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Vol. 17 AUGUST, 1952 No. 8

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SUBSTITUTION METHODS IN CAPACITANCE MEASUREMENT

Low capacitances, especially from 100 uufd. down, are particularly important in high-frequency circuits. These capacitances are selected by design but they can be of considerable concern also when they appear by accident as stray circuit parameters. The problem of checking small capacitance values accurately becomes apparent to the student of electrical measurements as soon as the limitations of conventional methods are noted. Familiar members of the small-capacitance domain are low-value fixed and trimmer capacitors, terminal-to-terminal capacitance, terminal-to-ground capacitance, lead capacitance, tube interelectrode capacitance, and socket terminal capacitance.

The direct measurement of small capacitances usually is complicated by stray capacitance in the measuring instrument itself. This stray characteristic is especially disturbing on the low ranges which normally would be used. For that reason, it is desirable to employ an indirect method of measurement, in order that the effects of all strays might be compensated automatically. Substitution methods fall into this category. There are several ways of using substitution methods with conventional test instruments to obtain greater accuracy of small-capacitance measurement. These methods are described in this article.

Principle of Substitution Method

Figure 1 shows a basic setup for substitution measurements of capacitance. This arrangement, which will serve to illustrate the method, often is employed in laboratories. Instruments required are a capacitance bridge and a variable capacitor with dial calibrated for direct reading in micromicrofarads.

The first step in using this arrangement is to set the variable capacitor to some capacitance (C_1) near its maximum and to connect it to the bridge. Short, rigid leads are used. Next, the bridge is adjusted for null. Thereafter, the bridge setting must not be disturbed. Note that this setting of the bridge includes all of the capacitance in the circuit — the total of strays and the capacitance setting (C_1) of the variable capacitor. Finally, connect the unknown small capacitance to termi-

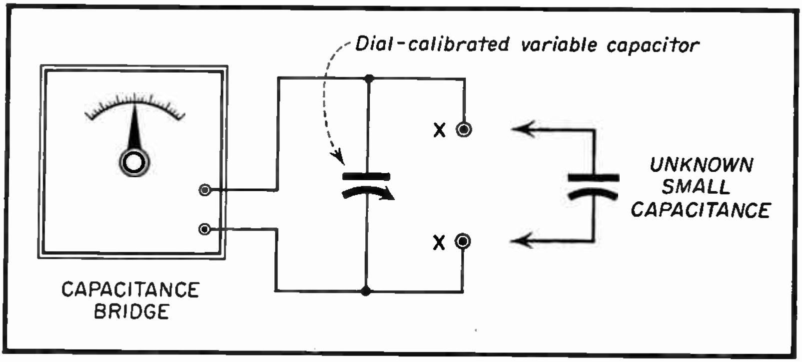

Fig. 1. Basic setup for substitution measurements.

nals X-X in parallel with the variable capacitor and bridge, using the shortest possible leads. Since the capacitance connected to the bridge now has been increased by the amount of the unknown, the bridge unbalances.

Null is restored by reducing the setting of the variable capacitor to a new capacitance, (C_1). This removal of capacitance from the original setting of the variable capacitor thus compensates for the presence of the unknown unit. The unknown capacitance then is equal to C_2—C_1, the difference between the two settings of the variable capacitor required for null. In other words, the unknown capacitance is equal to the amount of capacitance which must be subtracted by means of the variable capacitor in order to restore the circuit capacitance to its initial value.

Illustrative Example: The variable capacitor is set to 1000 uufd. and the bridge balanced to a sharp null. C_2 thus is 1000. The unknown capacitance (C_x) is connected into the circuit, and the variable capacitor setting reduced to restore null. At the new null point, the variable capacitor dial reads 988 uufd. which is the value of C_1. In this case, $C_x = C_2 — C_1 = 1000 — 988 = 12$ uufd.

This method of measurement affords higher accuracy than the direct method because (a) the initial null balance automatically compensates for stray shunting capacitances within the instrument and the setup and removes the necessity for correcting for the "zero" capacitance of the measuring instrument; and (b) the initial setting (C_2) of the variable capacitor is at or near the maximum capacitance of this unit, where settings are relatively free from disturbances due to small physical movements and to strays. Furthermore, smaller capacitance changes may be read on the dial of the variable capacitor than are possible with the bridge alone. Note that the bridge serves merely as a null indicator in this setup, the actual readings being taken from the dial of the variable capacitor.

The maximum capacitance which may be accommodated directly by this particular method of measurement is restricted by the difference between maximum and minimum capacitance settings possible with the variable capacitor used. Thus, if the capacitor dial is graduated for continuous reading between 100 and 1000 uufd., the maximum capacitance that can be measured is 1000—100, or 900 uufd.

Thus far, nothing has been said about power factor or Q balances of the bridge (if a bridge is used as the null indicator) and the effect of these balances upon the adjustments of the variable capacitor. Actually, there is no deleterious effect. The variable capacitor, being air-tuned, has a high Q value approaching infinity (low power factor), and the power factor balance may be assumed to apply only to the unknown capacitor under test.

The type of substitution method just described requires an accurately-calibrated, ruggedly-constructed variable capacitor. Standard units of this type are available in laboratory grade. When economy is a factor, however, as usually is the case with experimenters, service technicians, and small laboratories, a satisfactory substitute can be made using a soundly-built 100-, 500-, or 1000-uufd. tuning capacitor, preferably with plates cut for a straight-line capacitance curve. A micromicrofarad calibration of the dial may be provided by standardization against another capacitance standard.

Substitution Method for Large Capacitances

Large capacitances outside of the range of a bridge or other available capacitance-measuring instrument also may be checked by means of a substitution method of measurement. Although a number of service technicians give attention to this method from time to time, quite a few have become confused in the calculation.

Figure 2 illustrates the method. Here, a capacitor (C_s) of accurately-known value is connected in series with terminals X-X which are short-

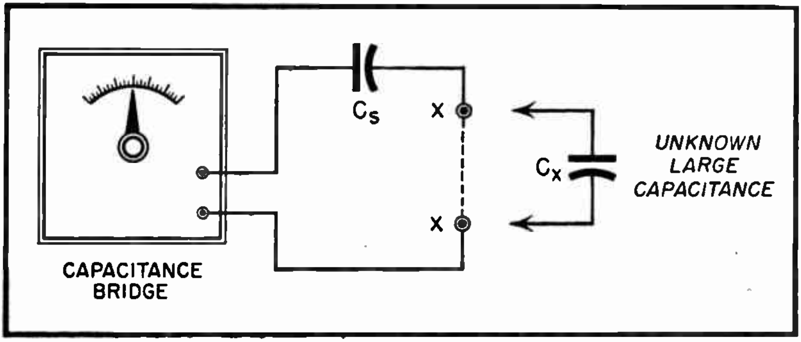

Fig. 2. Substitution measurement of large capacitance.

circuited temporarily by means of a short jumper. The capacitance reading for C_s then is read from the instrument and recorded as C_1. Next, the jumper is removed and the unknown capacitance connected to terminals X-X. The unknown thus is connected in series with C_s. The new capacitance, read from the instrument, is recorded as C_2. The unknown capacitance (C_x) is equal to:

$$C_x = \frac{C_1^2}{C_1 - C_2} - C_1$$

Illustrative Example: A 1000-uufd. capacitor is selected as C_s. The initial reading C_1 then is 1000. When the unknown capacitance is connected into the circuit, a reading (C_2) of 910 uufd. is obtained. The unknown capacitance (C_x) then equals:

$$\frac{1000^2}{1000-910} - 1000 = \frac{1,000,000}{90} - 1000 = 11,111 - 1000 = 10,111 \text{ uufd.} = 0.0101 \text{ ufd.}$$

Substitution Method in Capacitance-Tuned Bridges

Figure 3 shows the skeleton circuit of a capacitance bridge having a direct-reading variable capacitor, C_v, as its adjustable arm. Bridges of this type are used at both audio and radio frequencies.

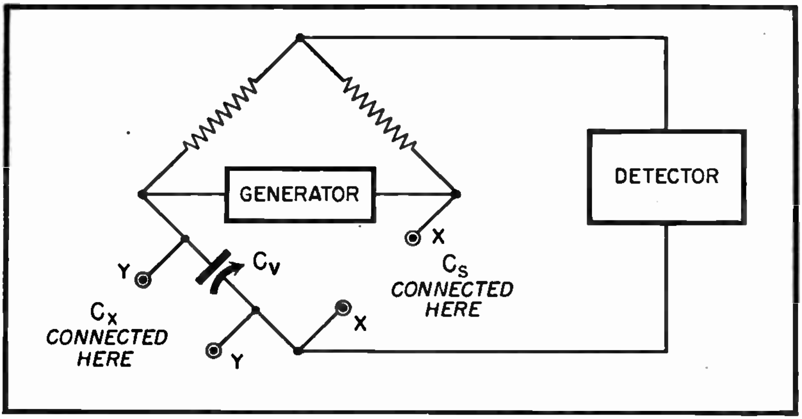

Fig. 3. Bridge adapted for substitution capacitance measurements.

The unknown capacitance normally is connected, for direct measurement, to terminals X-X, the bridge balanced by adjustment of C_v, and the unknown capacitance value read directly from the calibrated dial of C_v. The substitution method may be employed with this bridge, using the internal variable capacitor, C_v. Terminals Y-Y are provided for this purpose. Such terminals are available on some laboratory-type bridges of the capacitance-tuned type.

The bridge is set initially by connecting to terminals X-X a capacitor having a value near the full-scale setting of C_v. The accuracy of this capacitor is unimportant. The setting of C_v then is recorded as C_1. The unknown capacitance is then connected to terminals Y-Y, and capacitor C_v detuned to reduce its setting to restore null. At the new null point, the setting of C_v is recorded as C_2. The unknown capacitance then is determined from the relationship $C_x = C_1—C_2$.

It is to be noted that this variation, or any of the other methods of substitution measurement of capacitance, will not compensate automatically for stray capacitance in the unknown unit. Such strays are introduced by the leads to the unknown capacitor. The effect of lead capacitance may be nullified to some extent by connecting the leads alone first to terminals Y-Y and setting C_v for initial balance. The unknown capacitor then is connected to the leads carefully without disturbing their position. When the unknown capacitor has pigtail leads, it may be connected to terminals Y-Y for the initial setting, but with one pigtail disconnected and its tip separated from the corresponding Y terminal by a short distance, say 1/16 to 1/8 inch. After the initial setting, the lead is inserted into the Y terminal.

Other Instruments for Substitution Measurements

R. F. Oscillator. Any convenient, high-stability radio-frequency oscillator may be used for substitution capacitance measurements provided its tank tuning capacitor is provided with a direct-reading capacitance dial. The tuning capacitor first is set to its maximum capacitance (C_1) and the frequency of the oscillator measured with a convenient frequency meter. The unknown capacitor (C_x) then is connected in parallel with the tuning capacitor, using the shortest possible leads, and the tuning capacitor detuned to a second lower setting (C_2) to give the same oscillator frequency. The value of the unknown capacitance C_x is equal to $C_1—C_2$.

Q-Meter. The standard Q-Meter checks capacitance values at radio frequencies by means of the substitution process. The measuring circuit of the Q-Meter is shown in Figure 4. C_1 is a rather large variable capacitor, having a maximum capacitance near 500 uufd. C_2 is a small variable trimmer with a range of only a few micromicrofarads. With C_1 and C_2 both set to their maximum positions; the L-C circuit is resonated, as indicated by peak deflection of the v. t. voltmeter, by varying the frequency of the input radio-frequency voltage from an oscillator. The unknown capacitance then is connected to terminals X-X and C_1 or C_2 reduced to restore peak deflection of the meter. The unknown capacitance then is equal to the difference between the two tuning capacitor settings for meter deflection. For very small unknown capacitances, trimmer C_2 alone is varied, C_1 being left at its maximum capacitance setting.

Grid-Dip Oscillator. The grid-dip oscillator, familiar to most amateurs and service technicians, is employed in a manner similar to the Q-Meter. In this case, however, an external L-C circuit must be provided. The latter may consist of a rigid coil of a few turns of wire connected in parallel with a direct-reading variable capacitor. The variable capacitor is set to its maximum capacitance (C_1), the grid-dip oscillator coupled loosely to the coil and tuned for resonance as indicated by complete dip, and the reading C_1 noted. The unknown capacitance then is connected in parallel with the variable capacitor and the latter detuned

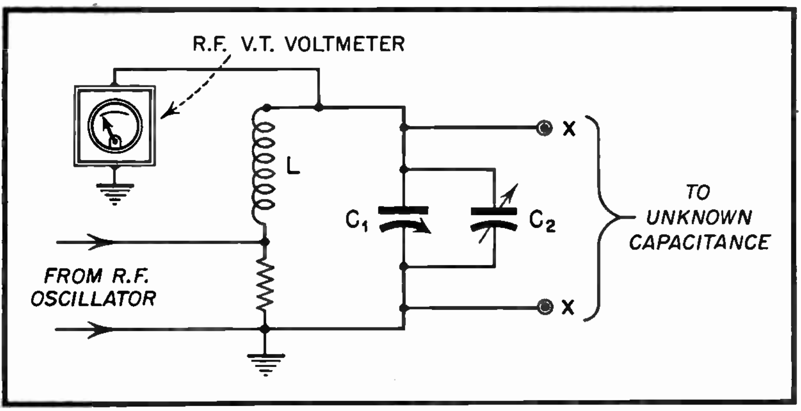

Fig. 4. Q-meter capacitance-checking circuit.

to re-establish resonance. The new variable capacitor setting is recorded as C_2, and the unknown capacitance determined from $C_x = C_1 - C_2$.

Twin-T Network. Another null instrument employing a variable capacitor in one of its arms is the Twin-T Impedance-Measuring Network, shown in rudimentary form in Figure 5. Like the other circuits, this network is set initially to null with the tuning capacitor, C_1, at its maximum capacitance. The unknown capacitance then is connected to terminals X-X in parallel with the tuning capacitor which then is detuned to restore null. As before, the difference between the two settings of the variable capacitor indicates the value of the unknown capacitance.

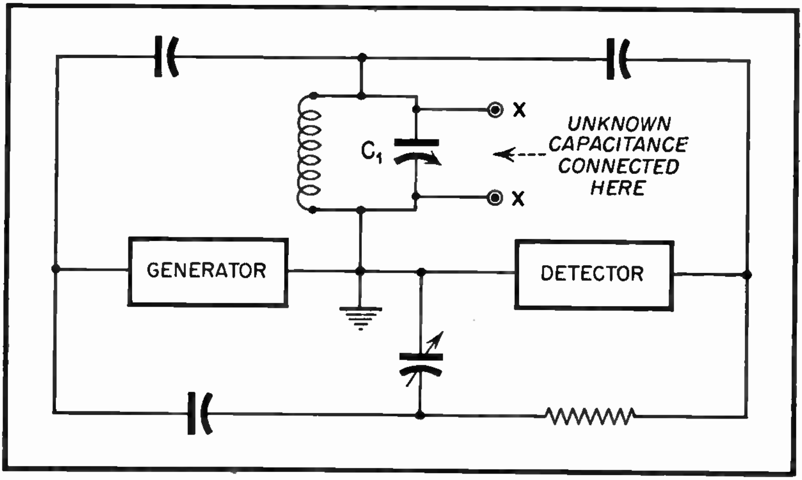

Fig. 5. Twin-T network.

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The Model BF-50 Capacitor Analyzer quickly and accurately measures all important characteristics of all types of capacitors. It offers the most accurate and thorough capacitor test of any instrument of its type, and may be operated on any 110-volt, 50-60 cycle power line.

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