Electronics for the Modern Scientist

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Preface

This textbook is predicated on the belief that modern scientists have an increasing need for a working knowledge of the principles of electronic design, signal analysis, and linear system theory. This belief has only begun to find acceptance among science educators since the inception of integrated circuits and the widespread research application of signal analysis and linear system theory. The introduction of these subjects to the scientific curriculum has been hampered by a scarcity of qualified teachers and by competition with more traditional subjects in an already crowded field of courses. Nevertheless, the more forward-looking universities are at least offering such material as elective subjects, and it is inevitable that eventually it will be required for graduate degrees in chemistry, physics, and some of the biological sciences.

Changes have occurred in scientific research that dictate the need for a knowledge of electronics and system analysis. Perhaps the most obvious is the increased electronic sophistication of research equipment itself. More and more electronic instrumentation is in use in all fields of science, and increasing numbers of instruments incorporate microcomputers. Of course not all scientists need to modify their instrumentation or do their own repairs. However, an understanding of the design and working principles of sophisticated instrumentation will enable any investigator to make more effective use of it. Moreover, the researcher who understands these principles will be better able to specify any needed modifications to a design engineer and to assure their proper implementation. The researcher who cannot do this will be limited not only in the types of experiments he or she can perform, but even in the types that can be conceived.

The need for a knowledge of system analysis is even more pressing. Theorizing in science involves the formulation of models. System analysis entails the formal development of such models, both at the descriptive level (when the behavior of a system is described, without any reference to underlying mechanisms) and at the level of hypothetical mechanism. In the field of physiology, for example, some researchers talk of physiological control systems with positive or negative feedback, and are often unaware of the simplest principles of control system theory, let alone its established applications to physiology. A biochemist, when taking periodic samples of blood in order to determine the time course of the appearance or disappearance of a biochemical substrate, must understand how to select the sampling frequency so as to avoid missing important frequency components in the deduced time-varying signal: too low a frequency may actually introduce spurious frequency components, resulting in a waveform quite different from the actual time course.

We believe that a scientific education must not only enable the student to understand past research but also equip him or her for a long scientific career. The areas of electronics and system analysis are as essential to the modern scientist's education as elementary computer science, calculus, physics, or statistics and probability. There is already a large body of research literature that is inaccessible to many graduates because they cannot understand the concepts or notation in system analytical approaches to research problems; their education is, in this sense, obsolete before they have their degree. Many medical students today are ill prepared to grasp the physical concepts underlying the theory of nerve membrane potentials because they do not have an adequate understanding of of electric principles; their education is obsolete before they even enter medical school!

The most important concepts in this textbook can be learned in one semester by a college junior or senior; all of the material can be mastered in two semesters. It is our hope that, after taking a course using this text, students will have sufficient understanding of system analysis and electronics design to be able to master more advanced material, as needed, either on their own or with minimal guidance. Since the text is intended for all scientific disciplines, we assume only a familiarity with elementary calculus, which all scientists need anyway. Even the student unfortunate enough not to have had calculus can understand most of the material if the teacher properly structures the course.

Every teacher will have his or her own preferred approach and will select different portions of this text and order them in different sequences. We have developed what we believe to be a logical sequence of material for didactic purposes, and we have deemphasized material that, in our view, will be considered optional in shorter courses by using smaller print. This textbook presents only theory: there is no material on construction techniques and no description of the many commercially available integrated circuits, and there are no laboratory exercises. To include these, although they are important, would make this text impractically large. The text covers a broad range of topics in electronics, but no attempt was made to be comprehensive. Instead, we hope that by presenting a "principles" approach to key concepts and topics in electronics, we shall make the reader comfortable with the subject and encourage him or her to go to other reference sources for in-depth treatments of particular areas of interest.

Paul B. Brown

Contents

1

Circuit Elements, Impedance, Network Analysis

Gunter N. Franz

Electronic instruments are designed for so many different applications that it would seem impossible to reduce the rules of design to a few basic principles. However, if we examine individual electronic instruments we notice that most of them are really constructed of similar components, the main difference being the way in which the components are interconnected to form the whole instrument. It is customary to call a purposefully connected set of electronic components an *electronic circuit*, or simply a *circuit*. The components are connected according to a *wiring diagram* or *schematic*.

The various types of components are represented by simple graphic symbols (rather than a replica of their actual appearance) in the wiring diagram. To simplify analysis and design of circuits, we often assume that the component symbols stand for *idealized* components. These idealized components are simple conceptual models of the real "hardware" and are called *circuit elements* or *model elements*. Circuits made up of idealized circuit elements are also referred to as *networks*.

In order to analyze a circuit or network we need to proceed from two sets of quantitative relations. The first is based on the quantitative description of the individual elements: the *element laws*. The second is derived from the way in which the circuit elements are interconnected to form the whole circuit: the description of *network topology*. Both sets are combined to give us the *network equations*. The solution of the network equations completes the analysis of the given network. This chapter deals with the basic tools of network analysis.

1.1 Circuit Elements: Basic Concepts and Definitions, Element Laws

We characterize circuit elements according to their manner of handling electric energy: *active* elements are sources of electric energy, whereas *passive* elements store, couple, dissipate or otherwise transform electric energy. Next we consider their complexity. Because current flow requires the current to enter the circuit element at one end (terminal) and leave it at another, the least complex elements must have two terminals, which together make up a port. Passive *two-terminal elements* or *one-ports* either store electromagnetic energy or dissipate it into heat. The coupling of electric energy, as in a transformer, requires *two-ports*, i.e., elements with three or four terminals. Active two-terminal elements are independent sources of electric energy. Controlled sources, such as amplifiers, generally require three or four terminals.

The quantitative characterization of an element requires that we know the relations between the currents entering (or leaving) its terminals and the associated port voltages. The resulting *element law* takes the form of an equation or graph describing the interdependence of a single current–voltage pair in the case of two-terminal elements.

In order to facilitate circuit analysis, the individual model elements are represented in the circuit diagram by special symbols and by an indication of the polarities of the voltages and currents. In Fig. 1.1a an arbitrary two-terminal element (represented by the rectangle) is shown with the measurement pair necessary to define the element law. If the current enters terminal 1, the measuring instrument in series (ammeter) shows a positive deflection. This direction of current flow implies that the electric potential at terminal 1 (e_1) is higher than that at 2 (e_2), hence the measuring instrument in parallel (voltmeter) shows a positive deflection, and we assign the associated positive polarity ($+$) to terminal 1 and a negative one ($-$) to terminal 2. It is important to use these conventions consistently in order to prevent

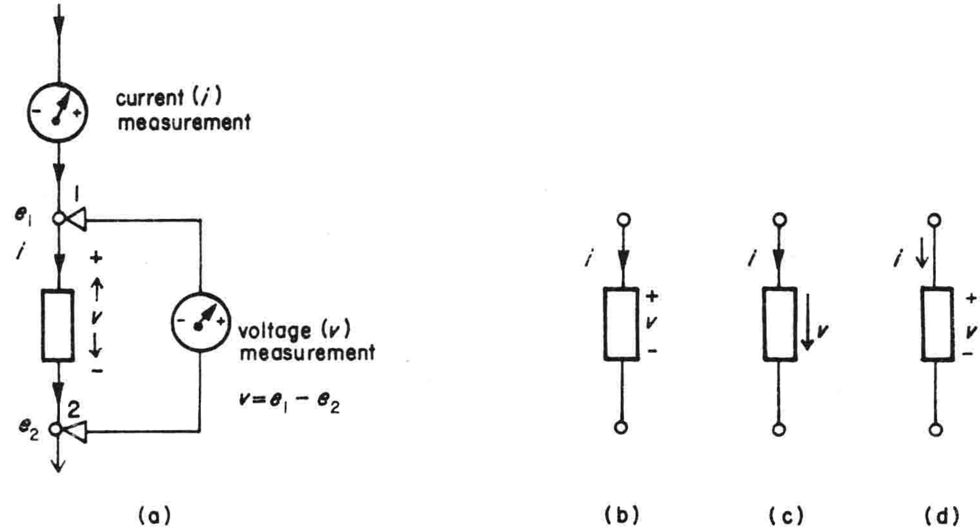

Figure 1.1 Polarities or associated reference directions for a general two-terminal element (one-port): **(a)** measurement of voltage–current pair; **(b)** preferred reference designation used in this chapter; **(c)** and **(d)** alternative reference designations.

errors. Figures 1.1b to 1.1d show three common ways of indicating the *reference directions* (*polarities, sign conventions*) for a two-terminal element.

REMARK: The convention to assign a positive sign or "direction" for the current when a net transfer of charge occurs from the terminal of higher electrical potential 1 to that of lower potential 2 is entirely arbitrary. The direction of flow of the actual charge carriers will depend on their polarity. Positive charges (such as positive ions in an electrolyte) will flow in the same direction as the current arrow in Fig. 1.1. Negative charges, such as electrons in metallic conductors, will flow in the *opposite* direction and accomplish the same net transfer of charges. For the purposes of circuit analysis it is immaterial how the charge transfer actually occurs. The *operational definitions* according to Fig. 1.1a are sufficient. Hence current is still indicated as flowing from 1 (+) to 2 (−) even if electrons flow in the opposite direction.

Table 1.1 contains the letter symbols and units of measurement of the electric variables of interest to us. The strict physical definitions of these quantities can be obtained from any good physics textbook.

It is customary to add prefixes to electric units for magnitude scaling by factors of 1000. Table 1.2 lists the factors and prefixes.

In order to facilitate future discussions of units of measurement we introduce the following short-hand notation:

> The expression [x] means "unit of measurement or dimension for quantity x," where x can be a variable or a parameter.

Table 1.1 Units of Electrical Variables

Variable	Letter Symbol	Unit	Unit Symbol
Charge	Q, q	coulomb (ampere-seconds)[a]	C (A·s)[a]
Current	I, i	ampere	A
Voltage, electrical potential difference	V, v E, e U, u	volt	V
Power	N, n P, p	watt (volt-ampere)[a] (joule/sec)[a]	W (V·A)[a] ($J\cdot s^{-1}$)[a]
Magnetic flux	Φ, ϕ	weber (volt-seconds)[a]	Wb (V·s)[a]

[a] The units in parentheses are numerically identical to the units listed first (International System of Units or SI Units).

Example 1.1. Use of the dimension or unit symbol

$[v]$ = volt (V)

$[i]$ = ampere (A)

After this presentation of introductory concepts we proceed to the discussion of the major types of two-terminal elements: dissipators, stores, and sources of energy.

Table 1.2 Factors and Unit Prefixes[a]

Factor	Unit Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

[a] Examples: 10^{-3} A = 1 mA; 10^{3} V = 1 kV; 0.63 A = 630 mA; 1200 W = 1.2 kW.

1.1.1 Dissipation: Resistors

Dissipation refers to the fact that practical conductors cannot carry electric currents without loss of energy. The energy drop per unit charge or voltage difference across the ends of the conductor is directly proportional to the current carried by the conductor according to Ohm's law. For the charge transfer within the conductor we may here assume a simple frictional resistance model. The friction encountered by the moving charges causes the degradation of electric energy into heat. In fact, the energy thus converted per unit time, or the *electric power dissipated*, equals the product of current (through the conductor) and voltage (across the conductor).

The appropriate circuit model element for dissipation is the *resistor*. In most instances, the idealization of this element rests on two assumptions: (1) Ohm's law is obeyed, and (2) temperature effects are negligible. (Aside from resistance changes, excessive heating may actually destroy a resistor. In order to avoid that, resistors are specified with a *power rating* or *wattage* (in watts) which should not be exceeded.)

REMARK: We assume that the wires connecting the various circuit elements in a circuit have negligible resistance. Hence the resistor symbol (Fig. 1.2a) is only used when "concentrated" resistance of appreciable magnitude has to be considered.

1.1.1.1 Ohm's Law and Linear Resistance

We assume that resistors are "ohmic," i.e., they obey Ohm's law. The symbol for such resistors with the associated reference directions is given in Fig. 1.2a. (The symbol in Fig. 1.2b is sometimes used. We reserve this symbol for unspecified or generalized two-terminal elements). The characteristic in Fig. 1.2c is a graphic description of the element law. From the straight line through the origin we deduce the following element law.

Element Law for Linear Resistors (Ohm's Law)

$$v = Ri \tag{1.1}$$

or

$$i = \frac{1}{R} v = Gv \tag{1.2}$$

where R = resistance and G = conductance

REMARK: With a resistor we may associate either the resistance parameter R or the conductance parameter G. These quantities give equivalent characterizations to the same physical process; accordingly, we use only one circuit symbol as in Fig. 1.2a. By adding the letters R or G we can indicate which parameter we are using.

Quantitatively, the proportionality constant or device parameter resistance R (or conductance G) is determined by an associated measurement pair for voltage and

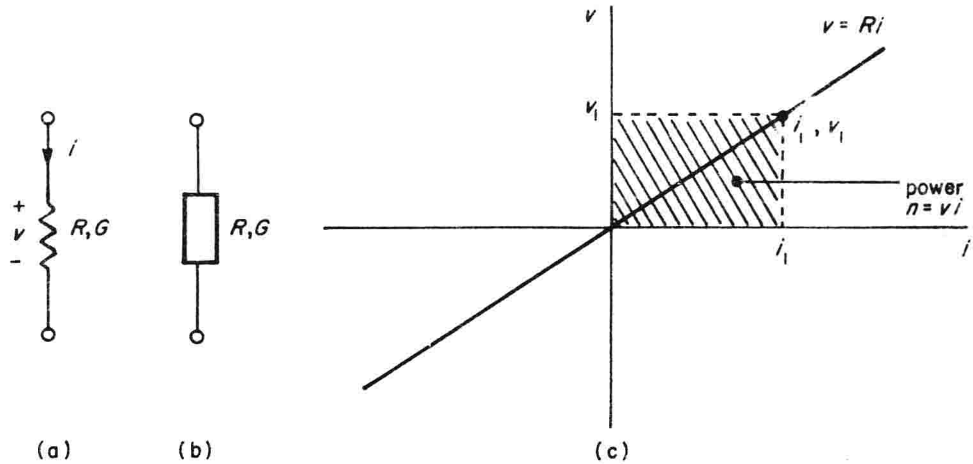

Figure 1.2 The linear resistive element (ohmic resistor): **(a)** preferred symbol with associated reference directions; **(b)** alternative symbol prevalent in the European literature; **(c)** element characteristic expressing Ohm's law. R = resistance parameter, $G = 1/R$ = conductance parameter for the same element.

current. If voltage and current are given in dimensions V and A, respectively (see Table 1.1), then we have

> Dimension for Resistance: $[R] = \text{ohm}$ (symbolized Ω)
> Dimension for Conductance: $[G] = \text{siemens}$ (symbolized S)

The dimensional relations between the variables and parameters introduced thus far are evident if we transform Eqs. (1.1) and (1.2) into dimensional equations:

$$[v] = [R] \times [i]$$

or

$$\text{volts} = \text{ohms} \times \text{amperes}$$

or

$$\mathrm{V} = \Omega \times \mathrm{A}$$

hence

$$\Omega = \frac{\mathrm{V}}{\mathrm{A}} \tag{1.3}$$

and

$$[i] = [G] \times [v]$$

or

$$\mathrm{A} = \mathrm{S} \times \mathrm{V}$$

hence

$$S = \frac{A}{V} = \frac{1}{\Omega} \qquad (1.4)$$

The scaling prefixes of Table 1.2 apply also to parameter units.

Example 1.2. Determination of resistance and conductance parameters with Ohm's law.

(A)

$v = 10$ V, $i = 1$ A, $R = ?$, $G = ?$

By Eqs. (1.1) and (1.3)

$$R = \frac{10\ \text{V}}{1\ \text{A}} = 10\ \Omega$$

and by Eqs. (1.2) and (1.4)

$$G = \frac{1\ \text{A}}{10\ \text{V}} = 0.1\ \text{S}$$

or

$$G = \frac{1}{R} = \frac{1}{10}\ \text{S}$$

(B)

$v = 100$ mV, $i = 5$ nA

$$R = \frac{100\ \text{mV}}{5\ \text{nA}} = \frac{100 \times 10^{-3}\ \text{V}}{5 \times 10^{-9}\ \text{A}} = \frac{1}{5} \times 10^{8}\ \Omega = 20\ \text{M}\Omega$$

Next let us reconsider energy dissipation in a resistor. The amount of charge dq transported through a resistor during an infinitesimally short time interval dt equals the number of charges moved per unit time (= current) multiplied by the interval dt:

$$dq = i\,dt \qquad (1.5)$$

From field theory it follows that the amount of energy de dissipated during dt is the product of voltage (energy change per unit charge) and the number of charges:

$$de = v\,dq \qquad (1.6)$$

With Eqs. (1.5) and (1.6) we have

$$de = vi\,dt$$

Hence the *rate* of energy dissipation or *power* is energy change per unit time:

$$p = \frac{de}{dt} = vi \qquad (1.7)$$

Equation (1.7) expresses formally what has been asserted earlier. The units of the power quantity are given in Table 1.1.