GALVANOMETERS, ELECTROMECHANICAL VOLTMETERS, AND AMMETERS

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Contents

Summary

Voltage measurement is an essential aspect of electrical engineering and of many other engineering disciplines. Basically, it is the determination of the electric potential difference between two points. The potential difference is the amount of work needed to move a unit charge from a reference point to a specific point against an electric field. The measurement unit for voltage is—in the International System of Units (SI)—the volt (symbol V). The volt is one of the fundamental electrical units.

A charged body in an electric field is subject to a force and if the body is not restrained, it will start moving in the electric field. The result of the movement of charged bodies from one point to another point in the space is the electric current. The current is the charge flow per unit time. The electric current is the rate of charge flowing in a cross-section of the conducting element in a second and its measurement unit is—in SI—the ampere (symbol A).

Instruments that measure voltages and currents are called voltmeters and ammeters, respectively. There are four distinct types of voltmeters and ammeters, which differ in the operating principles they are based on:

1. electromechanical instruments,
2. thermal type instruments,
3. electronic instruments, and
4. oscilloscopes or vacuum-tube instruments.

In this article, classical techniques, such as electromagnetic—including potentiometric measurements—and thermal-type ammeters and voltmeters are described. Relatively new electronic voltmeters and ammeters are described in *Electronic Ammeters and Voltmeters*. Discussions on oscilloscopes can also be found in that article.

1. Introduction

Voltage measurement is the determination of the electric potential difference between two points. The measurement unit for the voltage is—in SI—the volt (symbol V), which takes its name in honor of the Italian physicist, Alessandro Volta (1745–1827). The term voltage is also used to indicate the electric potential or the electromotive force. The volt is one of the fundamental electrical units.

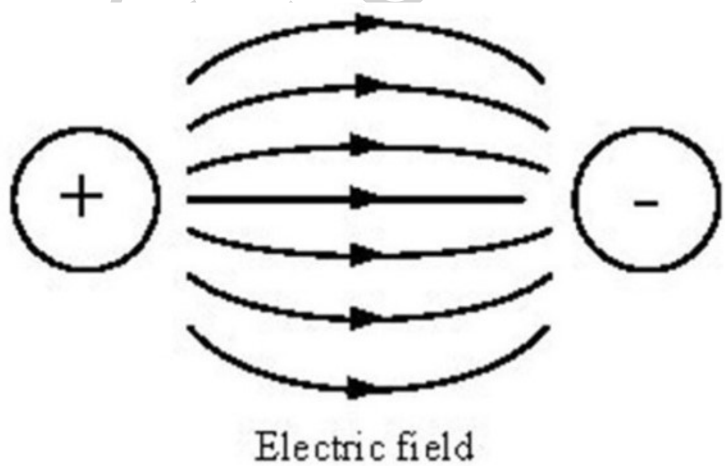

Figure 1. Electric potential difference between two charged bodies related to an electric field

In order to perceive how a difference in electric potential may arise, it must be taken into account that if there are two charged bodies, a force arises when one charged body acts upon the other. This force is represented by the electric field (see Figure 1). The potential is the amount of work needed to move a unit charge from a reference point to a specific point against an electric field. The work done in moving a charge is always relative to another charge, therefore, the potential difference is always relative to some reference point. Typically, the reference point is the earth, although any other reference point can be used. Nevertheless, in many applications, the relativity of potential is omitted and the reference point is usually taken to be at the ground. The ground is the body of the earth that can accept or supply charge without changing its characteristics.

Since the potential difference is taken as the work per unit charge, the unit of potential, the volt, is related to the unit of work or joule (symbol J) and the unit of charge or coulomb (symbol C) by:

$$1\ \mathrm{V} = 1\ \mathrm{J/C} \tag{1}$$

Although the concept of electric potential is useful in understanding electrical phenomena, it is worth noting that only the differences in potential energy are measurable. In general, it is commonly understood that the term voltage refers to potential difference, and that differences in potential energy are measured by voltmeters. According to the above statement, a charged body in an electric field is subject to a force. If the body is not restrained, it will start moving in the electric field. The result of the movement of charged bodies from one point to another point in space is the electric current. In the metallic conductors used in electric circuits, the charged bodies that can flow through the conductors are the electrons. A basic property of an electron is its charge (1.603×10^{-19} C). The electric current is the rate of charge flowing in a cross-section of the conducting element in a second, and its measurement unit is—in SI—the ampere (symbol A), which takes its name in honor of the French physicist, André Marie Ampère (1775–1836).

Since the current is taken as the charge flow per unit time, its measurement unit is related to the unit of charge and the unit of time (i.e., the second, symbol s) by:

$$1\ \mathrm{A} = 1\ \mathrm{C/s} \tag{2}$$

The current flowing through a circuit element can also be related to the properties of the circuit element and the voltage across its terminals by the well-known Ohm's law:

$$V = R\,I \tag{3}$$

where R is a quantity representing the electric behavior of the circuit element. Under DC conditions this quantity is called resistance and its measurement unit is—in SI—the ohm (symbol Ω), which takes its name in honor of the German physicist, George Simon Ohm (1789–1854).

The knowledge of the voltage located at the terminal of each circuit element—as well as the current flowing in each element—gives full knowledge of the circuit behavior. The measurement of voltages and currents, hence, is of the utmost importance, and extensively used in electrical and electronic engineering—especially in the power industry. Moreover, when electronic devices for signal processing are involved, such as those used in telecommunication systems, control systems, and informatics, the majority of the signals involved are in voltage form. Therefore, the voltage and current measurements constitute an important area in industrial and laboratory measurements, sensors, and systems.

Human beings possess good measurement systems within their own senses for many physical quantities, such as temperature, distance, and acoustic waves. Electric quantities, on the contrary, interfere with our life systems, and any attempt at sensing them directly may be severely harmful to our health. Therefore, we need instruments able to convert electric quantities into a form observable by ourselves. Instruments that measure voltages are called voltmeters, while instruments that measure currents are called ammeters.

There are four distinct types of voltmeters and ammeters, which differ in the operating principles they are based on:

1. *Electromechanical instruments.* These are based on the mechanical interaction between currents, between a current and a magnetic field, or between electrified conductors. This interaction generates a mechanical torque proportional to the voltage, or the squared voltage to be measured (in voltmeters), or proportional to the current, or the squared current to be measured (in ammeters). This torque is balanced by a restraining torque—usually generated by a spring—and causes the instrument pointer to be displaced by an angle proportional to the driving torque, and hence to the quantity, or squared quantity, to be measured. The value of the input voltage or current is, therefore, given by the reading of the pointer displacement on a graduated scale.
2. *Thermal type instruments.* These are based on the thermal effects of a current flowing into a conductor and their reading is proportional to the squared input voltage or current. These instruments are not as widely used as the electromechanical ones.
3. *Electronic instruments.* These instruments are based on purely electronic circuits, and attain the required measurement by processing the input signal by means of electronic semiconductor devices. The method employed to process the input signal can be either analog or digital—in the first case "analog" electronic instruments are obtained, while in the second case "digital" electronic instruments are obtained. A peculiar characteristic of the electronic instruments is that their input is voltage, and currents can be measured only after they have been converted into voltages.
4. *Oscilloscopes or vacuum-tube instruments*. These instruments are basically voltmeters, and their main characteristic is to allow a graphic representation—on a cathode ray tube (CRT)—of the input signal. The desired measurements can be performed directly on the displayed signal.

Table 1 shows a rough classification of the most commonly employed voltmeters and ammeters, according to their operating principle and their typical application field.

Class	**Operating principle**	**Subclass**	**Application field**
Electromagnetic	Interaction between currents and magnetic fields	Moving magnet	DC current and voltage
		Moving coil	DC current and voltage
		Moving iron	DC and AC current and voltage

Electrodynamic	Interactions between currents	–	DC and AC current and voltage
Electrostatic	Electrostatic interactions	–	DC and AC voltage
Thermal	Current’s thermal effects	Direct action	DC and AC current and voltage
		Indirect action	DC and AC current and voltage
Induction	Magnetic induction	–	AC current and voltage
Electronic	Signal processing	Analog	DC and AC voltage and current
		Digital	DC and AC voltage and current

Table 1. Classification of voltage and current meters

This article concentrates on the electromechanical and thermal instruments; information on the electronic instruments and oscilloscopes can be found in *Electronic Ammeters and Voltmeters*.

2. Measurement Fundamentals

2.1. Information Retrieval

Any measurement operation can be seen as the retrieval of particular information carried by the input signal. Particular care should, therefore, be taken in analyzing the nature of the input signal and assessing which kind of information has to be retrieved by the measurement operation.

In nature, most of the usual applications of electrical and electronic engineering, voltages, and currents exist in continuous form. This means that a generic voltage v and a generic current i can be represented by a continuous function of time t as:

$$v = v(t) \quad \text{and} \quad i = i(t) \tag{4}$$

Different kinds of signals, such as pulse signals or discrete signals can be also found in nature—especially at the atomic scale. Such signals, however, require to be measured with different kinds of instruments from the ones that are going to be illustrated here. For this reason, only continuous—or analog—signals will be considered in the following sections.

Voltages and currents can be constants with time, in the DC systems. This means that:

$$v = v(t) = V_{dc}, \text{ const.} \quad \text{and} \quad i = i(t) = I_{dc}, \text{ const.} \tag{5}$$

The whole information associated with such signals is fully known when the value of V_{dc} and I_{dc} is measured. Therefore, voltmeters and ammeters for DC systems are realized in order to measure V_{dc} and I_{dc}, respectively.

A second, very important class of signals in electrical and electronic engineering is *periodic* signals. A generic signal f is periodic of period T if the following relationship is verified:

$$f(t) = f(t + T) \tag{6}$$

Among the periodic signals, sinusoidal voltages and currents play a fundamental role in electric power systems. A sinusoidal signal is represented by the following expression as a function of time:

$$f\left(t\right) = \sqrt{2}A\sin\left(2\pi\, ft + \varphi\right) \tag{7}$$

where A is called root mean square (rms) value of the signal, f is the signal frequency and is equal to the inverse of the signal period ($f = 1/T$), and φ is the signal phase angle. Figure 2 shows an example of a sine wave.

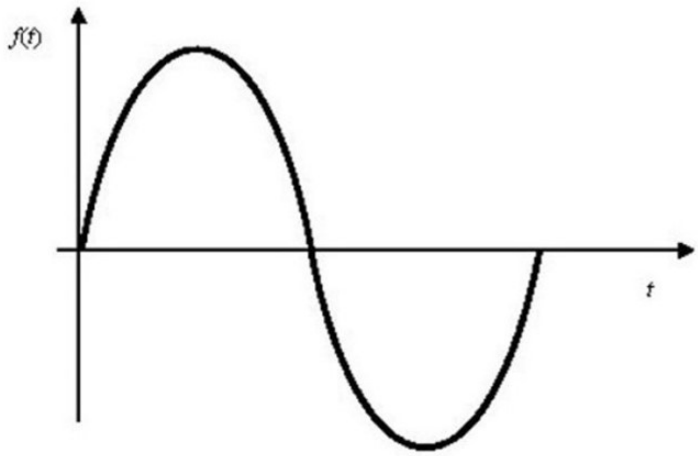

Figure 2. A periodic sinusoidal signal

The rms value is related to the signal peak value A_p by the constant factor $\sqrt{2}$, that is, $A_p = \sqrt{2}A$. Although this relationship applies only to the sinusoidal signals, the concept of rms value is valid for any periodic signal. In fact, the rms value of a periodic signal, with period T, is defined by:

$$A = \sqrt{\frac{1}{T}\int_T f^2\left(t\right)dt} \tag{8}$$

An important interpretation can be given to the rms value from the energy point of view. It can be proven that the electric power dissipated into a resistor with a resistance value, R, by a periodic current with rms value, I, is always RI^2, which is independent from the waveform of the current. It is also the same power dissipated by a DC current flowing into the resistor with $I_{dc} = I$. Similarly, the electric power dissipated into a resistor with resistance R when a periodic voltage with rms value V is applied to the resistor is V^2/R, which is independent from the voltage waveform. It is also the same power dissipated into the resistor when a DC voltage is applied to it with $V_{dc} = V$.

Another important value of a periodic waveform is the rectified mean value, since a number of physical phenomena are ruled by this value. It is defined by:

$$A_{\text{mean}} = \frac{1}{T}\int_T \left| f\left(t\right) \right| dt \tag{9}$$

When sinusoidal signals are concerned, there is a fixed relationship between the peak value A_{p}, the rms value A, and the rectified mean value A_{mean}:

$$A = \frac{1}{\sqrt{2}} A_{\text{p}}, \quad A_{\text{mean}} = \frac{2}{\pi} A_{\text{p}}, \quad \text{and} \quad A = \frac{\pi}{2\sqrt{2}} A_{\text{mean}} \tag{10}$$

The factor $\frac{\pi}{2\sqrt{2}}$ is called the form factor for a sinusoidal signal.

According to the above definitions, different quantities can be measured, starting from the same input signal, in AC systems under periodic conditions. Therefore, great care must be taken in selecting the most suitable instrument. Usually a single voltmeter or ammeter is designed to measure only one of the above quantities correctly. The meters are also usually designed to work correctly only for a given input waveform—generally a sine wave. The use of an instrument with input waveforms other than the rated one may lead to unpredictable measurement errors.

2.2. Measurement Uncertainty

One of the key points in measurement science is that a measured quantity cannot be known with infinite accuracy. This is obviously because the instruments employed are not ideal, and, therefore, their imperfections interfere with the input signal by modifying it. Instruments are subject to modifications because of changes in environmental factors, such as temperature, humidity, pressure, and so on. Furthermore, the input signal is subject to external electromagnetic interference (EMI), which adds noise components that may alter or even mask the input signal, thus causing the instrument to measure a different quantity from the expected one. Last, but not least, the operator may be not totally adequately trained to perform the measurement in the proper way, thus further decreasing measurement accuracy.

The above considerations lead one to conclude that the result of a measurement cannot be represented by a single value, since it is not possible to state how distant this value is from the actual value assumed by the measured quantity. More properly, a measurement result should be given as an interval within which the measured value is expected to fall with a given confidence. In other words, this interval represents a set of values that can be indifferently assigned to the quantity to be measured. The amplitude of this interval is related to all of the above listed factors that can interfere with the measurement process. The more the factors exist within the measurement environment, the wider will be the interval of the results.

The interval representing the possible values to be assigned to the measurement results is generally represented by means of its central value and the semi-amplitude of the interval. This last value is called measurement uncertainty, and is generally expressed as a percentage value of the given central value.

The possible reasons that the result of a measurement is not *a priori* equal to the value assumed by the measured quantity can be classified into two main classes: systematic reasons and random ones.

The systematic sources of uncertainty are those events that always affect the measurement process in the same way. A typical example of a systematic source of uncertainty is the different length of the beams in a balance. It is quite obvious that, if the systematic sources of uncertainty are detected, their effect on the measurement result can be compensated. In the case of a balance with different length beams this can be done by exchanging the position of the unknown weight and the standard weight on the balance pans, repeating the weighing, and averaging the two results obtained. If the systematic sources of uncertainty are not detected, no countermeasures can be taken in order to compensate their effects and they have to be treated as random sources.

The random sources of uncertainty are those events that affect the measurement procedure in a random way. A typical example of a random source of uncertainty is a white noise superimposed to the input signal. The effect of the random sources of uncertainty on the final measurement uncertainty can be evaluated by means of statistical computations, as shown by the IEC standard *Guide to the Expression of the Uncertainty in Measurement*.

If a population of N different measured values x_i, $i = 1, 2, \ldots, N$, of the same quantity x is available, the standard uncertainty is defined as the standard deviation $u(x)$ of the N measured values:

$$u(x) = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i - \overline{x}\right)^2}{N-1}} \tag{11}$$

where $\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$ is the mean value of the measured values.

Under the hypothesis that the measured values follow a given probability distribution (Gaussian, uniform, …) the standard deviation represents a given probability that a measured value falls in the interval $\overline{x} - u(x); \overline{x} + u(x)$. In order to increase the probability that a measured value of the input quantity falls within the given interval, the extended uncertainty is defined as the standard uncertainty multiplied by a proper coverage factor $U = ku(x)$. The coverage factor k allows for specifying the measurement uncertainty with the desired confidence level, starting from the standard uncertainty. The correct choice of the coverage factor is up to the operator, on the basis of the operator's experience and the actual measurement conditions. Some examples on how to evaluate the measurement uncertainty are given by the IEC standard *Guide to the Expression of the Uncertainty in Measurement*.

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Biographical Sketches

Dr. Halit Eren has received the degrees of B.Eng. (1973), M.Eng. in Electrical Engineering (1975), and Ph.D. in Control Engineering—all from the University of Sheffield, UK. Recently he has obtained an MBA from Curtin University of Technology, Perth, Western Australia. Dr. Eren has been lecturing at the Curtin University of Technology since 1983, first at the Kalgoorlie School of Mines and then at the School of Electrical and Computer Engineering. He has served as the Head of Department of Electronic and Communication for some time. His expertise areas are control systems; instruments, instrumentation, and networking; mineral processing; signal processing; and engineering mathematics. His principal areas of research are ultrasonic and infrared techniques, density and flow measurements, moisture measurements, fieldbus, telemetry, telecontrolers, mobile robots, hydrocyclones, and applications of artificial intelligence. He serves as a consultant to a number of industrial establishments. He has written numerous articles in books published by CRC Press and Wiley and Sons.

Alessandro Ferrero was born in Milano (Milan), Italy, in 1954. He received his M.S. degree in Electrical Engineering from the Politecnico di Milano in 1978. In 1983 he joined the Dipartimento di Elettrotecnica of the Politecnico di Milano as an Assistant Professor on Electrical Measurements. From 1987 to 1991 he was Associate Professor of Measurements on Electrical Machines and Plants at the University of Catania, Italy. From 1991 to 1994 he was Associate Professor of Electrical Measurements at the Dipartimento di Elettrotecnica of the Politecnico di Milano University. He is presently Full Professor of Electrical and

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