THE GENERAL RADIO
Experimenter

This Issue:

- The Measurement of Electrolytic Capacitors

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Figure 1.

THE MEASUREMENT OF ELECTROLYTIC CAPACITORS

The measurement of electrolytic capacitors requires specialized measuring instruments. High capacitance values, high dissipation factors, limited voltage ratings, and the need for dc bias are all factors, that influence the design of the capacitance bridge. Moreover, the residual impedances of the leads can be comparable with the impedances to be measured, and their effects must be eliminated if accurate measurements are to be made.

This article discusses the measurement conditions and the design of a new capacitance bridge to satisfy them.

Perhaps the largest capacitances that most of us have had to deal with were those in the problems given in circuit-theory textbooks[1] where all circuit elements were in ohms, henrys, or farads. While actual capacitors in the farad range didn't seem very practical, we realized it was the principle involved that was important and not the magnitudes. However, students these days may accept such grotesque circuit values without question and, in fact, may have seen capacitors of this value advertised or displayed at the recent IEEE Show demonstrating our new TYPE 1617 Capacitance Bridge (Figure

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[1] For instance, E. A. Guillemin, *Introduction to Circuit Theory*, John Wiley and Sons, New York, 1953.

1). One-farad capacitors may not become very common for some time yet, but capacitors of 0.1 farad and up are being made by several manufacturers, and capacitors of over 0.01F (10,000 μF) are not uncommon in low-voltage power supplies.

To avoid large errors from the impedances of the connecting leads, one should measure these large capacitors on a four-terminal bridge. One farad has a reactance of only 1.3 milliohms at 120 Hz, the standard test frequency, and the resistance of test leads may be many times larger. Even for capacitance values well below 1000 μF, two-terminal measurements of D may be subject to errors. For larger values, capacitance-measurement errors may be caused by lead inductances, even at frequencies as low as 120 Hz.

The new TYPE 1617 Capacitance Bridge is designed especially for measuring these large-valued capacitors, as well as other electrolytic types, most of which require the special measurement conditions prescribed by MIL or EIA specifications (see Table 1). The internal test frequency of 120 Hz is the fundamental of the ripple signal that would be applied to filter capacitors used in full-wave power supplies. While this is far from the only application for electrolytic capacitors, 120 Hz has been the generally accepted measurement frequency for all except the nonpolarized types used for motor starting and other special 60-Hz applications. The TYPE 1617 can be used with a suitable external generator* down to 40 Hz and up to 1 kHz over most of its

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* GR TYPE 1311-A or TYPE 1310-A.

TABLE I

Summary of EIA and MIL Specifications on Testing Electrolytic Capacitors

Specification and Capacitor Type	*Frequency*	*AC Level*	*Accuracy*		*DC Polarizing Voltage*
			C	*Loss*	
MIL C—3965 C Tantalum Foil and Sintered Slug Capacitors	120±5 Hz	Less than 30% of DCWV or 1 V, whichever is smaller	2%	*R* or P.F. 2%	C—Sufficient for no reversal of polarity. *D*—"Polarized Capacitance Bridge" Sum of ac and dc shall not exceed DCWV.
MIL C—26655-B Solid Tantalum Capacitors	120±5 Hz	Limited to 1V, rms	2%	*D*, 10%	C—Max bias 2.2 V. *D*—"Polarized Bridge", 2.2-V dc max.
RS 228 Tantalum Electrolytic Capacitors	120 Hz	Small enough not to change value	±2½%	*D*, 5%	Optional
MIL C-62 B Polarized Aluminum Capacitors	120±5 Hz	Limited to 30% of DCWV or 4 V, whichever is smaller	2%	*D*, 2%	No bias required if ac voltage less than 1 V. However, if bias causes differences, measurements with bias shall govern.
RS 154 B Dry Aluminum Electrolytic Capacitors	120 Hz	Small enough not to change value	±2½%	*R* or RC	Optional, but if substantial difference occurs, rated dc should be used.
RS 205 Electrolytic Capacitors for use in Electronic Instruments	120 Hz	Small enough not to change value	±2½%	*D*	Optional

range with no degradation in capacitance-measurement accuracy.

Test-Signal Level

The ac signal level is particularly important for tantalum types, which tolerate only a very low reverse voltage. The generator level switch has three positions: 2 V, 0.5 V, and 0.2 V, rms, maximum. This is the applied bridge voltage; the actual voltage applied to the unknown capacitor is somewhat less. The 0.5-volt maximum signal level has become an informal industry standard. The 2-volt level was included for increased sensitivity on the lowest capacitance range (0 pF − 1000 pF), and the 0.2-V position was added to allow a check to ensure that the level was "small enough not to change value," in the words of some specifications.

DC Bias

While dc bias is not specifically required by the MIL and EIA standards for capacitance measurements (see Table 1), it is specified for MIL dissipation-factor measurements of tantalum units. Also, the test conditions used by capacitor manufacturers, which vary considerably, usually incorporate dc bias. For tantalum capacitors, the bias specified is such that, when the ac signal is added, the sum will never go negative and will never exceed the rated voltage. A common practice is to use 1.5-volt dc bias with less than 0.5-volt ac signal. However, several manufacturers require that almost the full dc rated voltage be applied. To cope with such a large variation in the dc-bias requirements, the bridge includes an adjustable internal supply, with six ranges up to 600 volts. This covers the ratings of almost all electrolytic capacitors as well as those of most other types. External bias up to 800 volts may be applied.

The applied bias voltage is indicated on the panel meter, which also serves as the null indicator and as a leakage-current ammeter with full-scale ranges from 60 μA to 20 mA. The ultimate resolution of about 0.5 μA is adequate for most aluminum capacitors and some tantalum types. For others an external microammeter can be used.

Safety Features

Measurements on biased capacitors may be inherently dangerous, because lethal energy can frequently be stored in the capacitor being measured. Moreover, in order to get good ac sensitivity, a large bypass capacitor is required in the internal dc supply, which may also store dangerous energy in the instrument itself. The user and the instrument are protected by several features, including two warning lights and discharge circuitry. If bias is not required, three switches must all be improperly set in order to get a dangerous voltage.

D Range

Not only the wide capacitance range (1 pF to 1.1 F) but also a wide dissipation-factor range is needed to measure large electrolytic capacitors, whose *D* value is often well over 1 (100%) at 120 Hz. The *D* range of the TYPE 1617, which extends up to 10, would be awkward to use above unity were it not for the inclusion of the ORTHONULL® balancing mechanism, which is also a feature of our popular TYPE 1650 Impedance Bridge.[2] This

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[2] H. P. Hall, "Orthonull — A Mechanical Device to Improve Bridge-Balance Convergency," *General Radio Experimenter*, April, 1959.

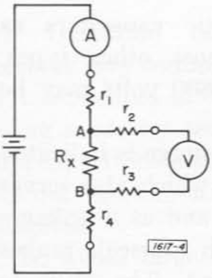

Figure 2. Voltmeter-ammeter measurement of a four-terminal resistor, R_x. The terminal resistances r_1 and r_4 have no effect, nor do r_2 and r_3 if the voltmeter impedance is infinite.

nonreciprocal ganging mechanism converts interacting bridge adjustments into independent ones so that the real and imaginary parts of the impedance can be balanced without a time-consuming sequence of adjustments and readjustments.

Brief Theory of Four-Terminal Measurements

Very low impedances must be measured by a four-terminal method when a high degree of accuracy is to be realized. This is the only way in which errors caused by the impedance of the connecting leads, terminals, and contacts (which may be much larger than the unknown impedance being measured) can be avoided. The simplest four-terminal measurement circuit is the voltmeter-ammeter method shown in Figure 2. This is a *transfer*-impedance measurement, because the impedance, Z_X, is the ratio of output voltage to input current, Z_{21}. From an inspection of this circuit, it is obvious why two terminals of a four-terminal standard are called the "current" terminals and two called the "potential" terminals. Although these terminal pairs are theoretically interchangeable because $Z_{21} = Z_{12}$ for a linear, passive, bilateral network, the current ratings of the two pairs of terminals may be quite different, as may other practical aspects of the design. Note that the unknown, R_X, is defined as the resistance between the junction of the upper two leads (point A) and the junction of the lower two leads (point B). The location of these junctions should be permanent in a low-impedance standard, independent of the position of connecting leads, and, therefore, such a standard must have four separate terminals.

More accurate impedance measurements can be made with a bridge, Figure 3, to avoid meter calibration errors. However, here the residual resistances, r_2 and r_4, appear in other bridge arms, where they can cause errors unless the resistances of these arms are high enough to make the residuals negligible by comparison. Note that r_1 and r_3 are in series with the source and detector and thus cause no error.

For precision measurements on low-valued resistors for example, the Kelvin double bridge is used (Figure 4). As shown, the unknown is compared with another four-terminal resistor, R_S. If R_A and R_B are sufficiently large, the main source of error is the branch containing r_4 and r_5 and results from the voltage drop, E_y, which may be appreciable because r_4 and r_5 are in series with low-impedance R_X and R_S.

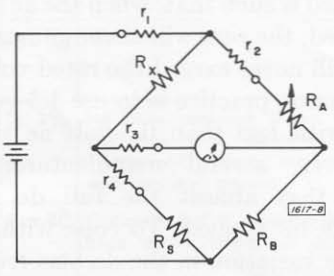

Figure 3. A Wheatstone bridge measuring a four-terminal resistor, R_x, with its residual terminal impedances shown in adjacent circuit branches.

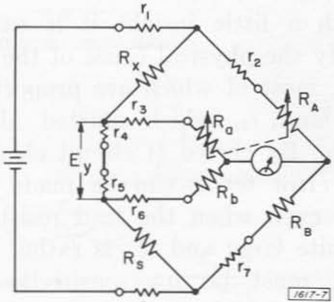

Figure 4. A Kelvin double bridge comparing two four-terminal resistors. The second set of ratio arms, R_a and R_b, divide the error voltage, E_y, proportionately.

The Kelvin bridge uses auxiliary arms, R_a and R_b, to divide this error voltage proportionately between the two halves of the bridge so that its effect is balanced and cancelled.

The excellence with which this second set of ratio arms (R_a and R_b) balances out the error voltage depends on the difference between their ratio, $\frac{R_a}{R_b}$, and that of the main arms, $\frac{R_A}{R_B}$. The balance expression is:

$$R_X = R_S \frac{R_A}{R_B} + \frac{R_b(r_4 + r_5)}{R_a + R_b + r_4 + r_5}\left(\frac{R_A}{R_B} - \frac{R_a}{R_b}\right)$$

As an example, if the unknown and standard resistances and the stray resistance, r_4 plus r_5, are all equal, and if R_A/R_B and R_a/R_b differ by 1%, the error will be ½%. In precision Kelvin bridges, the adjustable arms, R_A and R_a, track to much closer tolerance than this.

An obvious way to make a capacitance bridge that will measure very high capacitances is to adapt the Kelvin bridge principle to a conventional capacitance bridge, as shown in Figure 5. Any ac bridge for measuring complex impedances must have two adjustments (here C and D); to keep the ratio of the secondary arms equal to that of the main arms, two pairs of tracking adjustments are therefore necessary.

What kind of lead errors would we get with such a bridge? A farad has a reactance of 1.3 milliohms at 120 Hz, and the resistance of the connecting leads could easily be 20 milliohms (two feet of #20 wire). If we assume that R_A = 10 milliohms* and that R_N and R_n can track to 1%, the resulting capacitance error is 2%. The error would be of this magnitude over most of the top range (if $D_X = 0$). This design might be acceptable but is somewhat marginal.

A New Circuit for AC Four-Terminal Measurements

Another way to compensate for the error voltage, E_y in Figure 5, is to introduce, by some means, an equal voltage in the corresponding place in

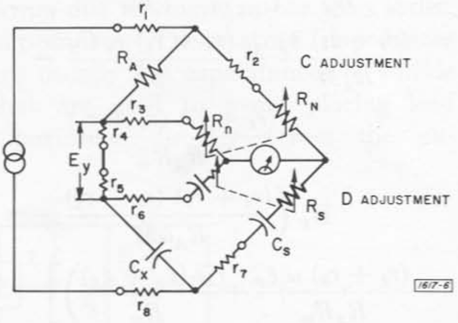

Figure 5. A four-terminal capacitance bridge using the Kelvin double bridge principle. For ac measurements on a complex impedance, two ganged adjustments are necessary.

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* This is the value of the ratio arm on the top range of the TYPE 1617. It must be very small to obtain reasonably good sensitivity.

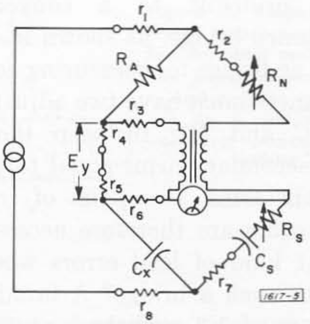

Figure 6. The basic circuit of the 1617, where a voltage equal (almost) to the error voltage, E_y, is placed in the opposite side of the bridge by a tightly coupled transformer.

the opposite side of the bridge. If this is done, no error results, because this extraneous voltage can be considered to be effectively in series with the generator and, thus, will change only the level of the voltage applied to the bridge.

An ideal transformer of 1:1 ratio would do this job perfectly if the R_N and C_S arms were of infinitely high impedance; it is surprising how well a small, practical transformer with practical values for R_N and C_S will actually do the job. For the circuit of Figure 6, the balance equation is:

$$C_X = \frac{R_N}{R_A} C_s \left[1 + \frac{r_p + r_s + r_3}{R_N} - \frac{(r_4 + r_5)\, \ell_p}{R_A M} + \frac{(r_4 + r_5)\, r_6\, C_X}{M} - \frac{(r_4 + r_5)\,(r_3 + r_p)}{R_A R_m} - D_X \left(\frac{(r_4 + r_5)\,(r_3 + r_6)}{R_A \omega M} - \frac{(r_4 + r_5)\, \omega\, \ell_p}{R_A R_m} + \frac{\omega\,(\ell_p + \ell_S)}{R_N} \right) \right]$$

where r_s, r_p, ℓ_s, ℓ_p, R_m and M* are defined by the transformer equivalent circuit of Figure 7.

With a little insight it is easy to identify the physical cause of the error terms, most of which are proportional to r_4 and r_5, which started all the trouble. By choice of circuit elements, these error terms can be made quite small, even when the lead resistances are quite large and R_A is rather small (as it must be for sensitivity considerations). The transformer in the TYPE 1617 uses Mumetal laminations to get a large mutual inductance and a bifilar winding that makes the leakage-inductance terms negligible. (Actually, the measured ratio $\frac{\ell \dagger}{\mathrm{M}}$ is $< 3 \times 10^{-6}$, which may seem unbelievable but which is actually not at all difficult to achieve in bifilar transformers.) The winding resistance and the other lead resistance, r_6, appear in the terms that cause the largest errors.

How well does this scheme work? For the circuit values used in the previous example ($R_A = 10$ mΩ, $r_4 + r_5 = r_6 = 20$ mΩ, $C_X = 1$ F), the error is approximately 0.1% (if D is small). The specifications allow less than 1% additional error in C or 0.01 in D for resistances of 0.1 ohm in any or all leads on the highest range or 1 ohm in any or all leads on the lower ranges. These values permit the use of connecting leads of considerable length, so that large ca-

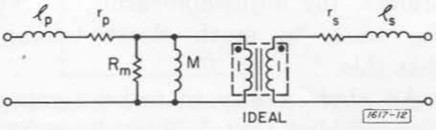

Figure 7. Equivalent circuit of the transformer.

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* Actually, a capacitor is placed across the transformer to resonate the mutual inductance, thus reducing the error terms containing *M*.

† $\ell = \ell_s = \ell_p$.

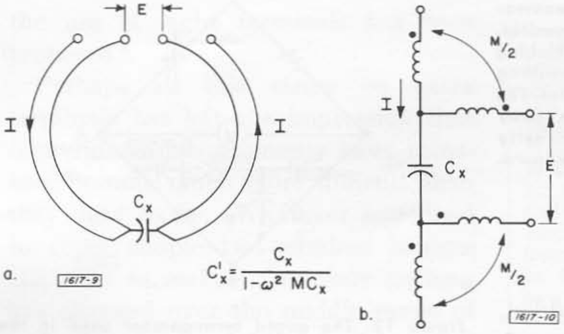


Figure 8. When the "current" and "potential" leads form concentric loops (8a), the resulting mutual inductance (8b) affects the value of the capacitance measured.

pacitors can be measured while remotely located.

A somewhat similar problem with a very similar solution has been reported by Foord, Langlands and Binnie.[3] Therefore, we cannot claim the principle as new, but we can say that we haven't seen a circuit exactly like ours before.

An Interesting Error—And Its Cure

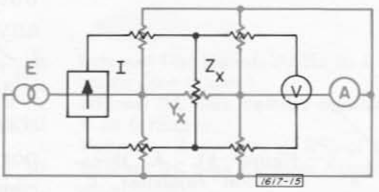
While four-terminal measurements remove the error caused by reasonable amounts of resistance and self-inductance in the connecting leads, mutual inductance between the "current" leads and the "potential" leads can cause appreciable error when the capacitance being measured approaches a farad. If concentric loops are formed by one-foot leads, as shown in Figure 8, the mutual inductance can be as much as 0.3 μH, which causes a 15% error, in a measurement of one farad at 120 Hz. This is a series-resonance effect, and it increases the measured value of capacitance, although the mutual inductance may be negative if one loop is reversed with respect to the other.

The cure is simple; just twist together either the current leads or the potential leads to reduce the mutual inductance. This removes the error almost entirely, leaving only the mutual coupling of the bridge terminals, which is almost completely negligible, even for measurements of one farad.

Three-Terminal Measurements, Too

At the low end of the capacitance range there is the dual situation of errors due to shunt, rather than series, impedances. These stray impedances are usually the capacitances of shields that are used to avoid placing lead capacitance directly across the un-

Figure 9. Superposed diagrams of the measurement of a four-terminal impedance, black, and a three-terminal impedance, red, showing duality. Note that only three circuit branches could define the three-terminal impedance, because two are redundant as shown.



$Z_X = \dfrac{\text{OPEN-CIRCUIT VOLTAGE}}{\text{INPUT CURRENT}}$ $Y_X = \dfrac{\text{SHORT-CIRCUIT CURRENT}}{\text{INPUT VOLTAGE}}$

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[3] T. R. Foord, R. C. Langlands and A. J. Binnie, "Transformer-Ratio Bridge Network with Precise Lead Compensation," *Proceedings of the IEE* (Eng), Vol 110, #9, p 86, September 1963.

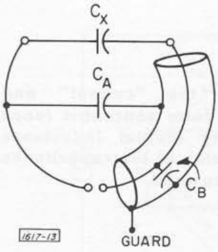

Figure 10. Measurement of a capacitor, C_x, with a shielded lead and the resulting stray capacitances. The shield prevents stray capacitance directly across the unknown.

known (Figure 10). With a shield added, there are capacitances from both terminals of the unknown to the shield, forming a three-terminal network (Figure 11). Many standard capacitors of low capacitance value are constructed as three-terminal devices to avoid lead errors[4]. To eliminate the effect of stray capacitances, various types of guard have been used in capacitance bridges.

In the TYPE 1617, the standard capacitor is large enough (0.5 μF) to allow considerable shunt capacitance without appreciable error, so that point A could have been used for a guard. In this case C_A would shunt the detector (no error), and C_B would shunt the standard. However, this point and both the unknown and the standard capacitors get full bias, and we do not encourage our customers to put 600 volts on the shields of their connections. Therefore, an isolating, 3-stage, unity-gain amplifier is used, which blocks the dc and still gives the necessary guard signal to reduce the effect of C_A (by a factor of about 1000) and to give a low output impedance that can tolerate a considerable load (C_B).

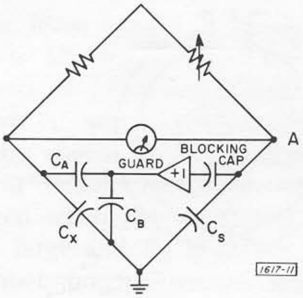

Figure 12. The guard arrangement used in the 1617. No voltage appears across C_A at null (ideally), and C_B just loads the amplifier.

Would You Believe 5 Terminals?

The TYPE 1617-A Capacitance Bridge has five terminals and is one of the world's few five-terminal bridges. One cannot help wondering if there is a measurement situation where all five terminals would be useful simultaneously. Suppose, for example, that one wanted to measure a one-microfarad capacitor that was 1000 feet away from the bridge. The leads should be shielded to avoid pickup, and a guard would be necessary to avoid a capacitance error unless a very low-capacitance cable were used. Likewise, if an accurate D value is desired, a four-terminal measurement should be made, because the lead resistance will probably be several ohms. Actually, we haven't tried this, but the TYPE 1617 ought to do it. If anyone tries it, we'd like to hear about it, particularly if it works.

While this example may not be a common problem, there is a very important problem in extremely high precision capacitance measurements where even five-terminals are not enough, and

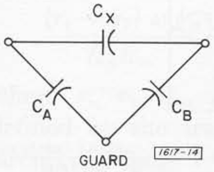

Figure 11. A three-terminal capacitor, C_x, with its "stray" capacitances, C_A and C_B.

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[4] John F. Hersh, "A Close Look at Connection Errors in Capacitance Measurements," *General Radio Experimenter*, July 1959.

the use of eight terminals has been proposed [5].

Perhaps all this stress on extra terminals has left the impression that capacitance measurements have somehow become much more difficult than they used to be. (Whatever happened to those simple two-terminal bridges GR used to make?) Certainly nothing has changed over the middle range of capacitance values, and only two terminals are required, as always. The TYPE 1617 is just as easy to use for capacitors of these values, particularly if one uses the two-lead, shielded cable harness, which connects the proper terminals together at the bridge. Also supplied is a four-lead harness for the measurement of those larger capacitors, for which other bridges are not satisfactory.

— HENRY P. HALL

Henry P. Hall, Group Leader of the Impedance Measurement Group in GR's Engineering Department, attended both Williams College and M.I.T., receiving in 1952 his A.B. from the former and his S.B. and S.M. in Electrical Engineering from the latter. He came to General Radio first as a cooperative student in 1949, becoming a full-time development engineer in 1952, Section Leader in 1963, and Group Leader in 1964. A member of IEEE, he has served on various committees of that and other professional and industry organizations. He is a member of Phi Beta Kappa, Eta Kappa Nu, Tau Beta Pi, and Sigma Xi.

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[5] R. D. Cutkosky, "Four-Terminal Pair Networks as Precision Standards," *IEEE Transactions on Communications and Electronics*, #70, January, 1964, p 19.

SPECIFICATIONS

Quantity	*Frequency*	*Range*	*Accuracy* *
Capacitance	120 Hz internal	0 to 0.11 F	± 1% ± 1 pF, smallest division 2 pF; resident ("zero") capacitance approximately 4 pF
		0.11 F to 1.1 F	± 2%
	40 Hz to 120 Hz external (useful down to 20 Hz with reduced accuracy)	0 to 1.1 F	Same as above with suitable generator
	120 Hz to 1 kHz external	0 to 1 F $\left(\frac{100}{f_{\mathrm{Hz}}}\right)^2$	± 1% ± 1 pF with suitable generator and precautions
Dissipation Factor	120 Hz internal or 40 Hz to 120 Hz	0 to 10 $\frac{f_{\mathrm{Hz}}}{120}$	$\pm 0.001 \pm 0.01\,C \pm 2\%$
	120 Hz to 1 kHz	0 to 10	$\left[\pm 0.001 \pm 0.01\,C\right] \frac{f_{\mathrm{Hz}}}{120} \pm 2\%$

* C is expressed in farads.

Lead-Resistance Error (4-terminal connection): Additional capacitance error of less than 1% and *D* error of 0.01 for a resistance of 1Ω in each lead on all but the highest range, or 0.1Ω on the highest range.

Internal Test Signal: 120 Hz (synchronized to line) for 60-Hz model; 100 Hz for 50-Hz model. Selectable amplitude less than 0.2 V, 0.5 V, or 2 V. Phase reversible.

External Test Signal: 20 Hz to 1 kHz with limited range (see above).

Internal DC Bias Voltage and Voltmeter: 0 to 600 V in 6 ranges.

Voltmeter Accuracy: ± 3% of full scale.

Internal DC Bias Current: Approximately 15 mA maximum.

Ammeter Range: 0 to 20 mA in 6 ranges. Can detect ½-μA leakage.

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SPECIFICATIONS *(Cont'd)*

Ammeter Accuracy: ±3% of full scale.

External Bias: 800 V maximum.

Power Required: 105 V to 125 V or 210 V to 250 V, 60 Hz, 18 W maximum. Models available for 50-Hz operation.

Accessories Supplied: Four-lead and shielded two-lead cable assemblies.

Accessories Required: None for 120-Hz measurements. The Type 1311-A Oscillator is recommended for measurement at spot frequencies, the Type 1310-A Oscillator for continuous frequency coverage.

Cabinet: Flip-Tilt; relay-rack model also is available.

Dimensions: Portable model — width 16¼, height 15, depth 9 inches (415, 385, 230 mm); rack model — width 19, height 14, depth behind panel 6⅛ inches (485, 355, 160 mm), over-all.

Net Weight: Portable model, 26 lb (12 kg); rack model, 28 lb (13 kg).

Shipping Weight: Portable model, 34 lb (15.5 kg); rack model, 43 lb (20 kg).

Catalog Number	*Description*	*Price in USA*
1617-9701	**Type 1617 Capacitance Bridge,** Portable Model (115 V, 60 Hz)	**$1195.00**
1617-9286	**Type 1617 Capacitance Bridge,** Portable Model (230 V, 60 Hz)	**1195.00**
1617-9206	**Type 1617 Capacitance Bridge,** Portable Model (115 V, 50 Hz)	**on request**
1617-9266	**Type 1617 Capacitance Bridge,** Portable Model (230 V, 50 Hz)	**on request**
1617-9820	**Type 1617 Capacitance Bridge,** Rack Model (115 V, 60 Hz)	**1195.00**
1617-9296	**Type 1617 Capacitance Bridge,** Rack Model (230 V, 60 Hz)	**1195.00**
1617-9216	**Type 1617 Capacitance Bridge,** Rack Model (115 V, 50 Hz)	**on request**
1617-9276	**Type 1617 Capacitance Bridge,** Rack Model (230 V, 50 Hz)	**on request**

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