

# Basic Electrical and Electronic Tests and Measurements

Michael Braccio

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RESTON PUBLISHING COMPANY, INC.

*A Prentice-Hall Company*

Reston, Virginia

**Library of Congress Cataloging in Publication Data**

Braccio, Michael.

Basic electrical and electronic tests and measurements.

Includes index.

1. Electric measurements. 2. Electronic measurements. I. Title.

TK275.B67

621.37'2

78-17136

ISBN 0-8359-0589-6

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*A Prentice-Hall Company*

Reston, Virginia 22090

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10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

# Preface

With the rapid advance of electronics technology, measurements are becoming increasingly important. The advent of digital technology has greatly increased the accuracy that can be realized in routine measurements. It is essential for the student to acquire a basic grasp of the science and art of measurements, starting with the basic processes. He should understand how the standards of measurement are derived and applied to technological procedures, and the accuracy that may be expected from them. A study of measuring processes is directly related to electrical circuit and field theory, and it serves as a review and an integration of many branches of the discipline. Electrical units originate in theoretical definitions and do not become available for use until they have been realized by a measuring process. Students should be thoroughly prepared for this broad field; some understanding should be acquired of basic high-precision methods, but not to the exclusion of less precise but more commonly used methods.

Development of the electrical units is considered in the first chapter, with a preliminary introduction to measuring techniques. The second chapter explains the elements of statistics and the sources of measurement errors. Basic distinction is made between accuracy and precision concepts, with discussion of instrument errors and observational errors. Resistance measurements are detailed in the third chapter, with attention to both linear and nonlinear circuit parameters. Practical approaches to the measurement of internal, output, and input resistance values are explained. In the fourth chapter, DC voltage measurements are covered. Students are sometimes confused by electron versus hole flow concepts, and this distinction is carefully illustrated. Tolerances on DC voltage values are explained, and changes in DC-voltage distribution owing to variations in grounding points

are exemplified. DC-voltage changes owing to transistor defects are also noted.

AC voltage measurements are discussed in the fifth chapter. Instrument requirements are explained and sources of error are enumerated. Instruments for the measurement of small AC voltages and tuned AC voltmeters are included in the text. Because technicians and engineers generally measure decibel values with AC voltmeters, correct techniques are detailed for these procedures. Waveform errors are pointed out and the practical management of nonsinusoidal waveforms is introduced. Oscilloscope tests and measurements are covered in the sixth chapter. Basic measurements of rise time, transient response, time constants,  $Q$  values, phase, and amplitude linearity are explained and illustrated. Fundamental waveform analysis is included. Essential television network tests and measurements with the vertical-interval test signal are introduced.

Audio measurements are considered in the seventh chapter. Frequency response, harmonic and intermodulation distortion, music-power capability, and impedance, inductance, and capacitance measurements are detailed. Stereo decoder separation measurements are included. A discussion of specialized audio units, such as the phon and the mel, is presented. In the eighth chapter, digital tests and measurements are discussed and illustrated. Digital signal characteristics are explained, with an introduction to the data domain versus the time-frequency domain. Operation of logic state analyzers is discussed as a preliminary procedure to detailed pulse analysis with the oscilloscope. Microprocessor tests and measurements are explained with specific consideration of the widely used 4004 and 8008 types.

The author is indebted to various manufacturers for illustrative and technical material, as noted throughout the text. He is particularly grateful to the Hewlett-Packard Company for their welcome cooperation in supplying state-of-the-art microprocessing test data. In addition, the author wishes to take this opportunity to thank his fellow instructors for their suggestions and constructive criticisms. This text is intended primarily as a teaching tool in our junior colleges, technical institutes, and vocational schools. It is also designed as an appropriate guidebook for the home-study student. In addition, on-the-job technicians and junior engineers will find this work a useful handbook for ready reference.

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# Development of the Electrical Units

## 1-1 General Considerations

Accurate electrical measurements are as essential to the electrical engineer or technician as an accurate tape line to the surveyor or an accurate time source to the navigator. As in any other technical field, progress depends on units of measurement that are reliable, accurate, and available to workers everywhere. Electrical scientists have gradually developed a system of such units to a refinement far removed from the crude beginnings of early investigators. Measuring instruments have simultaneously undergone extensive development. As an illustration, the digital voltmeter shown in Figure 1-1 provides considerably higher indication accuracy than the prior generation of analog-type voltmeters.

The early stages of electrical science from 550 B.C. to 1700 A.D. were characterized, as would be expected, by qualitative observations of electrical phenomena. In following centuries, the nature of electrical actions became better understood, and quantitative relationships were gradually established. The first electrical experiments were made by rubbing glass rods with silk, and observations were made of attraction and repulsion of unlike and like charges. From these early experiments, the gold-leaf *electrometer* was developed; this was the first voltmeter used by scientists. Although the electrometer was insensitive in comparison with present-day voltage-measuring instru-

## 2 DEVELOPMENT OF THE ELECTRICAL UNITS

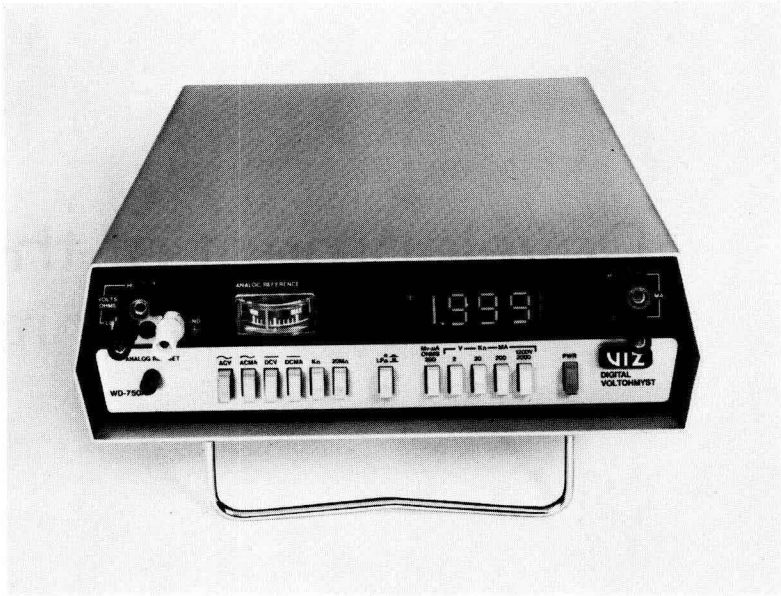


Figure 1-1. A highly accurate digital voltmeter. (Courtesy, VIZ)

ments, it opened a new era of quantitative observations of electrical phenomena.

Production of a steady flow of electricity became available with the invention of the voltaic pile by Volta in 1800. In turn, the quantitative investigation of electrical circuits started in 1827, when George Simon Ohm discovered the relationship or “law” that bears his name. Note that volt, ampere, and ohm units were not established until some years later. *Relative* current values were measured with a compass-needle and coil arrangement (tangent galvanometer). Voltage values were stated in terms of the potential supplied by a voltaic pile of specified construction. Resistance values were stated in terms of the resistance of a particular length of iron or copper wire with a diameter specified by the individual experimenter. By way of comparison, scientists, engineers, and technicians today employ high-precision standard resistors for instrument calibration (see Figure 1-2).

It became evident that a universal system of units was needed by all workers in the electrical field, and that these electrical units should be related to the established mechanical units of length, force, mass, and time. In 1832, Karl Friedrich Gauss measured the strength of the earth's magnetic field in terms of length, mass, and time. In 1849, Friedrich Wilhelm Georg Kohlraush measured resistance in terms of these units. Wilhelm Eduard Weber, in 1851, introduced a complete system of electrical units that were

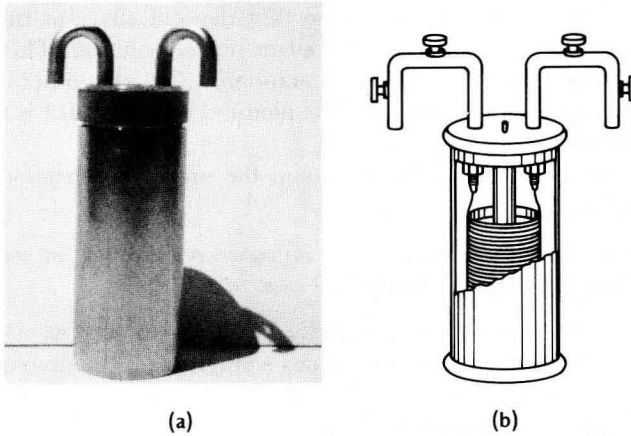


Figure 1-2. High-precision standard resistor: (a) appearance; (b) construction.

based on the mechanical units. Weber's principles form the basis of our present system of electrical measurements. In 1861, the British Association for the Advancement of Science started work on specification of the standard ohm, and announced the British Association unit in 1864. This consisted of a specified coil of platinum-silver alloy wire sealed in a container filled with paraffin. This standard continued in use for twenty years.

## 1-2 Absolute Units and Concrete Standards

Distinction is made between a theoretically defined electrical unit and a standard that is used in measurement procedures. For example, an ohm is defined in accordance with a logical system of electrical units. On the other hand, a resistance standard is designed for direct and convenient use in laboratory measuring arrangements. Otherwise stated, concrete working standards of resistance are utilized to determine the values of resistors which may be brought to the laboratory for calibration. The duty of maintaining the most precise standards (*primary* standards) is usually assigned to the national laboratories. All *secondary* standards, such as used in industrial laboratories, are calibrated against primary standards. The standard resistor illustrated in Figure 1-2 is an example of a secondary standard.

As noted previously, early determination of the electric current unit was made by means of a tangent galvanometer with respect to the earth's magnetic field. This method was abandoned subsequently owing to variations in the intensity of the earth's magnetic field, and because of disturbances from electric power lines and installations. Therefore, the interna-

#### 4 DEVELOPMENT OF THE ELECTRICAL UNITS

tional ampere was redefined in 1900 by an electrolytic standard by the London Conference as the current value that deposits silver at the rate of 0.00111800 grams/sec from a standard silver-nitrate solution. This electrolytic standard represented a primary standard. On the other hand, a calibrated (analog) current meter such as pictured in Figure 1-3 is termed a secondary standard.

The London Conference then defined the unit of electromotive force (voltage) as follows:

*An international volt is the potential difference produced by an international ampere flowing through an international ohm.*

However, the concept of a voltaic cell of some sort as a concrete standard of voltage had occurred to various workers from the time of Volta's invention. The Daniell cell (after Daniell) was first used as a concrete standard, but was subsequently abandoned because of its short life. Finally, in 1893, Weston produced a cadmium cell that has made a remarkable record for constancy of electromotive force (EMF) over long periods of time. An International Technical Committee that met in Washington in 1910 established the value of 1.01830 V for the EMF of the standard Weston cell. This cell employs a saturated cadmium-sulphate solution. A cell with an unsaturated cadmium-sulphate solution, however, is often preferred for shop

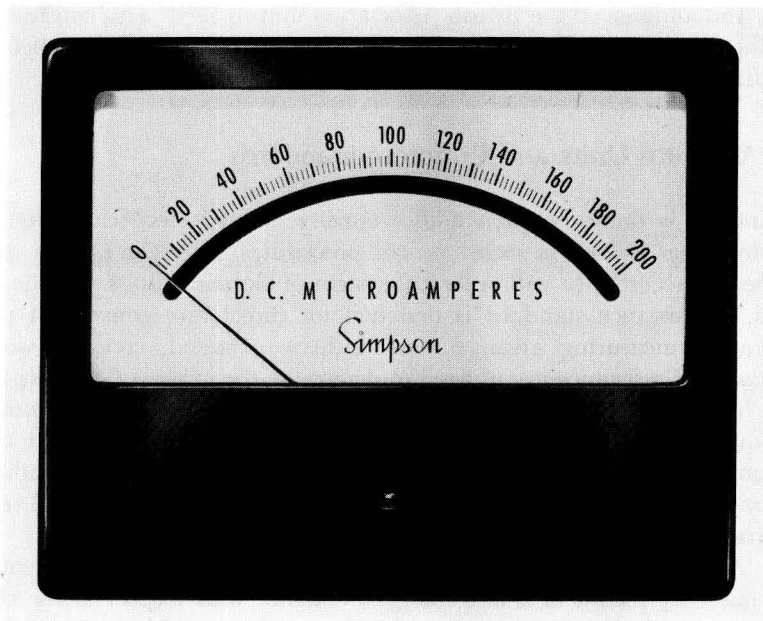
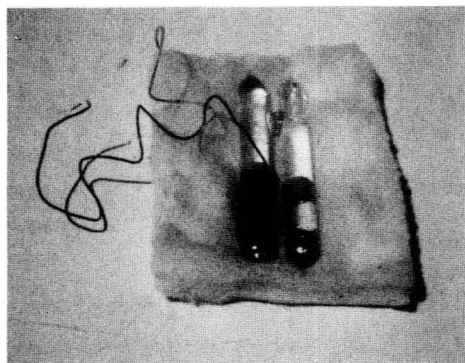
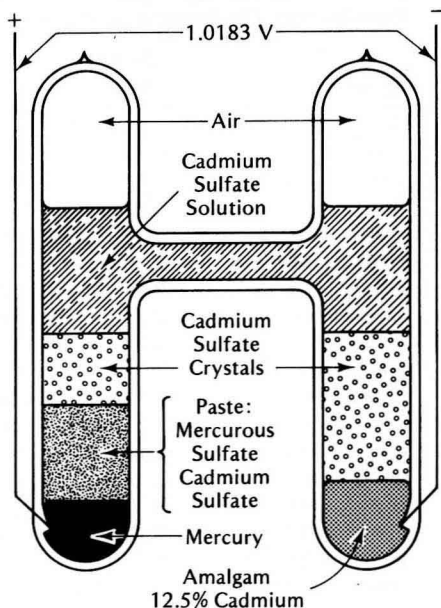


Figure 1-3. An analog-type current meter. (Courtesy, Simpson Electric Co.)



(a)



(b)

Figure 1-4 Weston-type standard cells: (a) appearance; (b) plan of a saturated cell.

use because of its very small temperature coefficient. An unsaturated cell, often termed a *shop cell* (Figure 1-4) is classed as a secondary standard.

### 1-3 SI Units

The International System of Units, or SI System, is derived from the metric system of physical units and denotes the French *Système Internationale d'Unités*. It was adopted, defined, and named in 1960 by the General Conference on Weights and Measures. The IEEE standards designate letter symbols for electrical engineering quantities in the SI System as listed in Table 1-1. Four of the basic units in the SI System are length, mass, time, and electric current.

### 1-4 Check of DC-voltage Calibration with Weston cell

High-accuracy dc voltmeters such as illustrated in Figure 1-1 are often checked with a Weston shop cell. A shop cell provides a terminal voltage from 1.0185 to 1.0190 V at 20°C. Although its accuracy is not as great as that of a saturated (normal) cell, a shop cell is adequate for checking the

**Table 1-1**  
**Letter Symbols for Quantities and Units in Electrical**  
**Engineering Designated in the SI System**

Quantity	Quantity Symbol	SI Unit	Unit Symbol	Identical Unit
charge	$Q$	coulomb	C	$A \cdot s$
current	$I$	ampere	A	
voltage	$V, E \dots U$	volt	V	W/A
electromotive force	$V$	volt	V	
potential difference	$V, \phi$	volt	V	
resistance	$R$	ohm	$\Omega$	V/A
conductance	$G$	siemen	S	A/V
reactance	$X$	ohm	$\Omega$	V/A
susceptance	$B$	siemen	S	A/V
impedance	$Z$	ohm	$\Omega$	V/A
admittance	$Y$	siemen	S	A/V
capacitance	farad	farad	F	C/V
inductance	$L$	henry	H	Wb/A
energy, work	$W$	joule	J	$N \cdot m$
power (active)	$P$	watt	W	J/s
power · apparent	$S \dots P$	voltampere	VA	
power · reactive	$Q \dots P^i q$	var	var	
resistivity	$\rho$	ohm · meter	$\Omega \cdot m$	
conductivity	$\gamma, \sigma$	siemen per meter	S/m	
electric flux	$\psi$	coulomb	C	
electric flux density, displacement	$D$	coulomb per square meter	C/m <sup>2</sup>	
electric field strength	$E$	volt per meter	V/m	
permittivity	$\epsilon$	farad per meter	F/m	
relative permittivity	$\epsilon, \kappa$	(numeric)		
magnetic flux	$\phi$	weber	Wb	V · s
magnetomotive force	$F \dots \mathcal{F}$	ampere (amp turn)		
reluctance	$R \dots \mathcal{R}$	ampere per weber	A/Wb	
		reciprocal henry	H <sup>-1</sup>	
permeance	$P \dots \mathcal{P}$	weber per ampere	Wb/A	
		henry	H	
magnetic flux density	$B$	tesla	T	Wb/m <sup>2</sup>
magnetic field strength	$H$	ampere per meter	A/m	
permeability (absolute)	$\mu$	henry per meter	H/m	
relative permeability	$\mu_r$	(numeric)		

accuracy of any service-type voltmeter. One practical advantage of a shop cell is that it does not have to be used with an elaborate potentiometric calibrating arrangement. In other words, a dc voltmeter can be connected directly to a shop cell, provided only that the current demand is not greater than 10 microamperes ( $\mu\text{A}$ ). For example, the digital multimeter shown in Figure 1-1 has an input resistance of 10 megohms on its dc-voltage ranges. Accordingly, this meter will draw approximately  $0.1 \mu\text{A}$  from a shop cell. Therefore, it is permissible to connect the test leads of the digital voltmeter directly to the terminals of the shop cell.

### 1-5 Check of DC-Voltage Calibration with Mercury Batteries

Low-sensitivity voltmeters draw appreciable current. For example, a 1000 ohm-per-volt multimeter operated on its 2.5-V range would draw approximately 0.4 milliampere (mA) from a shop cell. This is approximately four times the maximum tolerable current drain from the cell. Therefore, some other method must be utilized to check the calibration of a low-sensitivity voltmeter. When extremely high accuracy is not required, a mercury battery (Figure 1-5) is a satisfactory source of calibrating voltage. A mercury battery has a reasonably precise terminal voltage until its useful life is ended. This terminal voltage has a higher accuracy than the rated accuracy of typical service-type voltmeters. The mercury battery pictured in Figure 1-5 has

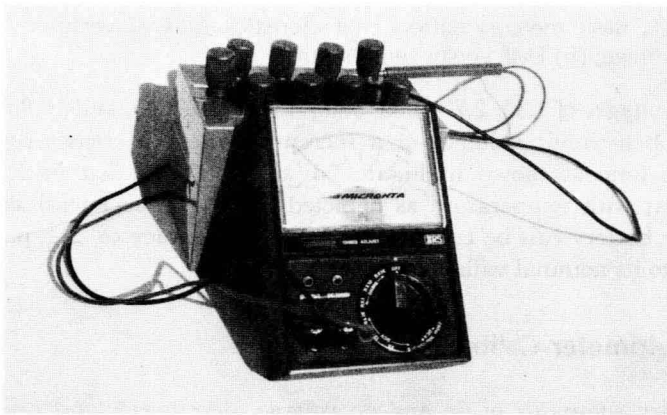
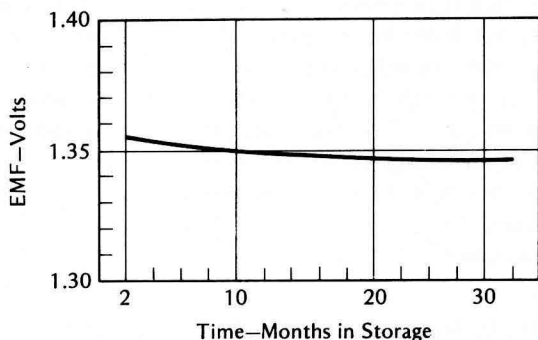


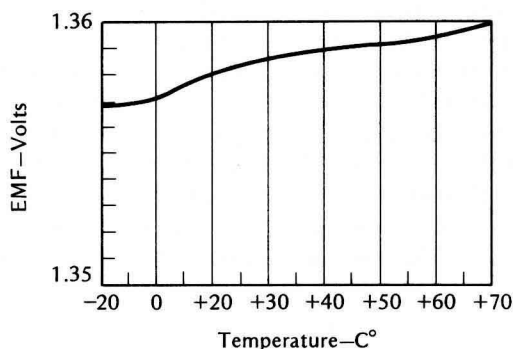
Figure 1-5. A shop-assembled mercury battery checks the indication accuracy of a 1000 ohm-per-volt multimeter on its DC-voltage ranges.



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(a)



(b)

Figure 1-6. Basic mercury battery characteristics: (a) EMF versus age in storage; (b) EMF versus temperature.

output voltages of 1.35, 2.70, 4.05, 5.40, 6.75, 8.10, 9.45, and 10.80 volts. The EMF (open-circuit voltage) of a mercury battery decreases slightly with shelf-life time as shown in Figure 1-6(a). Note also that its EMF varies somewhat with temperature as depicted in (b). As a general summary, a mercury battery can be regarded to have an accuracy of  $\pm \frac{1}{2}$  percent with respect to its nominal value.

### 1-6 Multimeter Calibrator

Secondary standards of dc and ac voltage, dc current, and resistance are utilized to calibrate multimeters. Most multimeters are designed for service application and have moderate accuracy. A typical secondary standard for