emphasized.

Chapter 9 contains discussion on special pulse circuits not covered earlier. A detailed discussion on the Schmitt trigger, UJT relaxation oscillator, and the use of 555 timer in astable, monostable, and ramp-generator mode is presented.

A brief discussion on pulse transformers and pulse-delay techniques is presented in Ch. 10. Its importance in pulse circuits is rapidly diminishing and therefore only a short discussion is devoted to it.

Chapter 11 is devoted to logic fundamentals and logic circuits available in various IC families. The process involved in the design of combinational switching networks, starting with a word problem and ending up with the required logic-gate network, is explained in detail. The operation of common IC gates in various IC families is explained. An effort is made to show that IC circuits are really miniaturized semiconductor discrete-component circuits. Important characteristics and associated terms used to identify IC parameters are discussed briefly.

The importance of the place that an experiment holds in the whole technical learning process cannot be overemphasized. "Hands on" experience is a must if one is to have a real understanding of circuit behavior. To this end, an appended experiment forms an integral part of each chapter. Each experiment has been laboratory- (student-) tested for instruction, clarity, order of performance, time period, and its relationship to the material presented in the chapter. It has been found that:

1. The experiment is well-suited to the material presented in the chapter.
2. The experimenter is able to follow the instructions and perform the experiment without any additional help.
3. A three-hour laboratory period is more than enough to completely finish the experiment, including the report. Our students record all the information pertaining to the experiment on the experiment sheets. They are required to answer the questions and write the discussion on separate sheets that are attached to the report.
4. Whenever topics to be covered in an experiment require a longer laboratory time, the experiment is divided into parts. In these cases, each part of an experiment is an entity in itself, and requires about three hours of laboratory time.

My heartfelt thanks go to my editor, Dr. Irving L. Kosow, without whose able guidance this book could never have become a reality. I am also grateful to various reviewers, especially, Prof. David M. Hata (Portland Community College), Prof. Arthur Seidman (Pratt Institute), Prof. Arthur Del Giorno (City Univ. of N.Y.) and Dr. Stephen R. Chesier (Purdue University) for constructive comments that helped me to focus on the important topics in pulse circuits.

I am grateful, too, to my dear wife, Rajinder, and my three children, Rav Iqubal, Sanjinder, and Sanraj (my helper), for putting up with me while I pounded away on the typewriter.

Santokh S. Basi

Contents

Chapter 3
Linear Wave-Shaping Circuits

Chapter 4
The Diode Switch

Chapter 5
The Transistor Switch

Chapter 1 Review of Basic Electrical Laws and Theorems

1-1 Objectives

The objectives of this chapter are to:

1. Review the units of electrical measurements and establish the conventional direction of current in a circuit.
2. Review the definition of resistance and briefly explain the differences between conductors and insulators.
3. Establish voltage-drop terminology as it relates to the conventional direction of current in a circuit.
4. Review Ohm's law and the units of resistance.
5. Review the concept of electrical power and the meaning of the power rating of a component.
6. Review the definition of capacitance.
7. Review the relationship between the charge on, the voltage across, and the capacitance of a capacitor.
8. Derive the equation for the instantaneous current in a capacitor.
9. Review the relationship that exists between the capacitance of, the voltage across, and the dc current charging a capacitor.
10. Review the definition of inductance.
11. Review capacitive reactance of a capacitor to a sinusoidal ac voltage.
12. State the equation for the instantaneous voltage across an inductor.
13. Review the conditions that occur when a dc current flows in an inductor.
14. Review inductive reactance of an inductor to a sinusoidal ac voltage.
15. Review Kirchhoff's current and voltage laws.
16. Review methods of calculating equivalent impedance when two or more impedances are connected in series and/or in parallel.
17. Review Superposition and Thévenin's theorems.

1-2 Self-Evaluation Questions

Watch for the answers to the following questions as you read the chapter. They should help you to understand the material presented. When you have finished the chapter, return to this section and be sure that you can answer all of these questions. Then test your understanding by working out solutions to the problems at the end of the chapter.

It is strongly recommended that the questions be satisfactorily answered before attempting to solve the Problems (Sec. 1-17).

1. Explain in your own words the following terms used in describing electric circuits:
   a. Potential.
   b. Current.
   c. Conventional direction of current.
2. Define resistance and outline the basic properties of a:
   a. Conductor.
   b. Insulator.
3. Show how the voltage at a point in a circuit with respect to another point in that circuit is commonly expressed.
4. State and explain Ohm's law.
5. Define electrical power and explain what is meant by a *watt*.
6. Show how the electrical power being dissipated in a circuit is calculated.
7. Define capacitance and explain what is meant by a *farad*.
8. State the relationship that exists between the potential difference across a charged capacitor and its capacitance.
9. State the equation for the instantaneous current in a capacitor.
10. State the equation for the instantaneous voltage across a capacitor.
11. Explain why the voltage across a capacitor increases as a constant (dc) current charges it.
12. State the equation used to calculate the capacitive reactance of a capacitor when the operating voltage is a sinusoidal.
13. Define *inductance* and explain what is meant by a *henry*.
14. State the equation for the instantaneous current in an inductor.
15. State the equation for the instantaneous voltage across an inductor.
16. Explain what happens to the voltage drop across the inductor if the current in it is dc.
17. State the equation used to calculate the inductive reactance of an inductor when the operating voltage is a sinusoidal.
18. State and explain the Kirchhoff's voltage (KVL) and current (KCL) laws.
19. Show how to calculate the equivalent impedance when two or more impedances are connected in **a.** series; **b.** parallel.
20. State and explain the Superposition theorem.
21. State and explain Thévenin's theorem.

1-3 Potential Difference and Current

Most electrical power sources (generators or batteries) have two output terminals. The basic function of a power source is to develop and (continuously) provide a surplus of electrons at one output terminal and a deficiency of electrons at the other output terminal.

This results in a difference of potential between the two terminals that is measured in *volts* (V). The output terminal having a surplus of electrons is called the *negative* terminal and the output terminal having a deficiency of electrons is called the *positive* terminal.

When an electric circuit is connected to (across) a power source (usually called the "source"), it provides a path for electrocharge flow. The rate of charge flow is known as *current* (I) in the circuit. The practical unit of current measurement is an *ampere* (A). A current of one ampere is said to be flowing at a point in a circuit if an electronic charge of one coulomb (C) is moving past that point every second. Stated in equation form:

$$I = \frac{Q}{t} \text{ amperes (A)} \tag{1-1}$$

where:

Q is the charge in coulombs (C)
t is the time in seconds (s)

The instantaneous value of current may be calculated by differentiating Eq. (1-1). Accordingly,

$$i = \frac{dq}{dt}, \text{ rate of charge flow in coulombs per second (C/s)} \tag{1-2}$$

where:

i is the instantaneous value of current (A)
dq/dt is the incremental flow of charge per incremental unit of time taken over an infinitesimally small increment of time (C/s)

The electrons in an electric circuit drift from the negative to the positive terminal. However, it is a standard practice to denote the direction of current from the positive to the negative terminal. This is called the *conventional direction.* The arrow symbol on all semiconductor devices shows the flow of current in this the conventional direction. *Conventional current* is used in this book as it is extensively used in most engineering literature throughout the world.

1-4 Resistance (*R*)

When a potential difference is applied to a closed electric circuit, a charge begins to drift. All circuit materials present a certain amount of opposition or *resistance* to the rate of charge flow or current. Some materials present more opposition to the flow of charge than others.

Resistance is that property of a material that *opposes* a current and dissipates electrical energy. The *electrical* energy is converted by the circuit property of resistance and is usually dissipated in the form of *heat* energy. The equation symbol for resistance is R.

Materials that present very little resistance to current are called *conductors*. Materials that present a high resistance to current are called *insulators*. Materials between these two extremes are called *semiconductors*.

The standard unit of resistance measurement is an ohm, usually abbreviated by a Greek letter omega (Ω). A material is said to possess a resistance of one Ω if a one-volt potential difference across it results in one ampere of current in it.

The standard symbol for a resistor is shown in Fig. 1-1. It shows a current of I amperes flowing through it. The potential at point a is V_a and at point b is V_b. The potential difference between points a and b is written as V_{ab}. V_{ab} means the potential at point a with respect to b and is equal to $V_a - V_b$. Obviously, then, V_{ba} means the potential at point b with respect to a. In Fig. 1-1, V_a is more positive than V_b. For this reason, the conventional direction of current is from a to b.

Ohm's law relates all three quantities (R, I, and V_{ab}). It states that the current in a resistor is directly proportional to the potential difference (*voltage drop*) across it. The constant of proportionality is the resistance (R) of the resistor. If the potential difference across a resistor is doubled, its current will also double. Mathematically, Ohm's law is:

$$R = \frac{V}{I} \text{ ohms } (\Omega) \qquad (1\text{-}3a)$$

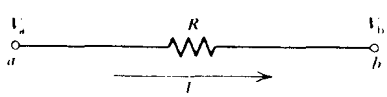

Figure 1-1 Current in and voltage-drop across a resistor.

or, rearranging terms,

$$V = I \cdot R \text{ volts (V)} \tag{1-3b}$$

where

V is the voltage drop across the resistor in volts (V)
I is the current in the resistor in amperes (A)
R is the resistance of the resistor in ohms (Ω)

Example 1-1
Voltage drop across a 5-kΩ resistor is measured as 25-V. Calculate the current in the resistor.

Solution

$$I = \frac{V}{R} \tag{1-3}$$

$$= \frac{25 \text{ V}}{5 \times 10^3 \ \Omega}$$

$$= 5 \times 10^{-3}$$

$$= \mathbf{5\ mA}$$

Note that Ohm's law (Eq. 1-3) holds true for **dc** as well as for **ac** circuits. However, when analyzing **ac** circuits, it is important to consider the magnitude as well as the direction of phasor quantities (see Sec. 1-11).

1-5 Power (*P*)

As mentioned earlier, the power source works to maintain a constant potential difference, also known as the *electromotive force* (emf), between its output terminals while supplying a steady current to an electric circuit. The electrical power supplied by the source is converted to other energy forms by the circuit. The practical unit of electrical power is the *watt* (W). Power as the rate of doing work is also measured in *joules per second* (J/s). One watt of power is equivalent to work done at the rate of one joule per second, that is, 1 W = 1 J/s.

Consider a power source with a terminal potential difference (voltage) of V volts, supplying a current of I amperes to a circuit.