THE General Radio EXPERIMENTER

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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

CONNECTION ERRORS IN CAPACITANCE MEASUREMENTS

Also IN THIS ISSUE

● **WHEN A CAPACITOR** is connected into a circuit, some type of connecting wires must be used. These wires will have capacitances to each other and to other parts of the circuit, with the result that the capacitance actually introduced into the circuit is different from that of the capacitor alone. Even when one capacitor is substituted for another, using exactly the same leads, the capacitance of these connections may be different in the two cases, particularly if the two capacitors differ in size and shape. Such connection errors, while negligible in many cases involving large capacitances, become of importance in the measurement and intercomparison of small capacitances and of standards.

How many different types of connection capacitances are there and what are their magnitudes? An actual example will serve to illustrate them. Suppose that two Type 722 Precision Condensers are to be connected together. With their panels touching, their terminals are three inches apart. Let these terminals be connected by two No. 16 bare copper wires spaced ¾ of an inch apart (standard General Radio spacing). The wire should be bare to eliminate both the extra capacitance intro-

Figure 1. The accuracy to which the calibration of a Type 722-D Precision Condenser (shown at right) can be specified depends to a considerable degree upon the errors discussed in this article.

duced by the insulation, whose dielectric constant is greater than unity (3 perhaps), and the added dielectric loss in this insulation. The wire should be of small diameter because its capacitance varies as the logarithm of the ratio of its diameter to some other length, spacing of the wires, or distance to ground. Precision condensers are two-terminal capacitors with one terminal connected to the panel and shield. One of the connecting wires is, therefore, connected to the panel and to ground.

There are three types of capacitance involved: capacitance between the two wires, capacitance between the high wire and the panel, and capacitance between the high wire and ground. The calculated values of these three capacitances are 0.22 $\mu\mu$f, 1.07 $\mu\mu$f, and 0.79 $\mu\mu$f respectively. They are, however, by no means additive. The grounded wire shields the panel so that part of the capacitance to the panel is transferred to the grounded wire. Similarly, part of the capacitance to an infinite ground is transferred to the panel which is shielding it. The actual total capacitance is 1.19 $\mu\mu$f. This is certainly not negligible when measuring capacitances of 1000 $\mu\mu$f or smaller.

It should then be sufficient, when connecting two capacitors in parallel, to add the capacitance of the added capacitor and the connecting wires. Unfortunately, the latter, as indicated above, is not a constant for a given pair of wires, but depends greatly upon the distance of these wires to all grounded panels and hence on the size and shape of the added capacitor. It is, therefore, usual in substitution measurements to keep the leads connected to the standard capacitor with the unknown in position and with its grounded terminal already connected. The high lead is in position and just not touching the high terminal of the unknown. Such a disposition of apparatus is shown in Figure 2. Having made a sufficient measurement, such as balancing a bridge, for this condition, the unknown capacitor is connected into circuit and the second balance made. In this manner the effect of the leads is taken into account, for this should be the same in both measurements. It appears, however, that the capacitance measured depends upon the original separation of the high lead and the high terminal of the unknown.

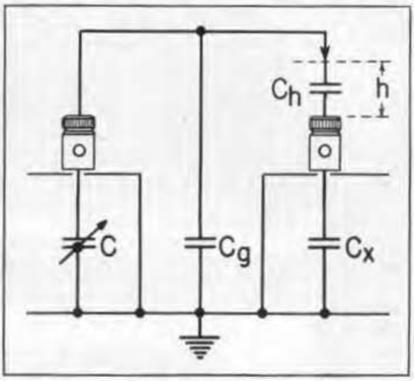

Figure 3. The stray capacitances C_g and C_h produce errors in the measurement of the unknown capacitor C_x.

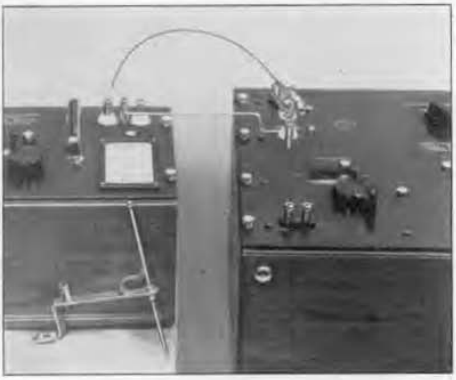

Figure 2. This fine wire connector, by means of which Curve *A* of Figure 5 was obtained, is used in calibrating all precision capacitors in our laboratories. An older type of connector is shown leaning against the capacitor cabinet and produces a much greater error as shown in Curve *B* of Figure 5.

Figure 3 illustrates the various capacitances which enter the problem. For the first measurement the high lead has a total capacitance C_g to ground and a capacitance C_h to the high terminal of the unknown capacitance C_x, both of these capacitances corresponding to a certain separation h. The total capacitance of the system is

$$C + C_g + \frac{C_h C_x}{C_h + C_x}.$$

The high lead is then brought into contact with the high terminal, making $h = 0$ and $C_h = \infty$. The standard condenser is then changed to a capacitance C' such that the total capacitance of the system is the same as before. The change in capacitance ΔC of the standard capacitor is

$$\Delta C = C_x + \Delta C_g - C_h$$

where C_h is written for $\frac{C_h C_x}{C_h + C_x}$ because in general C_h is very small compared to C_x. Other observations are then made for different distances of separation h, and the capacitance changes ΔC plotted against h, as shown in Figure 4. If in moving the high lead over the distance h, the ground capacitance C_g does not change, i.e., $\Delta C_g = 0$, the plot of ΔC against h will have a horizonal asymptote, which is the true value of C_x. Even under the most favorable conditions, there will be some change in this ground capacitance as the spacing h is changed. If the high lead is a fine wire and is kept a considerable distance from all grounded surfaces, the change in C_g will be approximately a linear function of h. The plot of ΔC will then have a slanting asymptote whose intercept is the value of C_x. The finer the wire and the greater the distance to ground, within limits, the more nearly horizontal is this asymptote. For a large wire near the grounded panels the change in C_g is such that this plot of ΔC has a maximum and changes by such a large amount that it is impossible to draw an asymptote.

Observations made with a Type 716-A* Capacitance Bridge on a Type 722-D Precision Condenser are plotted in Figure 5. Curve A was obtained with the connector shown mounted on the bridge in Figure 2. The fine steel wire is kept as far from the grounded panels as possible and is raised by means of a cam which is mounted on the triangular support. The slanting asymptote is well defined and gives a value of 99.13 $\mu\mu$f for the capacitance of the unknown capacitor. The curve has this value for a separation h of ¼ inch. Hence, with this connector and a ¼-inch separation, it should be possible to measure capacitance within ± 0.01 $\mu\mu$f. Curve B was obtained using the connector which is shown leaning against the precision capacitor. Only the vertical rod moves, and its capacitance to ground should change only slowly. The supporting bar is, however, wide enough to shield the rod and cause the ground capacitance to change rapidly as the rod is raised. Hence all measured values of ΔC are low, and no asymptote can be drawn. The panel of the precision capacitor was next depressed 5 inches and

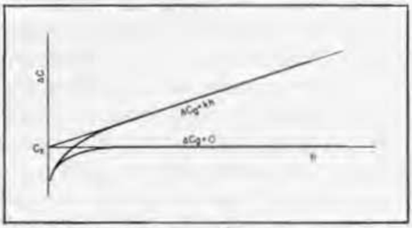

Figure 4. Theoretically, the measured capacitance of an air capacitor plotted as a function of the distance h shown in Figure 3 has either a horizontal or a slanting asymptote.

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* The current model is Type 716-C described in the April issue of the *Experimenter*.

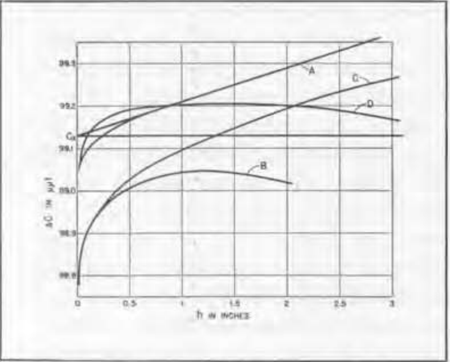


Figure 5. Different types and arrangements of connectors produce differently shaped plots of measured capacitance against the distance *h*. Curve *A*, taken with the fine wire connector of Figure 2, is the only one of the four curves which has a well-defined asymptote.

Curve *C* obtained. This shows a great improvement over Curve *B*, but the slanting asymptote is not easily defined. The critical separation *h* is 1⅜ inches. Curve *D* was obtained with No. 16 parallel wires at the same height from the panel as the hole in the terminal. There is no possibility of drawing an asymptote, and the critical separation is only 0.1 inch.

The fine wire connector is now used for all accurate capacitance measurements in the General Radio testing laboratory. The critical separation of ¼ inch is always obtained by adjustment of the height of the high terminal and the cam then used to make quick connection or disconnection. Observations can be repeated to 0.01 μμf and to 0.02 μμf even when the capacitors are removed and then reassembled. Different types of capacitors, both standard and unknown, can affect the value of the critical separation so that 0.1 μμf is at present set as a conservative error.

There are, of course, many ways of connecting capacitors in parallel so that their capacitances add with only slight error. TYPE 509 Condensers are built to be stacked one on top of another. Plugs projecting downward from the terminals fit into the jack tops of the terminals below. The plugs add a capacitance of about 0.5 μμf. The error from stacking in this way is less than 0.01 μμf.

When the power factor of a capacitor as well as its capacitance is to be measured, extra care must be taken to keep the contact resistance of the connections low. The equivalent series resistance of a capacitor varies inversely both as the capacitance and as the frequency. Even at a frequency of 1 kilocycle the resistance of a 1 μf capacitor of power factor 0.0005 is only 0.08 ohm. The use of plugs and jacks under these circumstances is questionable.

In the most precise work the capacitor is provided with a third terminal connected to guard electrodes or to the shield from which the main terminals of the capacitor are now insulated, and the bridge is provided with a guard circuit to which the extra terminal is connected. By these devices the connection capacitances and their power factors are removed from the direct measurement.

— ROBERT F. FIELD

VARIAC OVERLOAD PROTECTION

The problem of overload protection for Variac auto transformers is greatly complicated by certain inherent (and desirable) Variac characteristics. These are the ability of Variacs safely to withstand comparatively heavy overloading for short periods (as in motor starting or lamp circuit inrush) and the variation of copper loss with brush position which permits a substantial increase in allowable load currents at, or near, zero or line voltage settings.

Short-term overloads are permissible because of the thermal inertia inherent in Variacs, as in any device having appreciable mass and good thermal conductivity. The excess heat released in the overload period is quickly distributed throughout the structure and absorbed so that excessive temperatures will not be reached in a short time. This is a most important consideration for the user as it means that his Variac rating need not be increased in order to handle starting or surge conditions normally encountered.

Obviously, the use of a protective device incapable of passing safe short-term overloads would unduly limit the usefulness of a Variac. This, then, precludes the use of fuses (even "slow-blow" types) if the fullest use of the Variac is to be realized, and calls for the time-current integrating type of protector which automatically allows short-term overloads within the safe limits of Variac operation.

The variation in allowable load current poses a still more difficult problem, and one for which we have no satisfactory universal solution. If full advantage is to be taken of the maximum allowable load current, the protective device cannot be expected to function where the allowable current curve drops to a minimum. Here, then, is a condition that calls for the exercise of judgment on the part of the user, who, being familiar with the requirements to be met under his service conditions, can best decide whether to provide maximum protection at the sacrifice of increased current draw for some settings, or to sacrifice some protection in the interest of being able to obtain maximum current.

Several protective devices of the necessary time-current type are commercially available. Of these, the magnetic-trip delayed-action circuit breaker, made by the Heinemann Circuit Breaker Co., Trenton, New Jersey, seems most efficient and reliable.

Since the vast majority of Variac users do not employ protective devices, the direct incorporation of a protective device into Variacs seems uneconomical in view of the increased cost that would result.

Heinemann Breaker No. 0411TS is recommended for all present production Variacs, and may be obtained in all values of either rated or maximum current over the range required. Maximum protection to the Variac will be provided by connection of this breaker in series with the brush lead.

— Gilbert Smiley

METER CALIBRATION WITH THE VARIAC

One of the many uses of the Variac is in supplying calibrating voltages and currents for electrical indicating instruments such as voltmeters, ammeters, and wattmeters. The accompanying diagrams show a circuit for a-c instrument calibration used by Professor R. M. Marshall of Purdue University.

The circuit of Figure 1 is used for current calibrations. The source is a 60-cycle generator, although, if ordinary line voltage variations can be tolerated, ordinary a-c lines can be used. Variac No. 1 is used to adjust the current to give full-scale reading on the instrument to be calibrated, which is connected between the ± terminal and the terminal most nearly representing the full-scale value. With Variacs No. 2 and No. 3 set at maximum, No. 1 is adjusted until the instrument reads full scale or slightly beyond. Zero deflection then corresponds to the zero settings of No. 2 and No. 3. The full range of Variac No. 2 then covers the range of the instrument from zero to full scale. Variac No. 3 changes the current 1/20th as fast as No. 2. The range and precision of control in terms of full-scale deflection are thus the same, regardless of the instrument impedances.

Two current transformers are used so that all tests can be made in terms of a 5-ampere standard instrument. Each current transformer has several ranges. The standard instrument can be connected to one of the instrument transformers or directly in series with the meter under calibration. The transformers must be shorted as shown, if they are not connected to the standard instrument. The seven resistors are used to stabilize the circuit and to bring the current more nearly into phase with the line voltage. This arrangement gives approximately 100% power factor for wattmeter tests.

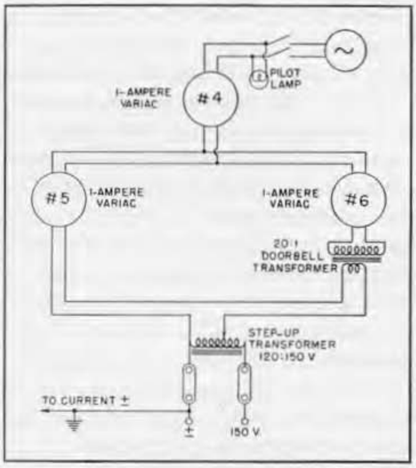


Figure 2. Circuit for potential calibrations.

The potential circuit of Figure 2 operates in a similar manner. The two terminals provided take care of all instruments rated up to 150 volts. For higher voltages an additional transformer can be inserted at the points where links are shown. The standard instrument is connected in parallel with the instrument under test.

A grounded connection between the current and potential circuits is provided as shown in Figure 2. When a wattmeter is being tested, the potential terminal leading to the multiplier should be connected to the 150-volt terminal rather than to the + terminal, in order to avoid a high potential between the wattmeter coils.

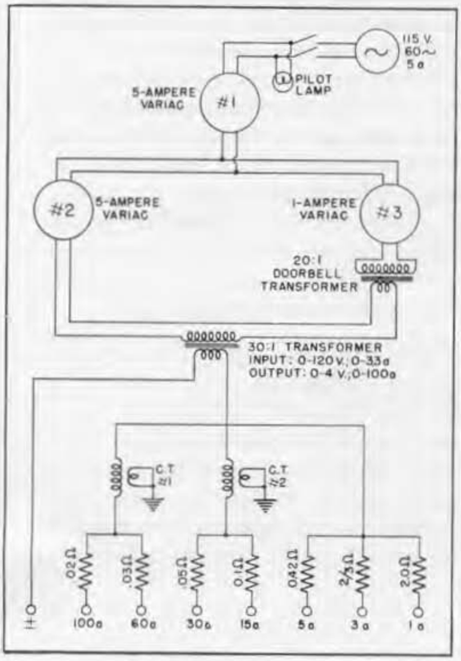


Figure 1. Circuit for current calibrations.

ASK FOR THIS TAG BEFORE RETURNING EQUIPMENT FOR REPAIR

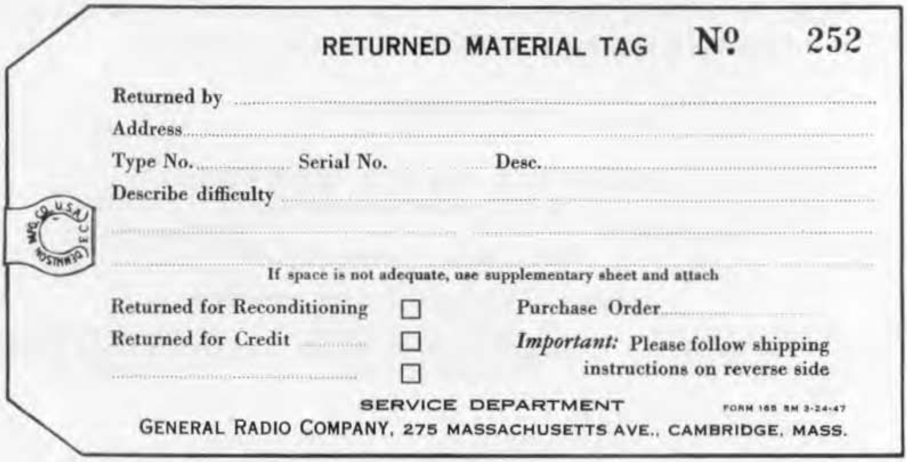
Instruments are often returned to us with purchase orders specifying "Repair." We then thoroughly recondition the instruments and recalibrate them to the same laboratory testing specifications that are used for newly manufactured equipment. Occasionally, after receiving the repaired instrument, the customer will report that the instrument still exhibits the same erratic fault or intermittent operating defect that occasioned the original return, and it is necessary to send the equipment back a second time.

To prevent this, we have been spending a greater than normal time in testing repaired instruments. Only in this way can we be sure of catching defects that would not occur in new instruments. Such a procedure, as records show, inevitably increases repair costs, and the charges billed to the customer are often as much as 10% greater than normal. Much time and money can obviously be saved if we know when the instrument is returned exactly what is wrong with it.

Consequently, we are now requesting that our new returned-material tag be attached to all returned instruments. Before returning equipment to us, please write for this tag, which gives shipping instructions and has space for describing the conditions that need correction. There will be a delay in handling returned equipment unless this tag is attached. Material returned for credit or replacement cannot be accepted unless we authorize it by issuing a returned-material tag.

Please cooperate with us in speeding up the handling of returned equipment by using this tag. The type numbers and serial numbers of the instruments to be returned should be specified when you request the returned-material tag from our Service Department.

—H. H. Dawes



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MISCELLANY

THE ARTICLE on "Connection Errors" by R. F. Field is reprinted with minor changes from the January, 1938, issue of the *Experimenter*. It has been out of print for several years, and we have had lately a considerable demand for it. This article is still timely, perhaps more so now than when originally published.

The TYPE 722 Precision Condenser is the accepted standard of capacitance for the radio and electronic industries. To realize fully its inherent accuracy, the mechanism of connection is important. The method recommended here has been used in the Standardizing Laboratory at the General Radio Company for a number of years.

Two other articles of importance to those interested in capacitance measurement and standardization will be published in the next few months. One of these will concern the accuracy of the TYPE 722 Precision Condenser, and the other will discuss the projected change from the current international values of electrical units to the new absolute values.

TECHNICAL PAPERS — "The Evaluation and Control of Noise," by Ivan G. Easton, at the Annual Safety Convention of the Greater New York Safety Council, March 27; "Measurement and Analysis of Sound and Vibration," by William R. Saylor, at the April 8 meeting of the Central Indiana Section, Instrument Society of America, at Indianapolis; "Design of an F-M Monitor," by Charles A. Cady, at the Chicago I.R.E. Conference, April 19; "Recent Developments in Instrumentation," by Ivan G. Easton, at the April 21 meeting of the Measurements Section of the A.I.E.E., Philadelphia; "Current-Time Curves in Insulation Resistance Measurement," by Robert F. Field, at the Northeastern District Meeting, A.I.E.E., Worcester, Massachusetts, April 23.

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