J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

VOLTMETERS

The electrical quantity *voltage* cannot be directly observed. A *voltmeter* is an instrument for measuring voltage. The indicating scale of a voltmeter may be calibrated in volts, nanovolts, microvolts, millivolts, kilovolts, or megavolts (not common). Electronic, oscilloscope, electrostatic, and electromagnetic voltmeters are some of the frequently used voltage-sensing instruments. The oscilloscope is basically an electronic voltmeter that also displays the voltage as it changes for visual interpretation: a pictorial presentation with a time dimension.

A dc (direct-current) voltmeter measures the constant voltage between two points. There are many different kinds of dc voltmeters. An ac (alternating-current) voltmeter contains an ac-to-dc converter that accepts an ac-voltage input and produces a dc voltage at its output that is proportional to the input voltage. An ac voltmeter may be calibrated to indicate effective or root-mean-square (rms), peak, or peak-to-peak values of sine waveforms.

There are two main classes of voltmeters.

First, in traditional voltage-measuring instruments the voltage is used to develop a mechanical force, usually an electromagnetic torque, that in turn causes motion of a pointer. The pointer displacement is proportional to the input voltage. The majority of these instruments are permanent-magnet moving-coil (*PMMC*) instruments. The instruments that use this meter movement technique are referred to as *analog voltmeters*. More recently analog voltmeters have undergone refinements to include very sensitive moving coils and electronic circuitry to improve their performance and accuracy. An analog voltmeter can be used to measure both dc and ac voltages, and may be a separate instrument or part on an analog multimeter.

Second, digital electronic technology has enhanced the capability and functionality of measuring instruments in general. In *digital voltmeters* (*DVMs*) an analog voltage signal is converted to binary numbers using an analog-to-digital converter (*ADC*). The binary numbers are changed to decimal display form. A digital voltmeter can be used to measure both dc and ac voltages. It can be a separate instrument or part of a general-purpose multimeter such as a *digital multimeter* (*DMM*) that can measure voltage, current, and other electrical quantities. Digital voltmeters are simple, flexible, more accurate and versatile, less prone to operator error, and less expensive than analog voltmeters, and they may be designed to be more compatible with other electronic and digital equipment. Therefore, this article will discuss analog voltmeters only briefly and concentrate on digital voltmeters.

Analog Voltmeters

An analog instrument uses a pointer that moves over a calibrated continuous range to indicate the results of a measured quantity. Figure 1 shows a typical analog voltmeter with a needle as an indicator over a calibrated scale. The pointer displacement is proportional to the input voltage. In an analog voltmeter the input voltage produces a proportional deflection force (or torque), which causes the needle to move over the calibrated scale to indicate the input voltage value. There are four basic methods that are used to produce the deflecting force:

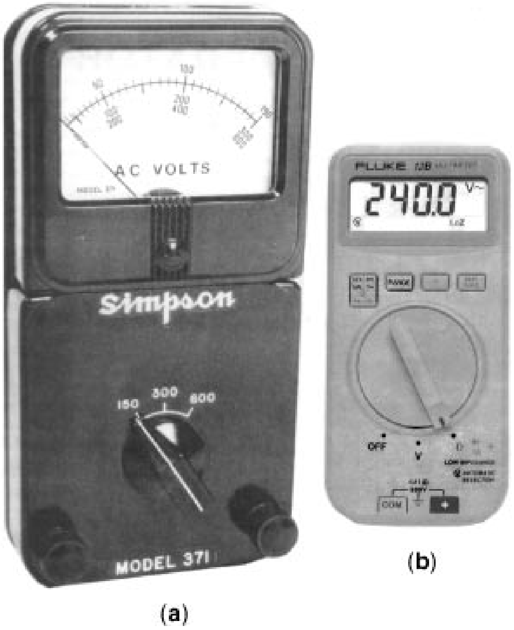


Fig. 1. (a) Analog voltmeter, simpson model 371 (courtesy of Simpson). (b) Digital voltmeter, Fluke model 12B (courtesy of Fluke).

(1) Thermal
(2) Electromagnetic: PMMC, moving-iron, electrodynamic, or induction movement
(3) Electrostatic
(4) Electronic

The first three moving-pointer instruments have some important limitations that include their inability to measure low voltages and having low input impedance. The electronic analog voltmeter has high input impedance, and it can also measure low voltage by using its amplification circuits to raise the low voltage to a high, measurable level. A brief description of analog meters follows.

Thermovoltmeters. Thermal instruments are based on the heating effect of electric current.

Hot-Wire Meters. A typical thermal instrument consists of two wires: a hot wire stretched between two adjustable posts, and a second wire (with a pointer) attached to the center of the hot wire and connected over a pulley to a spiral spring. When current flows through the hot wire, it expands, pulling the second wire over the pulley and causing the pointer to move over a calibrated scale. The spiral spring provides the controlling torque. More sensitive and accurate thermocouple instruments have replaced hot-wire instruments.

Thermocouple Voltmeters. Figure 2 illustrates the principle of the thermocouple instrument. It consists of a junction of two dissimilar metal wires welded to a heating wire. When current being measured is passed through the heating wire, the junction heats up and voltage is developed across it. The heating power is proportional to the square of the current through the hot wire. The voltage at the junction is a dc voltage, which is proportional to the temperature difference between the hot and cold junctions.

The free ends of the thermocouple wires are connected to the centers of two copper straps that are electrically insulated from the heater. This ensures that the ends of the thermocouple wires are at a temperature that is the mean of the temperatures at the ends of the heater element. When current flows through the

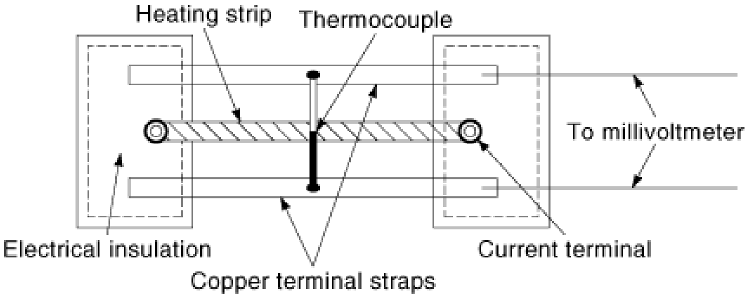


Fig. 2. Compensated thermocouple probe terminal used in a thermocouple instrument.

heater, the temperature at the center of the heater is greater than that at the ends (which remain at ambient temperature). The voltage generated at the heated junction is due to the heating effect only. The generated voltage is dc, and is proportional to the temperature difference between the hot and cold junctions.

A thermocouple voltmeter is obtained by connecting multiplier resistors in series with the heater. The scale of the voltmeter is calibrated to indicate voltage, rather than the square of voltage, and the voltmeter can be directly calibrated to indicate rms value. The instrument can measure either dcr rms ac. This is a characteristic of a *transfer instrument*, which can be calibrated to read dc and then used to measure ac.

Electromagnetic Voltmeters. The PMMC and the electrodynamic instruments are the two most important analog instruments that operate on the electromagnetic principle. The three forces that are exerted in such instruments are the deflecting force, the controlling force, and the damping force.

Permanent-Magnet Moving-Coil Voltmeters. A PMMC instrument is essentially a low-level dc ammeter that can be used as a voltmeter by connecting appropriate-value resistors in series with the moving coil. By using rectifier circuits with the PMMC instrument, it can also be used as an ac voltmeter. Figure 3(a) shows an illustrative internal view of a PMMC instrument. It has a lightweight moving coil pivoted between the poles of an external horseshoe permanent magnet. When current I flows through the coil, the coil sets up a magnetic field that interacts with the magnetic field of the permanent magnet. The coil experiences a force F, and the net effect on the coil is a rotational deflecting torque T, which acts against a restoring spiral spring as shown in Fig. 3(a). The deflecting torque developed by the moving coil is given by

$$T_{\mathrm{D}} = BILND \qquad (1)$$

T_{D} = deflecting torque (N·m)
B = flux density in the air-gap (T)
L = length of the coil (m)
N = number of turns of the coil
D = coil diameter (m)

The controlling torque due to the restoring spring is proportional to the amount of angular displacement of the pointer and is given by

$$T_{\mathrm{C}} = K\theta \qquad (2)$$

K = constant
θ = angular displacement (rad)

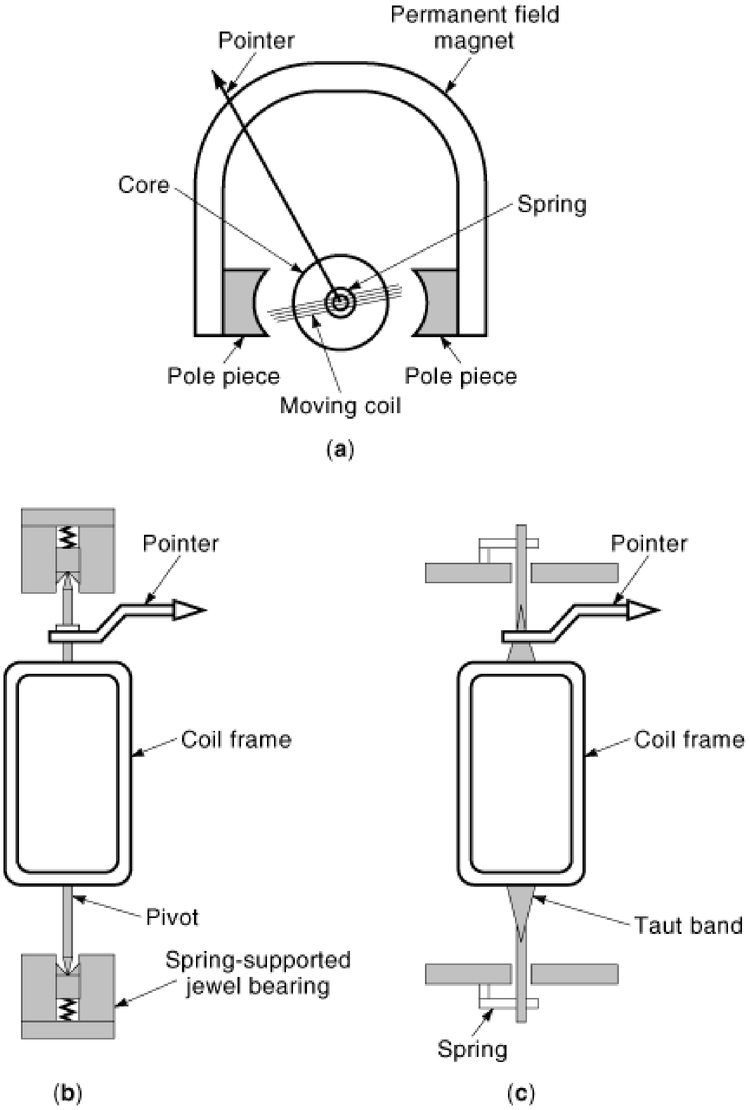


Fig. 3. PMMC instrument: (a) Permanent magnet and coil to produce the deflecting force. (b) Pivot-and-jeweled-bearing suspension system. (c) Taut-band suspension system.

The deflecting and controlling torques are equal:

$$T_C = T_D$$
$$K\theta = BLIND$$

The parameters B, L, N, and D are constants, and therefore,

$$\theta = K'I \tag{3}$$

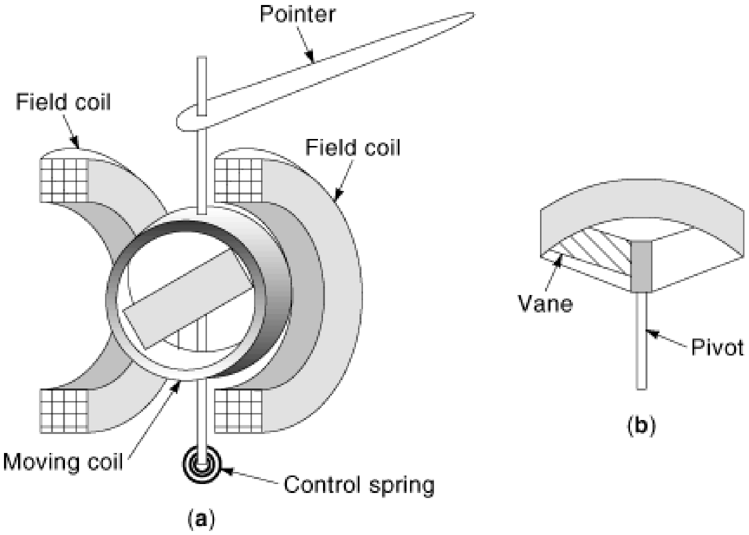


Fig. 4. Electrodynamic instrument: (a) The moving coil rotates between the two fixed coils. (b) Air damping system in an enclosed vane.

where K' is a constant. Equation (3) shows that the amount of angular displacement is proportional to the current flow in the coil.

The coil frame is made of aluminum, which is a nonmagnetic material. Eddy currents, induced in the coil frame, set up a magnetic flux that opposes the coil motion. This creates a damping force to minimize oscillations of the coil frame.

The moving system is precisely pivoted upon one of two common suspension systems. The *pivot-and-jeweled-bearing* system requires a pair of spiral-spring control systems at the ends of the coil frame as shown in Fig. 4(b). The spiral springs absorb the shock on the instrument if it is dropped on a bench.

More expensive and high-performance PMMC instruments use a *taut-band* suspension system as shown in Fig. 3(c). The coil frame is suspended on two flat metal ribbons (phosphor bronze or platinum alloy) held under tension by springs. The anchor springs pull the suspension bands very tight to support the coil frame. The taut band serves also as a suspension and restoring-torque spring. The taut-band suspension system makes the PMMC instrument extremely rugged.

Electrodynamic Voltmeters. The electrodynamic instrument is a transfer instrument that can be calibrated on dc and then used to measure ac. The basic electrodynamic instrument has two coils—a fixed coil winding and a moving coil winding (with attached pointer, and pivoted) as shown in Fig. 4(a). Current through the stationary field coils generates a magnetic field. When current flows through the pivoted coil, the coil sets up a magnetic field that interacts with the magnetic field of the stationary coil. The moving coil experiences a force causing the coil and pointer to be deflected. Spiral springs as shown in Fig. 4(b) provide the controlling force and the necessary connecting leads to the pivoted coil. A similar suspension system arrangement to that used in the PMMC instrument is used here. All the flux path of the electrodynamic instrument is in air, so that the field flux is smaller than that of the PMMC instrument. However, the moving coil of the electrodynamic instrument requires larger current than in the PMMC instrument to produce the same torque.

The deflecting torque is dependent on the field flux, coil current, coil dimensions, and number of turns. The field flux is directly proportional to the current I_F through the field coils, and the moving-coil flux is directly proportional to the current I_M through the moving coil. The same current flows through the field coil and the moving coil. That is,

$$I = I_{\mathrm{F}} = I_{\mathrm{M}}$$

The deflecting torque is given by

$$T_{\mathrm{DE}} = CI^2 \tag{4}$$

where C is a constant. The angular displacement is given by

$$\theta_{\mathrm{E}} = K''I^2 \tag{5}$$

where K' is a constant. The scale of the instrument is nonlinear and calibrated to indicate I instead of I^2. The scale therefore indicates rms current, which for dc is the actual value. The instrument can be read as dc or rms ac and it can be calibrated on dc and then used to measure ac.

Figure 5 shows the fixed and moving coils of the electrodynamic instrument connected in series. The current direction in Fig. 5(a) sets up south (S) poles at the top and north (N) poles at the bottom of each coil. Because like poles repel and unlike poles attract, the moving coil rotates in the clockwise direction, causing the pointer to move to the right from the zero position on the calibrated scale. In a similar fashion, the current direction in Fig. 5(b) sets up S poles at the bottom and N poles at the top of each coil. Once again the moving coil rotates in the clockwise direction and the pointer moves to the right from zero position. The electrodynamic instrument is therefore not polarized. The major disadvantages of an electrodynamic voltmeter are its low sensitivity and its nonlinear scale.

Figure 5(c) shows how the instrument can be connected for use as a voltmeter. A voltmeter utilizes a multiplier resistor (manganin or constantan) in series with the fixed and the moving coils. The multiplier resistor is calculated for use with dc voltage, but the scale can also be read as rms ac voltage.

Electrostatic Voltmeters. The electrostatic voltmeter is the only instrument that measures voltage directly, rather than the current it produces. It consists of a fixed plate (metal) and a moving semicircular plate (also metal) with a pointer attached as shown in Fig. 6. When a voltage is applied between the plates, the fixed plate attracts the moving plate. The moving plate aligns itself with the fixed plate, causing the pointer to move on a calibrated scale. The angular deflection is proportional to the square of the applied voltage, so this also is an rms instrument. The scale is calibrated to indicate voltage directly. The rms value is numerically equal to the dc value, and therefore the instrument reads either dc or ac rms voltage. Its reading is not affected by the waveform.

Electronic Analog Voltmeters. Electronic analog voltmeters use transistor and operational-amplifier circuits, and the PMMC as the deflection mechanism. Figure 7 shows a typical operational-amplifier-based analog voltmeter circuit. An electronic analog voltmeter has a user-selectable attenuator and can be used to amplify low voltages to levels that can be measured by the deflection instrument. The input resistance is also high.

Digital Voltmeters

The Fluke 12B hand-held (or pocket-type) DVM (part of a DMM) is shown in Fig. 1. Low-end, inexpensive hand-held DVMs can be used to measure voltages up to 1000 V. More capable benchtop DVMs offer greater accuracy, high resolution, faster update, wide measurement ranges, built-in memory, and remote control capabilities.

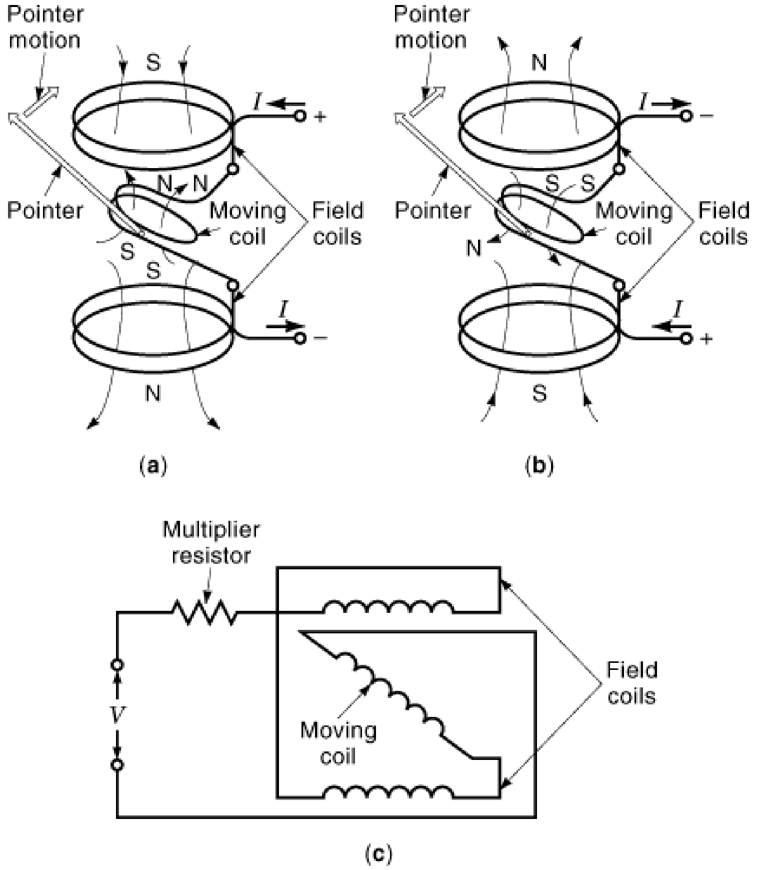


Fig. 5. Electrodynamic instrument: (a) Current flowing from top to bottom produces pointer deflection in the clockwise direction. (b) Current flowing from bottom to top produces pointer deflection in the same clockwise direction. (c) For use as a voltmeter, the fixed and moving coils are connected in series with a multiplier resistor.

The general functional block diagram of a digital voltmeter is shown in Fig. 8. The signal conditioning circuit converts the input voltage (ac and dc) into analog dc. In a typical digital voltmeter the analog dc varies from −2.5 V to +2.5 V or from 0 to +5 V. In some digital voltmeters the analog dc range is in millivolts, and this is accomplished through range scaling (automatic or manual). The signal-conditioning circuit also reduces the power required from the input signal. The digital hardware can consist of any combination of electronic devices, including ADCs, comparators, microcontrollers/microprocessors, digital signal processors (*DSPs*), sample-and-holds, and digital displays.

Like analog meters, digital voltmeters employ several techniques for converting input signal voltage to analog dc voltage. The three most important types are true-rms-responding, average-responding, and peak-responding converters.

True-RMS Digital Voltmeters. The term *root-mean-square* (*rms*) means to sum the squares of individual points, take the mean of the sum, and take the square root of the mean. The rms value of an ac voltage is equal to the dc voltage value that will generate the same amount of heat in a resistive load as the ac voltage.

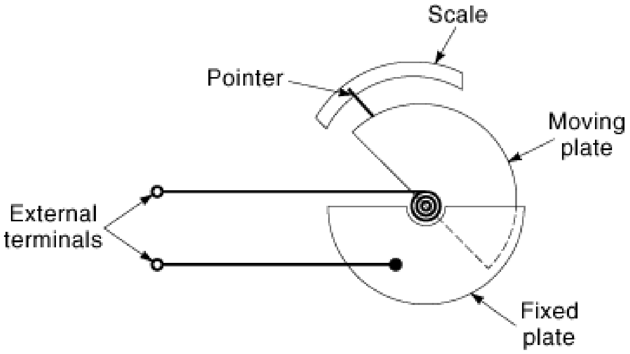


Fig. 6. Electrostatic movement.

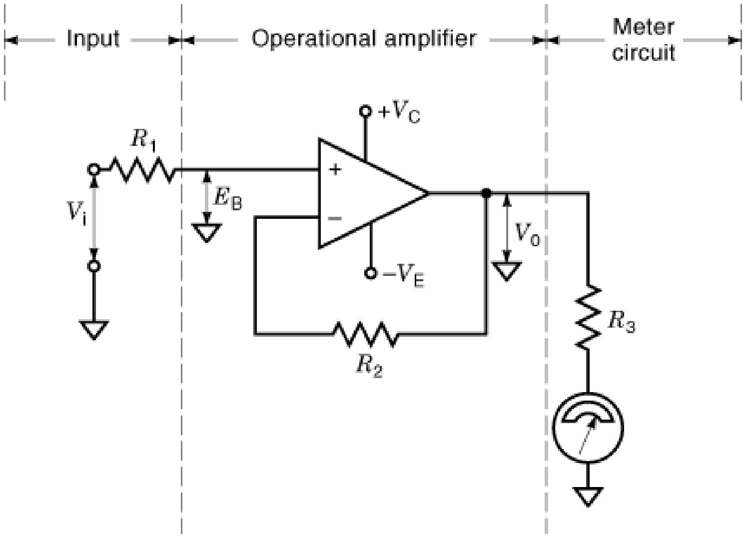


Fig. 7. Operational-amplifier electronic analog voltmeter.

Consider a dc voltage V_d across a resistor R. Then the power dissipated P_d is given by

$$P_d = \frac{V_d^2}{R} \tag{6}$$

Consider an ac voltage with rms voltage V_r. The average power P_a through the same resistor is given by

$$P_a = \frac{V_r^2}{R} \tag{7}$$

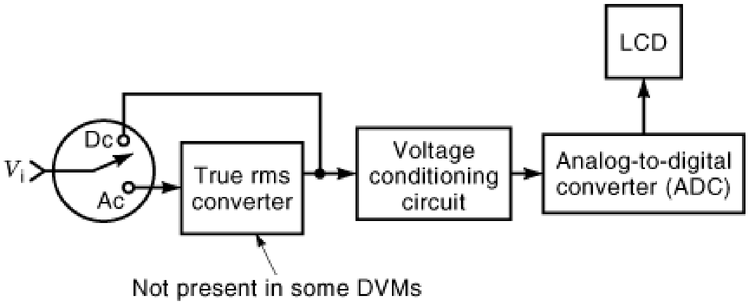


Fig. 8. Functional block diagram of a digital voltmeter.

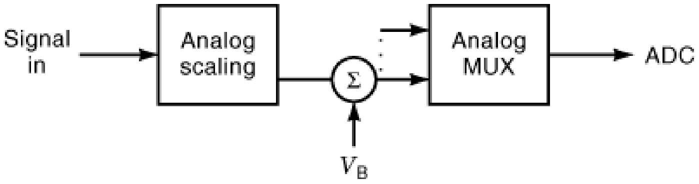


Fig. 9. Signal conditioning circuit for a unipolar ADC.

Consider an input voltage waveform V_i with period T. The average power P_a due to the ac voltage over T is given by

$$P_a = \frac{1}{T}\int_0^T \frac{V_i^2}{R}\,dt = \frac{1}{R}\left(\frac{1}{T}\int_0^T V_i^2 dt\right) \tag{8}$$

Setting Eqs. (7) and (8), equal it can be shown that V_r is given by

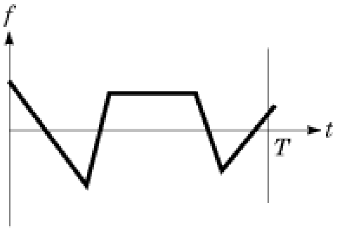
$$V_r = \sqrt{\frac{1}{T}\int_0^T V_i^2\,dt} \tag{9}$$

Figure 9 depicts a signal conditioning circuit, while Fig. 10 shows an original voltage waveform input to the conditioner. Consider N samples of either Fig. 10(b) or Fig. 10(c) to be $v_1, v_2, \ldots, v_k, \ldots, v_N$. The mean is given by

$$V_m = \frac{1}{N}\sum_{k=1}^{N} v_k \tag{10}$$

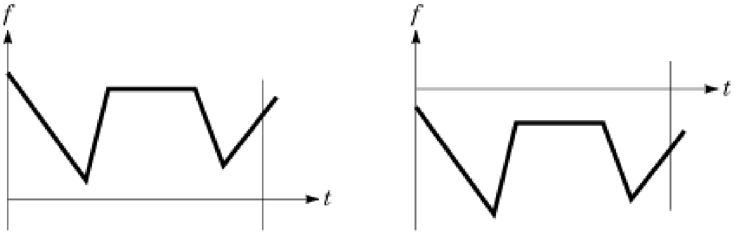
The standard deviation is given by

$$\sigma = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(v_k - V_m)^2}$$



Original signal

(a)



Positive-biased signal

(b)

Negative-biased signal

(c)

Fig. 10. Biased signals.

If G is the gain of the biased signal v, then the rms value of the signal v is given by

$$V_{\mathrm{r}} = G\sigma = G\sqrt{\frac{1}{N}\sum_{k=1}^{N}(v_k - V_{\mathrm{m}})^2} = G\sqrt{\frac{1}{N}\sum_{k=1}^{N} v_k^2 - V_{\mathrm{m}}^2} \quad (11)$$

Equation (11) will correct for any drift in the offset of the analog signal conditioning circuitry, for voltage bias, and for any offset in the signal. If the original signal is assumed to have zero mean (which is usually the case, since it is typically transformer-derived), then the rms value is given by

$$V_{\mathrm{r}} = G\sqrt{\frac{1}{N}\sum_{k=1}^{1} v_k^2} \quad (12)$$

The input voltage signal is sampled at a rate at least twice the highest frequency component of the input signal (the Nyquist rate). The mathematical operations of Eqs. (10) and (11) or (12) are performed by digital controller hardware such as a microcontroller, a microprocessor, or a digital signal processor (*DSP*). Typical processors include Intel microcontrollers 8031/51 and 80188/86, and Motorola microcontrollers M68HC11/HC16.

Average-Responding Digital Voltmeters. The average of an ac voltage V_{i} of period T is given by

$$P_{\mathrm{c}} = \frac{1}{T}\int_0^T V_{\mathrm{i}}\,dt \quad (13)$$

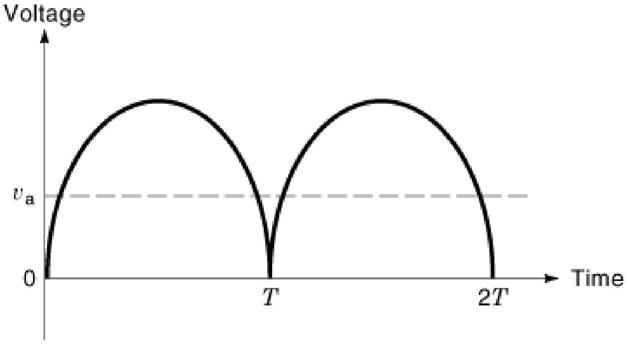


Fig. 11. Full-wave rectification for average-responding voltmeter.

For sine waves the average voltage of V_i is zero. The dc (rms) value is usually the desired quantity, because the heating capacity of the waveform is the quantity of interest. Sometimes, however, the average value for a sine wave is taken to mean the true average of the full-wave rectified waveform. Figure 11 shows two cycles of a full-wave rectified sine wave. For rectified sinusoidal waveforms, if the average can be measured, then the rms value can be calculated as

$$V_r = \frac{\pi}{2\sqrt{2}} V_a = 1.11 V_a \qquad (14)$$

Average-responding digital voltmeters perform the mathematical operations of Eq. (10) to obtain the mean, and obtain the rms value from Eq. (14). Such a voltmeter is not generally accurate, but it is inexpensive.

Peak-Responding Digital Voltmeter. The sine wave is the most common ac voltage. Figure 12 shows a typical sine wave. The peak value V_p is related to the rms V_r by the equation

$$V_r = \frac{V_p}{\sqrt{2}} \qquad (15)$$

Equation (15) is accurate for only pure sine wave signals. In its simplest form the peak-responding digital voltmeter determines the highest absolute sampled value of the input waveform; the mean of several sampled peaks is used. Harmonics, especially second and third harmonics, can contribute several percent of error in peak-responding digital voltmeters. Peak-responding digital voltmeters are not well suited for accurate measurements of nonsinusoidal waveforms, but they are inexpensive.

Other Digital Voltmeters.

Ramp-Type Digital Voltmeter. Figure 13 shows the functional block diagram of a ramp-type digital voltmeter. The heart of this type of voltmeter is a ramp-type ADC. Other electronic devices include a seven-segment display and drivers, a latch, and a counter. The reference voltage varies linearly from slightly below zero to the full-scale voltage V_F. At the start of the conversion, the binary counter resets and the ramp generator starts (slightly below zero). When the ramp crosses zero, the output comparator 2 goes high, thereby incrementing the counter. As soon as the ramp output is slightly greater than V_i, the output of comparator 1 goes high to stop the clock pulses from reaching the counter, and the counter stops. If N is the content of the

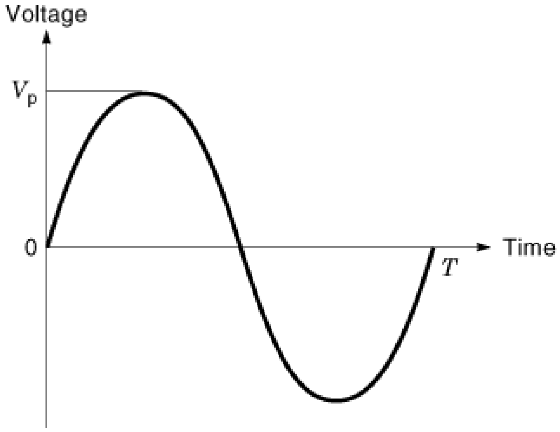


Fig. 12. Sine wave.

counter at the end of conversion, then V_i is given as

$$V_i = \frac{KN}{f_c}$$

where
K = slope of the ramp (V/s)
f_c = clock frequency (Hz)

If the slope of the ramp is, $K = V_F/2^n$, then

$$V_i = \frac{V_F}{2^n} \tag{16}$$

Equation (16) shows that the counter output N represents the value V_i. The ramp slope depends on R and C, which are temperature-dependent, and this dependence represents a major limitation.

Dual-Slope-Integrator Digital Voltmeter. The dual-slope-integrator digital voltmeter overcomes the problems associated with the ramp-type digital voltmeter. Figure 14 shows the functional block diagram of a dual-slope-integrator digital voltmeter. During the time T_1 the capacitor C is charged at a rate proportional to the unknown voltage V_i. The voltage produced, V_o, is proportional to V_i. The control logic then switches the integrator to the reference voltage V_f, and C discharges at a rate proportional to V_f during T_2. During the charging of the capacitor,

$$\frac{V_o}{T_1} = \frac{V_i}{RC}$$

During the discharging,

$$\frac{V_o}{T_2} = \frac{V_f}{RC}$$

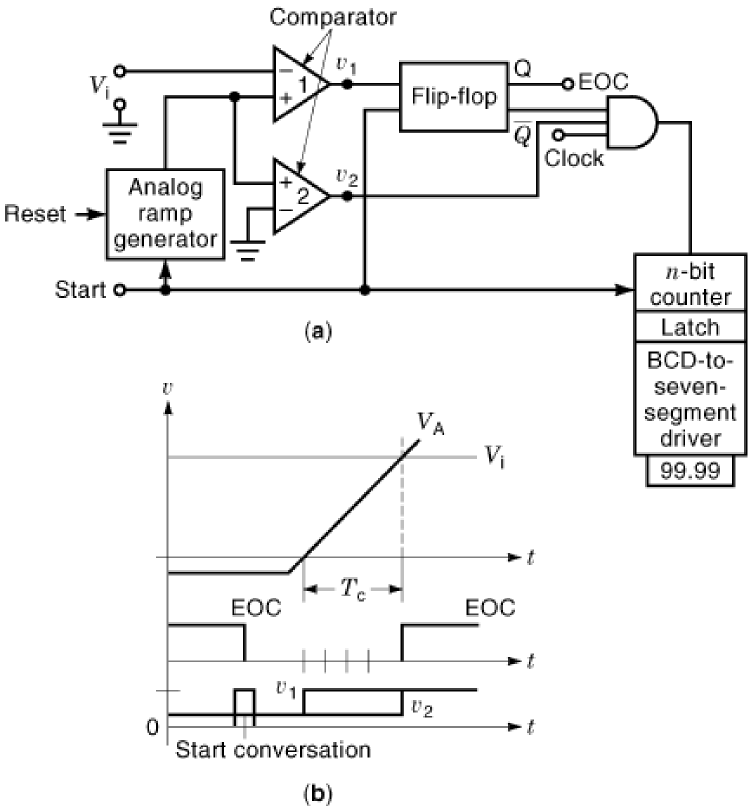


Fig. 13. A ramp-type digital voltmeter.

Therefore,

$$V_i T_1 = V_f T_2$$

so that

$$V_i = \frac{T_2}{T_1} V_f \tag{17}$$

The display represents the average of several readings taken per second. The dual-slope digital voltmeter is used in high-precision instrumentation systems.

Digital Voltmeter Trends.

Virtual Digital Voltmeter. A virtual digital voltmeter is a PC-based instrument that converts a PC and a data-acquisition card (*DAQ*) into a full-function digital voltmeter. The availability of high-performance computers, along with advanced software and graphical user interfaces, allows the software running on the computer to emulate and even surpass the capability of traditional instruments. The basic measurement functions are obtained using printed circuit boards inserted into the computer or card cage. The software running the computer is often referred to as a *virtual instrument* (*VI*).

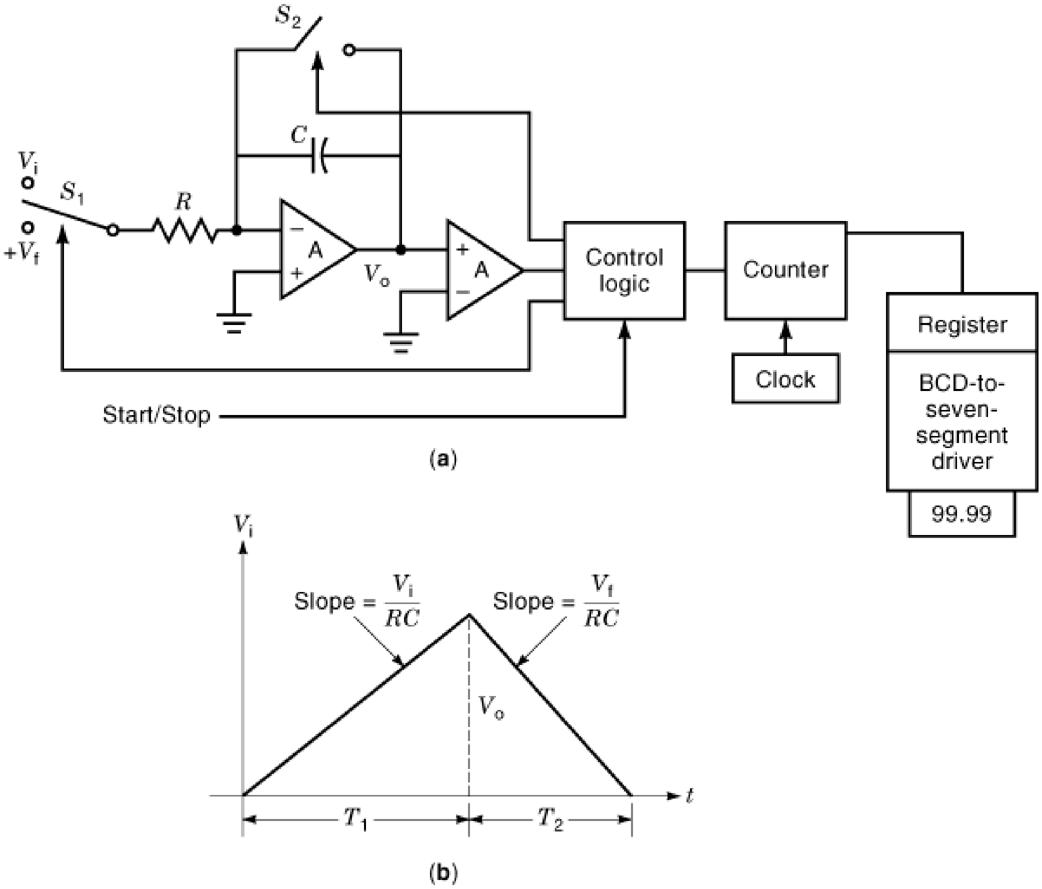


Fig. 14. A dual-slope-integrator digital voltmeter.

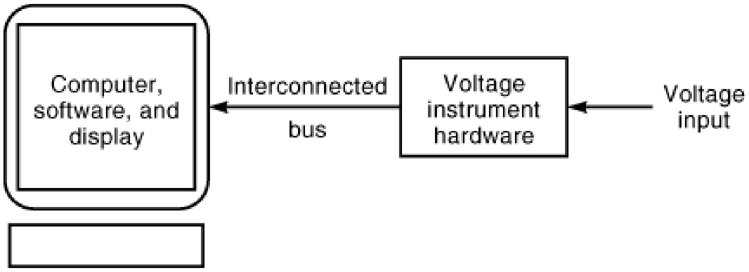


Fig. 15. The major components of a virtual instrument system.

The basic components of a virtual voltmeter include a computer, the virtual instrument software, a bus structure that connects the computer with the voltage data acquisition hardware, and the voltage data acquisition hardware. Figure 15 shows the block diagram of the virtual digital voltmeter. A virtual digital voltmeter that measures ac and dc voltages usually comes as part of a general virtual DMM. Input ranges are either autoranged or user-selectable from 1 mV to +2.5 V.

The virtual digital voltmeter is built around a PC, and therefore there is complete integration of data, computer memory, and other applications. A virtual instrument can also load and save voltage waveform data to other spreadsheet formats, log waveform data, generate waveform reports with timestamps and comments, and print waveform data. National Instruments provide a virtual bench (*VirtualBench*) package that combines DAQ boards, PC cards (PCMCIA), input/output port devices, and software to take advantage of the latest desktop and notebook PC technology to deliver a collection of full-function PC-based instruments. The PowerLogic section of Square D Company provides generations of circuit monitors (with voltage as part of measurements) that can communicate with desktop as well as portable computers.

Creating a VI subsystem is greatly simplified by using programming environment, such as LabVIEW. The data acquisition, processing, display, and database management are all supported on one computer. A VI provides features for modern instrumentation and measurement development, and upgradability.

Digital Voltmeters for Nonelectrical Measurements. A voltmeter can be used as a data acquisition and control device for monitoring nonelectrical quantities. For example, programmable coefficients let a user customize a digital voltmeter so that voltage measurements can be interpreted as pressure, temperature, pH, and battery voltage levels, thereby taking greater advantage of the meter's expandability and flexibility. The PowerLogic section of Square D Company provides a broad range of digital voltmeters (as part of DMMs) that can be customized for various other nonelectrical functions such as monitong pressure and temperature.

Special Voltmeters. Special voltmeters (analog and digital) have been developed for many special applications. High-frequency waveforms, distorted waveforms, very low-level voltages (microvolt and nanovolt ranges) with high source resistance, noise voltages, and drifting voltages are some of the problems dealt with by using special voltmeters. Voltmeters for measuring low-level voltages (with high source resistance) have high sensitivity (on the order of nanovolts) and high input resistance (on the order of gigohms).

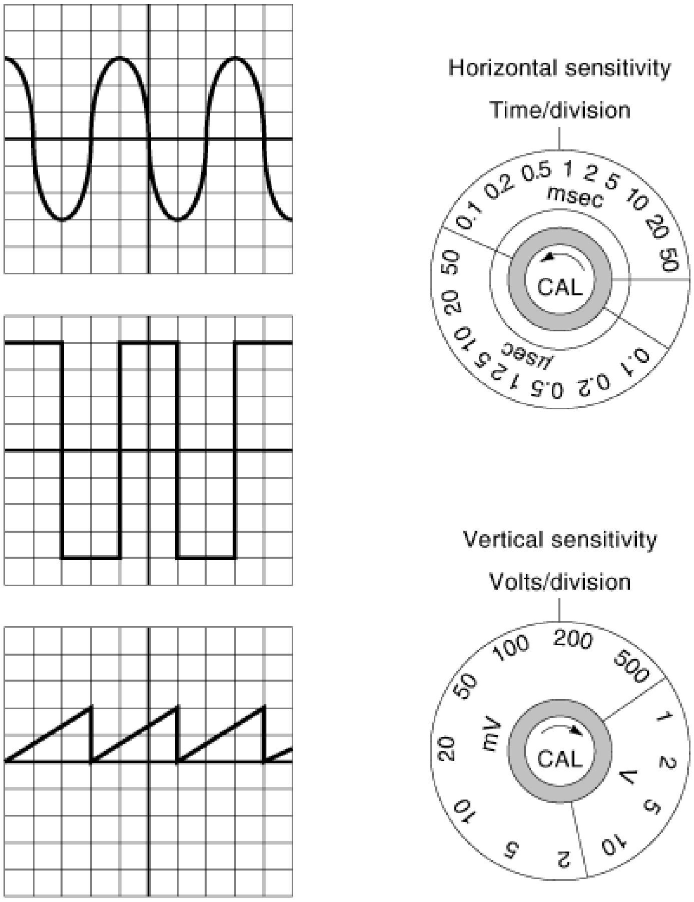
The oscilloscope is fundamentally another special kind of electronic voltmeter that can be used to measure very rapidly time-varying voltage waveforms. Electrometer instruments and nanovoltmeters are two examples of special voltmeters designed to detect minute voltages in circuits with high input impedances, in the range of gigohms. These minute voltages are usually present in chemical and biological analyses.

Oscilloscopes. The oscilloscope is basically a voltmeter with very high internal resistance, typically in the order of 1 MΩ to 1 TΩ. However, the oscilloscope not only measures voltage but also displays the measurement. The oscilloscope projects on a cathode-ray tube a graph, which shows the voltage magnitude on a vertical axis and time on a horizontal axis. This presents a picture of the behavior of the voltage as a function of time. Figure 16(a) shows three different waveforms with different amplitudes and time periods. These voltage waveforms are functions of time plotted on the oscilloscope screen. A "volts/division" control knob sets the vertical scale of the display, and the horizontal scale is set by a "time/division" control knob as shown in Fig. 16(b). For example, consider a sinusoidal waveform with horizontal control set at 2 ms/division and the vertical scale set at 5 V/division. Then the voltage varies from a maximum of $+15$ V to a minimum of -15 V and repeats every 4 ms. The waveforms shown in Fig. 16(a) are all periodic waveforms; the oscilloscope continuously generates new graphs of voltage versus time, one on another, making the waveforms look stationary.

The oscilloscope can also be used to display and measure nonperiodic waveforms. One way to handle a nonperiodic waveform is to cause the oscilloscope to make one simple graph of the waveform for a short time period. The waveform is photographed and then stored. This process is known as *single-sweep operation*.

The oscilloscope may introduce many errors and associated problems that can mislead a user. The voltage measurement accuracy depends on the displayed amplitude. The accuracy of the vertical scale is typically specified as $\pm 3\%$ of full scale (FS) and the accuracy of the horizontal sensitivity as $\pm 5\%$. The overall measurement accuracy is approximately $\pm 4\%$. The frequency response is typically specified as dc to perhaps 100 MHz for a general-purpose oscilloscope. More expensive oscilloscopes have higher cutoff frequencies, typically several hundred gigahertz.

The operation of the various parts of the oscilloscope is essentially the same for analog and digital models.



(a) (b)

Fig. 16. (a) Typical signal waveforms that may be seen and measured on an oscilloscope screen. (b) The appearance of the sensitivity control knobs of the horizontal and vertical amplifiers.

Electrometer Voltmeters. An electrometer is a very high-sensitivity instrument for measuring voltages. Its sensitivity is in the range of nanovolts and input resistance on the order of terohms. A typical electrometer voltmeter can have its lowest voltage range ±1 μV FS with an input resistance of 1 MΩ. Solid-state versions of the electrometer (with field-effect transistor input) have special construction with the use of suitable insulating materials such as Teflon, and special treated surfaces. They are generally compact and reliable, and have high-sensitivity dc amplifiers to keep the inherent drift at workable levels. Other difficulties with electrometers include electrostatic pickup, physical motion, and leakage currents.

The electrometer is used to measure ac voltages and both positive and negative dc voltages, but it is basically a dc instrument.

Microvoltmeters and Nanovoltmeters. Microvoltmeters and nanovoltmeters are employed for measuring minute dc voltages. Analog microvoltmeters and nanovoltmeters are basically PMMC instruments connected to stable, high-gain amplifiers. These amplifiers tend to exhibit long-term inherent drift. To overcome that problem, the dc voltage is usually converted to ac, which is amplified and then reconverted to dc to drive the movement of the meter. This process is sometimes called *carrier amplification*.

Digital microvoltmeters and nanovoltmeters are preferred in many cases because they are less costly where very high sensitivity is required, they have high input impedance, and they can be manufactured to have high resolutions. The most sensitive ones have 10 nV FS with accuracy on the order of ±2%, and typical input impedances ranging from 1 kΩ to gigohms, depending on the voltage scale.

Measurement Errors. Like any other electronic equipment or instruments, digital voltmeters have some errors and inaccuracies. In addition to instrument errors, there are operator and observer errors, systematic errors, and random errors. Some of the sources of errors to be discussed below apply to analog voltmeters as well.

An error is a difference between the measured value of a quantity and its true value. Sources of errors in instrument readings are due to many elementary factors. Our discussion will be largely limited to the common elementary errors that arise in the voltmeters themselves. There will be brief mention of some of the common errors directly related to their use.

Temperature Errors. Voltage changes due to temperature variations are the most common source of errors in low-level dc voltage measurements. Many components of a voltmeter are very sensitive to changes in temperature and to heating. Most laboratory instruments are designed for use at normal ambient temperature of about 25°C. High-precision voltmeters are calibrated from time to time at the desired temperature.

Drift Errors. Electronic components age and may cause instruments to exhibit long-term drift, causing them to lose their calibration. Calibrating the instruments frequently enough to detect drift before the errors become intolerable can minimize this problem.

Settling-Time Errors. The wearing of bearings and the effect of pivot friction can cause pointers to jerk when the measured quantity is gradually changed. These are common sources of errors in analog voltmeters. The stress on spiral springs may cause them to creep. When the instrument is de-energized, the pointer may not return to zero for a couple of minutes. The creeping can cause errors. For best accuracy, it is good to allow ample time for the instrument to stabilize before performing any measurement.

Gain and Zero-Offset Errors. Gain errors in electronic voltmeters result from changes in the amplifier gains, divider ratios, or internal reference voltages. The gain of the amplifier is affected by temperature variations and aging of the components.

Offset errors result from amplifier offset voltages. A mechanical zero-adjusting mechanism can be found on most electronic voltmeters, and other facilities may be provided for electrical zero setting. Zero settings must be checked frequently before measurements are taken.

Frequency Errors. If a voltmeter is used to measure a voltage whose frequency is different from that used for the calibration of the voltmeter, errors can result. A lookup frequency correction table can be useful in correcting for such errors.

Waveform Errors. A voltmeter that is intended to measure the rms value of a sinusoidal waveform may give incorrect readings if it is used to measure a nonsinusoidal one. Waveform errors are to be expected in some types of voltmeters.

Common Specifications. Instrument errors form the basis for some of the common specifications written to describe the quality, capabilities, size, and features of an apparatus or instrument. In this section some of the common specification terms describing the errors and relating to the digital voltmeter are examined, and some means of minimizing the errors are examined. Some of the specifications also apply to analog voltmeters.

Range. Table 1 shows typical range specifications of a digital voltmeter. A typical range is from 100 mV to 1000 V. The range may be either automatic or user-selectable. A user- selectable range gives the greatest accuracy and the largest possible numerical display. In most digital voltmeters an ADC is used to convert an analog dc voltage signal (scaled range varied from −2.5 V to +2.5 V or 0 V to +5 V) into binary numbers. An

Table 1. Range Specifications

Quantity	Range (V)
V_{ac}	0.1 to 1.999/19.99/199.9/1000
V_{dc}	0 to 1.999/19.99/199.9/1000

Table 2. Specifications for Range, Accuracy, and Resolution of a Typical Voltmeter

Dc Voltage			Ac Voltage (True Rms Responding)					
					Accuracy			
Range	Resolution	Accuracy	Range	Resolution	45 Hz to 1 kHz	to 10 kHz	10 kHz to 20 kHz	20 kHz to 50 kHz
±200 mV	100 μV	±(0.1% of reading +1 digit)	200 mV	100 μV	±(0.5% of reading +2 digits)		±(1.0% of reading +2 digits)	±(5% of reading +3 digits)
±2 V	1 mV		2 V	1 mV				
±20 V	10 mV		20 V	10 mV				
±200 V	100 mV		200 V	100 mV				
+1000 V	1 V		750 V	1 V	±(0.5% of reading +2 digits)	NOT SPECIFIED		

n-bit ADC creates 2_n different binary numbers. An input signal V_i is given by

$$V_i = \frac{V_f}{2^n} X \tag{18}$$

where X is the nearest n-bit binary integer and V_f is a known reference voltage of the ADC.

Resolution. The resolution of a digital voltmeter will depend on the degree to which small changes in an analog dc voltage level can be observed. The roundoff of X introduces roundoff errors in V_i. The resolution of the ADC is given by

$$\Delta = \frac{V_f}{2^n} \tag{19}$$

Clearly, the precision of V_i from Eq. (18) improves with decreasing the converter resolution Δ and increasing n.

The resolution of a digital voltmeter depends on the resolution of the ADC. Generally, the finer the resolution, the more expensive the ADC becomes.

The resolution is expressed in several ways, depending on the voltmeter type. For example, it can be expressed as a percentage of the FS reading of the voltmeter (say, 1 in 1000 at FS). The resolution of a dc voltmeter is limited only by its internal random noise. However, system amplifiers and ADCs generally limit the resolution of ac voltmeters. The number of significant digits available in the DVM readout may also express the resolution of the DVM. Table 2 shows typical voltage resolutions for the Fluke 8010A/8012A DMM.

Accuracy. The accuracy is a measure of how close a measurement is to the true value of the measured quantity. Accuracy is a difficult specification to interpret, because the true value of the physical variable of interest may not be available. There are four basic specifications for accuracy when dealing with DVMs. These specifications are used to determine the maximum deviation of the measured value V_v from the true value V_t

or the full-scale value V_F, expressed in percent of V_t or V_F respectively. Two specifications are based on the following equations:

$$\text{percent of reading} = \frac{100(V_v - V_t)}{V_t} \tag{20}$$

$$\text{percent of FS} = \frac{100(V_v - V_t)}{V_F} \tag{21}$$

The number of significant display digits of the DVM is also taken into consideration, because it will be pointless to specify the accuracy of a DVM as 10% when the DVM can only display two significant digits.

Two additional types of specification used are

$$X = V_v - V_t \tag{22}$$

$$X_{\text{count}} = V_{\text{vcount}} - V_{\text{tcount}} \tag{23}$$

X = smallest readout division in volts
X_{count} = smallest readout division in counts
V_{vcount} = measured value in counts
V_{tcount} = true value in counts

For expensive and highly accurate DVMs a combination of Eqs. (20) to (23) is used to specify the accuracy. For example, typical specifications may read ±(0.005% of reading + 1 μV) and ±(±0.5% of FS + 2 digits). In Table 2 some important accuracy features of a Fluke DVM (part of a DMM) are shown in this way.

The accuracy of the DVM depends on the quality of its internal components.

Sampling Rate and Bandwidth. In the real world a periodic signal of interest may be either sinusoidal or a sum of sinusoids at multiples of the fundamental frequency, collectively called *harmonics*. In today's electrical systems, distorted voltage and current waveforms (harmonic distortion) are becoming increasingly common. Harmonics that are not allowed for in algorithms used in a DVM can contribute several percentage points of error.

In DVMs with ADC, samples of the ac analog voltage must be taken at a rate greater than two times the highest frequency present in the ac signal (the Nyquist rate). Expensive DVMs (which can be part of DMMs) utilize advanced digital sampling algorithms similar to those of portable voltage and current waveform analyzers. Using high-speed sampling, large numbers s of harmonics are taken into account for more accurate voltage measurements. The frequency response of a high-accuracy DVM might be stated as follows:

Frequency Range (Hz)	Highest Harmonic
23 to 65	31st
350 to 440	3rd

For example, using high-speed sampling, such a DVM can accurately allow for harmonic information through the 31st harmonic for a distorted 60 Hz voltage signal (bandwidth of 23 Hz to 1.86 kHz). Some manufacturers claim a bandwidth of 0.5 Hz to 300 kHz in their DVM instruments. Table 2 provides the bandwidth specifications for the Fluke 8010A/8012A for ac voltage measurements.

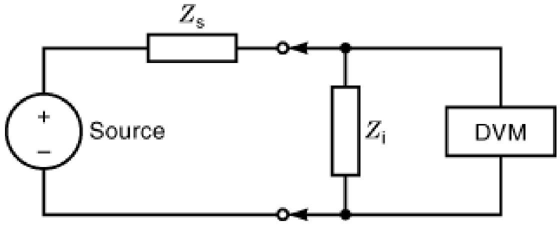


Fig. 17. Voltage loading effect.

The voltage sampling rate of a DVM determines the maximum number of harmonics that can be allowed for.

Sensitivity. The sensitivity is the smallest voltage that a DVM can respond to; it is measured from zero and may be as low as 1 μV. A DVM is more sensitive than an analog voltmeter. The sensitivity of an ADC-based DVM will depend on several factors, including the resolution of the ADC. Equation (19) provides a basis for the sensitivity specifications of an ADC-based DVM. The sensitivity also determines the precision with which the DVM makes voltage measurements. A DVM with a high-resolution ADC will be a very sensitive voltmeter.

There is confusion between sensitivity and resolution, because there is little difference between the two. The sensitivity of dc voltmeters is limited only by internal random noise and often differs little from its resolution. A voltage range of 1 V dc or smaller can correspond to a 61/d-digit measurement. A voltage range of 10 mV dc then corresponds to a 41/-digit measuremen

Generally, ac voltmeters require signal levels greater than 1/ of FS to respond to an input signal, and they exhibit significant difference between their sensitivity and their resolution. A typical 51/-digit ac meter can provide a full-scale range of 100 mV, and a sensitivity of 0.25 mV on that range.

Precision. Precision refers to repeated observation of the same measured quantity. For example, a 10 V instrument can be read to a measurement precision of 1 mV. That is, if a measurement is made repeatedly, 1 mV is the smallest voltage difference that can be observed. The measurement resolution is 1 mV.

Input Impedance Burden. A voltmeter is always connected across the points between which the voltage is to be measured. The voltmeter should not itself be a load; ideally it should have infinite input impedance (be an open-circuit device). Low input impedance causes errors in voltage measurement. Figure 17 shows a voltmeter with input impedance Z_i connected in parallel with (across) a source V_s with impedance Z_s. The measured voltage V_v is given by

$$V_v = \frac{Z_i}{Z_s + Z_i} V_s \tag{24}$$

The error factor is $Z_i/(Z_s + Z_i)$. It is easiest to control the input impedance Z_i of the DVM during the design.

The input impedance or resistance is usually known and typically the specification is 10 MΩ with a shunt capacitance specification of less than 75 pF. The front end of the signal-conditioning circuits of a DVM is usually designed to have high input resistance to minimize the voltmeter loading effect and thereby lower the input impedance burden of the DVM.

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