

## ELECTRONIC VOLTMETERS AND AMMETERS

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### Contents

1. Introduction.
2. Analog Meters
  - 2.1. DC Analog Voltmeters and Ammeters
  - 2.2. AC Analog Voltmeters and Ammeters
  - 2.3. True rms Analog Voltmeters
3. Digital Meters
  - 3.1. Dual-Slope DVMs
  - 3.2. Successive-Approximation ADCs
  - 3.3. AC Digital Voltmeters and Ammeters
  - 3.4. Frequency Response of AC Meters
4. Radio-Frequency Microvoltmeters
5. Vacuum-Tube Voltmeters and Oscilloscopes
  - 5.1. Analog Oscilloscopes
  - 5.2. Digital Storage Oscilloscopes (DSOs)
  - 5.3. Portable Oscilloscopes
  - 5.4. High-Voltage Oscilloscopes
- Appendix
- Glossary
- Bibliography
- Biographical Sketches

### Summary

Voltage and current measurements are essential parts of engineering and science. Instruments that measure voltages and currents are called voltmeters and ammeters, respectively. There are two distinct types of voltmeter and ammeter, which differ from each other by the operating principle that they are based on: electromechanical instruments and electronic instruments, which also include oscilloscopes.

Electromechanical voltmeters and ammeters, including thermal-type instruments, represent early technology, but still are used in many applications. Basic elements of voltages and currents from the basic physical principles have been introduced in the electromechanical voltage and current measurements section. Also, voltage and currents standards have been dealt with in detail in other articles.

In this article, modern electronic voltmeters and ammeters are discussed. Some information is given on oscilloscopes as one of the important voltage measuring devices, although they are generally not classified as voltmeters or ammeters. The analog electronic voltmeters and ammeters in the form of DC, rectifier-based AC, and true rms devices are explained in detail. Digital meters are introduced, as are types of voltmeters and ammeters operating on different techniques of analog-to-digital signal converters. A list of some manufacturers of electronic voltmeters, ammeters, and oscilloscopes is given in Appendix 1.

## 1. Introduction

The development of semiconductor devices, including operational amplifiers, had an impressive impact on measurement instruments, including voltmeters and ammeters. Voltmeters and ammeters, in particular, have moved steadily from conventional electromechanical architectures to electronic ones. In general, electronic meters—and indeed many electronic devices—can be represented as three-port circuits, as in Figure 1.

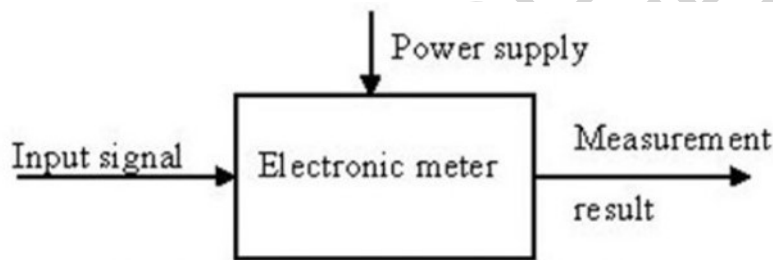


Figure 1. Three-port representation of electronic meters

In the three-port model, the input signal enters the instrument through the input port, which is usually characterized by a high impedance. The majority of electronic meters require high-input impedance; they can, therefore, be regarded as voltmeters that present a negligible load for the signal source. In addition, electronic ammeters can be realized from the basic principles of voltmeters by means of variations in the input stages described in the chapter dedicated on the electromechanical instruments of this encyclopedia.

Once the input signals are suitably processed, the measurement result is provided by the output port in either analog or digital form. In this article, discussion will concentrate on the nature of the input signals, signal processing, and the output requirements to display the measurement results, along with the power needed to energize the device.

The electric power required to energize the meter's internal circuits and the output display components is supplied to the meter itself through the power-supply port. In contrast to electromechanical types, the need for an external power supply is one of the main characteristics of electronic meters. Though this may appear as a drawback—especially when portable meters are concerned—it should be considered that the external power supply allows the device not to draw, or draw minimal, energy from the signal source for the measurements. This explains why electronic voltmeters do not load

the signal source as much as their electromechanical counterparts. It also leads to many other important advantages of modern electronic meters over traditional electromechanical ones, such as the accurate measurement of very small amplitude and high-frequency currents and voltages.

The high-level, low-noise performance of present-day electronic devices allows for realizing meters that are as accurate as, and sometimes even more accurate than, the most accurate electromechanical meters. Since they do not require the extensive use of precision mechanics, they are presently less expensive than electromechanical meters, and are slowly, but constantly, replacing them in almost all applications.

In accordance with the processing of input signals, measurement, and display requirements, electronic meters are divided into analog meters and digital meters.

Analog meters attain the required measurements by continuous-time processing of the input signals using analog circuits. The measurement results are displayed either in analog form, for instance, as an electromechanical meter, or in digital form, by converting the output signal into a digital format.

On the other hand, digital meters attain the required measurements by converting the analog input signal into a sequence of digital samples uniformly spaced in time in the early stages of the signal processing. The input signals are, therefore, processed in the discrete-time domain, and the measurement results are usually displayed in a digital form. It is worthwhile to note that the distinction between analog and digital meters does not refer to the way the measurement results are displayed, but to the domain—continuous-time or discrete-time domain—in which the input signals are processed in the main body of the devices.

The basic component in digital meters is the analog-to-digital converter (ADC) that takes care of converting the analog samples of the input signals into proportional digital values.

This article concentrates on analog electronic meters, digital voltmeters (DVMs), ADCs, and digital measurement systems. Vacuum-tube voltmeters and oscilloscopes are also discussed since they are among the most widely employed electronic meters.

## **2. Analog Meters**

An electronic analog voltmeter is primarily based on an electronic amplifier for input signal processing and a DC ammeter—usually an electromechanical meter—to display the output signal of the amplifier. The operating principle consists of the generation of the output DC current of the amplifier proportional to the input signal to be measured. This DC current flows into the DC ammeter, thus forming a DC moving-coil milliammeter.

Analog meters are usually voltage measurement systems, with a high-input impedance—as high as a few megaohms. Current measurements can be also realized by properly modifying the input stages of the voltage-measuring devices. The internal resistance of the realized ammeters is in the range of a few ohms.

When a voltmeter is configured, different full-scale values can be obtained by using selectable-ratio voltage dividers if the input voltage is higher than the amplifier dynamic range. The same objectives can also be achieved by selecting the appropriate amplifier gains if the input voltage stays within the amplifier's dynamic range.

For the ammeters, different full-scale values can again be obtained by using selectable-input shunt resistors in order to convert the input currents into voltage signals covering the dynamic range of the operational amplifier.

The main features of analog meters are high gain and wide bandwidth for AC measurements. The relative measurement uncertainty of the instrument can be as low as the 0.1% of the full-scale value. However, the reading errors may be much higher, since human judgment and interpretation are involved. Because of these features, electronic analog voltmeters may have better performances than electromechanical ones within the same price range of devices.

## 2.1. DC Analog Voltmeters and Ammeters

Figure 2 shows a typical basic structure of a DC analog voltmeter. Assuming that the operational amplifier has an ideal behavior, it can be readily checked that current  $I_m$ , flowing in the milliammeter A, is given by:

$$\begin{aligned} I_m &= I_o + I_2 = \frac{U_o}{R_o} + \frac{U_o}{R_2} \\ &= -U_i \frac{R_2}{R_1} \frac{R_2 + R_o}{R_2 R_o} = -\frac{U_i}{R_1} \left( 1 + \frac{R_2}{R_o} \right) \end{aligned} \quad (1)$$

If  $R_1 = R_2$  is taken—and the same resistances are far greater than  $R_o$ —Eq. (1) becomes:

$$I_m = -\frac{U_i}{R_o} \quad (2)$$

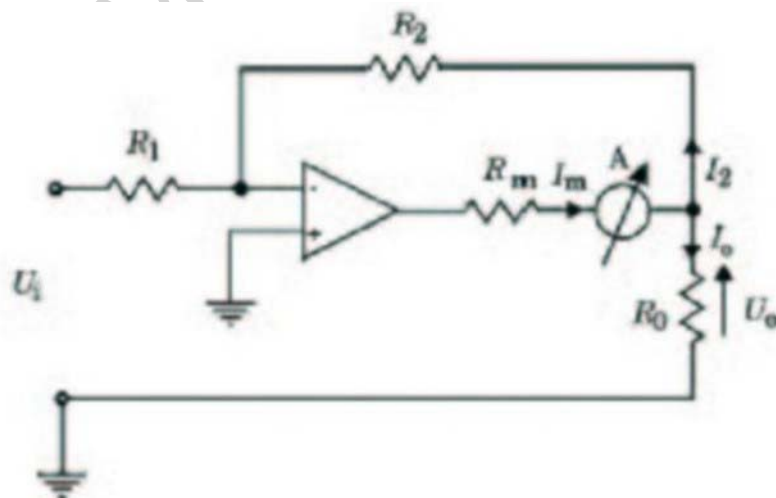


Figure 2. Electronic DC analog voltmeter structure

Eq. (2) shows that the milliammeter reading is directly proportional to the input voltage through resistance  $R_o$  only. This means that—once the milliammeter full-scale value is set—the voltmeter full-scale value can be changed—within the dynamic range of the amplifier—by changing the value of  $R_o$ . This way, the full-scale value of the meter can be changed without changing the input impedance.

The structure in Figure 2 can be used as a DC ammeter if the current  $I_i$  to be measured is converted into voltage  $U_i$  by means of the shunt resistor  $R_s$ . Provided that  $R_s \ll R_1$ , the milliammeter reading is given by:

$$I_m = -\frac{U_i}{R_o} = -\frac{R_s}{R_o} I_i \quad (3)$$

The ammeter full-scale value can again be set—within the dynamic range of the amplifier—by changing  $R_o$  only, without changing the ammeter external resistance  $R_s$ .

## 2.2. AC Analog Voltmeters and Ammeters

The principle of operation of most AC voltmeters is based on measuring voltage amplification—or attenuation—and its conversion into another physical quantity. The basic structures consists of voltage dividers and AC voltage amplifiers. The analog methods of AC voltage conversion are used in both analog AC voltmeters and digital ones. Usually, such analog methods provide AC voltage conversion into DC voltage by using AC–DC converters. Depending on the type of AC–DC converter, the DC voltage can be made proportional to average, rms, or peak value of the AC voltage. The AC–DC converters can be:

- average AC–DC converters (half-wave or full-wave rectifiers),
- rms AC–DC converters, or
- peak AC–DC converters (peak detectors).

Recently, AC voltmeters have been designed using the method of sampling conversion—synchronous or random sampling. However, such methods of conversion are used both in analog AC voltmeters and in digital ones. For example, the True RMS Analog Millivoltmeter 9301A and the RF Digital Millivoltmeter 9303 Racal-Data Instruments use a random sampling method. Another example is in the Hewlett Packard 3458A, in which multimeter three methods of conversion are used: the analog rms method, the synchronous sampling, and the random sampling method.

In digital AC voltmeters based on analog methods of AC voltage conversion, the DC voltage is converted into digital form by means of ADCs. The methods of conversion include dual-slope, successive approximation techniques, and integrating types, as well as sigma–delta ADCs.

In many applications, AC analog voltages and currents are measured by means of DC analog voltmeters and ammeters with an addition of a rectifying circuits in the input stage. A typical basic structure for an AC analog voltmeter can be derived directly from that of Figure 2, modifying it as shown in Figure 3.

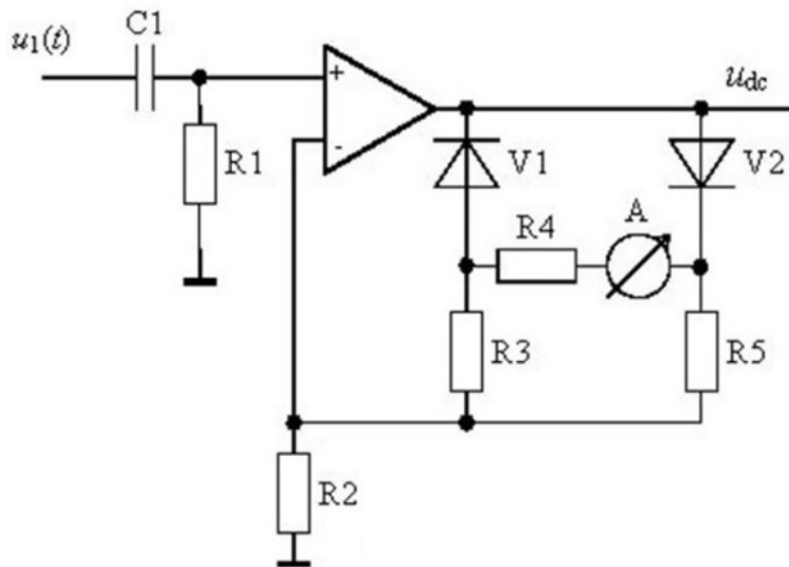


Figure 3. Rectifier-based AC analog voltmeter

Because of the high input impedance of the electronic amplifier,  $i_2(t) = 0$ , and hence current  $i_m(t)$  flowing through the milliammeter, A also flows through the load resistance, and, therefore,  $i_m(t) = i_o(t)$ . Since the amplifier is connected in a voltage-follower configuration, the output voltage is given by:

$$u_o(t) = u_i(t) \quad (4)$$

Due to the presence of the input diode, current  $i_m(t)$  is given by:

$$i_m(t) = \frac{u_i(t)}{R_0} \quad (5)$$

when  $u_i(t) > 0$ , and  $i_m(t) = 0$  when  $u_i(t) \leq 0$ .

The DC moving-coil milliammeter measures the average value  $\bar{I}_m$  of  $i_m(t)$ , which—under the assumption of sinusoidal signals—is related to the rms value  $U_i$  of  $u_i(t)$  by:

$$\bar{I}_m = \frac{2\sqrt{2}}{\pi R_0} U_i \quad (6)$$

The realized meter is actually an average detector, which can be used as an rms detector by labeling the DC milliammeter scale according to Eq. (6), provided that the input signal is a sine wave. Therefore, the realized instrument is not a true rms meter.

The structure in Figure 3 can readily be changed into an ammeter by converting the current to be measured  $i_i(t)$  into voltage  $u_i(t)$  by means of a shunt resistor  $R_s$ . In this situation, the average value  $\bar{I}_m$  of  $i_m(t)$  is related to the rms value  $I_i$  of the sinusoidal input current  $i_i(t)$  by:

$$\bar{I}_m = \frac{2\sqrt{2}}{\pi} \frac{R_s}{R_o} I_i \quad (7)$$

The same considerations as those reported for the AC voltmeter apply.

The structure of Figure 3 can be improved to the structure shown in Figure 4, where the input rectifying stage realizes a full-wave rectifier.

The output signal coming from amplifier  $A_1$  is given by:

$$u_1(t) = \begin{cases} -u_i(t) & \text{for } u_i(t) \geq 0 \\ 0 & \text{for } u_i(t) < 0 \end{cases} \quad (8)$$

where  $u_i(t)$  is the instrument input voltage. If capacitor  $C$  is supposed to be not connected, the output voltage of amplifier  $A_2$  is given by:

$$u_o(t) = -[u_i(t) + 2u_1(t)] \quad (9)$$

Taking into account Eq. (8), this output voltage can be also written as:

$$u_o(t) = \begin{cases} u_i(t) & \text{for } u_i(t) \geq 0 \\ -u_i(t) & \text{for } u_i(t) < 0 \end{cases} \quad (10)$$

thus proving that the circuit in Figure 4a realizes a full-wave rectifier. In the case of a sinusoidal input signal, the signal waveforms are shown in Figure 4b.

When capacitor  $C$  is connected in the feedback loop of amplifier  $A_2$ , the last stage of the circuit in Figure 4a is changed into a first-order, low-pass filter. The circuit output voltage is then given by the average value of  $u_o(t)$ :

$$\bar{U}_o = \overline{|u_i(t)|} \quad (11)$$

In the case of a sinusoidal input voltage, its rms value  $U_i$  is related to  $\bar{U}_o$  by:

$$\bar{U}_o = \frac{2\sqrt{2}}{\pi} U_i \quad (12)$$

and  $\bar{U}_o$  can be measured by a DC voltmeter.

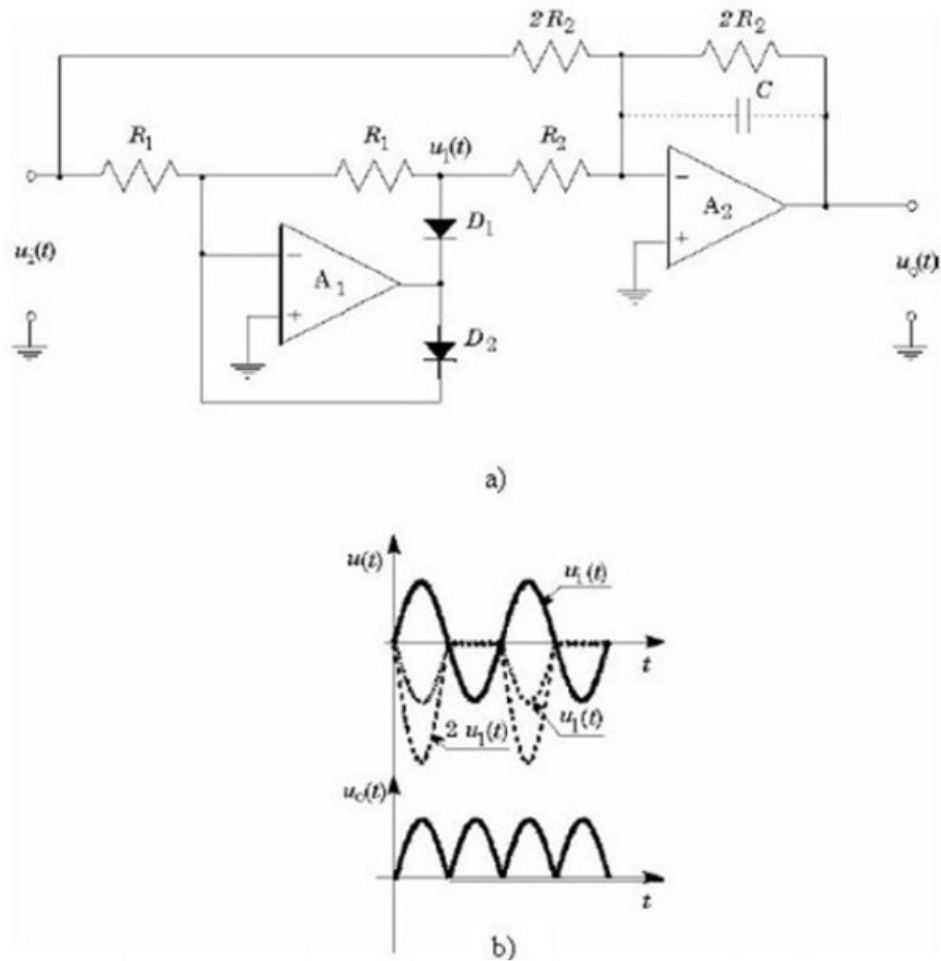


Figure 4. Average voltage AC–DC converter voltmeter: a. Structure; b. Signal waveforms

Once again the realized meter is actually an average voltage detector, that can be used as an rms detector only if the input signal is a sine wave. Therefore, the realized instrument is not a true rms meter.

The structure in Figure 4a can readily be changed into an ammeter by converting the current to be measured  $i_i(t)$  into voltage  $u_i(t)$  by means of a shunt resistor  $R_s$ .

In this situation, the average value  $\bar{U}_o$  is related to the rms value  $I_i$  of the sinusoidal input current  $i_i(t)$  by:

$$\bar{U}_o = \frac{2\sqrt{2}}{\pi} R_s I_i \quad (13)$$

The same considerations as those reported for the AC voltmeter apply.



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### Biographical Sketches

**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 Electronic Measurements at the same department. His current research interests are concerned with the application of digital methods to electrical measurements and measurements on electric power systems. He is a fellow member of IEEE, a member of AEI (the Italian Association of Electrical and Electronic Engineers), a member of ANIPLA (the Italian Association on Industrial Automation), and was also Chairman of the Milano Section for the two-year term 1997–1998, a member of the Italian Informal C.N.R. Group on Electrical and Electronic Measurements, and a member of the North Italy Chapter of the IEEE IM Society.

**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, Perth, Western Australia. 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, telecontrollers, mobile robots, hydrocyclones,

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