MODERN ELECTRONIC VOLTMETERS

VACUUM-TUBE AND TRANSISTOR VOLTMETERS

SOL D. PRENSKY

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To magazine editors
Fred Shunaman (RADIO-ELECTRONICS)
and
Ed E. Grazda (ELECTRONIC DESIGN)
Esteemed mentors (and tormentors)

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PREFACE

How the simple VTVM has grown! The robust evolution of vacuum-tube voltmeters has now developed into the study of electronic voltmeters so that it may include the transistor versions. Moreover, the many uses of the VTVM in radio and TV servicing have been considerably expanded by the increased measuring capabilities of advanced electronic voltmeters and now include highly important industrial and laboratory applications.

This text will give the reader a thorough understanding of modern electronic voltmeters; first, by reviewing fundamental principles of the basic instrument; then by covering well-established, service VTVM and transistor voltmeter test procedures. Finally, the author investigates, in detail, the more advanced electronic voltmeters used in shop and industrial and scientific work. This expanded view of the electronic voltmeter encompasses the highly sensitive d-c microvoltmeters (employing chopper-stabilized amplifiers), the high sensitivity a-c (or audio) voltmeters, and the extremely high impedance electrometer type of voltmeter. It also includes sensitive current measurements in the micromicroampere (picoampere) ranges and covers industrial versions of the voltmeter in the form of millivolt recorders and digital voltmeters.

A very real need exists for the sort of solid technical proficiency that combines "know-how" operation with a "know-why" understanding of operating principles. The progressive technician can acquire a firm foundation for such proficiency by devoting his attention to the basic principles of electronic amplification incorporated in the various forms of electronic voltmeters. Building in this way on his practical experience, his increasing competence will move him up to higher technical levels, known by such names as engineering technician, instrument technologist, or the like.

As an aid to such greater professional competence, the text highlights representative examples of models typical of both general-purpose and advanced types of instruments. Simplified or functional schematic diagrams are used liberally, accompanied by reasonable emphasis on practical applications.

Throughout the detailed exposition of the advanced instruments, concepts for further study are discussed. The last chapter combines these specialized instrumentation concepts into a view of voltage-measuring instruments applied to the nuclear, chemical, and biomedical fields. A carefully selected list of references is provided for the continued pursuit of a desired specialty.

Grateful acknowledgement is made to the instrument manufacturers who supplied technical information and illustrations, as indicated by the credit lines shown on their very helpful material. The skillful secretarial work of Miss Linda Lesiger also assisted greatly.

Very special thanks are due to my wife, Dinah, for her patient encouragement and able assistance.

Brooklyn, N. Y.
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BASIC PRINCIPLES OF ELECTRONIC VOLTMETERS

1-1. COMPARING THE ELECTRONIC VOLTMETER WITH THE MOVING-COIL METER

The electronic voltmeter, whether it appears as a vacuum-tube voltmeter (VTVM) or a transistor voltmeter (TVM), is an important basic measuring instrument in the electronics field. Its predecessor, the *moving-coil voltmeter,* utilized the historic *D'Arsonval movement* [1].* This moving-coil mechanism (shown in Figs. 1-1 and 1-2), in its basic form of *d-c galvanometer* or *d-c milliammeter,* is still the prime instrument for measuring current. The moving-coil *voltmeter* is derived from this basic mechanism by the addition of a series resistor (as shown in Fig. 1-1A) and is the familiar form commonly used for ordinary voltage measurements.

In many instances, however, the moving-coil voltmeter is not able to furnish a satisfactory reading. Such instances occur, for example, when the voltage to be measured is too low, or, alternatively, when

*Numbers in brackets refer to the numbered references in Appendix 1. These references are excellent sources for a more thorough consideration of basic principles reviewed in this chapter and elsewhere in the text.

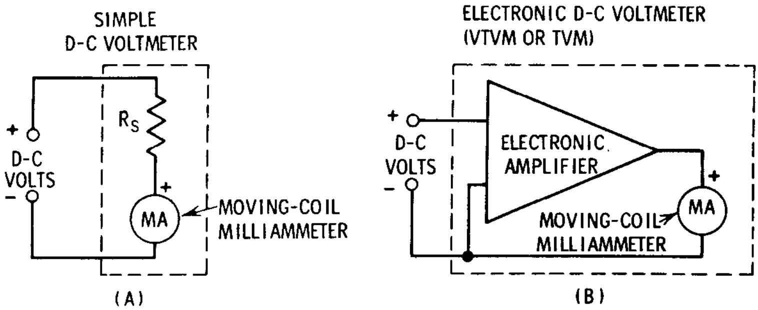


FIG. 1-1. A schematic comparison of a simple voltmeter (A) and an electronic voltmeter (B).

the current taken by the voltmeter causes too great a disturbance in the circuit being measured. Such difficulties have been overcome by a vital advance over the structure of the basic moving-coil mechanism — by adding an electronic amplifier (as shown in Fig. 1-1B), we obtain the *electronic* voltmeter, an instrument whose extended capabilities provide the reliable voltage measurements that the non-electronic, moving-coil voltmeter cannot supply.

The Basic Moving-Coil Meter — A Review

The construction details of the D'Arsonval moving-coil mechanism are shown in Fig. 1-2. This basic moving-coil meter, while always responding to d-c current, is the foundation unit for voltmeters and ohmmeters, in addition to being a milliammeter. It is also known as a *multimeter,* or, more commonly, a *volt-ohm-milliammeter* (VOM) when all its functions are combined in one instrument. As can be seen in Fig. 1-2D, the basic d-c meter essentially depends upon the motor action produced when a small current flows through the movable coil, which is pivoted (Fig. 1-2C) so that it will rotate between the poles of a permanent magnet (Fig. 1-2A).

Most commercial forms of the basic meter, as used in a multimeter (VOM), provide full-scale deflection when the current in the movable coil is either 1 milliampere (for the less-sensitive types) or 50 microamperes (for the more common, more sensitive types). In either case, a simple d-c voltmeter is produced by the addition of a series resistor (R_S in Fig. 1-1A). For a basic 0–1 ma meter, the full-scale deflection of 1 ma is obtained when 1 volt is applied by making the value of R_S equal to (1 v)/(1 ma), or 1000 ohms. Such a meter therefore contains 1000 ohms of resistance for each volt in the full-scale range and is accordingly known as a *1000 ohm-per-volt meter*. Similarly, for a basic 0–50 microampere meter, to obtain full-scale deflection of 50 μa when 1 volt is applied, resistor R_S must be equal to (1 v)/(50 μv), or 20,000 ohms. This meter (the most widely-used meter in service instruments) is known as a *20K ohm-per-volt meter*. With the latter meter, a voltage range of 0–3 volts dc, for example, would be obtained when the value of R_S is made to be 20K $\times$ 3, or 60,000 ohms.

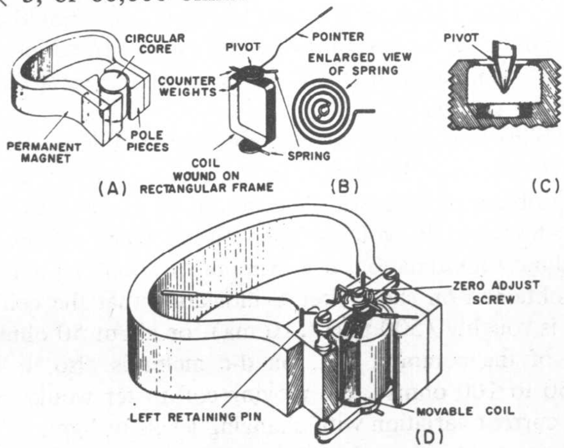


FIG. 1-2. Construction details of a D'Arsonval moving-coil mechanism.

In a comparable manner, the basic d-c meter is arranged to measure various ranges of *current* by appropriate *shunts,* and various ranges of *resistance* by the inclusion of a battery and appropriate *limiting resistors*. When all of these functions are tied together by appropriate switching action, a multimeter, or VOM, is obtained [1].

It may be mentioned in passing, at this point, that *taut-band meters* of the moving-coil type provide full-scale deflection with as little as 2 microamperes. With such a meter, a non-electronic voltmeter of the moving-coil type can be produced that has a sensitivity as much as twenty-five times as great as the more usual 20K ohms/v meter, resulting in a voltmeter having 25 $\times$ 20K or 500K ohms/v. If such a meter were used on a 0–300 volt d-c range, its input impedance would be 150 megohms — even greater than that of the constant 11 megohm input impedance of the usual vacuum-tube voltmeter (VTVM). This condition, however, would only be true for very high voltage ranges; on a lower range of 0–3 volts, the input impedance would be only 1½ megohms. This situation, combined with the fact that a meter of such great sensitivity is very easily burnt-out, considerably limits the use of VOM meters in applications where the VTVM, with its high input impedance, can replace them.

Desirable Features of the Moving-Coil Meter

When emphasizing the advantages of the electronic voltmeter (which are summarized in the next section), we should not forget the strong points of the basic moving-coil meter. In its most common form of a 0–1 ma meter, *it is still the simplest and most direct means for measuring current.*

Its suitability for simple current measurement is particularly evident in low-voltage or low-impedance circuits. As an example, consider the problem of measuring the output of a solar cell, which can deliver up to about ½ volt on open circuit when exposed to light. Under ordinary illumination, a maximum of about 10 ma of current might be obtained on short circuit, indicating that the cell's internal resistance is roughly (500 mv)/(10 ma), or about 50 ohms. As the resistance of the common 0–1 ma d-c meter is also in this range (around 50 to 100 ohms), the moving-coil meter would give a true picture of current variation with changing levels of light.

In contrast to this, an electronic voltmeter measures current indirectly by sending the current through a known resistor and then measuring the voltage developed across this resistor. This indirect method offers another difficulty because the known resistor must be made large enough to give a measurable voltage drop. Thus, if the true current being measured at some low light level is only ½ ma, in order to get a reading of ½ volt, for example, the known resistor would have to be 1000 ohms. This relatively high value of extra resistance inserted into the circuit would substantially reduce the current flow and would accordingly result in misleading readings. In general, therefore, the inherently low impedance of the moving-coil meter constitutes a desirable feature for measurement of current.

Moreover, when the moving-coil meter is used in a VOM arrangement, it provides greater simplicity and convenience than the electronic voltmeter, which usually requires connection to the a-c line.

For these reasons, the VOM version of the moving-coil meter remains a highly desirable instrument for all those situations where its limited measurement ranges and its relatively low impedance do not interfere with its convenient use. We turn to the electronic voltmeter, on the other hand, when the advantages offered by its extended ranges and relatively high impedance are important.

Main Advantages of the Electronic Voltmeter

The electronic voltmeter is generally characterized by an *electron device* which supplies an additional function of amplification to the basic motor action of the moving-coil voltmeter. This device may be either a vacuum-tube or transistor circuit. When a transistor circuit is used for amplification, the instrument is called a transistor voltmeter (TVM). Frequently, however, because of the popularity of the well-established vacuum-tube voltmeters, the term *VTVM* is used to include both the tube and transistor versions of voltmeter (instead of the more technically correct term, *electronic voltmeter*). In any case, whether a VTVM or TVM, the element of electronic amplification in the electronic voltmeter, along with many other (but not all) elements present in the VOM, appreciably extends and adds to the meter's capabilities.

The added flexibility gained by the use of electronic amplifying circuits in the electronic voltmeter enables us to obtain highly-sensitive *voltage* measurements without producing an appreciable disturbance in the circuit being measured. In addition to this amplifying feature, the electronic circuit takes advantage of the inherently small inertia possessed by the electron to produce a speed of response to the incoming signal much faster than either mechanical or even purely electrical action can offer. Such fast response in electronic voltmeters allows us to obtain precise measurements at very high signal frequencies.

These highly desirable features of the electronic voltmeter may be summarized as *great sensitivity, high input impedance,* and *very high frequency range*. These qualities all stem from the basic principles underlying the electronic circuit. It is therefore important, at the outset, to be clear about the nature of electronic action, particularly in regard to those factors that distinguish electronic action from the more familiar principles of electrical action.

1-2. ELECTRICAL CONDUCTION AND ELECTRONIC ACTION

The study of electronic action extends the concepts of electrical conduction, usually in wires, into the area of the flow of electrons in a vacuum, a gas, or a semiconductor. Accordingly, *electronics is the study of the action of electron devices, such as the vacuum tube, the gas tube, and semiconductor devices.* (The semiconductor in the two-element form is usually called a *crystal diode;* in the three-element form it is usually called a *transistor.*) The study of these active electron devices in circuit form also takes into account components normally associated with electrical circuits. It thus includes the action of passive elements such as resistors, inductors, and capacitors. For this reason, there naturally is considerable similarity between electronic and electrical circuits.

While recognizing the tendency of the two areas to overlap in borderline cases, it is very helpful at the outset to emphasize the essential distinction between them: the relatively unhampered flow of electrons in an electron device affords an opportunity for a *very sensitive and accurate control action* that results in a tremendous variety of practical applications that go far beyond those possible with electrical devices. If, for example, we compare an electrical incandescent lamp with an electronic tube, it will be found that the flow of the free electrons in the vacuum tube makes possible such added versatile actions as *amplification, rectification,* and *oscillation* — actions that are not obtainable from ordinary wire conduction alone. The ease with which such control action can be accomplished is made strikingly visible in such electronic applications as the cathode-ray tube and associated amplifiers. Here we are able to follow and display the results of electron motion that changes at the rate of many millions of times per second (in the megacycle range).

This remarkable control ability stems primarily from the inherently small mass (or inertia) of the electron. In an electron device, such as a vacuum or gas tube (and also in solid-state semiconductor devices), the electrons are in an environment where they can move about relatively freely. In such an environment we can take advantage of their extremely small inertia to exert a much more flexible control over their actions, as compared to wire conduction where we can exert control only over the relatively-slow "electron-drift." Consequently, the possibilities for fine control by the use of electronics go far beyond the capabilities of electrical equipment. It is this combination of the amplifying properties of the electron device and its flexible control characteristic that provides the basis for the host of developments in the electronic measurement field that are constantly expanding in number and variety.

Strictly speaking, electronic action may be considered as a particular variety of electrical phenomena in general. The distinguishing factor to keep in mind is that the category of electronic applications generally presumes the presence of an electronic device, which has added properties quite apart from the familiar examples in the electrical equipment category that depend primarily on the conduction of electricity in wires.

Since the electron device is so much concerned with the motion of electrons freed from conducting wires, it will be helpful, at this point, to examine the *electronic structure* of the atoms that produce these highly mobile electrons.

1-3. ATOMS AND ELECTRONS: THE STRUCTURE OF MATTER

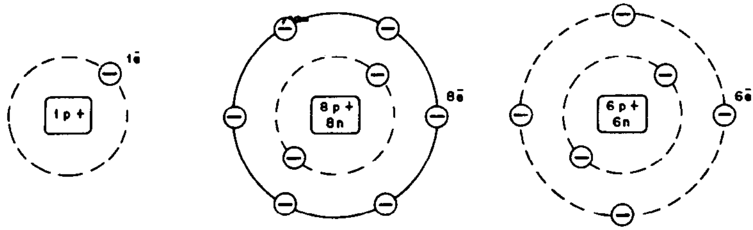
Molecules and Atoms

A thorough understanding of the nature of electronic (and electrical) action begins with a consideration of the fundamental structure of matter. A very brief review of the structure of the atom — the basic building block of all material things — will help to clarify many electronic functions. These functions are possible because of the fundamental principle of the structure of matter: *all matter is made up of atoms — atoms, in turn, are essentially composed of negatively-charged electrons, positively-charged protons, and electrically-neutral neutrons.*

The postulation that all matter is made up of atoms applies to all states of matter — solid, liquid, and gaseous. Thus, various combinations of electrons, protrons, and neutrons constitute the 103 different basic atoms, or elements.

A familiar example of matter, such as a drop of water, will serve to demonstrate the atomic structure of matter. If we divide the drop into smaller and smaller particles, we will eventually obtain the smallest possible quantity that still retains the properties of water.

This minute particle is known as a single *molecule* of water. This single molecule, identical in all respects to the myriad of other molecules making up our water drop, is designated by the chemical formula H_2O, signifying that it is made up of only three atoms: two atoms of hydrogen (2H) and one atom of oxygen (O).



(A) HYDROGEN (H)
Atomic no. (Z) = 1
Atomic wt. (A) = 1

(B) OXYGEN (O)
Atomic no. (Z) = 8
Atomic wt. (A) = 16

(C) CARBON (C)
Atomic no. (Z) = 6
Atomic wt. (A) = 12

FIG. 1-3. Simplified symbolic representations of atoms. The hydrogen atom (A) and the oxygen atom (B) are normally in an electrically neutral condition, with the number of external negative electrons balancing the charge of the positive protons in the nucleus. The atomic number (Z) indicates the positive charge in the nucleus; the atomic weight (A) shows the total weight of all of the nucleons (for carbon (C) this is 6 protons and 6 neutrons).

Turning our attention now to the atom of hydrogen (the simplest of all the elements), we find that it is made up of just one electron and one proton. An idealized model of the hydrogen atom (Fig. 1-3A) depicts the single electron orbiting the atomic nucleus, which consists of just the single proton. The atom of oxygen (Fig. 1-3B) can similarly be described and pictured as containing eight protons and eight neutrons in its nucleus, with eight external or orbital electrons arranged in two rings (or shells) around the nucleus.

As a second example, examination of carbon dioxide (whether as a gas in exhaled breath or in its pure form, solid "dry ice") will disclose a molecular configuration described by the formula CO_2, signifying that each molecule of carbon dioxide is composed of one atom of carbon (C) and two atoms of oxygen (2O). This introduces another element, carbon, whose atomic structure (Fig. 1-3C) consists of a nucleus containing six protons and six neutrons that is surrounded