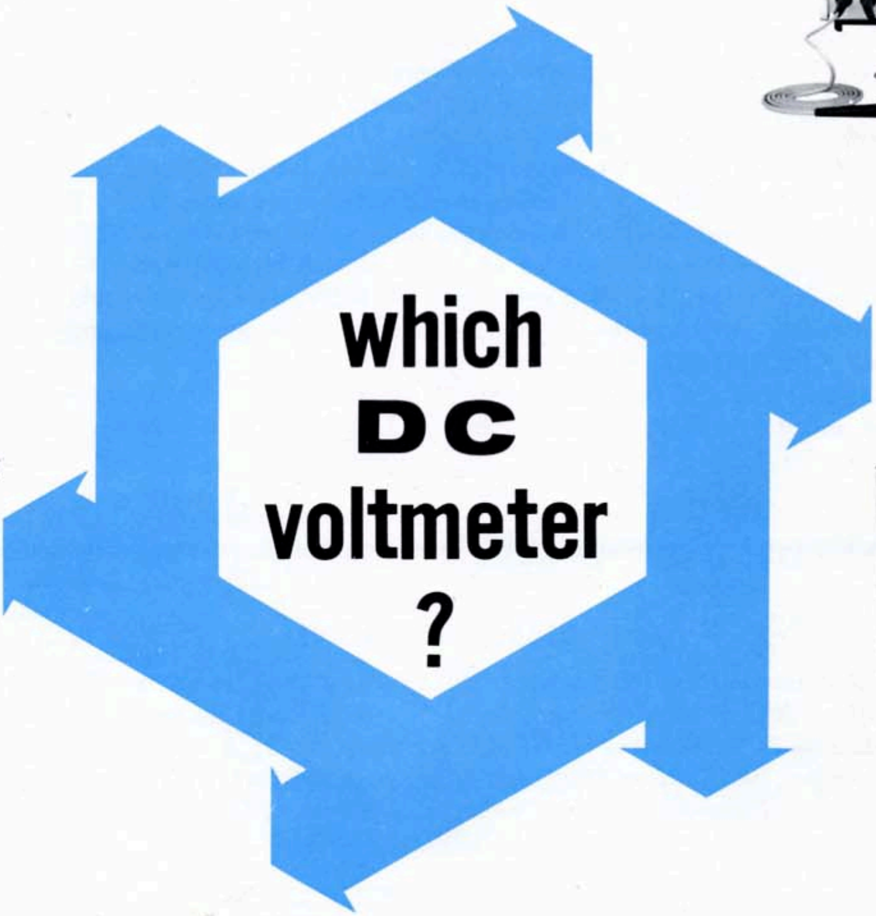
HEWLETT hp PACKARD

APPLICATION NOTE 69

AUGUST 15, 1965



which DC voltmeter ?

INTRODUCTION

"The most appropriate instrument for dc voltage measurement is the least costly instrument which will reliably give the accuracy needed for the conditions which apply." These are the words of the Conclusion of this Application Note, and they are equally appropriate to the introduction.

Appropriate selection of dc voltage measuring equipment involves an understanding of the principles of operation which underlie the performance of each instrument, and a knowledge of the available options with their capabilities and limitations. Several varieties of modern dc voltmeters are reviewed here in principle and in application.

Specifying such a meter involves hazards of over or under specifying—on the one hand offering the possibility of omitting necessary characteristics, on the other of committing oneself to more cost than the function justifies. A full chapter, therefore, is devoted to a guide of specifying.

The need to read dc voltages rapidly and accurately in the presence of interfering signals has led to the development of several new instruments. Their need can be determined, and their capabilities can be fully exploited only with a rigorous analysis of the measurement situation. Straightforward means of applying such an analysis are described here; their use will pay ample dividends in selecting the least costly instrument which will really do the job, and in avoiding any waste of its capabilities.

Basic to all voltage measurements is universal agreement of common definitions and standards. These are derived and explained in the closing chapter of this Application Note.

ACKNOWLEDGMENT

Application Note 69 combines contributions from many members of the Loveland R & D Staff, especially from Paul Baird and Don Schulz. Paul Baird holds a BS in Mathematics from Oklahoma State (1950), a MSEE from Colorado University (1953) and an Engineer's degree from Stanford (1959). Donald Schulz holds a BSEE and MSEE from University of Wisconsin (1955). Both are experts in dc instrument design and dc standards.

WHICH DC VOLTMETER?

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Which DC Voltmeter?

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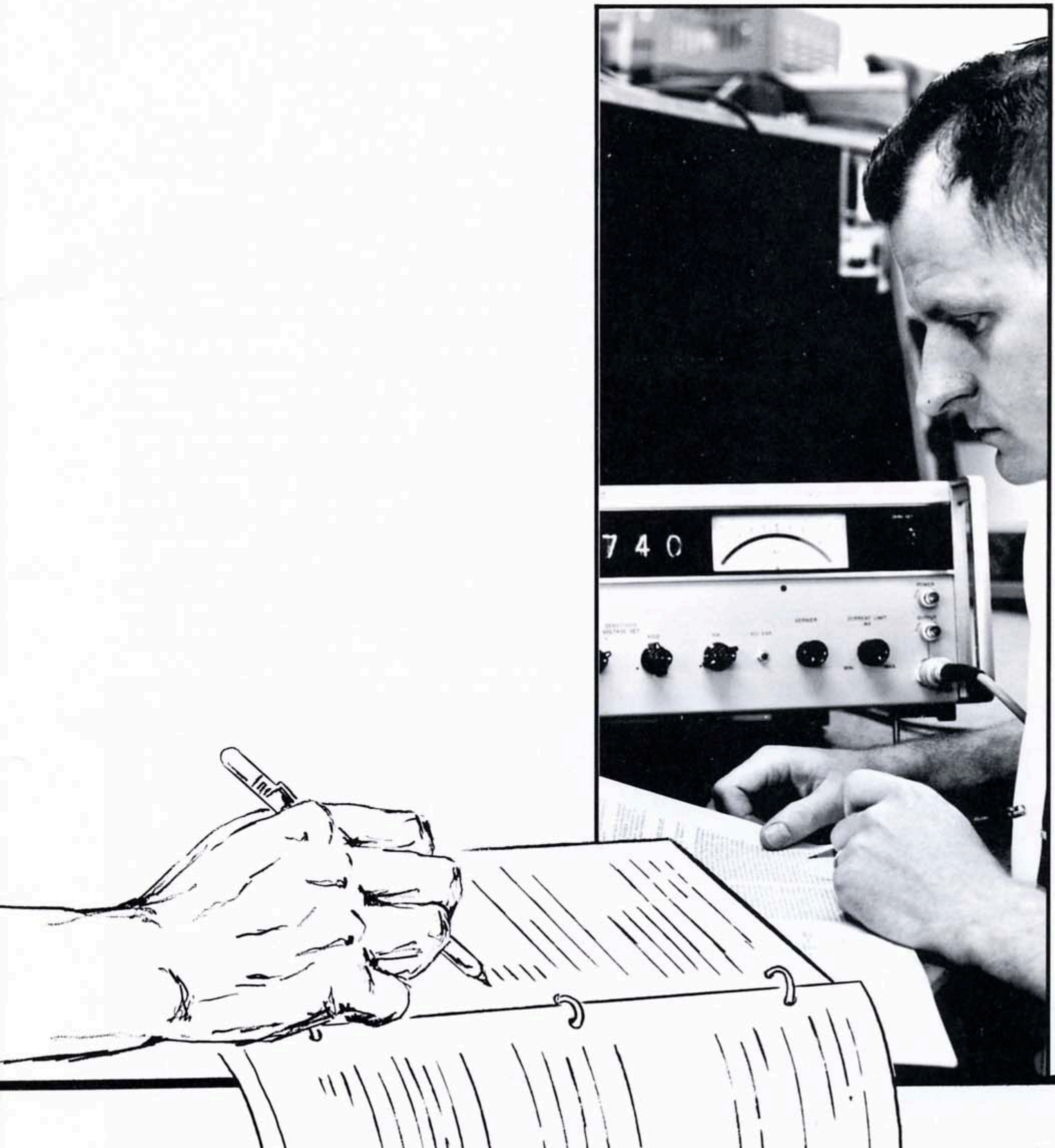

Electronic DC Voltmeters

CHAPTER I

ELECTRONIC DC VOLTMETERS

A. Introduction

Operating principles for various dc voltmeters are briefly described in this chapter. Classifications used are somewhat arbitrary since many combinations of techniques are in use. Although there was no intent to classify by price, the voltmeters in section C tend to cost more than those of section B; and those of section D tend to cost more than those of section C.

B. Amplifier Driven Meter Types*

Introduction

1. This familiar type voltmeter, which uses a dc amplifier to drive a meter indicator, offers adequate performance for many applications. The amplifier is used to obtain sensitive ranges and higher input impedance than can be obtained with a simple meter movement and range multiplier resistors. The input impedance of electronic types is frequently high enough that corrections for the loading effect of the voltmeter upon the circuit are not required. Typical accuracies range from 0.5% to several percent.

An extra bonus is a recorder output which delivers a dc voltage proportional to the meter indication. The voltmeter can thus be used as a narrow band dc amplifier. In addition, other functions such as dc amperes and ohms may be provided.

Although most of the amplifiers are designed for line operation, battery operation is sometimes provided. Battery operation is useful in two situations: (a) where remote field operation is required, and (b) where the ultimate in isolation from the power line is required to minimize the effects of power line voltages, which in some cases may cause erroneous readings.

2. Meter Movements—The meter movement readout should continue to be popular since it is economical and suitable for many jobs. It also lends itself well to special, nonlinear scales.

The pivot-jewel suspension is being replaced more and more by the taut-band suspension. This has resulted in excellent repeatability with hysteresis virtually eliminated. The newer meter's excellent repeatability, in turn, makes practical the individually calibrated meter scale. Both of these improvements, taut-band suspension and individually calibrated faces, are standard in most —hp— analog voltmeters. Figure 1-1 illustrates the value of individually calibrated meter faces by showing the scales for two different meters superimposed.

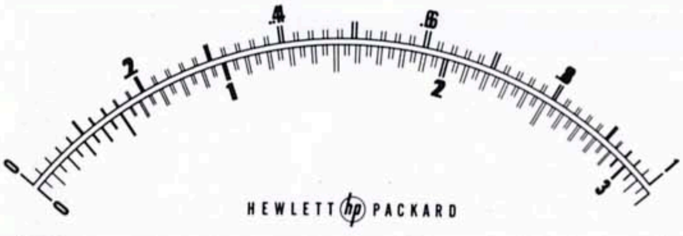

Figure 1-1. Photograph of Meter Scale Double Exposed.

3. Amplifier Techniques—DC amplifiers can be classified as (a) direct-coupled types and (b) chopper types. Most of the chopper types have narrow bandwidths of typically zero to one Hz (cps). This is usually adequate for driving a meter movement. The —hp— Model 414A Autovoltmeter, however, uses a chopper-stabilized amplifier which has much wider bandwidth.

Direct-coupled amplifiers are attractive by their economy and find application in the lower-cost electronic voltmeters. Although high input impedance and low dc drift have been individually achieved, it is difficult to achieve both simultaneously. Matched bipolar transistors, for instance, have been used to achieve drifts of a few microvolts per degree Centigrade. To provide base current paths, however, it is necessary to either shunt the amplifier input, thus reducing input resistance, or limit the maximum source resistance to a few kilohms. A vacuum tube or field effect transistor, on the other hand, can offer many megohms of input resistance; but the lowest range may be of the order of 1/10 to one volt. Further advances are expected in the state of the art. Figure 1-2 shows the direct-coupled amplifier used in the —hp— 410B.

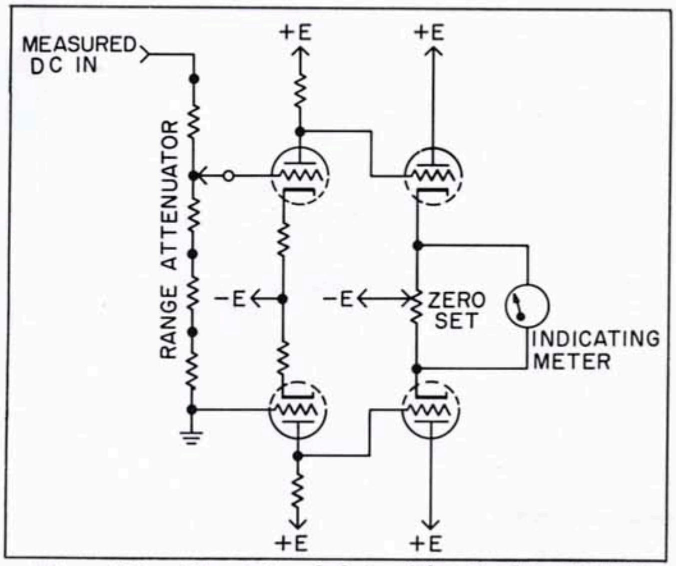

Figure 1-2. Direct Coupled Amplifier Used in HP410B

To provide ranges of a few millivolts or microvolts full scale, chopper amplifiers are generally used. Currently available choppers can convert the input dc to a proportional ac with zero offsets of a microvolt or less. The ac signal is first amplified and then converted back to dc (demodulated).

Overall scale-factor accuracy is assured by substantial dc feedback from the output back to the modulator. This feedback also develops a high dc input resistance which, for the amplifier itself, often reaches 1000 megohms or more. The input resistance presented to the voltmeter terminals is determined by the input attenuator, which is necessary for different input voltage levels.

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*—hp— Models 410B, 410C, 412A, 413A, 419A, and 425A.

The Hewlett-Packard Company has led for several years in the use of photocell choppers. A photocell (or photoresistor) has many megohms of resistance when unilluminated, and a few hundred or thousand ohms when illuminated with a neon or incandescent bulb. The transition time between these two conditions (high and low resistance) at present limits the maximum chopping rate to a few huundred Hz. Usually four photocells are mounted in one assembly with a simple neon oscillator. This provides a demodulator as well as a series-shunt, half-wave modulator. Figure 1-3 illustrates a typical chopper amplifier.

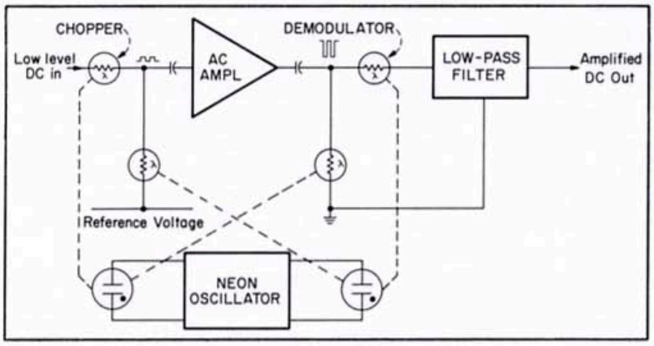

Figure 1-3. Non-Mechanical Photo-Conductive Chopper

4. Automatic Features—Automatic polarity and range selection features have now been made available. The operator can thus detect polarity and measure any voltage within the range of the instrument without setting controls. Except on the bottom ranges, the meter indication is automatically maintained between 1/3 and full scale while the range also is automatically displayed. These features are offered in the 414A Autovoltmeter. Unusually good accuracy has been achieved on this model. Figure 1-4 compares accuracy versus reading for this instrument and for instruments whose accuracy is specified as 1% or 2% of full scale.

C. Potentiometric Types With Manual or Analog Readout

1. Manual Balance[*] (commonly denoted "Differential Voltmeter"). By adjusting a precision voltage divider, the unknown voltage is balanced against a reference voltage. The difference is detected by a sensitive null detector. Starting with the most significant digit, the largest digit which can be extracted from the unknown voltage without reversing the null detector polarity is manually determined. The sensitivity of the detector is then increased and the operator similarly proceeds to extract the second most significant digit. This process is continued until the ultimate sensitivity of the nullmeter is reached. Figure 1-5 illustrates the basic concept, but with a fixed null sensitivity.

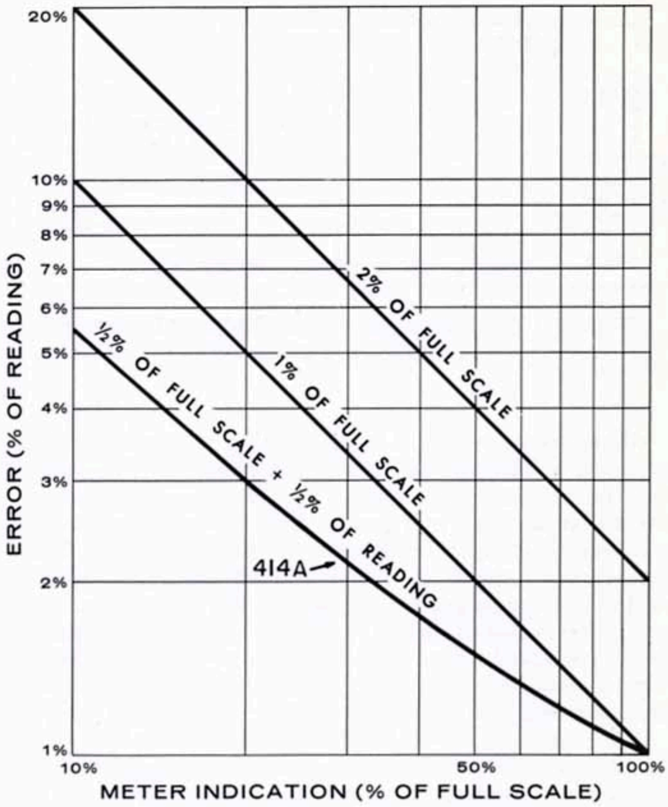

Figure 1-4. Analog Voltmeter Scale Accuracy

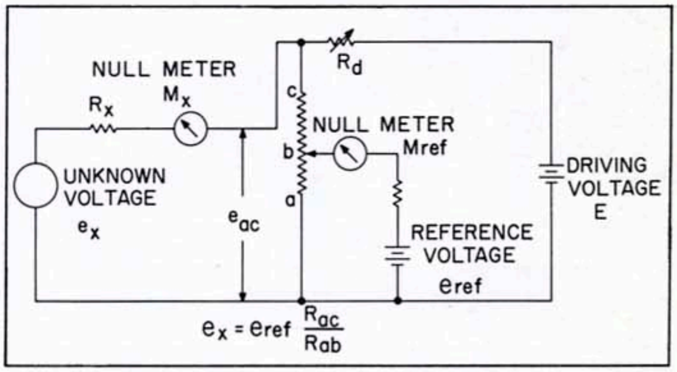

Figure 1-5. Simplified Conventional Differential Voltmeter

The potentiometric method is highly accurate[**] because precise voltage dividers and very stable voltage references are available. This type of voltmeter is well suited to applications where the higher speed of an automatic digital voltmeter is not required. In addition, however, the —hp— Models 740A and 741A also perform as dc standards, power amplifiers, and high impedance conventional voltmeters (see section A of this chapter). These latter features are not offered by digital voltmeters.

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[*] —hp— Models 740A and 741A.

[**] —hp— Currently offers 0.005% to 0.02% absolute accuracy.

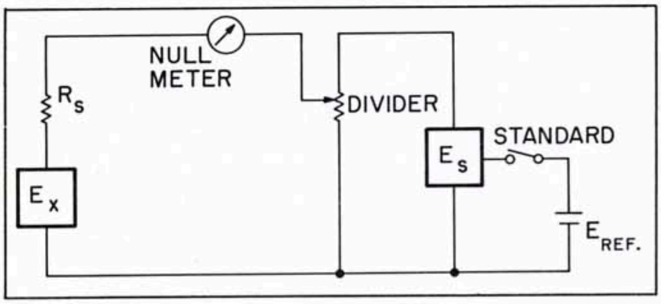

Figure 1-6. Potentiometric Method of Measuring Unknown Voltages

In reference to Fig. 1-6 we see that to measure high voltages, a high voltage standard is required. This need may be overcome by inserting a voltage divider between the source and the null meter. This, however, results in relatively low input impedance for voltages higher than the reference standard. This low input impedance is undesirable because accurate measurements may not be obtained if substantial current is drawn from the source that is being measured. Most differential voltmeters used today offer impedance approaching infinity only at a null condition, and then only if an input voltage divider is not used.

To overcome these limitations, Hewlett-Packard has developed an input isolation stage which develops an input resistance exceeding 10^9 ohms and handles inputs up to 1000 volts dc. This high resistance, usually a good approximation to an open circuit, is maintained independent of null condition. The isolation stage consists of a series-connected pair of amplifiers, a low-level chopper-stabilized amplifier and a high-voltage amplifier. Overall feedback greater than 100 db assures gain accuracy and produces the high input impedance.

The high level amplifier is the key to obtaining a high voltage output using low-voltage power supplies and solid-state design. Voltage regulation is provided by pulse-width modulation of an internally generated square wave. This controls a transistor switch which drives a step-up transformer, a rectifier, and filter circuit.

High sensitivity, stability, and high-input impedance are achieved in the meter circuits. These are achieved by careful design of the solid-state, chopper-stabilized, feedback amplifier. Null sensitivity is provided through decade pushbuttons, which select the proper amount of amplifier gain and connect the decade dividers to the measuring circuit.

The voltage reference supply is a Zener diode encased in an oven with highly regulated, proportionally controlled temperature. This results in stabilities better than .0015%/month. Most differential voltmeters use a Kelvin-Varley decade divider which provides a constant impedance load to the reference supply. Such a divider uses 11 resistors per decade. A binary technique developed by Hewlett-Packard (patent applied for) is electrically similar to the Kelvin-Varley divider but uses only four resistors per decade. This reduces initial cost, as well as calibration time.

An important feature of this new technique is the method by which the dividers* may be calibrated in the field. An internal switch connects the resistors of the decades in a bridge combination. The front panel meter serves as a null indicator so that trimming resistors can be adjusted to establish resistor ratios to extreme accuracy.

Figure 1-7 shows a block diagram of the –hp– 741A AC/DC Differential Voltmeter/DC Standard. This model offers precise ac measurements up to 100K Hz, in addition to features already mentioned.

2. Servo Balance**—Intermediate accuracy *** between the amplifier-driven meter types and the manually-balanced potentiometric types is offered by the servo balance technique. The technique is characterized by a servo motor, amplifier, gear train, slidewire potentiometer, and linear scale. As long as there exists any difference between the input voltage and the voltage at the slider of the potentiometer the motor is energized to rotate in the appropriate direction to drive the difference toward zero. In the complete absence of friction, loading, or backlash, a perfect null would be obtained, since the error is integrated to form a correction. The pointer is attached to the slider of the

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*Applies to –hp– Model 740A.

** Mosley Model 22

***The Mosley Model 22 offers 0.2% of full scale accuracy.

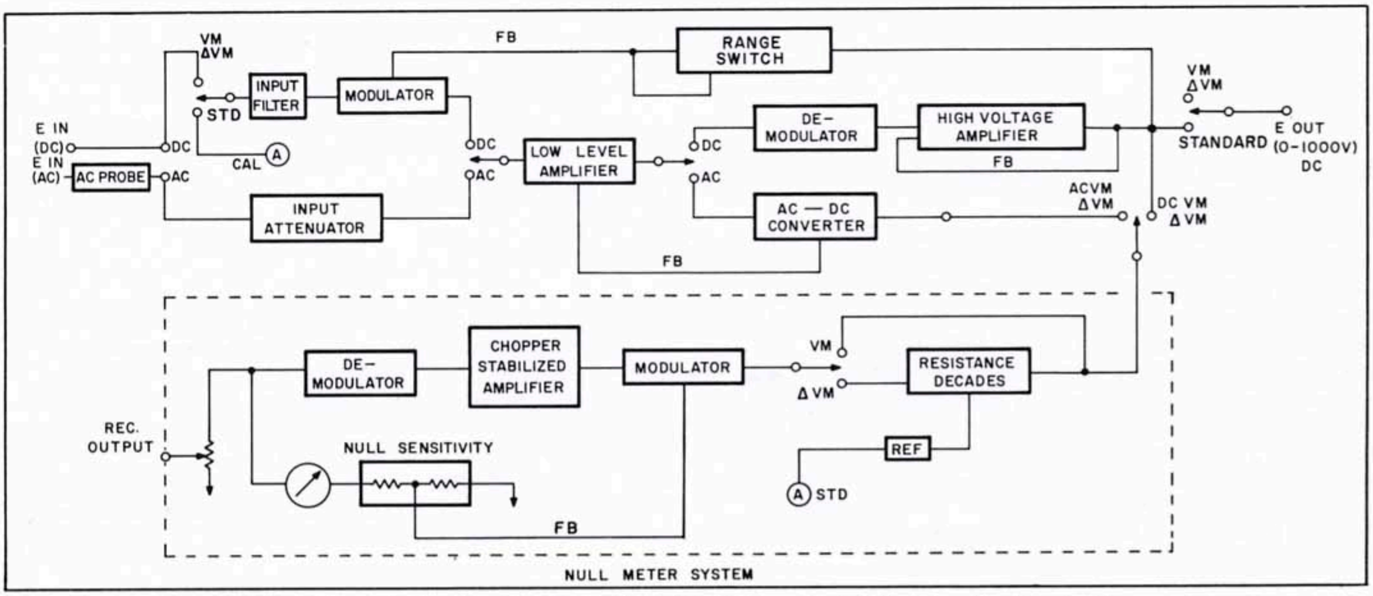

Figure 1-7. Hewlett-Packard ac/dc Differential Voltmeter/dc Standard

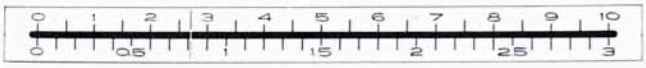

Figure 1-8. Fourteen Inch Mirror-Backed Scale Used On Mosley Model 22 DC Servo-Voltmeter

potentiometer. Figure 1-8 shows the 14″ mirror-backed linear scale used on the –hp– Model 22 DC Servo Voltmeter. The lowest range is 3 mv full scale, which allows resolution of better than one microvolt.

D. Automatic Digital Readout Types

Introduction

Digital voltmeters (DVM's) display measurement as discrete numerals rather than as a pointer deflection on a continuous scale commonly used in analog devices.

Several advantages in DVM characteristics sometimes lead to selection of a DVM in preference to analog measurement methods. Direct numerical readout in DVM's reduces human error and tedium, eliminates parallax error and increases reading speed. Automatic polarity and range-changing features reduce operator training, measurement error, and possible instrument damage through overload. Digital instruments are available to measure ac and dc voltages, dc currents and resistance. Many also have outputs to make permanent records of measurements with printers, card and tape punches, and magnetic tape equipment. With data in digital form, it may be processed with no loss of accuracy.

1. Ramp Types
   (a) Voltage-To-Time Conversion°. This technique is used to form a class of digital voltmeters. The operating principle of the ramp digital voltmeter is to measure the length of time it takes for a linear ramp to change from the input level to ground (or vice versa). This time period is measured with an electronic time-interval counter and displayed on in-line indicating tubes. The advantages of this type of instrument can be low price and simplicity.

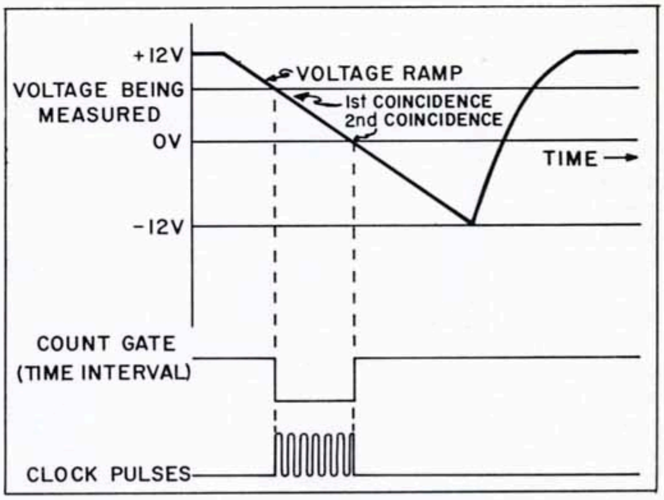

Figure 1-9. Voltage To-Time Conversion

Conversion of a voltage to a time interval is illustrated by the timing diagram of Figure 1-9. At the start of a measurement cycle, a ramp voltage is initiated. The ramp is compared continuously with the voltage being measured; at the instant they become equal, a coincidence circuit generates a pulse which opens a gate. The ramp continues until a second comparator circuit senses that the ramp has reached zero volts. The output pulse of this comparator closes the gate.

The time duration of the gate opening is proportional to the input voltage. The gate allows clock pulses to pass to totalizing circuits, and the number of pulses counted during the gating interval is a measure of the voltage. Choice of ramp slope and clock rate enables the totalizing circuit to readout directly in millivolts (e.g. a slope of 400 v/sec and clock rate of 400 kc).

If the input were a negative voltage, coincidence with it would occur after zero coincidence.° Circuitry senses which coincidence occurs first and switches the polarity indicator accordingly.

The virtue of the voltage-to-time conversion as a digitizing technique lies in its simplicity. Furthermore, slowly varying input voltages do not disturb the operation of the voltmeter, as often happens with null-seeking voltmeters which may continually hunt for, but never achieve a balance.

A block diagram of the –hp– 3440A Digital Voltmeter (Figure 1-10) shows the basic parts of a system typical of time encoding. A voltage ramp is generated and compared

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°–hp–Models 405BR, 405CR, 3440A

°Refer to Fig. 1-9.

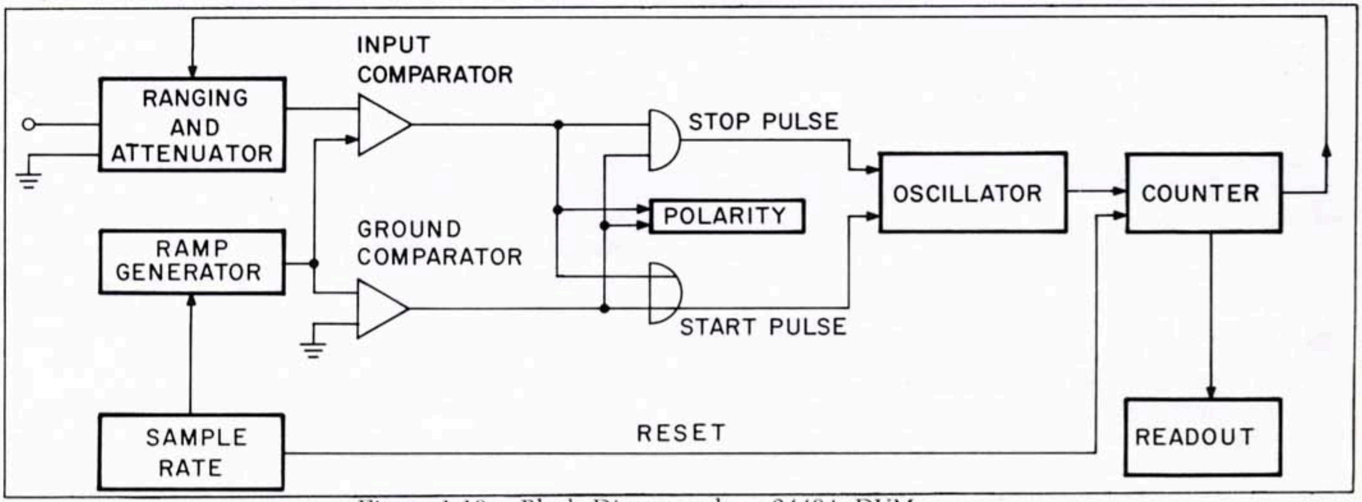

Figure 1-10. Block Diagram –hp– 3440A DVM

with the unknown voltage and with zero voltage. Coincidence with either voltage starts the oscillator, and the electronic counter counts the cycles. Coincidence with the second comparator stops the oscillator. The elapsed time is proportional to the time the ramp takes to travel between the unknown voltage and zero volts, or vice versa. The order in which pulses come from the two comparators indicates the polarity of the unknown voltage. The accumulated reading in the counter can be used to control ranging circuits. The comparators used in the –hp– 3440A are of a unique, solid-state circuit design, contributing to a system which is fast, economical, and has high input impedance.

The system used in the 3440A allows one to make an economical DVM with adequate speed and accuracy for a majority of production and bench test requirements. The 3440A has an accuracy of ±0.05% of reading with reading rates up to 5 per second. These features, coupled with its capability of 10 μv resolution* and four-digit readout, make it the economical choice.

(b) Staircase Ramp

A related technique requires generation of a staircase ramp reference by means of a digital to analog converter. The steps correspond to the least significant digit, so time intervals need not be closely controlled. Coincidence between the input and the staircase must be detected. The digital-to-analog converter then contains the digital result.

2. Potentiometric Types

(a) Successive Approximation—The successive approximation type of digital voltmeter converts the input voltage into digital form by a series of approximations and decisions. This type of voltmeter consists of a digital storage register (digital accumulator), a digital-to-analog converter, a comparison network (error detector), a precision voltage reference, and control circuitry. The input voltage is compared first with the most significant bit. The actual comparisons are made successively in binary form. If the input voltage is less than the most significant bit of the reference the most significant bit of the register is cleared and the next lower bit is switched in for comparison. The process of switching in the next lower significant bit is continued until a decision is made on all digits. At this point, the voltmeter has completed its measurement.

The accuracy of this technique is limited by the comparator sensitivity, reference supply, digital-to-analog converter and the resolution of the instrument. Its advantages are speed, accuracy and fixed encoding time. However, because the successive-approximation method is sensitive to noise, an input filter is required if it is necessary to suppress superimposed noise, and thus limits speed of response.

The staircase ramp technique (already mentioned) can be considered to be a variation of the above. The staircase ramp is slower, however, and does not have a fixed encoding (measurement) time. Fixed encoding time is often desirable in automatic data acquisition systems, where it is often convenient to use a fixed reading rate.

(b) Continuous Balance—The continuous balance type of digital voltmeter performs a digital measurement by comparing the unknown voltage against a voltage derived from a stable reference supply. If a null does not exist, a voltage derived from the reference is modified by an incremental value representing a unit of the least significant digit. This process continues until null is achieved. However, when the input voltage varies because of superimposed noise, null is never reached; and the digital voltmeter hunts, never reaching an answer.

Servo (motor and gear) variations of this technique also exist. The digital readout can be a mechanical counter.

3. Integrating Types*—An integrating digital voltmeter measures the true average of the input voltage over a fixed encoding time, in contrast to successive-approximation, continuous-balance and ramp types of digital voltmeter, which measure the voltage at the end of the encoding interval. Measurement at the end of the encoding interval can easily coincide with a burst of noise, thus creating a discrepancy in the DVM's indication. A widely used technique to accomplish integration is the use of a voltage-to-frequency converter, as indicated in Fig. 1-11. The circuitry functions as a feedback control system which governs the rate of pulse generation, making the average voltage of the rectangular pulse train equal to the dc input voltage.

A positive voltage at the input results in a negative-going ramp at the output of the integrator. The ramp continues until it reaches a voltage level that fires the level detector, which, in turn, triggers a pulse generator. The pulse generator produces a rectangular pulse with closely controlled width and amplitude just sufficient to draw enough charge from capacitor C to bring the input of the integrator back to the starting level. The cycle then repeats.

The ramp slope is proportional to the input voltage. A higher voltage at the input would result in a steeper slope, allowing a shorter time duration for the ramp. Consequently, the pulse repetition rate would be higher. Since the pulse repetition rate is proportional to the input voltage, the pulses can be counted during a known time interval, to derive a digital measure of the input voltage. While a voltage ramp is generated in this type of DVM, the amplitude is only a fraction of a volt; and the accuracy of the analog-to-digital conversion can be high because it is determined not only by the characteristics of the ramp, but also by the charge in the feedback pulses.

The primary advantage of this type of analog-to-digital conversion is that the input is "integrated" over the sampling interval, and the reading represents a true average of the input voltage. The pulse repetition frequency "tracks" a slowly varying input voltage so closely that changes in the input voltage are accurately reflected as changes in pulse repetition rate. The total pulse count during a sampling interval therefore represents the average frequency, and thus, the average voltage. This is important when noisy signals are encountered. The noise is thereby averaged out during the measurement without requiring input filters that would slow the voltmeter response time. Furthermore, the voltmeter achieves essentially infinite rejection of power line hum when the measurement interval is an exact multiple of the hum waveform period; this is the most prevalent source of signal noise.

A second advantage is that the pulse circuits provide a convenient means of coupling the information out of a

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*—With hp–3443A or 3444A Plug-Ins.

*Dymec 2401C.

guard circuit.* The Dymec DY-2401C Integrating Digital Voltmeter has a floating input, and all of the voltage-to-frequency conversion circuitry is housed within a guard shield. Figure 1-12 shows a simplified block diagram of the technique used. The integrator, pulse generator, and level detector generate a train of pulses. The total number of pulses over a specified period is directly proportional to the integral of the input signal over this same period of time. This arrangement makes it possible to transformer-couple the signal to the digital circuits outside the guard, and thus enables complete isolation of the measuring circuit itself.

This model applies especially well to measurements of extremely noisy signals, even rejecting noise up to 100% of full-scale, peak value. It is also capable of 1 μ v resolution; full scale readings down to 99.999 mv can be made without an accessory amplifier.** If high reading rates are required, the DY-2401C can take readings with three-digit resolution at rates up to 50/sec. Speed is an outstanding feature of the optional auto-ranger; less than 34 milliseconds are required to select the correct range. This speed, along with its complete remote control ability, makes it ideal for system applications. Another unique feature is the ability to measure the volt-second integral of an arbitrary waveform. It also can be used as an electronic counter to measure frequency or period.

4. Integrating/Potentiometric Types*—A new high in DVM measurement accuracy, obtained by a unique analog-to-digital conversion technique, is found in the –hp– solid-state Model 3460A Digital Voltmeter.

The 3460A, which might be regarded as an automated differential voltmeter, offers extremely high accuracy and resolution.

By using techniques which exploit the best features of several systems, a totally new result has been achieved in this model. Besides being an integrating type voltmeter which continually measures the true average of the input voltage, it also is a potentiometric type, relying primarily on resistance ratios and a stable reference voltage to assure high accuracy.

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*See Chapter III also.

**9.9999 mv with Dymec 2411A Amplifier.

*–hp– 3460A. Patent pending.

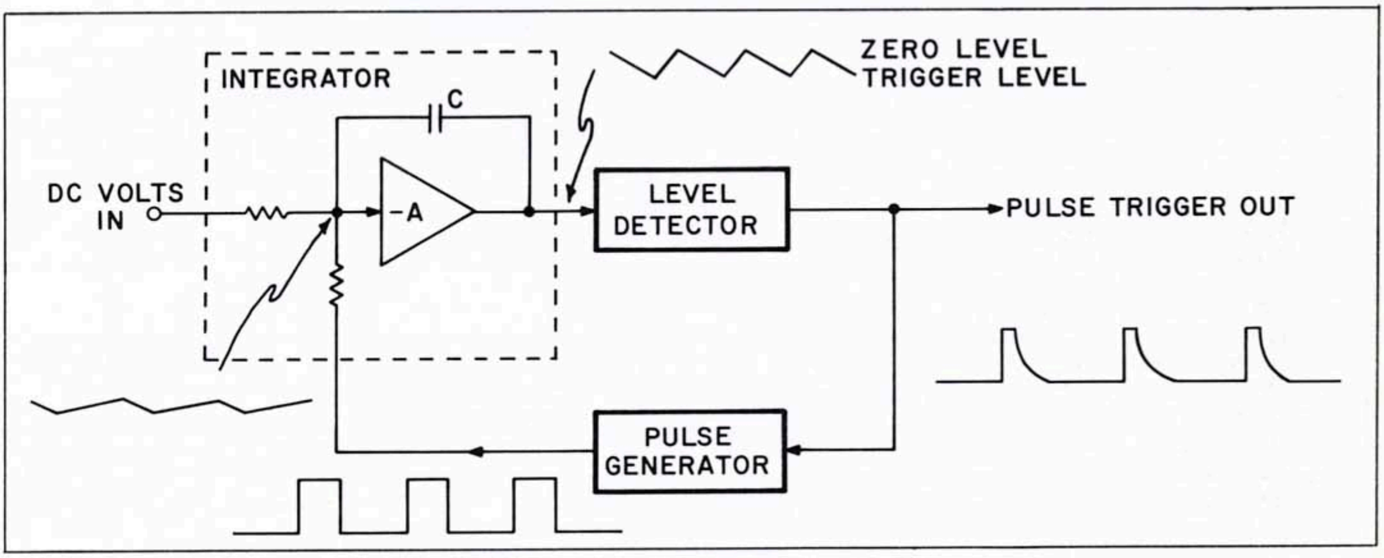


Figure 1-11. Voltage-to-Frequency Conversion

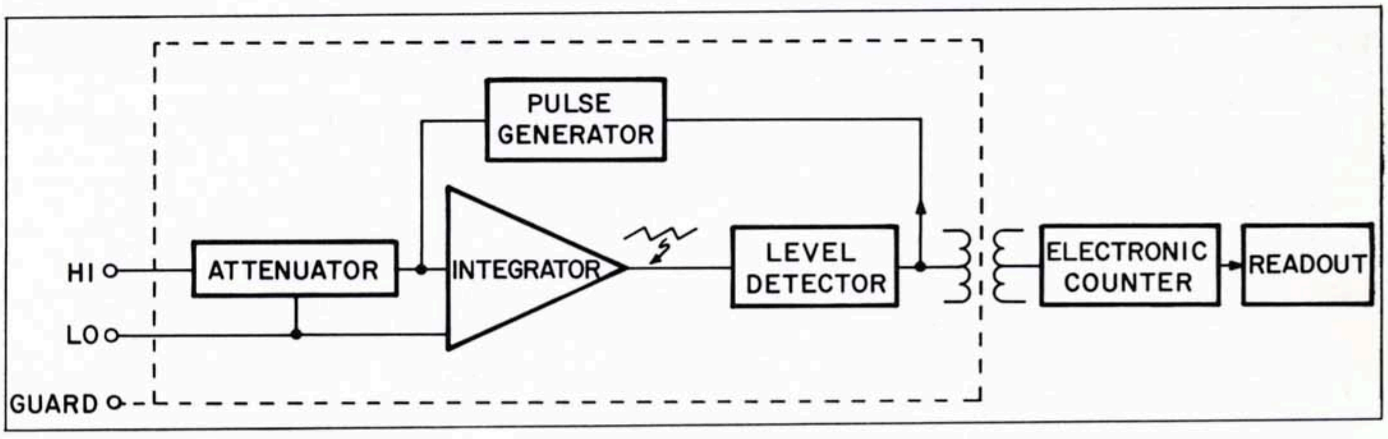


Figure 1-12. Block Diagram –dy 2401C Digital Voltmeter

A block diagram of Integrating-Potentiometric Digital Voltmeter is shown in Figure 1-13. Note that the voltmeter is divided into three sections: a voltage-to-frequency (V/F) converter, a counter, and a digital-to-analog (D/A) converter. A reading is taken in two steps.

First, the voltage-to-frequency converter generates a pulse train with a rate exactly proportional to the input voltage. This pulse train is gated for a precise time interval and is fed to the first four places in a 6-digital counter. The stored (undisplayed) count is transferred to the D/A converter, which produces a highly accurate dc voltage proportional to the stored count. This voltage is subtracted from the unknown voltage at the input to the V/F converter, and the V/F gain is raised in preparation for the second gate.

Next, the pulse train from the V/F converter is again gated–this time to the least significant place in the 6-digit reversible counter. At the end of the second gate period, the total count is transferred to the 6 digit display. The counter display is indicative of the integral of the input voltage.

The –hp– 3460A should be chosen for applications which require extremely high accuracy (±0.005%) and high speed with high resolution. The 3460A takes up to 15 readings per second with more than 5-digit resolution (1.20000 full scale). These readings can all be made in the presence of large common-mode signals. Other features are automatic ranging, remote ranging and remote triggering. Noise averaging is obtained through use of the integrating technique. This voltmeter can reject superimposed noise up to either 1% or 6% of the full scale range, depending upon the speed. The integration feature also allows a maximum reading rate, even with noisy signals, since no input filter is required.

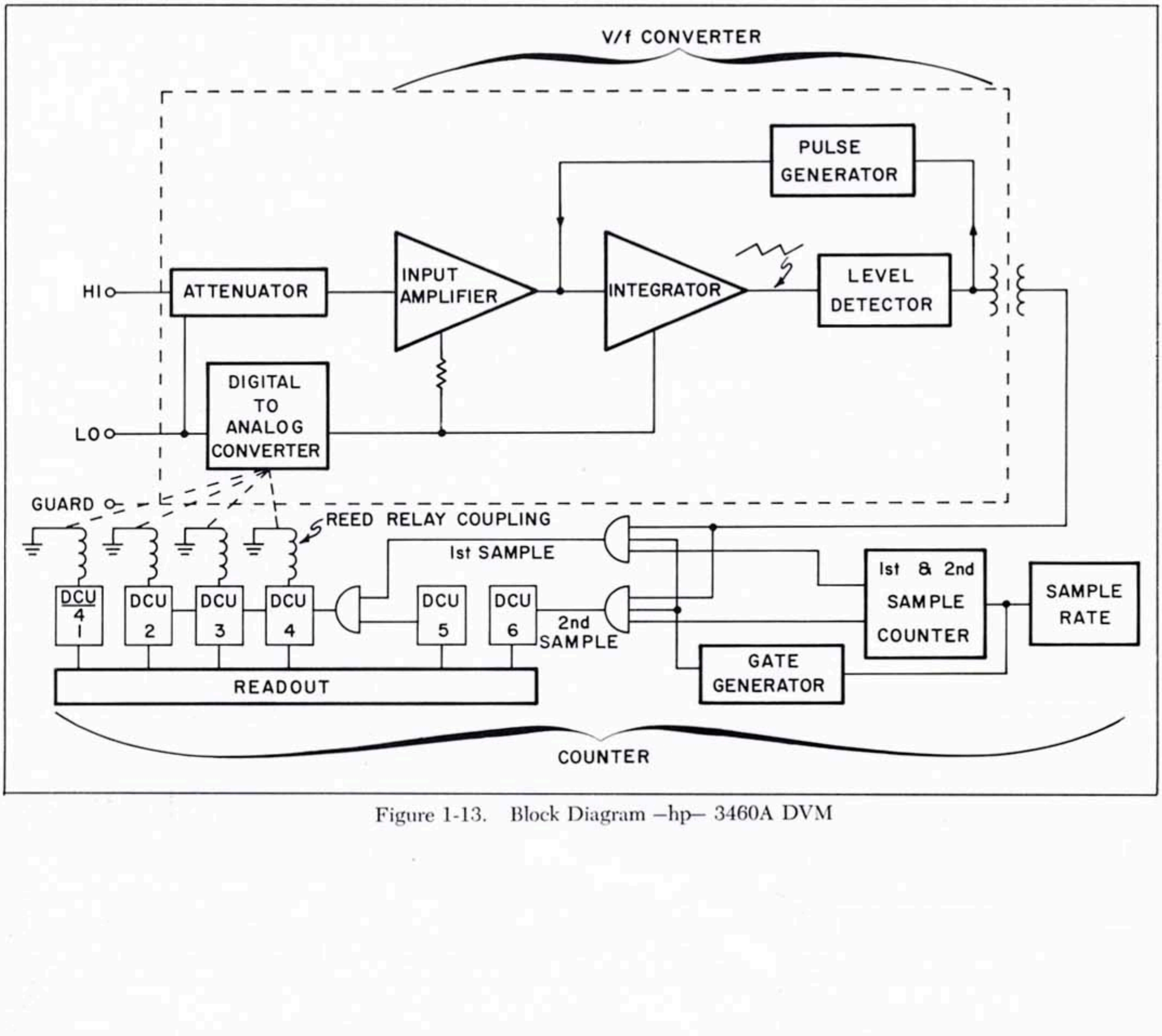
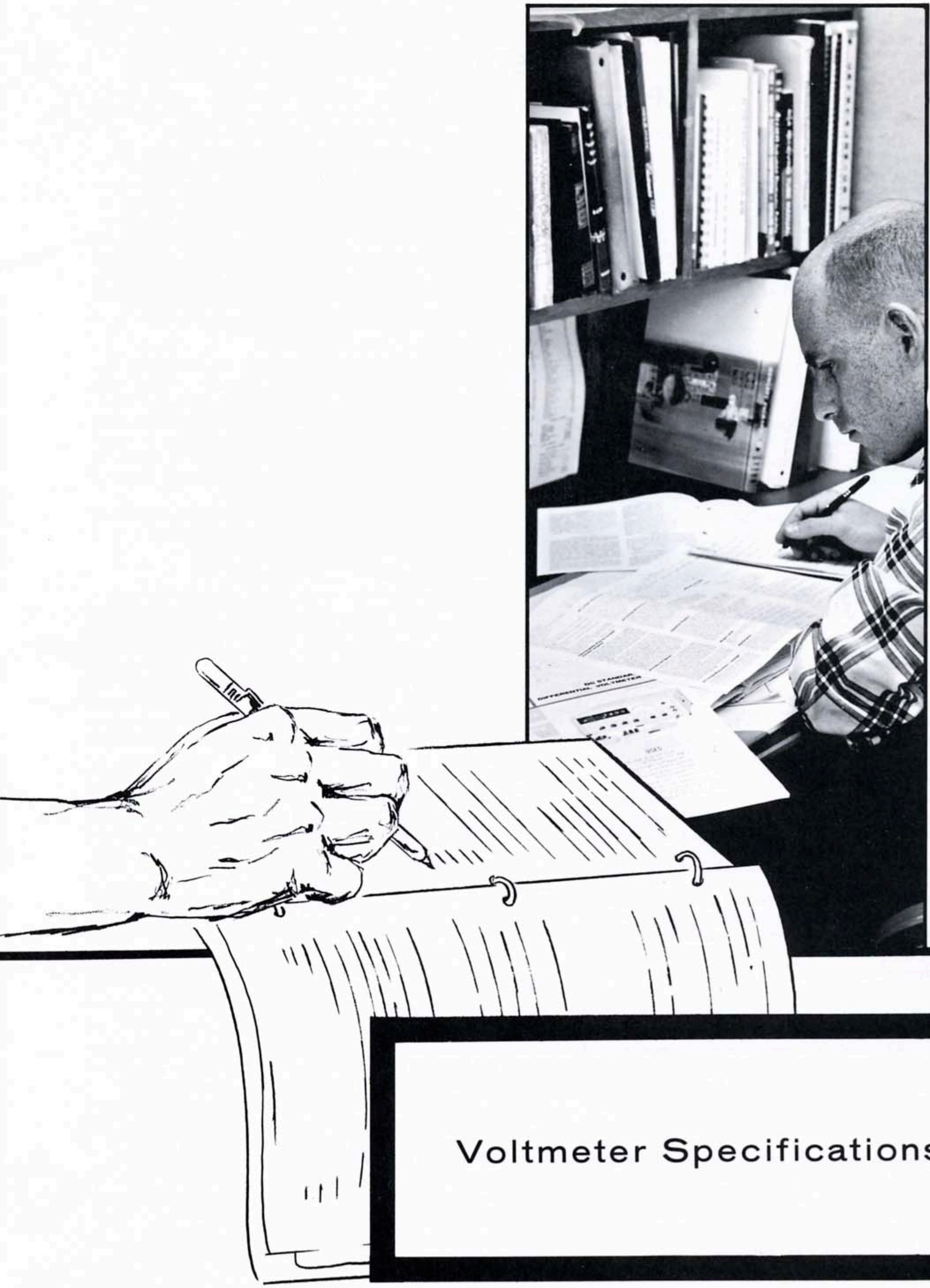


Figure 1-13. Block Diagram –hp– 3460A DVM



Voltmeter Specifications

CHAPTER II

VOLTMETER SPECIFICATIONS

A. Introduction

Specifications are written in order to detail a *complete description* of the parts of a whole, such as the quality, capabilities, size, features, terms, etc., of a particular item. In general, the more detailed and explicit the description, the greater the cost is likely to be. The conflicting requirements of a "complete description" and low cost lead to many compromises in the quoted specifications of an instrument.

The utility and simplicity of specifications must also be considered as criteria when quoting voltmeter specifications. A specification which applies on all ranges, at all levels of operation, and over a wide range of environmental conditions is easily understood. Furthermore, such a broad specification eliminates measurement errors if one forgets that the summation of several effects may lead to a much greater potential error than was anticipated. For these reasons, a specification which applies over a broad range (Method I) is the best type for general purpose equipment. An example of two methods of specifying the accuracy of a general purpose DC analog voltmeter is tabulated in Table 2-1.

Table 2-1

Accuracy Specification of a DC Voltmeter with Meter Readout

Method I:	
Voltmeter Accuracy:	±1% of full scale on any range
Temperature Range:	10 – 40°C
Method II:	
Accuracy at 25°C:	
Amplifier – 1 mv range	0.1% of reading
Attenuator	0.2% of reading
Meter tracking	0.2% of full scale
Temperature Coefficient	
Amplifier	±.005% of reading/°C
Attenuator	±.005% of reading/°C
Meter	±.01% of full scale/°C
Zero Offset	±.01% of full scale/°C

There may be circumstances which make it desirable for both the customer and the manufacturer to limit or qualify a specification in an unusual manner, especially when working near the limits of the state of the art. There are always special situations due to instrument design techniques and application needs which lead to special cases. These special cases have prevented the adoption of a standard specification, although proposals have been made, along with pleas for more detailed, concise and brief specifications with greater uniformity.[1]

As the state of the art advances, it becomes more important that the terms we use in our discussions become better defined and refined. Some of the questions and major considerations involved in each specification are brought forth so that users may consider their relevance to each application. It is unlikely that one will find any voltmeter which defines all the specifications noted, simply because the expense cannot be justified for general applications under present market conditions. In case of a special application, one should contact the manufacturer's sales engineer. Hewlett-Packard voltmeters are checked and calibrated to more conservative limits than their commercial specifications. As the industry continues to mature, efforts to achieve some ground for common understanding should become more numerous.

B. Ranges

The range of voltages over which the instrument can be operated within specification should state the full scale ranges and resolutions available. Resolution may be stated by quoting the number of significant digits available in the readout. A useful figure of merit may be obtained by defining the number of digits as follows: Number of Digits = $\log_{10}$ Full-Scale Reading. (Decimal point moved to extreme right.)

Full Scale Reading	Number of Digits (rounded off to two places)
3.00000	5.5
1.20000	5.1
1.0000	4
1.000	3

The resolution of analog instruments should normally be quoted as one minor scale division. Alternatively, pictures of scales may be provided with analog instruments, since non-linear scales may still confuse the resolution interpretation. Any "overranging" features should be noted along with the method of readout. Methods of range selection (manual, automatic, remote, etc.) may be stated in this section.

C. Performance Rating[2]

1. *Accuracy*: A statement of the largest allowable error, expressed as a percentage or an absolute value. Four types of accuracy statements normally used are defined below.

   a. % of reading specified (≥)

$$\frac{(100)\,|(\text{Indicated Value})-(\text{True Value})|}{\text{True Value}}$$

   b. % of full scale specified (≥)

$$\frac{(100)\,|(\text{Indicated Value})-(\text{True Value})|}{\text{Full Scale Value}}$$

   c. x units of the smallest readout division expressed in counts. ≥

$$|(\text{Indicated Value})-(\text{True Value})|$$

(If the full scale reading is 1.19999 volts, ±2 counts means the maximum error is ±20 microvolts.)

   d. x volts ≥ | Indicated Value - True Value |

Due to design limitations of most types of voltmeters, it is necessary to express the accuracy as a sum of two errors, one proportional to reading and the other proportional to full scale. (This is avoided in some instruments by limiting the minimum input voltage.)

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[1] Proposed American Standard Requirements for Automatic Digital Voltmeters, and Ratio Meters.
Part 1—Direct-Current Instruments. ASA Std. C39.6.

[2] Part of the format of this section is taken from reference (1) above.

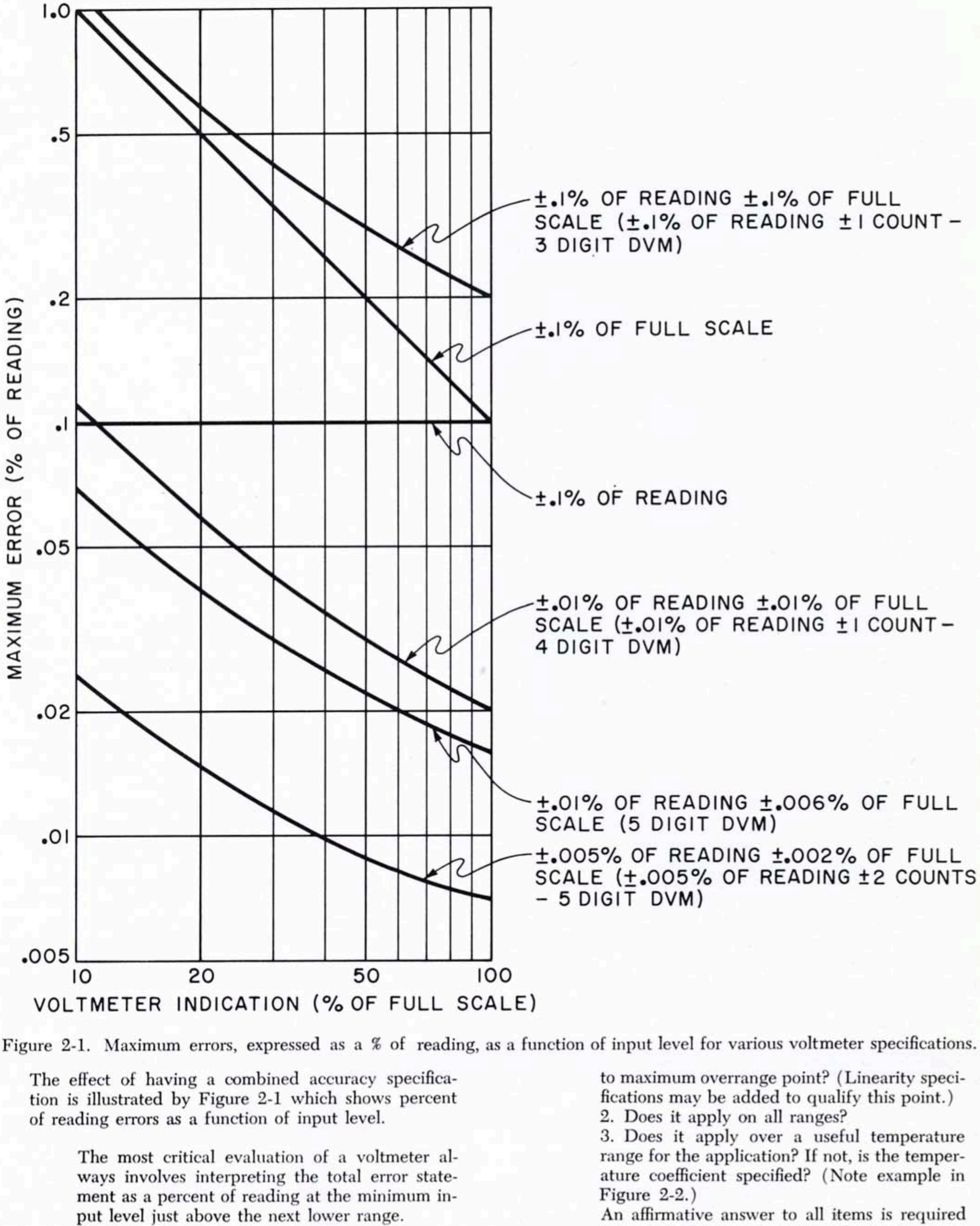


Figure 2-1. Maximum errors, expressed as a % of reading, as a function of input level for various voltmeter specifications.

The effect of having a combined accuracy specification is illustrated by Figure 2-1 which shows percent of reading errors as a function of input level.

The most critical evaluation of a voltmeter always involves interpreting the total error statement as a percent of reading at the minimum input level just above the next lower range.

Considerations regarding accuracy:

For a thorough evaluation of accuracy, the following questions should be considered:

1. Does it apply at all input voltage levels up to maximum overrange point? (Linearity specifications may be added to qualify this point.)
2. Does it apply on all ranges?
3. Does it apply over a useful temperature range for the application? If not, is the temperature coefficient specified? (Note example in Figure 2-2.)

An affirmative answer to all items is required for a complete accuracy specification. Accuracy ratings generally apply for a zero-impedance source; the same accuracies can be achieved for higher source impedances by cal-

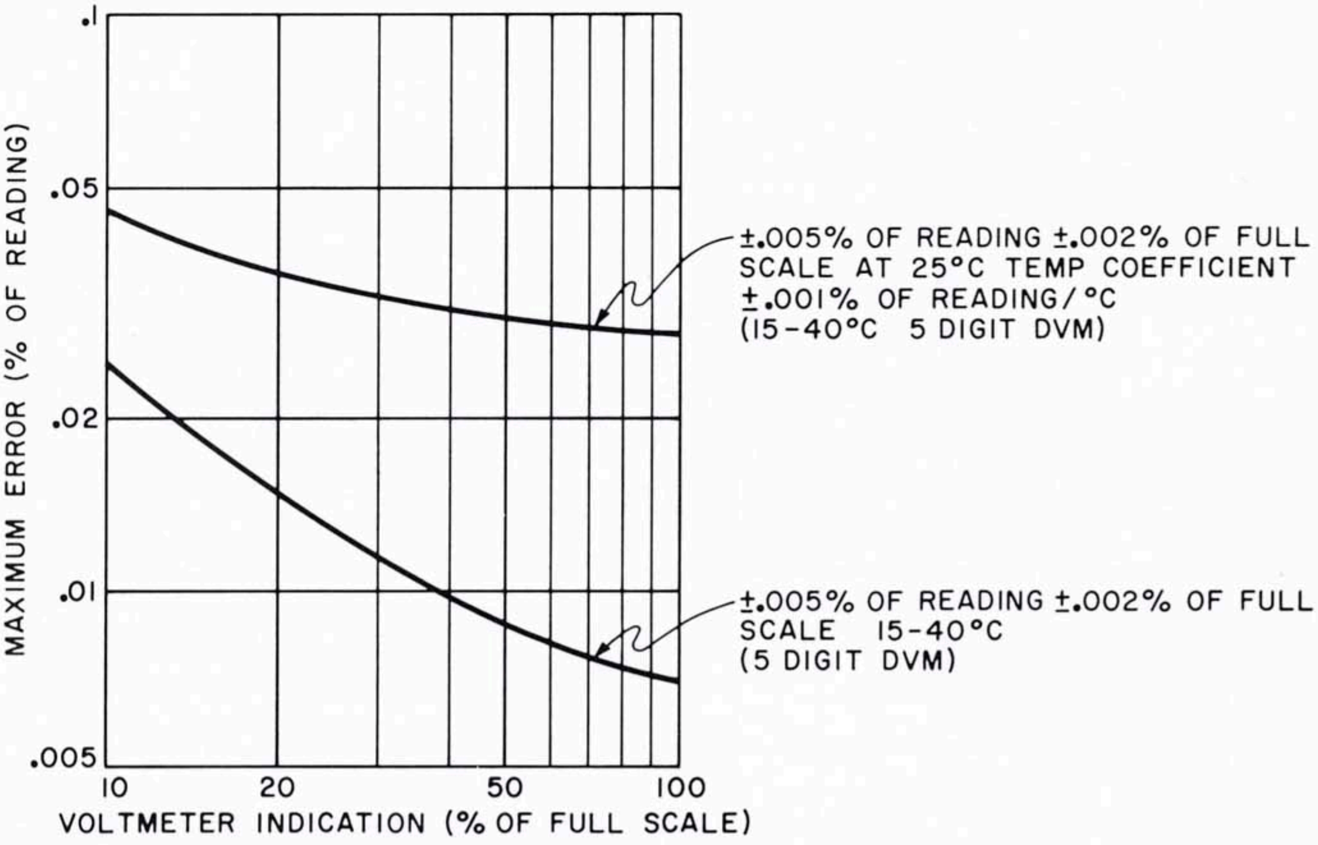


Figure 2-2. Comparison of maximum errors of two forms of voltmeter temperature specification.

culating the effect of the loading of the voltmeter-input resistance on the source.

2. *Stability*—The time period over which an instrument is guaranteed to remain within a defined accuracy rating. Expressions such as "short" and "long" term must be defined in order to be meaningful. In the absence of this specification, one must be acquainted with the manufacturer's design practice. This requirement permits the use of front-panel calibration and zero controls which can be adjusted without external equipment, which are a part of the normal operating procedure.
3. *Response Time*—The time required for a voltmeter to reach a reading within its accuracy limits, including delays due to filters, after a transient input condition occurs. Normally, the worse case time should be specified, which includes large or small increments of change, polarity changes, and range changes. (The latter two items only apply in the case of automatic equipment.) Alternatively, the delays due to polarity and range changes may be specified separately. If the instrument does not respond to small increments which are equal to the resolution—that fact should be noted. The response time should always be quoted as a limiting period, "fast" or "high" speed should be avoided. In the case of equipment which is manually operated, response time may be ignored if it is short compared to normal operator response time.

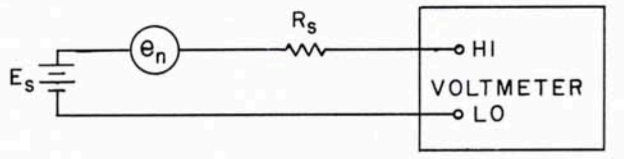
   Reading Period: The time period required for the voltmeter to complete one encoding operation.

   Reading Rate: 1/(Reading Period)

   Reading rate and period definitions do not apply to analog or manually operated equipment.
4. *Input Characteristics*
   a. Input resistance is the dc loading presented to the circuit under test by the voltmeter. In some voltmeters, its value may vary with time. The value at the time of final measurement is critical. This is the number that must be used when calculating loading effects. In some designs, the instrument may have a variable input impedance during a measurement—this should be noted along with the limits upon it.
   b. Input impedance—For some applications it is not adequate to know just dc resistance, since loading as a function of frequency must be evaluated. In the case of most dc instruments, input filters are involved; the expression for input impedance becomes very complicated over a wide frequency range. For this reason the specification may be covered by stating limiting values of shunt capacity and resistance at 10K Hz or higher frequency.
   c. Source Impedance Limits—If the instrument will not operate within its performance rating unless the source impedance is limited, those limits

should be defined.

d. Normal-Mode Interference Rejection—An unwanted signal in series with the dc voltage to be measured, i.e. superimposed noise (Refer to E_n of Fig. 3)



1. Normal mode interference ratio=

$$\frac{e_n \text{ (Peak Volts)}}{\text{Voltmeter Error (Peak Volts)}}$$

2. Normal mode rejection = Peak value of e_n which restricts voltmeter error to be less than specified.

(Frequencies of e_n to be specified)

Figure 2-3. Definitions of normal-mode rejection.

This quantity may be expressed in two ways:

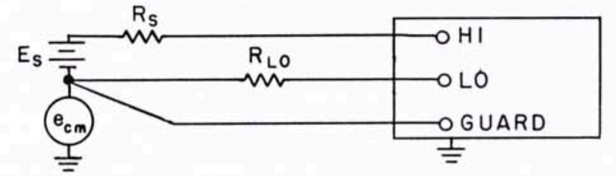
1) As the ratio of the normal-mode voltage to the resulting error in the display at a particular frequency. This ratio should apply at all signal levels from zero to full scale.

2) Some voltmeters are designed to totally reject an interfering signal up to a given level. At the critical level, the circuit saturates, and the rejection ratio reduces to unity or less. In such cases, the normal mode interference rejection should be quoted as an absolute voltage level which is not to be exceeded.

5. *Isolation Parameters*—The need for various isolation features and detailed definitions of those features is covered in a companion paper (3). For that reason, the required specifications of isolation parameters are included for completeness, without extensive definitions or discussion.

   a. Common–Mode Interference Rejection – will usually be expressed as a ratio; but may, in some cases, be limited to an absolute level. Other limitations in the applications of this specification should also be stated if they apply. Typical limitations include the following:

      1) Voltage ratings—between chassis and low, chassis and guard, guard and low, etc.



1. Common mode interference rejection =

$$\frac{e_{cm} \text{ (Peak Volts)}}{\text{Voltmeter Error (Peak Volts)}}$$

2. Common mode rejection = Peak value of e_{cm} which restricts voltmeter error to be less than specified.

Qualifications to specification:

a. Frequencies at which specification applies - (at least dc and line frequency)

b. Limitations to R_{lo}

Figure 2-4. Definition of common mode interference rejection.

      2) Impedance limitations—In most instruments the impedance which can be placed between the signal source and low is limited and should therefore be specified.

      3) It should be noted that the specification does not apply if auxiliary equipment is attached to the voltmeter output.

   b. Short-Circuit Current and Impedance—A line operated unit will generally have some line voltage between its low terminal and guard, between low and chassis, or between chassis and guard. It may also have dc voltages of consequence between those points if the insulators are not of the highest quality. The degree of interference can be evaluated by specifying the Norton equivalent of each of the three pairs of terminals mentioned above. (Norton equivalent is useful because it is much easier to measure at the impedance levels normally encountered.) That is, the short-circuit current at dc and at line frequency and the output impedance for each pair of terminals should be quoted. Note that in the case of a voltmeter which can be isolated from chassis, but which has no guard, only one pair of terminals is applicable.

   c. Asymmetrical isolation parameters—Occasionally voltmeters are designed with switches and/or circuits which make the isolation parameters a function of range and/or polarity. This should either be noted in the specifications or the worst case quoted. A typical example of this is the technique of reversing the polarity by switching the input leads.

   d. Remarks regarding isolation parameters—The isolation parameters may be critical in some applications, but insignificant in many others. Specifying them in detail in every case may lead to a higher cost instrument and to quoting complicated specifications which are not of general interest. As a result, it has not been common practice to quote isolation specifications in detail for every type of voltmeter. As the state of the art advances and the need to make low level measurements under adverse conditions becomes greater, more attention needs to be directed to these specifications.

D. Input-Output Characteristics

1. Analog types—specifications of recorder output such as: Dynamic range, output impedance, accuracy, noise level, etc. should be included.
2. Digital types
   a. Input—Trigger levels and control signals required. Amplitudes, rise times, durations, currents, etc., that may be required or significant.
   b. Output—Types of output codes, logic levels, voltage levels, source impedances, and output command signals should be specified.

E. Operational Features—Voltmeters tend to have many special features which may logically fall into a particular performance category, or which may not be related to any of them. Some of the items which should be considered when selecting a voltmeter are enumerated below. They may be mentioned at any of several locations in the specifications and are merely listed here in a miscellaneous category. Often items of this type are covered in descriptive literature accompanying a specification.

1. Modes of ranging—manual, automatic and remote (if not quoted in "ranges" of specification).
2. Type of readout—if not self-evident.
3. Performance limitations caused by "sensitivity" and "threshold" controls.
4. Presence or absence of display storage in digital types of voltmeters.
5. Special modes of operation. e.g., voltmeter reads if input changes by a prescribed amount, or if input exceeds certain limits, etc.
6. Modes of polarity selection—automatic, manual, or possibly none.

F. Extreme Operating Conditions—At least two major categories should be considered here. First, over what range of conditions will the instrument operate within specified performance? This should be a realistic range which covers the conditions met in most laboratories, production areas, and indoor facilities where voltmeters are used. Note that the specifications should not be qualified over this range. A second range of conditions should apply for the non-operating instrument. Transportation of equipment generally exposes it to extremes of temperature, humidity, shock and pressure which necessitates designing to very rugged standards. The characteristics which must be considered when evaluating a total instrument design are enumerated below:

1. Temperature
2. Relative Humidity
3. Atmospheric Pressure
4. Vibration and Shock
5. Operating Position
6. Sustained Input
7. Overloaded Input
8. Warm-Up Time
9. Conducted and Radiated Radio Frequency Interference

A customer is generally best protected on specifications of this type by purchasing his instrument from a reliable manufacturer who guarantees his products. Quality instrument manufacturers design their products so that they will perform within specifications over a wide range of environmental conditions. The manufacturer's sales engineer can help evaluate the compatability of standard instruments to each application. In many cases, an instrument can be supplied for an actual test of a particular application. This procedure assures the customer of satisfactory performance without burdening him with the extra expense of detailed environmental specifications for every application.

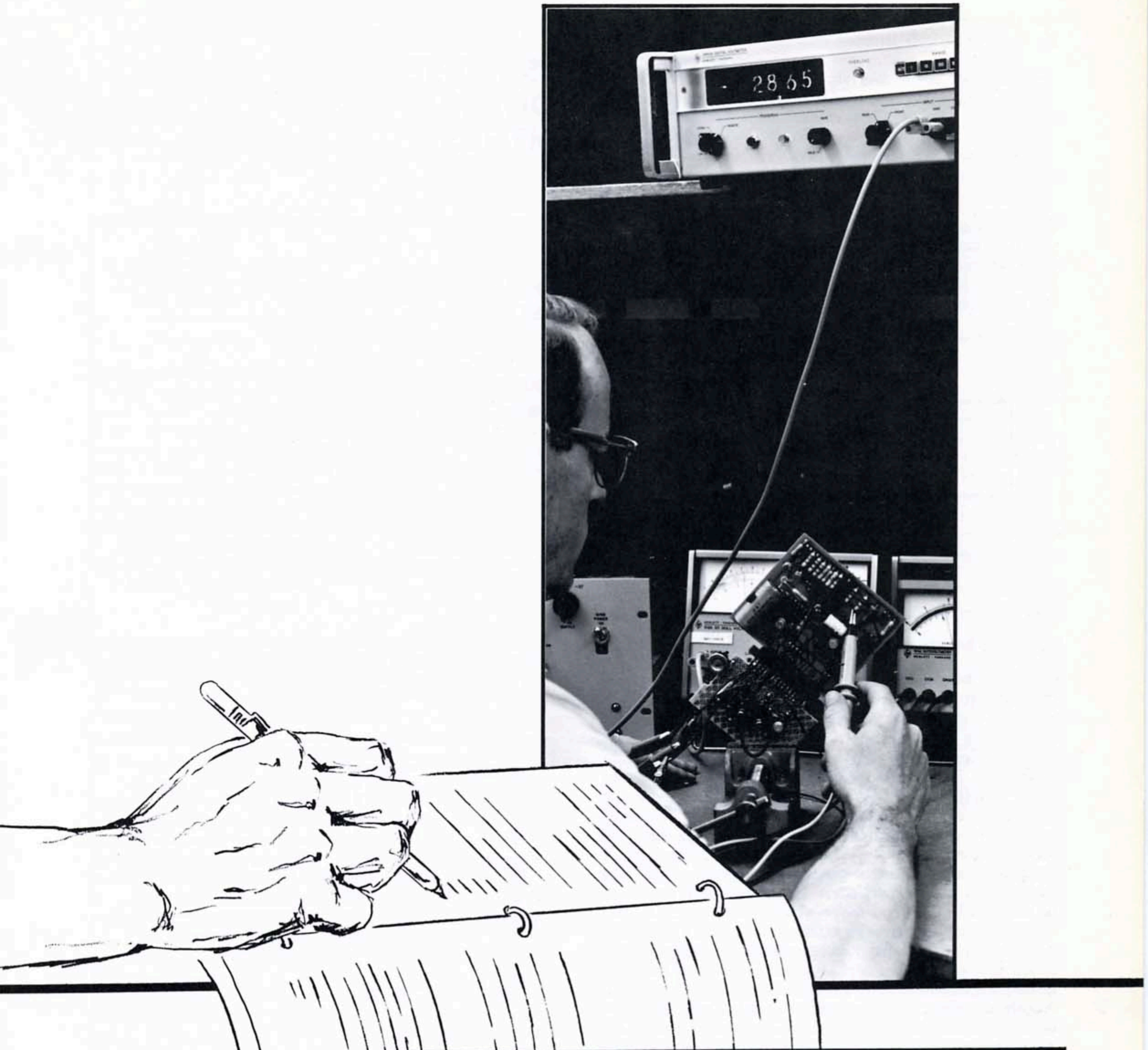
G. General—The general specifications enumerated below are often critical to a given application. They should be included as a matter of convenience.

1. Physical
   a. Dimensions
   b. Weight
   c. Type terminals
2. Power requirements
   a. Line voltages, including tolerable limits for operating specifications.
   b. Line frequencies
   c. Battery requirements, if any.
3. Accessories
   a. Connectors
   b. Special service tools
   c. Related equipment
4. Price—Include extras and optional features.

The specifications discussed in some detail above are summarized in Table 2 for your convenience. As Table 2-2 is reviewed, exceptions to a given specification should be noted in its category.

TABLE 2-2
VOLTMETER SPECIFICATIONS

A. *Ranges*—Including Resolution
B. *Performance Rating*
   1. Accuracy—Exceptions or Limitations to be Considered.
      a. Level sensitivity
      b. Range limitations
      c. Temperature limitations
   2. Stability
   3. Response time
   4. Input characteristics
      a. Resistance
      b. Impedance
      c. Source impedance limits
      d. Normal-mode interference rejection
   5. Isolation parameters
      a. Common-mode interference rejection
      b. Common-mode short circuit current and impedance
      c. Asymmetrical isolation parameters
C. *Input—Output Characteristics*
   1. Analog types
      a. Output impedance
      b. Accuracy
      c. Noise level
   2. Digital
      a. Input requirements (amplitudes, rise times, durations, etc.)
      b. Output (codes, logic levels, source impedances, etc.).
D. *Operational Features*—Modes of operation, features, etc., not covered in other specifications.
E. *Extreme Operating Conditions*
   1. Temperature
   2. Relative humidity
   3. Pressure
   4. Vibration and shock
   5. Operating position
   6. Sustained input
   7. Overloaded input
   8. Warm-up time
   9. Conducted and radiated radio frequency interference
F. *General*
   1. Physical
   2. Power requirements
   3. Accessories
   4. Price



Extraneous Noise and DC Voltage Measurements

CHAPTER III

EXTRANEOUS NOISE AND DC VOLTAGE MEASUREMENTS

A. Introduction

In its simplest form a dc voltage measurement is visualized as shown in Figure 3-1. E_s and R_s are the Thēvenin equivalent of the source, and R_{in} is the input resistance of the voltmeter. The voltmeter is calibrated to read E_x; unless the voltmeter is a potentiometric type, E_x will be less than E_s by an amount $\frac{Rs}{Rs + Rin}$ X 100%. R_{in} should be much larger than R_s to reduce this error. If the voltmeter is a potentiometric type, (often denoted differential[•]) an internal voltage is developed to buck against E_s, allowing $E_x = E_s$.

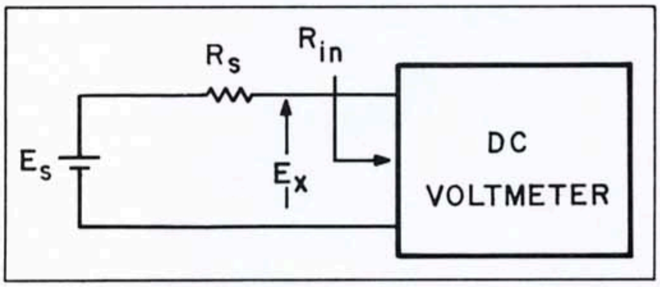


Figure 1: A Simple Measurement Model

Unfortunately for the voltmeter user, the Thēvenin equivalent, E_s and R_s, is quite inadequate to represent many real-life situations. The potential difference to be measured frequently exists between two points, neither of which is at earth ground. Instrument cabinets, however, are maintained at earth ground for safety; and one side of the power line is at earth ground. Further, ac noise[••] is frequently superimposed upon (in series with) the dc to be measured. Common mode noise, both ac and dc, frequently exists between the measurement points and earth ground. A line-operated voltmeter will always inject some power line noise between chassis and common, chassis and guard, or guard and common (whichever apply). Thermal or galvanic emfs, which are indistinguishable from the dc to be measured, may exist in the user's circuit and voltmeter connections.

B. Modeling the Source

To model the user's source for the situation just described, we introduce a three-terminal generalization of the two-terminal Thēvenin circuit. This model, shown in Figure 3-2, is valid for a linear, reciprocal network with internal sources. (Other models are also possible.)

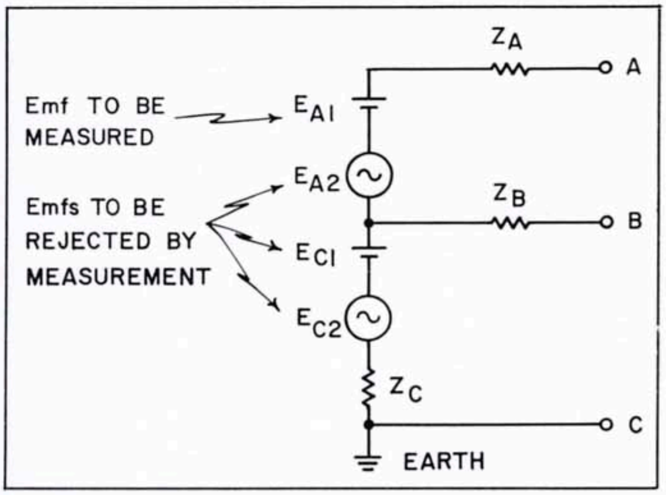


Figure 3-2: Model For Three Terminal Source

To illustrate the model of Fig. 3-2, let us assume the schematic of Figure 3-3. By sequentially looking into a pair of terminals with the other terminal open, we find Za + Zb = 500, Zb + Zc = 375, Zc + Za = 375, so that Za = 250 Zb = 250, and Zc = 125 ohms.

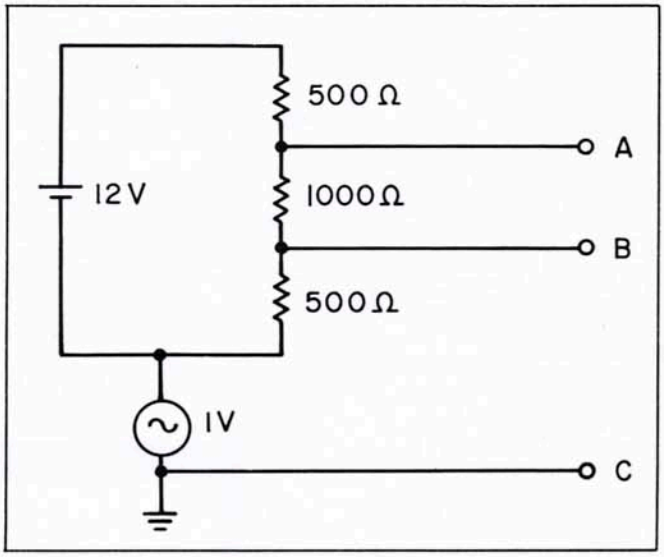


Figure 3-3: Illustrative Schematic

Also $E_{a1} = 6V$, $E_{a2} = 0$, $E_{c1} = 3V$, $E_{c2} = 1V$ The equivalence shown in Figure 4 is established.

[•] The term differential is also used in a different sense to apply to amplifiers which use two matched input stages to achieve common mode rejection.

[••] All emfs other than the dc to be measured are here denoted "noise," whether random or not.

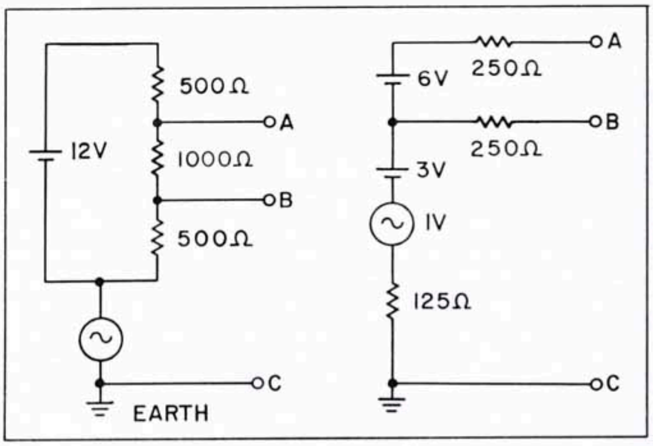


Figure 3-4: Equivalence of Two Sources

C. Superimposed AC

The noise generator E_{a2} (see Fig. 3-2) is variously denoted "series" noise, "normal" noise, or "superimposed" noise; its rejection is often expressed in db. The conventional way to suppress E_{a2} is to include a low pass filter at the voltmeter input. The low-pass filter unavoidably slows the step response of the voltmeter. A commercial digital voltmeter, for instance, attenuates superimposed noise by 30 db minimum at 60 Hz and requires 0.5 sec for 99.95% response to a step input. A more recent design, the integrating voltmeter, has the readout respond to

$$\int_0^T \left[e_{a1}(t) + e_{a2}(t) \right] dt .$$

If, for instance, $T \equiv 1/60$ sec then 60 Hz series mode noise is completely suppressed without use of a filter. For all voltmeter types a threshold value may exist for E_{a2}; anything exceeding this value causes a drastic degradation in performance.

D. Superimposed DC and Very Low Frequency Noise

Through data sheets, the manufacturer informs the user how well zero drift and related problems have been controlled in the instrument design. The voltmeter zero can always be checked by shorting the input terminals. In addition, a small zeroing (or bucking) voltage is often provided by the voltmeter to minimize offset problems.

Such offset problems are easily generated accidentally by the user in his own circuit. When unexpected readings are taken,the voltmeter may, therefore, be correct.

Thermal emfs of a few microvolts are easily generated by means of junctions of dissimilar metals. Some magnitudes are given in Table 3-1. As far as a dc voltmeter is concerned such emfs are indistinguishable from the dc signal to be measured. If dissimilar metal junctions are unavoidable in the user's circuit, temperature equalization can be accomplished by close physical spacing or by using an isothermal box. Such emfs may not be purely dc. An air draft may cause slow thermal fluctuations, which cannot reasonably be filtered out.

TABLE 3-1: Thermoelectric Effect in Metals

METAL	Microvolts/°C Against Platinum at 0°C
Aluminum	3.8
Antimony	47.0
Bismuth	–65.0
Copper	7.4
Iron	16.0
Palladium	– 5.6
Silver	7.1
Constantan	–34.4

Galvanic emfs are also easily generated. For example, a sensitive voltmeter was placed across two adjacent terminals of a bakelite strip. Warm, moist air was then blown onto the bakelite. Emfs of one millivolt, or more, were developed as long as the bakelite was moist. A dry environment, cleanliness, and best quality insulators help minimize galvanic emfs.

In addition to the thermal effects already mentioned, very low frequency disturbances can be generated by electrostatic and triboelectric effects. The user's body potential may be considerably off earth ground, depending perhaps upon the floor material. As a hand approaches an unshielded voltmeter, charges redistribute causing the voltmeter to respond. Triboelectric emfs, due to bending of an input cable, are other possibilities.

E. Common Mode AC and DC Noise

The generators E_{c1} and E_{c2} of Figure 3-2 are denoted dc and ac common mode noise generators respectively (3V and 1V in Fig. 3-4(b). Note that if the source is connected to a perfect voltmeter which leaves A, B, and C open circuited, E_{c1} and E_{c2} do not contribute to a difference voltage between A and B. The ability of a voltmeter to reject E_{c1} is denoted the dc common mode rejection. To be specific, assume $E_{a1} = E_{a2} = E_{c2} = 0$, but $E_{c1} \neq 0$. Denote the voltmeter response E_0. Then dc common mode rejection in db $= 20 \log_{10}\left(\frac{E_{c1}}{E_o}\right)$. A similar definition for rejection of ac common mode noise is:

$$\text{ac common mode rejection} = 20 \log_{10} \frac{E_{c2}\ (\text{peak})}{E_o\ (\text{peak})}$$

with $E_{a1} = E_{a2} = E_{c1} = 0$ but $E_{c2} \neq 0$. It is generally necessary to specify impedances Z_a and Z_b (especially Z_b) and the frequency considered. When E_{c2} exceeds some threshold value, saturation of voltmeter amplifiers often begins, and the common mode rejection decreases drastically in a non-linear manner. This threshold value may, however, be greater than the limitation of voltage breakdown.

F. Floating Measurements, Guarding

Since floating but unguarded voltmeters make up the bulk of low-cost general purpose intruments, consideration of a three terminal source connected to a floating* but not guarded** voltmeter is given in Figure 3-5.

The voltmeter has a finite input impedance, Z_{in}, and unintentional impedances Z_1 and Z_2 which usually can each be represented as leakage resistance with stray capacitance in parallel. In low cost instruments Z_2 is likely to be a capacitor inserted for reasons to be discussed later. Otherwise Z_2 is unintentional. Z_3 illustrates the possibility of a stray impedance connecting to an internal part of the voltmeter.

The voltage to be measured is E_{a1}, assuming that thermal or galvanic emfs have not modified its value. Ideally E_x should equal E_{a1}. It can now be seen that dc drops proportional to E_{a1} and E_{c1}, can be developed across Z_A and Z_B resulting in $E_x \neq E_{a1}$, and that E_{c2} now causes an ac voltage to be developed across terminals A and B. If the ac voltage is not adequately attenuated in the voltmeter, it will use part of the dynamic range of the input amplifier. If the effect is large enough, the amplifier

*Common is disconnected from earth ground.

**An external connection is made to an internal chassis.

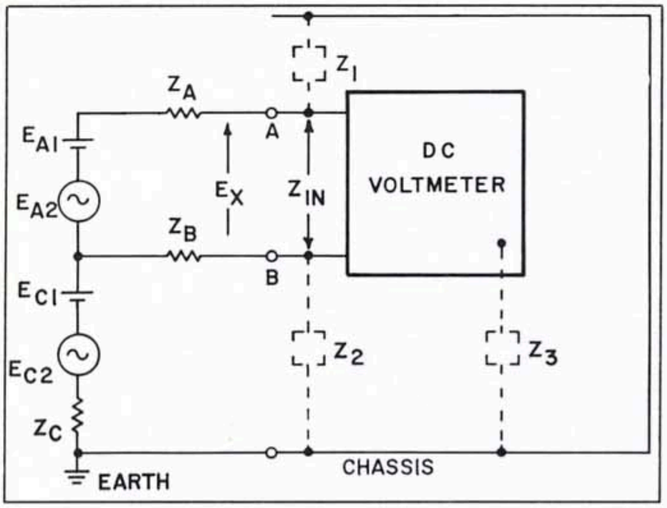


Figure 3-5: Floating Measurement Example

will distort, so that the zero or scale factor, or both, are shifted.

To illustrate, a dc error caused by $Z_1 \neq \infty$, let $E_{c1} =$ 500 volts dc common mode while $Z_B = 0$ and $Z_2 = Z_3 = \infty$. Suppose the voltmeter has a dc probe containing a one megohm resistor to minimize capacitive loading of the source by the cable capacity. While this resistor is part of the voltmeter, it is convenient to identify it as Z_A. A simple calculation shows that to develop less than one millivolt dc across Z_A the required value of Z_1 is $5 \text{ x } 10^{11}$ ohm or more. Depending upon the required sensitivity, this performance may be unacceptable, even though Z_1 is already at a value difficult to maintain under a condition of high humidity.

To increase ac and dc common mode rejection, consider the improved arrangement of Figure 3-6.

Figure 3-6 is intended to cover instruments in several price ranges. In lower-cost instruments, the inner chassis may or may not be a complete box.and is usually connected to common. Although this relieves the user of the problem of what to with the extra terminal, it should be recognized that ac and dc currents can then flow in loop Z_B, Z_4, Z_C and thereby develop a drop across Z_B. A dc drop across Z_B is an error, and an ac drop is extra superimposed noise. Otherwise the circuit is better. The previously troublesome Z_1 now merely shunts the amplifier input impedance. Z_2 is shorted out, and Z_3 is ineffective in injecting a signal to an internal part of the amplifier. The inner chassis results in drastic improvement of common-mode rejection, even when tied to common. Imperfections are leakages from terminals A and B around the inner chassis to the outer chassis, and also a finite Z_4.

Further improvement in common-mode rejection is possible if the inner chassis is made available as a separate (guard) connection. (Note that where two connections are considered in the simplest form, from the source to the voltmeter, this has now grown to four!) To make best use of the guard, it should be driven from the node of the equivalent wye so that driving current does not flow through Z_B or Z_A. (Also note if Z_C should approach infinity while E_{c1} and E_{c2} were fixed, then E_{c1} and E_{c2} would be dropped across Z_C so that common-mode rejection problems would not exist.) If this can be achieved, Z_1, Z_2, and Z_3 are "bootstrapped" and appear to be open circuits when perfection is attained. (To improve an imperfect situation, Z_1, Z_2, and Z_3 should be large.)

There may not exist in the user's source any physical point from which to drive the guard without making special provision.* An example of such special provision is given in Figure 3-7. If the user connects guard to common at the voltmeter, he will not achieve the full noise rejection capability of the voltmeter.

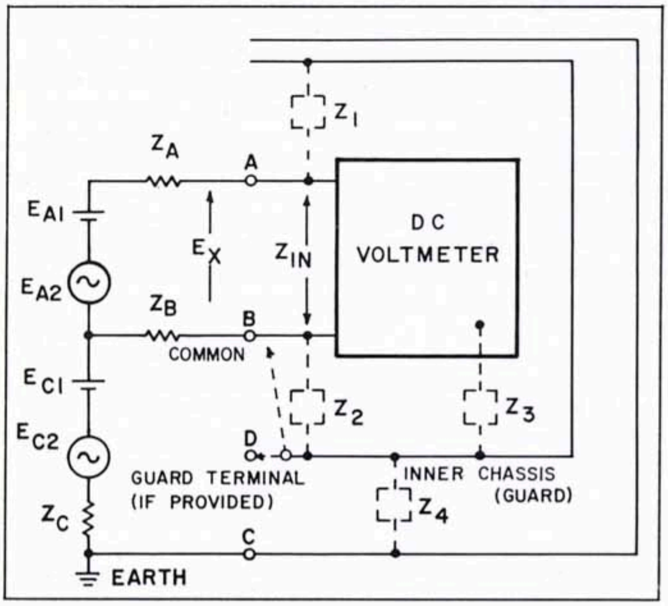


Figure 3-6: Improved DC Measurement

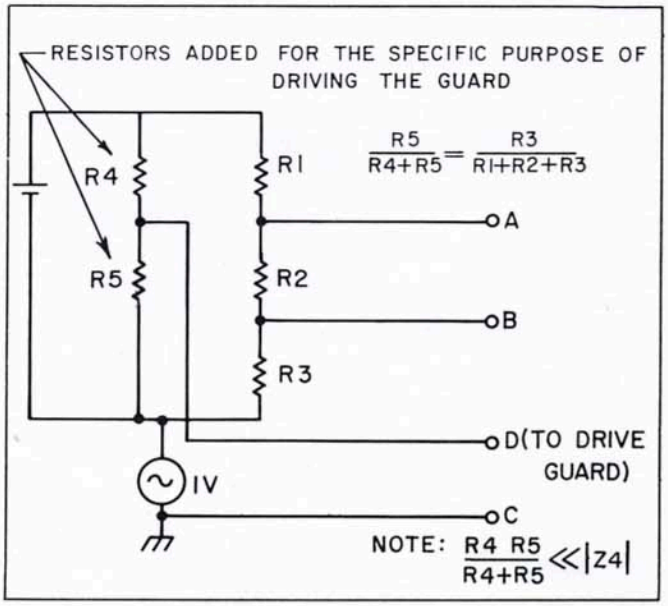


Figure 3-7: Example of Provision For Driving The Guard

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*The node of the equivalent wye may not physically exist.

G. Isolated Grounds

Up to this point we have ignored the problem of providing outputs referenced to earth or other arbitrary ground. Such isolation may be important to preserve best guarding. On lower-cost instruments, where small errors are tolerable and the main objective is a visual display, this problem is usually left unsolved. The recorder output, if any, remains referenced to input common[*]. If the recorder can float, the voltmeter can still be used unguarded.

Alternately, the measurement result can be transmitted through the inner chassis to circuits physically located between the two chassis. The inner and outer circuits then have separate, isolated power supplies. Digital information can be transmitted optically, by shielded pulse transformers or by shielded relays. The shield in each case would attach to the inner chasis. Figure 3-8 shows an example of shielded reed relays. A shielded transformer is generally used to transmit analog information. The modulation-demodulation process must generally operate open loop, and thus limits the accuracy. Even so, this last approach is used by some commercial instruments. There may, in fact, be nothing within the inner chassis other than a modulator.

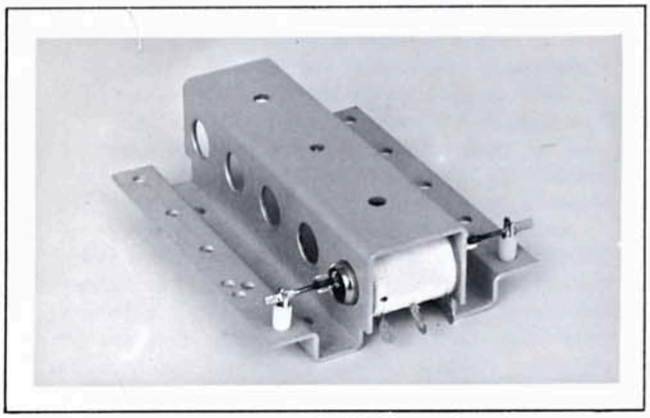

Figure 3-8: A Shielded Reed Relay

H. Injected Noise

A frequently overlooked problem is ac injection into the source by the floating instrument. The ac occurs at the power-line frequency and at its harmonics, plus some random noise. The trouble exists due to imperfect shielding in the power transformer or associated components.

Some insight into this problem can be gained from the highly simplified Figure 3-9, which considers a floating, but unguarded, instrument.

The desired condition is that no ac voltage appear between earth ground and common. In the absence of capacity, Cu, Ey would be zero (as desired) provided Cv = Cw. With Cv ≠ Cw and Cu ≠ 0, normally Ey ≠ 0. The fundamental component of Ey can be nulled by an appropriate capacitor Cx, either in the position shown or across Cv. Figure 3-10 shows a small capacitor installed in a commercial instrument for this purpose. Harmonics cannot be nulled, even with use of the center-tapped secondary, because IZ drops exist in the windings. To minimize Ey, it is fairly common to insert a capacitor, C_2, between earth ground and common. Since the ac is injected by means of small winding capacities, Ey varies inversely with the size of C_2. The existence of C_2 is otherwise objectionable, as discussed earlier, and some compromise is settled upon.

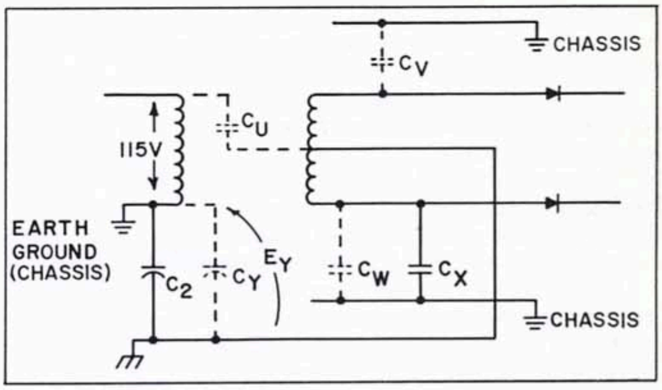

Figure 3-9: AC Injecting Example

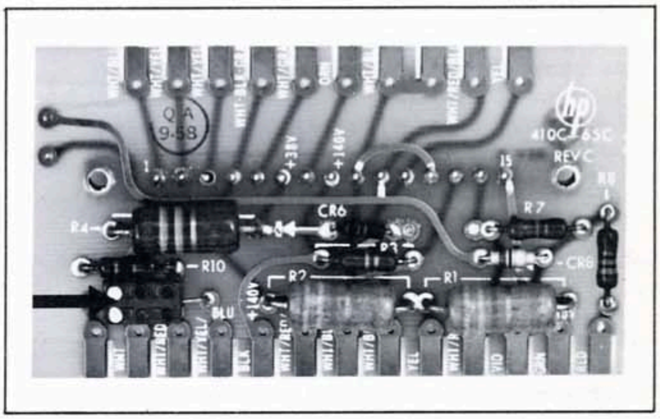

Figure 3-10: Capacitor Installed to Null Ey

To further illustrate ac injection, consider Figure 3-11. The user may have had no common-mode signal on his common prior to attaching the voltmeter. The common mode rejection of the circuit is being tested,

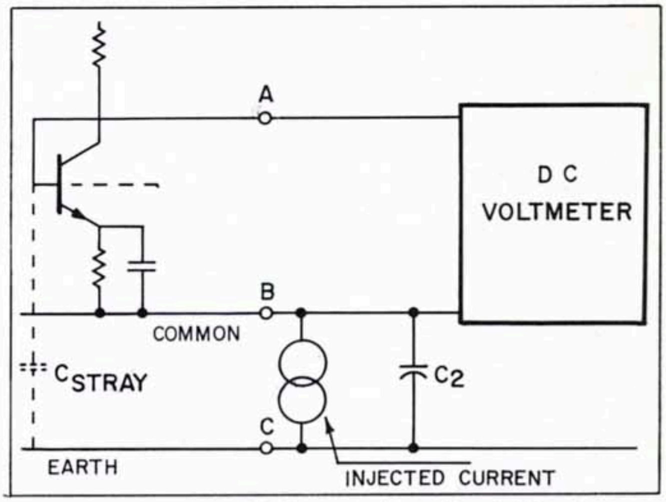

Figure 3-11: AC Injection Into User's Circuit

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[*] One solution is the use of a voltmeter, differential in the sense of having two matched input stages. Such a voltmeter can have its power supply common with a third wire tied to an arbitrary ground within the tolerance limitation of the input stages.

and existence of an impedance, such as C stray, may allow ac to be developed across the transistor shown. This may result in amplifier saturation.

In principle, ac injection can be laid to rest with appropriate shielding, as illustrated in Figure 3-12. The various capacities which exist may be substantial in magnitude (undesirable), but are all in harmless positions to inject ac. If a separate guard is to be used, then a separate guard shield is inserted between the primary and secondary shields, making a total of three shields.

In low-cost instruments, the shielding is less than perfect, and an injected current of a few tenths of a microampere is not unusual. In a guarded instrument, the injected currents may be only a few hundredths of a microampere.

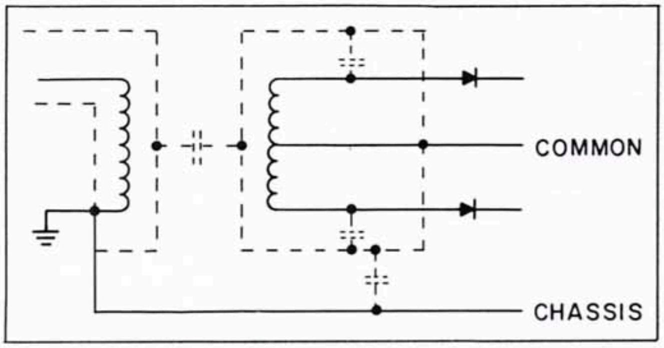
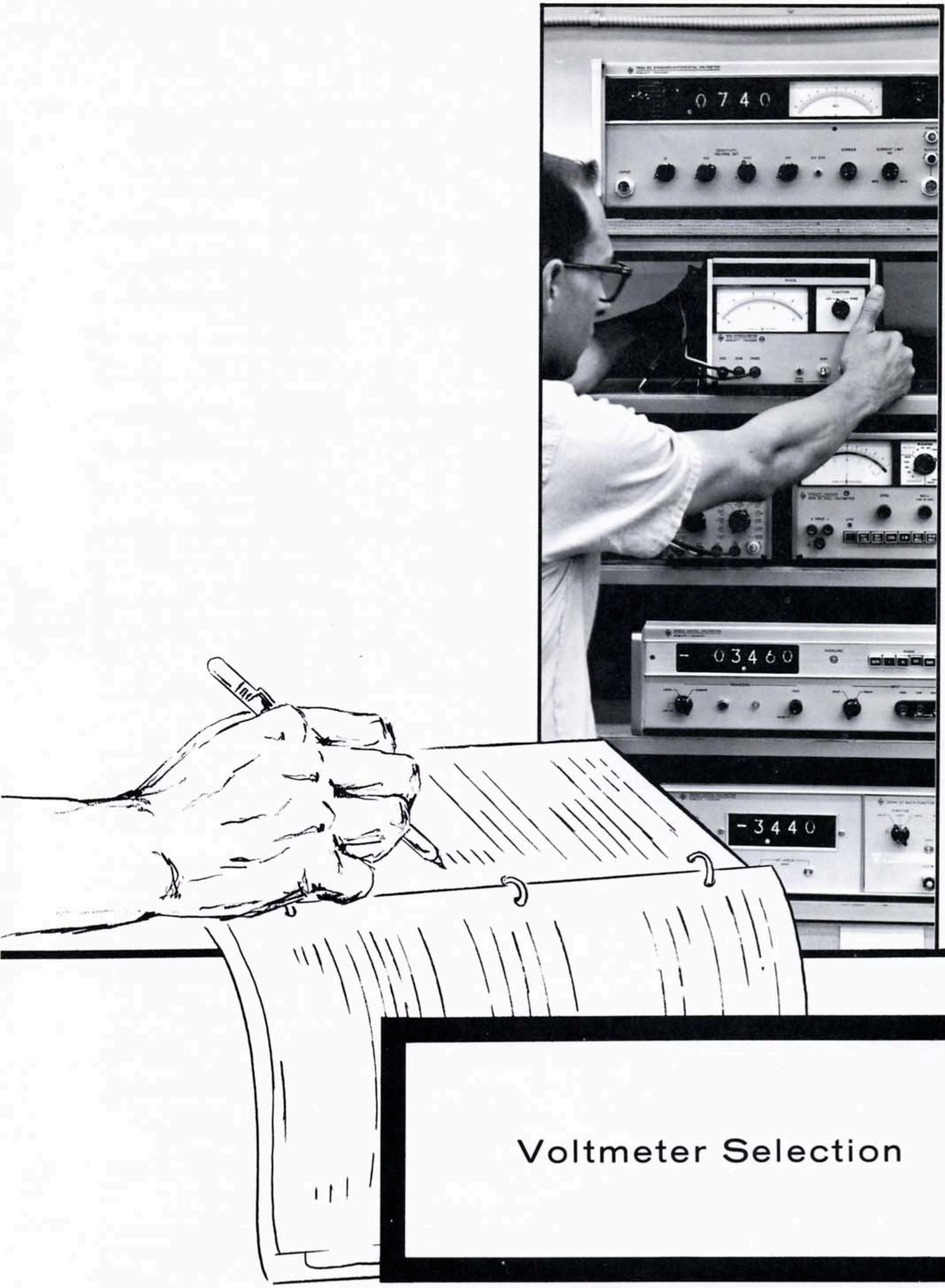


Figure 3-12: Shielded Transformer



Voltmeter Selection

CHAPTER IV

VOLTMETER SELECTION

A. Introduction

A knowledge of voltmeter operation principles aids in proper selection. The choice of a dc voltmeter is governed largely by the intended application and relative cost.

If a voltmeter is to be used with a data acquisition system, then binary-coded decimal (BCD) output and remote programming ability may be necessities. Compatability of codes, voltage levels, and speeds with related equipment should be determined.

When selecting a voltmeter to make accurate measurements in the presence of noise[*], the voltmeter must be able to discriminate the real signal from the noise appearing at its input terminals. Noise rejection by integration permits both high accuracy and speed in the presence of severe noise conditions. Many analog instruments offer excellent noise rejection capabilities (up to 100 times full scale) at very modest costs.

Common-mode pickup is frequently a severe measurement problem. Guarding or battery operation, either of which virtually eliminate the effects of common-mode noise, may therefore be of prime importance when selecting a dc voltmeter.

For production-line and other operator-controlled measurements, automatic ranging may be of prime importance; while laboratory applications may be more concerned with accuracy and resolution. Each category of dc voltmeter uses a different system to convert dc voltage to useful readout information. These various techniques were chosen to maximize performance while minimizing cost.

A review of the chapter on specifications can serve as the outline for selection of a voltmeter. A tabulation of requirements versus specifications may well serve as a preliminary selection tool to narrow the choice down to the best instrument. Table 4-1 illustrates some of the questions to be considered as an application is evaluated. It is axiomatic that cost is proportional to performance in most cases. If one asks for more performance than the maximum or minimum required of the application, unnecessary expense is likely to be incurred. However, one category of specification may be weighed against another. For example, very accurate measurements (±.005%) may be made at a reasonable cost if one is willing to operate a meter manually as in the case of a manually operated potentiometric meter. On the other hand, if the speeds of several readings per second are required, a ±.005% measurement must be made with an automatic voltmeter and associated data recording system. Such a system will cost much more than the manually operated voltmeter.

TABLE 4-1
VOLTMETER CONSIDERATIONS

Specifications	Application Consideration
A. Ranges	A. What are the *maximum* and *minimum* voltages to be measured?
B. Accuracy	B. What is the *minimum* acceptable accuracy? Is the resolution of the instrument consistent with this accuracy? Over what range of temperature, operating conditions, line voltage, input levels, etc., is this necessary?
C. Stability	C. What is the *minimum* acceptable period between calibrations? Must the instrument operate unattended for extended periods? Is a built-in calibration control acceptable?
D. Response Time	D. What is the *maximum* acceptable time? Must this time include range and polarity changes?
E. Input Characteristics	E. a. What is the *minimum* input resistance required? Can calculations be made to correct for loading? b. Is a variable input resistance acceptable? c. Is the input impedance at higher frequencies critical? d. What are the source impedance restrictions? Will these affect the operation of the instrument? e. How much superimposed (normal mode) voltage will the voltmeter be subjected to? At what frequencies?
F. Isolation Parameters	F. Will the instrument be subjected to common mode signals? If so, at what frequencies and voltage levels? Is the voltage rating adequate? Is battery operation or guarding required for adequate performance? Can the voltmeter tolerate the anticipated actual unbalance in source impedance? What affect does auxiliary equipment have on the isolation of the voltmeter? Are the affects of currents injected into the measuring circuits critical?
G. Input-Output	G. Will the voltmeter be required to operate with external equipment? What signal levels will be required? What codes are used; what logic levels? Is remote control of range required? —of function?
H. Extreme Operational Features	H. Is automatic operation required? Is the readout acceptable? Will multi-function operation be required? Will operator fatigue be a problem? (If so, display storage should be considered.)
I. Extreme Operating Conditions	I. Are severe environmental conditions anticipated? If so, has the manufacturer's representative been consulted?
J. General	J. Is the size acceptable? Is proper power available?

B. Considerations When Selecting A Voltmeter.

While many exceptions can be cited for each case, the

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[*] Refer to Chapter III.

following generalizations should be helpful when considering the selection of a voltmeter.

A voltmeter's cost will INCREASE as:

1. The accuracy is upgraded
    a. 5% – .1% Analog and servo meters
    b. .1% – .005% Potentiometric and digital meters
    c. .005% – .001% Standards laboratories
2. *The speed of readings is increased*
    a. 5 sec/reading–Manually operated potentiometric
    b. 1 - 5 sec/reading–Analog–Some digitals
    c. 1 sec/reading–Automatic voltmeters
3. *The voltmeter is required to read smaller voltages*
4. *The stability is improved*
5. *The isolation is improved.* (Not necessary if isolation is obtained with battery operation.)
6. *Input-output features are added.*
7. *The extremes of operating conditions are extended.*

C. A Voltmeter's Cost is Affected by:

1. Type of readout and readout storage provision.
2. Amount of superimposed noise rejection.
3. Provisions for addition of various accessories and modifications.
4. Convenience and service features designed into it.
5. Quality of components, construction, cabinet, etc.

The adaptability and convenience with which a voltmeter can perform other functions is often a consideration when selecting a voltmeter. Instruments which measure resistance, current, ac voltage, ratio, etc., are available in many combinations. The basic specifications for current (1965) Hewlett- Packard dc voltmeters are summarized in Figures 4-1, 4-2, and 4-3. Figure 4-1 describes multi-function instruments, while Figure 4-2 covers available

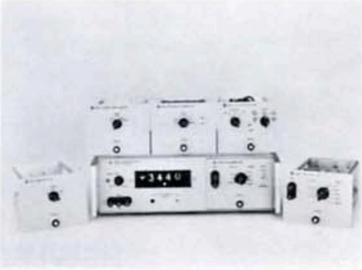
FIGURE 4-1
HEWLETT-PACKARD MULTI-FUNCTION VOLTMETERS

			
FUNCTIONS	410B (Analog)	410C (Analog)	412A (Analog)
DC VOLTAGE Accuracy	±3% full scale	±2% full scale	±1% full scale
Range	1 to 1000 v full scale, 7 ranges	15 mv to 1500 v full scale, 11 ranges	1 mv to 1000 v full scale, 13 ranges
Input Impedance	122 megohms	100 megohms	10 to 200 megohms depending upon range
DC CURRENT Accuracy		±3% full scale	±2% full scale
Range		*1.5 μa to 150 ma full scale, 11 ranges	1μa to 1 amp full scale, 13 ranges
Input Resistance		Decreasing from 9 k ohms on 1.5 μa scale to approx. 0.3 ohm on the 150 ma scale	Decreasing from 1 k ohm on 1 μ amp scale to 0.1 ohm on 1 amp scale
AC VOLTAGE Accuracy	±3% of full scale, 20 cps to 700 mc	±3% of full scale, 20 cps to 700 mc	
Range	1 to 300 v full scale, 6 ranges	½ to 300 v full scale, 7 ranges	
Input Impedance	10 megohms/1.5 pf	10 megohms/1.5 pf	
RESISTANCE Accuracy	±5%	±5%	±5%
Range	10 ohms to 10 megohoms, (center scale) 7 ranges	10 ohms to 10 megohoms, (center scale) 7 ranges	1 ohm to 1 megohm (center scale) 9 ranges

*Special Current Ranges ±1.5, ±5 and ±15 n amps may be measured on the 15, 50, and 150 millivolt ranges using the voltmeter probe with ±5% accuracy and 10 megohms input resistance.

dc instruments for low level measurements. Digital Voltmeters are covered in Figure 4-3. All of the Hewlett-Packard voltmeters illustrated have been designed with the requirements of a maximum number of measurements in mind. Each category of dc voltmeters uses various techniques chosen to maximize performance while minimizing cost. A Hewlett-Packard instrument is available to meet your specific application requirements.

FIGURE 4-1 (CONT'D)
HEWLETT-PACKARD MULTI-FUNCTION VOLTMETERS

			
FUNCTIONS	414A (Auto-Ranging Analog)	741A (Potentiometric)	3440A (Digital)
DC VOLTAGE Accuracy	±½% full scale + ±½% reading	±0.02% ±10µv	±0.05% of reading ± 1 digit
Range	5 mv to 1500 v full scale, 12 ranges	1v to 1000v full scale, 4 ranges	4 digit presentation of 99.99 mv, 999.9 mv, 9.999v, 99.99v and 999.9v
Input Impedance	10 to 100 megohms depending upon range	$>10^9$ ohms (independent of null)	10.2 megohms
DC CURRENT Accuracy			±0.2% + 1 digit full scale
Range			4 digit presentation of 99.99 µa, 999.9 µa, 9.999 ma 99.99 ma and 999.9 ma with 5% overrange
Input Resistance			0.4 ohms to 1 k ohm
AC VOLTAGE Accuracy		±0.05% + 0.01% full scale 20 cps to 100 kc	±0.1% of reading, 20 cps to 100 kc
Range		1 v to 1000 v full scale, 4 ranges	4 digit presentation of 9.999, 99.99 and 999.9 volts full scale
Input Impedance		1 megohm <5 pf	10 megohms 20 pf
RESISTANCE Accuracy	±1% of reading ± ½% of full scale		±0.3% of reading ± 1digit of full scale
Range	5 ohms to 1.5 megohms 12 ranges (full scale-linear).		4 digit presentation of 999.9 ohms, 9.999 k ohms, 99.99 k 999.9 k ohms and 9.999 megohms, 5 ranges, linear scale

NOTE

Typical Accuracy Listed. For Specific Data, Refer to Technical Data Sheet or Consult Your Local HP Sales Engineer

CURRENT MEASUREMENTS

If the input impedance of the voltmeter used is constant, currents can be measured on the dc voltage scale by dividing the input impedance into the full scale voltage range. Using this method, current measurements in the pa and na are possible.

FIGURE 4-2

HEWLETT-PACKARD LOW LEVEL DC VOLTMETERS

			
SPECIFICATION	413A NULLMETER	419A NULLMETER	740B DIFFERENTIAL
RANGE	±1 mv to ±1 KV end scale 13 ranges	±3 μv to ±1 KV end scale 18 ranges	0 to 1.000000 v in 1μv steps 0 to 10.00000 v in 10μv steps 0 to 100.0000 v in 100μv steps 0 to 1000.000 v in 1mv steps
ACCURACY	±2% of end scale	±2% of end scale	±(0.002% of setting + 0.002% of range) at 23°C ±1°C with <70% humidity
INPUT IMPEDANCE	10 to 200 megohms depending upon range	100 K ohms to 100 megohms (infinite when nulled)	$>10^9$ ohms independent of null
FLOATING	YES	YES	YES
GUARDED	NO	Guarding features because of battery operation (chassis should be isolated from ground)	YES
INPUT FILTER	YES	YES	YES
BATTERY OPERATION	NO	YES	NO

FIGURE 4-3
HEWLETT-PACKARD DIGITAL VOLTMETERS


dy 2401C


HP 3440A with Plug-Ins

DIGITAL VOLTMETER	ACCURACY	NUMBER OF DIGITS†	SPEED READINGS/SEC	Resolution	AC Volts	DC Volts	DC Amps	Ohms	Manual Ranging	Auto Ranging	Floating Input	Guarding (CMR)	Printer Output	Remote Ranging	Remote Triggering	Plug-Ins	Systems Application	Ramp	Integrating	Potentiometric
2401C	0.01%	5.48 4.48 3.48	1 9 50	1μv 10μv 100μv	* *	x		* *	x	x	x	x	x	x	x		x		x	
3439A	0.05%	4	5	10μv	x	x	x	x	x	x	x			x		x		x		
3440A	0.05%	4	5	10μv	x	x	x	x	x	x	x		x	x	x	x	x	x		
3459A	0.008%	5.08	2	100μv		x			x	x	x	x	***		x		x		x	x
3460A	0.005%	5.08	7 15	10μv 100μv	* *	x x		* *	x	x	x	x	x	x	x		x		x	x
HO4-3460A	0.005%	6.08	1	1μv		x			x	x	x	x	x	x	x		x		x	x

†Log_{10} Full Scale Reading (with decimal moved to right of last digit)
Amplifiers may be used to increase resolution

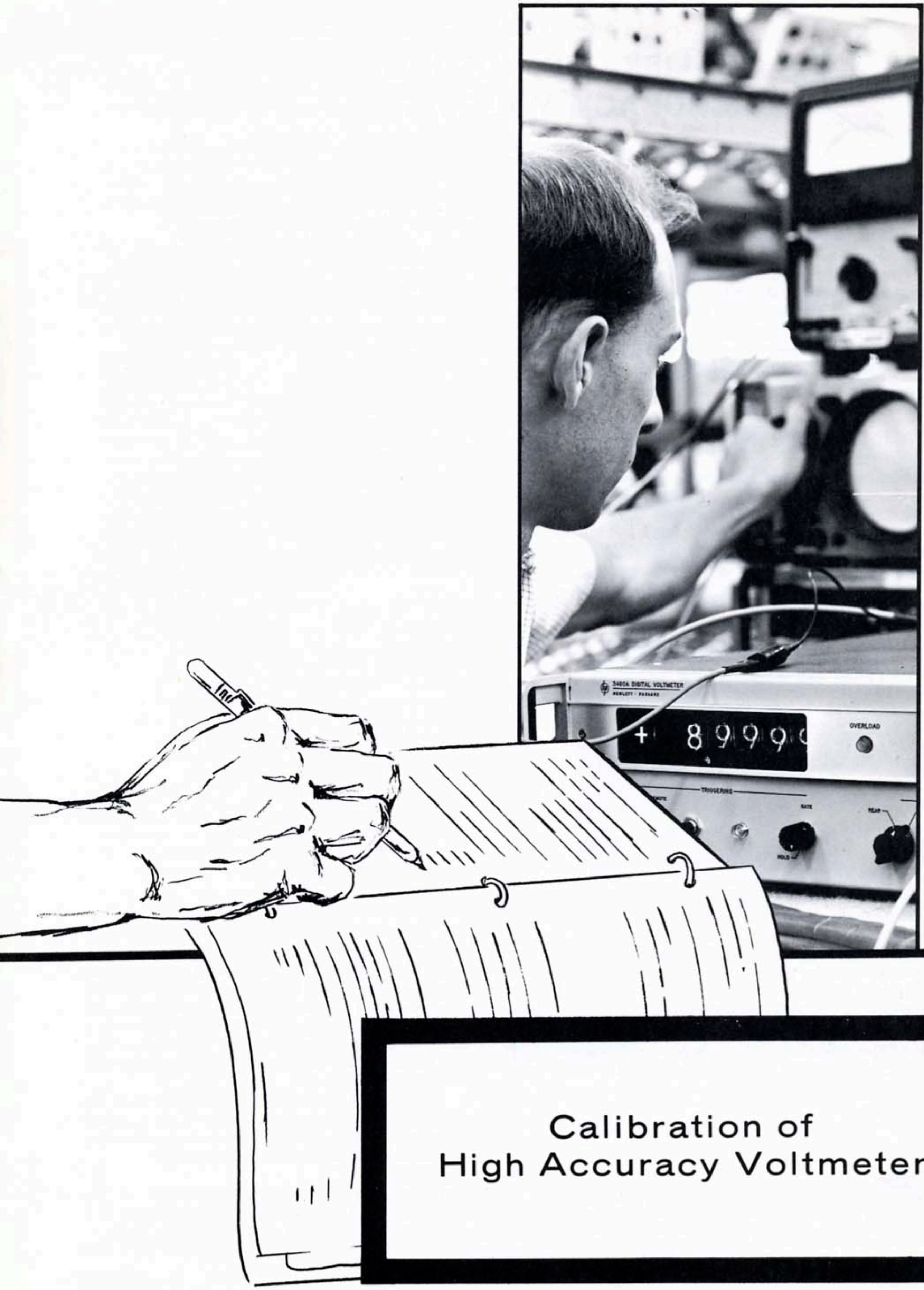
* dy 2410 AC/OHMS CONVERTER
*** Optional


HP 3460A


HP HO4-3460A

CONCLUSION:

The most appropriate instrument for dc voltage measurement is the least costly instrument which will reliably give the accuracy needed for the conditions which apply. A wide range of instrumentation is available. The special usefulness of several have been described. Finding a good match of these capabilities to each engineering need will justify a thorough study of specifications and performance.



Calibration of High Accuracy Voltmeters

CHAPTER V

CALIBRATION OF HIGH ACCURACY VOLTMETERS

A. Introduction

The discussions in the preceding chapters have assumed a common understanding of the unit of electromotive force. Actually, it is only since 1948(2) that one could assume such common agreement. The following section discusses recent definitions, and outlines methods of applying them to the calibration of voltmeters. With rugged and accurate transfer sources, null detectors and active sources currently available, standards laboratory accuracies can be maintained on the production line as well as in the laboratory.

B. Definition of the Volt:

Several definitions of the volt have been proposed, depending upon which quantities within that system are considered fundamental.° Two definitions will be reviewed here.

1. *Absolute Units*: Figure 5-1 diagrams a method for determining the volt in terms of mass, length and time. The permeability of free space is taken as $\frac{4\pi}{10^7}$ in the rationalized M-k-s-a (meter-kilogram-second-ampere) system of units. The ampere may be determined by measuring the force exerted by a current which flows through parallel wires or concentric coils. This in turn requires a measure of time, mass, and length.

   The ohm may be derived from the reactance of a standard inductor. The inductance can be calculated from the dimensions of the inductor and the permeability of free space. Then with a knowledge of frequency (time), the resistance of a resistor can be compared to the inductor's reactance. Recent determinations have been made using the reactance of a capacitor which can be calculated.

   With the value of resistance and current based on absolute units, one volt is defined as the voltage developed across an absolute ohm when an absolute ampere flows through it. The uncertainty in the absolute value of the volt as maintained by NBS is ±7 ppm or ±7 μv in one volt.°°

2. *Legal Units*: All voltages in the United States are defined with respect to the *National Reference Group of Standard Cells.* This is a group of 44 saturated cells of the cadmium sulfate type which are carefully controlled and evaluated to insure long term stability. The variation of the National Reference Group is less than 0.12 μv/year. Highly stable cells can be calibrated to within ±1 μv when referenced to a working group of cells which are referenced to the National Reference Group.(9, 10) Since stable standard cells are stable to within ±1.2 μv/year, a laboratory outside of NBS can maintain a reference voltage to within better than ±2 μv/year if it has a number of cells and obtains yearly calibrations.

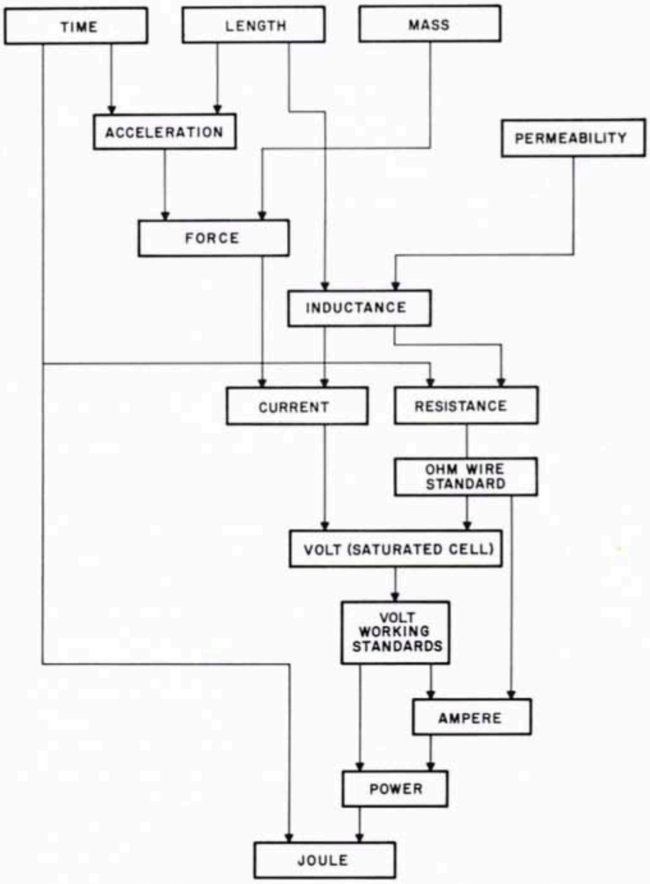


Figure 5-1
A Pattern for the Derivation of Electrical Units from Fundamental Standards

Voltmeters produced by most manufacturers are calibrated with references traceable to the National Reference Group. Voltage accuracy specifications are quoted with respect to that standard.

C. Transferring the Standard Voltage:

Unsaturated standard cells have been the classic working standard of voltage for the past several decades. As Zener diodes develop, it seems safe to predict that they will

°Extensive bibliographies on topics related to establishment and maintenance of electrical units are available. The reader is referred in particular to references 4) and (5) in the bibliography which list over 300 references.

°°This information appears on the back of NBS certificates for saturated standard cells.

rapidly replace the standard cell in many applications. These devices are rugged, shippable and cannot be harmed by short circuits in a properly designed circuit. With the help of aging and individual selection for stability, their performance can easily rival the stability of unsaturated cells. (7) (Figure 5-2)

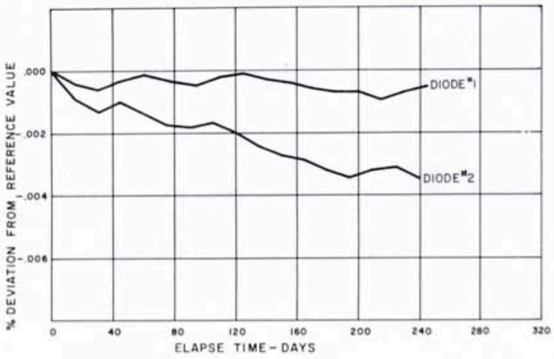


Figure 5-2
Examples of Long Term Zener Diode Stability

By mounting a Zener diode in a temperature controlled environment, and adding convenient attenuators, Hewlett-Packard has designed a device which makes it possible to compare standard cell voltages with 2 ppm transfer accuracy. (Model 735A Transfer Standard, Figure 5-3.)

The output of this device can be used at the 1 volt level with better than 10 ppm transfer accuracy. (Results of < 5 ppm are typical.) This transfer standard can be used in production environments since it has T. C. < 1 ppm/°C to maintain voltage accuracies previously available only in a well managed standards laboratory.

D. Low Level Null Detectors:

The DC reflecting galvanometer has been the traditional null detector for metrology laboratory use. Detectors of this type must be carefully aligned and treated with care to avoid destructive overloads.

TABLE II
Comparison of Galvanometers to Electronic Detector

Feature	Most Sensitive DC Reflecting Galvanometers	Battery Operated Electronic Detector (419A)
Current Sensitivity	10 pa/mm	.67 pa/mm
Period	40 sec	< 2 sec (after 10^6 overload)
Input Resistance	100KΩ*	**
Voltage Sensitivity	50 nv/mm	67 nv /mm
Period	7 sec	< 2 sec (after 10^6 overload)
Input Resistance	25Ω*	**
General Purpose Voltmeter	No	3μv to 1000 v full scale

*Value of input resistance includes external resistance required for critical damping with high sensitivity galvanometers tabulated.

**The current drawn by the electronic null detector approaches zero by utilizing the built-in nulling feature. The incremental resistance is always 100 KΩ or higher.

Table II compares the performance of the most sensitive DC reflecting galvanometers to an electronic detector (Model 419A, Figure 5-3) that has sixteen times the current sensitivity and reads accurately within two seconds after a million times overload. Readings can be made up to 20 times faster and by a much less skilled person since it is unlikely that the electronic detector will be damaged by overloads.

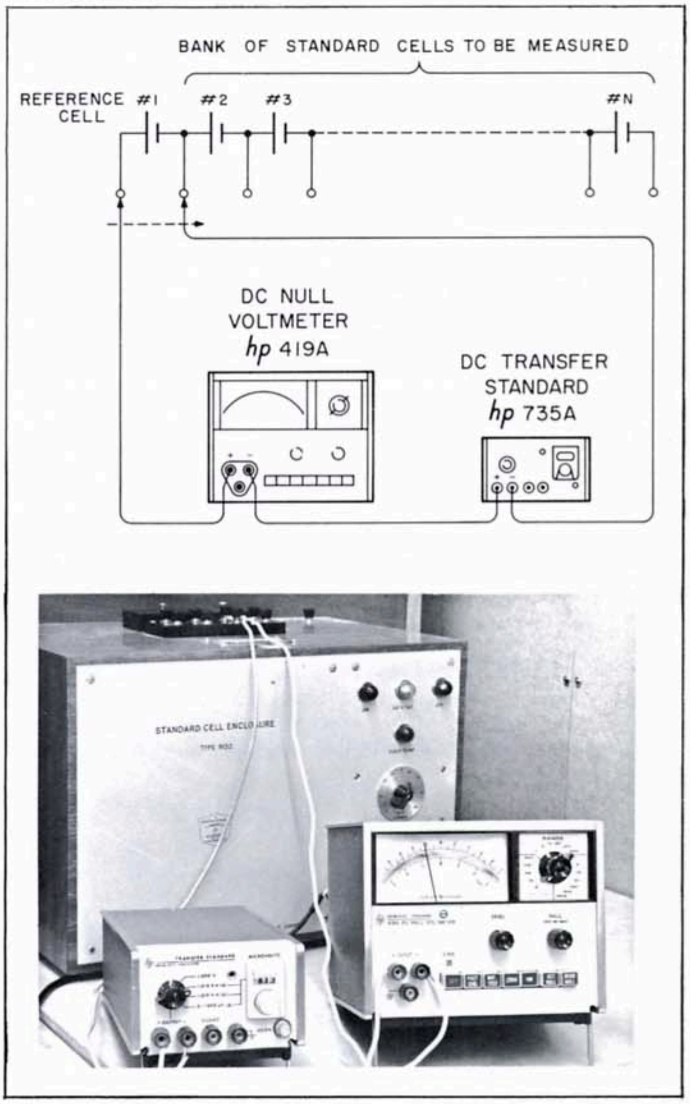


Figure 5-3
Calibration of a Zener Reference Transfer Standard With a Standard Cell.

In order to resolve 0.1 ppm with a detector with 0.1 μv resolution, the voltage applied to the unknown must be at least 1 volt. The power level in precision resistors is often limited to 0.1 watt, so with 1 volt applied to it, the resistance must be 10 ohms or greater. At all source impedances above 10 ohms, the high impedance detector is preferred. It provides better than 0.1 ppm resolution, power line isolation, rugged 1 million times overload capability, and general purpose usefulness in one convenient package. It is readily applied in situations requiring many calibrations at unusually high accuracies.

E. Resistor Dividers:

The calibration of resistance ratios can be completely independent of the value of resistance. Hence, absolute resistance standard are not required to produce precision ratios (10). In other words, a resistance divider can be calibrated in terms of one of the resistors in the divider. To do this, it is most convenient if the resistors are of such values that they can be compared on a 1:1 basis or if the summation of a portion of the string is equal to another resistor in the divider. Permanent connections should be made between each resistor, with current and voltage leads available at the node between each resistor. This facilitates proper procedures to insure calibration independent of lead resistances. Dividers can be calibrated to ratio accuracies of better than 5 ppm using these techniques. Procedures will depend upon the resistance values, voltage levels, temperature range, and ratio value required.

F. Self-Calibration of An Active Source:

The principle of self-calibration of resistance dividers can be extended to active sources if they are designed so that the resistors can be conveniently matched in 1:1 ratios. That is, a 1:1 ratio can be established with good accuracy by inverting the positions of the resistors in a Wheatstone bridge. When they are adjusted so that they can be inverted without upsetting the bridge balance, they must be exactly equal. Figure 5-4 illustrates this principle.

Having established an exact 1:1 ratio (< 2 ppm error), this can be used as the reference for establishing ratios between other resistors used in a Binary-Coded or Kelvin-Varley resistance divider. The linearity of the divider and, hence, of the output of the active source, can approach 5 ppm by the application of this technique to all of the decades used to establish the output voltage of the active source. (Figure 5-5). An extension of this technique is used to adjust the 10:1 resistance dividers used in a range attenuator.

Having established the linearity of the active source, it is only necessary to calibrate the absolute level of the output voltage at one point, preferably near full scale. This is conveniently accomplished with the 1 volt transfer device (hp 735A) and null detector (hp 419A) mentioned earlier.

G. Production and Control:

The establishment of accurate standard voltages is an important and necessary step in the calibration of voltmeters. However, the voltmeter must be designed with adjustments capable of resolving increments substantially smaller than the specified accuracy in order to maintain realistic safety margins. Readouts of voltmeters may limit the resolution with which adjustments can be made unless some other null detector can be attached to the voltmeter to increase resolution. For example, the hp 3460A has a readout resolution of ±10 ppm at full scale. Since the commercial specification is ±70 ppm at full scale and the in-plant specification is much better, the readout resolution

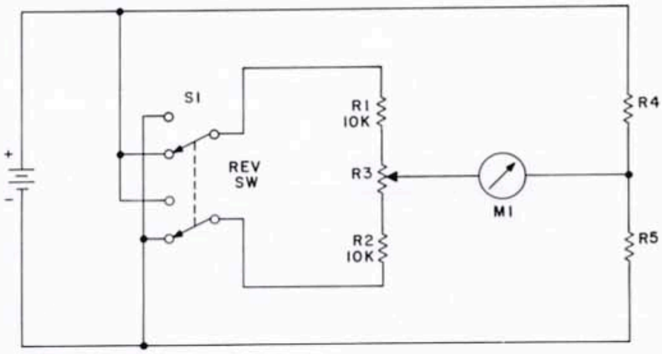


Figure 5-4
Circuit for Establishing Exact 1:1 Resistance Ratio

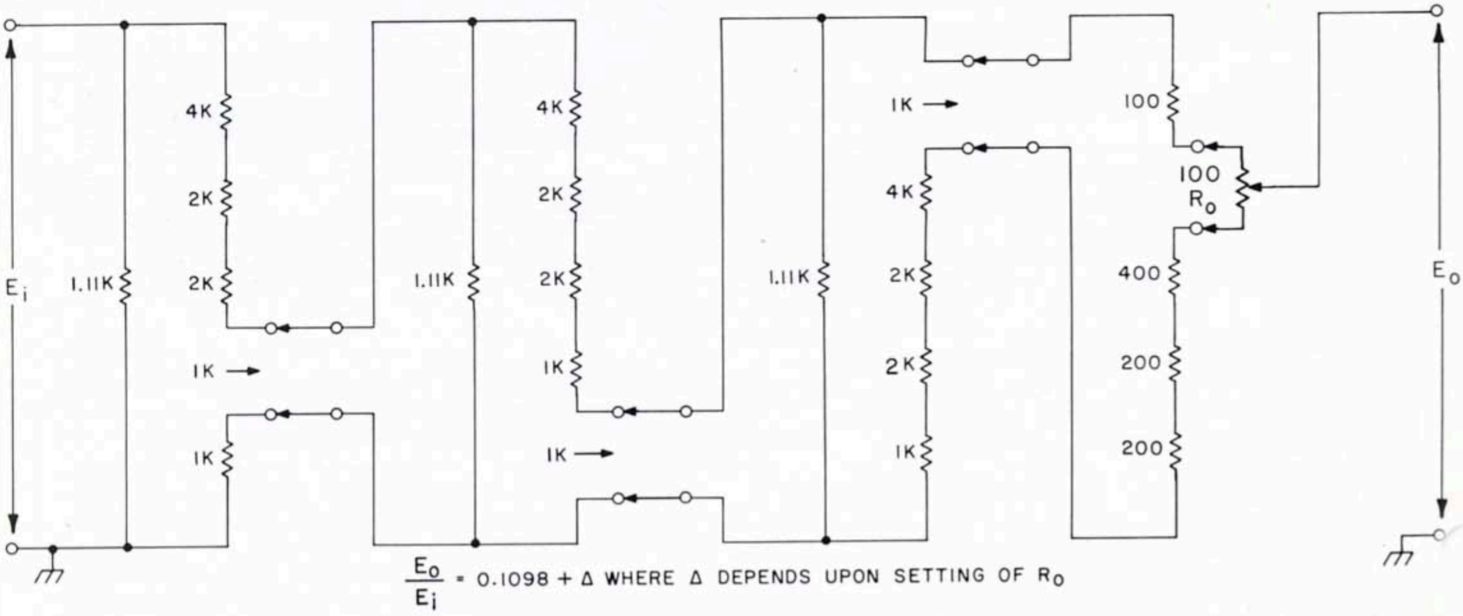


Figure 5-5 Illustrative Schematic Diagram of a Binary-Coded Resistive Divider.

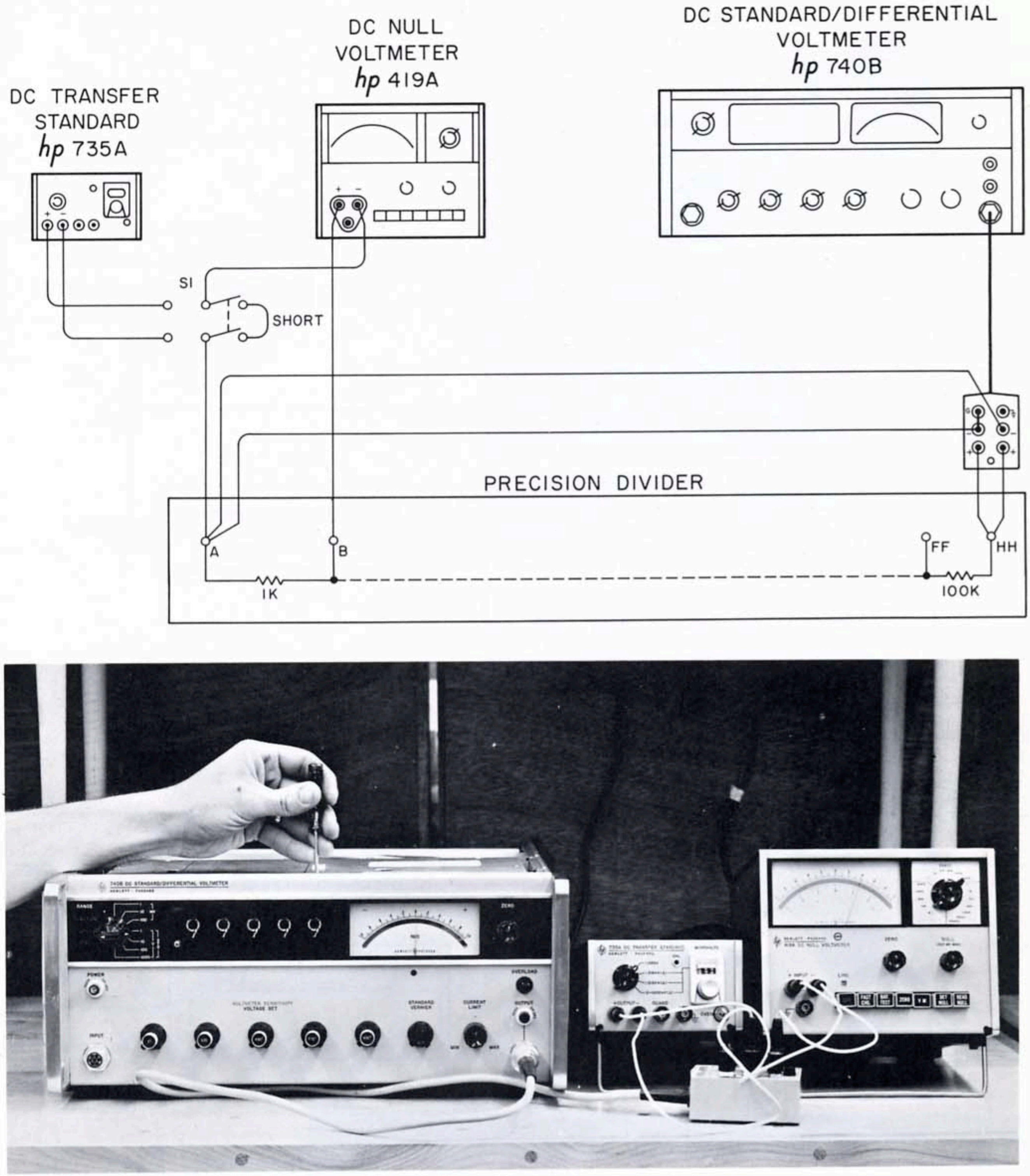


Figure 5-6 Calibration of the Full-Scale Voltage Level of a dc voltage standard.

is not considered adequate for final adjustment. By viewing the output of the integrating null detector in the instrument with a counter, readout resolution can be increased by a factor of ten. The combined resolution of the reference adjustment, attenuator adjustments, internal calibration adjustments, and the readout are such that the voltmeter can be initially set up with a ±5 ppm of full scale uncertainty with respect to the working voltage standard on all ranges. The resolution of the full scale range adjustments is ±1 ppm.

The diagram of Figure 5-7 illustrates how the equipment and procedures mentioned in the preceding sections of this chapter can be combined to insure voltage levels with < 15 ppm uncertainty.

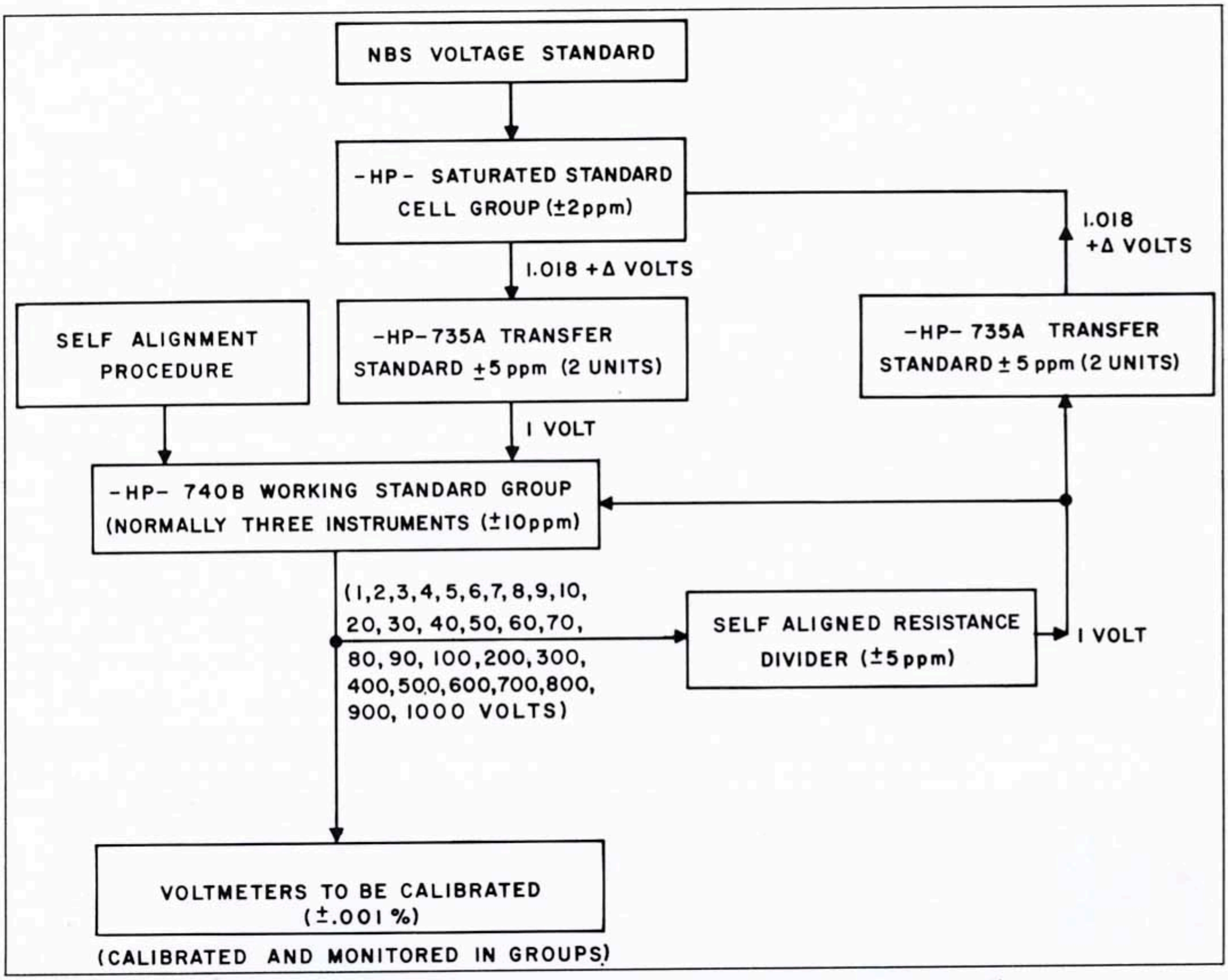


Figure 5-7 Flow of Procedure and Equipment Used to Calibrate Voltmeter to ±15 ppm

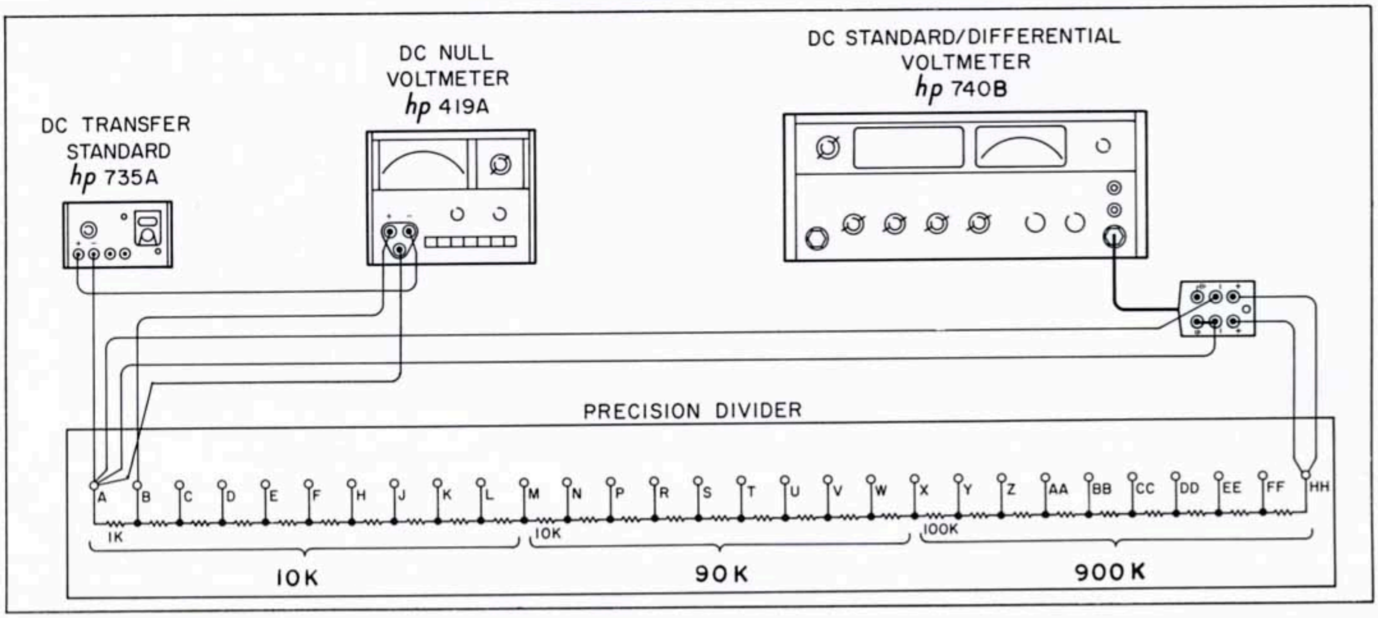


Figure 5-8: Block Diagram For Establishing a Precision 1 to 1000 Volt Source or For Checking the Calibration of the Source

Figure 5-7 shows how working standards are maintained with an accuracy of ±17 ppm referred to the NBS voltage standard. For especially critical applications, such as the one above, the self alignment is checked with an external divider which has been aligned to better than ±5ppm. This makes it possible to establish working voltages up to 1000 volts with less than ±10 ppm uncertainty with respect to the house standard (12). (Figure 5-8)

Three working standards are maintained in different phases of the test cycle as shown in Figure 5-9.

If any instrument varies more than .001% of full scale from the standard, correlation checks among standards and transfer standards can immediately locate the weak link.

By insuring that no instrument varies more than 5 ppm from the working standard and by tracing the working standard back to the saturated reference group with ±10 ppm maximum error, (Figure 5-8) overall calibration ±15 ppm is achieved.

H. Conclusions:

The dc voltage measurement art has advanced to the point where it is possible to produce instruments of high accuracy (±0.005%). For general purpose application, these specifications must apply over a range of operating conditions. The availability of Zener references, electronic null detectors, and alignable working voltage standards has made it possible to establish convenient procedures for the calibration of these instruments in production environments.

The electronic engineer can be assured of a high degree of confidence when making DC voltage measurements if he considers all of the facts of the measurement. These include an appreciation of operating principles, a proper evaluation of specifications, an awareness of problem areas, the selection of the proper voltmeter for the job at hand, and an understanding of the basic meaning of a volt and of its reference source. The above problems are evaluated and solved by careful attention to detail in all steps of a voltmeter's production from design to delivery.

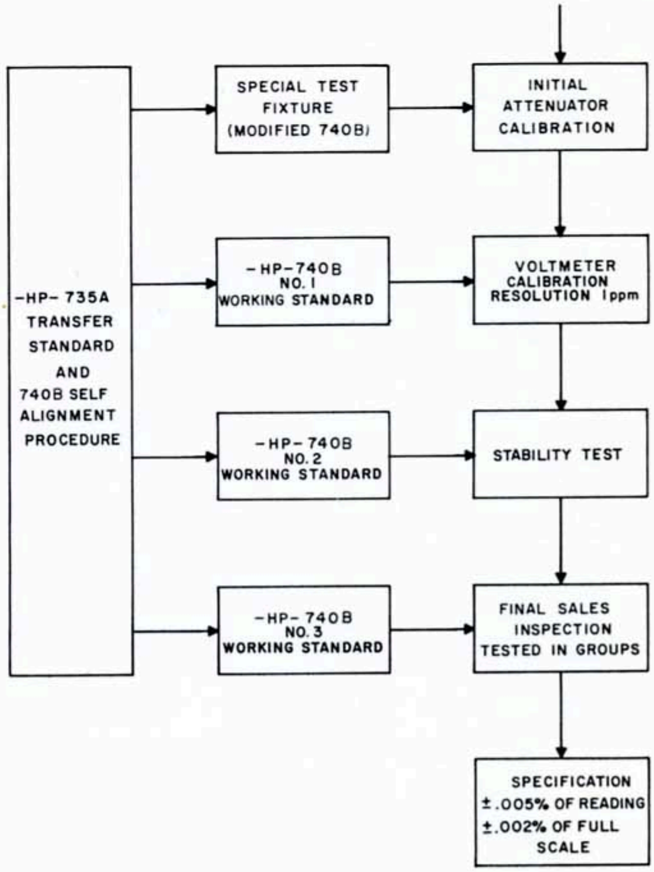


Figure 5-9
Use of Independent Sources at Each Test Station Insures a High Confidence in the Final Calibration Accuracy

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