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The Measurement of Impedance from Very-Low to Very-High Frequencies

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Impedance measurement, as every engineer knows, is a simple process. Connect the device we want to measure to a suitable bridge, adjust the dials for a null and read the impedance components from the dial settings. With reasonable care these answers are correct for what the bridge sees, but what do they mean? Are they in a form we can use? We usually want to know the characteristics of a component under the proposed conditions of use.

If a suitable bridge is available, the measurement obviously should be made at the desired frequency, voltage and temperature. To make measurements that are useful, we have to decide:

1. Why is the measurement being made?
2. What use will be made of the results?

IMPEDANCE CHARACTERISTICS

Besides measurements of resistive and reactive components, there are two sets of definitions of first importance in deciding what to measure: one consists of expressions for the loss components; the other is the difference between, and the relations between, series and parallel components.

Dissipation Factor and Storage Factor—An important characteristic of an inductor or a capacitor is the ratio of resistance to reactance, or of conductance to susceptance. This ratio is termed dissipation factor D and its reciprocal is storage factor Q. These ratios are defined in Fig. 1 in terms of phase angle θ and loss angle δ. Dissipation factor is directly proportional to the energy dissipated, and storage factor to the energy stored, per cycle. Power factor is defined as

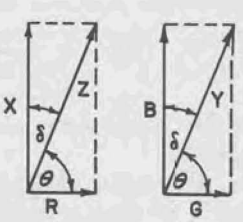
$$PF = \cos\theta = \sin\delta$$

and differs from dissipation factor by less than 1 percent when their values are less than 0.1.

Dissipation factor, which varies directly with the loss, is used commonly for capacitors and to a lesser extent for inductors. Its reciprocal, storage factor Q, is more often used for inductors because it is a measure of the voltage step-up in a tuned circuit. The bridge can often be arranged so that the control for the resistive balance can be calibrated in dissipation factor or in storage factor for a given frequency.

Another quantity, *loss factor,* often used in specifying dielectric properties, is the product (KD) of the dielectric constant and the dissipation factor.

Series and Parallel Components—The impedance of any device can be expressed in terms of either series or parallel components. One cannot tell from a single measurement whether resistive and reactive elements in combination are actually in parallel or in series, but regardless of the physical configuration, the resistive and reactive components can be measured and expressed as:



$$D = \cot\theta = \frac{R}{X} = \frac{G}{B} = \frac{1}{Q} = \tan\delta$$

Power Factor = $\cos\theta = \frac{R}{Z}$

$$Q = \tan\theta = \frac{X}{R} = \frac{B}{G} = \frac{1}{D} = \cot\delta$$

R and X are series resistance and reactance

G and B are parallel conductance and susceptance

Fig. 1-Vector diagram showing the relations between D and Q, and angles θ and δ.

1. Series impedance components;
2. Parallel impedance components;
3. Admittance components.

The choice is a matter of convenience for the problem at hand.

The relations between these various systems (see Fig. 2) are

$$R_P = \frac{1}{G_P} = \frac{R_s^2 + X_s^2}{R_s} = R_s(1 + Q^2)$$

$$X_P = \frac{1}{B_P} = \frac{R_s^2 + X_s^2}{X_s} = X_s(1 + D^2)$$

so that

$$C_P = C_s\left(\frac{1}{1 + D^2}\right) \qquad C_s = C_P\,(1 + D^2)$$

$$L_P = L_s\left(1 + \frac{1}{Q^2}\right) \qquad L_s = L_P\left(\frac{Q^2}{1 + Q^2}\right)$$

where

$$Q = \frac{X_s}{R_s} = \frac{R_P}{X_P} = \frac{B_P}{G_P} \quad D = \frac{1}{Q} = \frac{R_s}{X_s} = \frac{X_P}{R_P} = \frac{G_P}{B_P}$$

It should be noted that only for values of Q below 10 (or $D > 0.1$) does the difference between series and parallel reactance exceed 1 percent. It is obvious that if there were no losses in the reactive elements (i.e., $Q = \infty$), series and parallel reactance would be equal. For very low Q's, however, the difference is marked; when $Q = 1$, the parallel reactance is twice the series reactance.

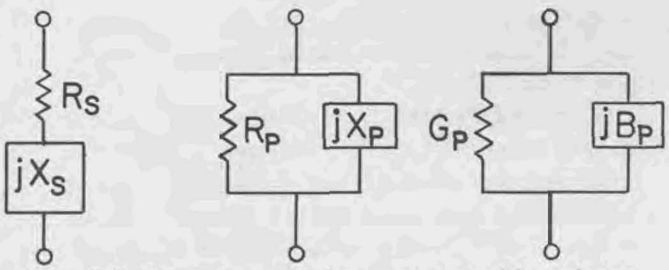


Fig. 2-Series and parallel components of impedance.

Whether a bridge measures series or parallel components depends upon its configuration. The bridges shown in Figs. 5a and b, for example, will yield parallel values for the unknown. Similarly, the bridges of Figs. 5c and d will give series values.

With these relations in mind, we can consider the characteristics of the thing to be measured:

1. Is it R, L or C? If this cannot be determined by inspection, a "universal" bridge that measures all three quantities will quickly settle the question.

2. In what form should the answer be? Parallel or series parameters, impedance magnitude and phase angle, or admittance? Do we want the result in capacitance and dissipation factor (if the unknown is a capacitance) or do we want ohms reactance and ohms resistance? There are bridges available to read out all of these quantities.

At radio frequencies, low impedances usually are measured as series elements, higher impedances as parallel. Bridges that read in ohms usually are designed for low-impedance measurements; those for high-impedance are more likely to read in mhos (probably micromhos).

While one set of parameters can be converted to the other, there are instances where only one will yield useful information. For example, a parallel circuit near resonance should be measured in terms of parallel parameters, while an inductor below its frequency of maximum Q should be measured as a series circuit.

Similarly, if the loss in a capacitor is predominantly series resistance, series parameters are indicated; if the loss is mainly in the dielectric or in leakage resistance, parallel parameters will present the best picture of what is happening. These considerations are usually important only when D approaches 0.1, which is the point where the difference between series and parallel capacitance is 1 percent. More precision is not required ordinarily on high-loss capacitors.

3. Is the unknown a non-linear element? If it is an inductor with a ferro-magnetic core, at what excitation level is the measurement to be made? An inductor for use in a low-level filter can be measured on an ordinary inductance bridge; measurement of power-supply chokes, however, require a so-called incremental inductance bridge with provision for both d-c and a-c excitation.

The measurement of iron-cored inductors requires too lengthy a treatment to be considered in detail here, but when the quantity to be measured varies in magnitude with the applied voltage, obviously the measurement must be made under known and controlled conditions.*

4. What are the physical aspects of the unknown impedance? Will the impedance of leads to the bridge be significant? Is it so bulky that its capacitance to ground will be a factor? Where lead impedance and terminal capacitance are of such magnitudes as to affect the result, a 3-terminal measurement is necessary. This can be done by three separate measurements and the desired result calculated, but a better method is to use a transformer bridge or a guarded bridge.

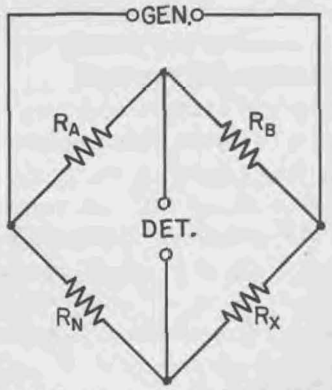
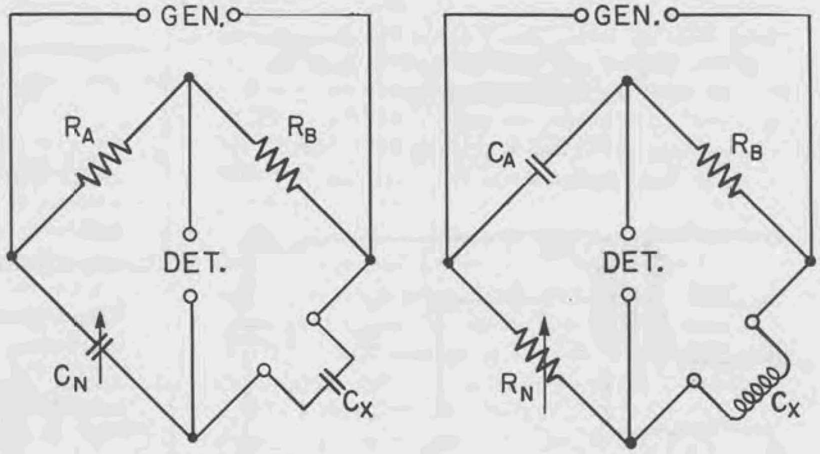


Fig. 3—Basic Wheatstone bridge circuit.

5. What accuracy and what precision are desired in the measurement? One cannot achieve an absolute accuracy quite as good as that of his standard, since some allowance must be made for measurement errors. The precision of the measurement, i.e., the resolution of the bridge, must be substantially better than the desired accuracy of measurement. (The terms precision and accuracy are often confused; precision is the resolution with which a quantity can be measured. Accuracy has to do with the closeness with which we can relate

**See "Iron-Cored Coils for Use at Audio Frequencies", General Radio Co., West Concord, Mass.*

Fig. 4—Bridge circuits in which like reactances, C_N and C_X, and unlike reactances, C_A and L_X are compared.



our measurement to the value of accepted standards. It is well to remember that high precision does not require accuracy, but high accuracy requires precision.)

BRIDGE FUNDAMENTALS

Knowledge of the basic characteristics of the common types of bridges will help us choose a bridge for a particular measurement.

Bridge Circuits—Most impedance bridges are a-c adaptations of the fundamental Wheatstone bridge circuit, Fig. 3, which has been used for the measurement of d-c resistance for more than a century. It measures unknown resistance in terms of calibrated standards of resistance from the relationship

$$\frac{R_A}{R_B} = \frac{R_N}{R_X}$$

which is satisfied when the voltage across the detector terminals is zero. This null method of measurement is inherently capable of very high precision.

The basic circuit of Fig. 3 is also applicable to alternating-current measurements. With impedances substituted for resistances, two conditions of balance must be satisfied, one for the resistive component and one for the reactive components. The equations of balance can be written in either of the following forms:

$$R_X + jX_X = \frac{Z_B}{Z_A} Z_N \quad (2) \qquad G_X + jB_X = \frac{G_B}{G_A} Y_N \quad (3)$$

Equation (2) expresses the unknown in terms of its *impedance* components, while equation (3) expresses the unknown in terms of its *admittance* components. To satisfy these equations, at least one of the three arms A, N or B must be complex.

The unknown reactance can be measured in terms of a similar reactance in an adjacent arm or an unlike reactance in the opposite arm, as indicated in Fig. 4.

Resistive Balance—Fig. 5 shows the four basic methods in common use for balancing the loss component of the unknown impedance. These are: (a) resistance in parallel with the standard reactance, (b) capacitance in series with a resistive arm, (c) resistance in series with the standard reactance and (d) capacitance in parallel with a resistive arm.

The Transformer Bridge—Modern design transformers, when used as ratio arms in a bridge, can yield much more accurate voltage ratios than can conventional resistive arms. In the circuit of Fig. 6 the bridge equations are

$$C_X = C_A(M) \quad (4) \qquad\qquad R_X = R_N(M) \quad (5)$$

where M is the turns ratio of the two sections of the transformer.

In all these bridges, the positions of generator and detector can be interchanged without affecting the bridge equations.

Other Null Circuits—Other types of networks can be used to give zero transmission. One other type is the parallel-T network of Fig. 7, which has advantages for high-impedance measurements at radio frequencies. An important characteristic of this circuit is that one side of the unknown, one side of the gen-

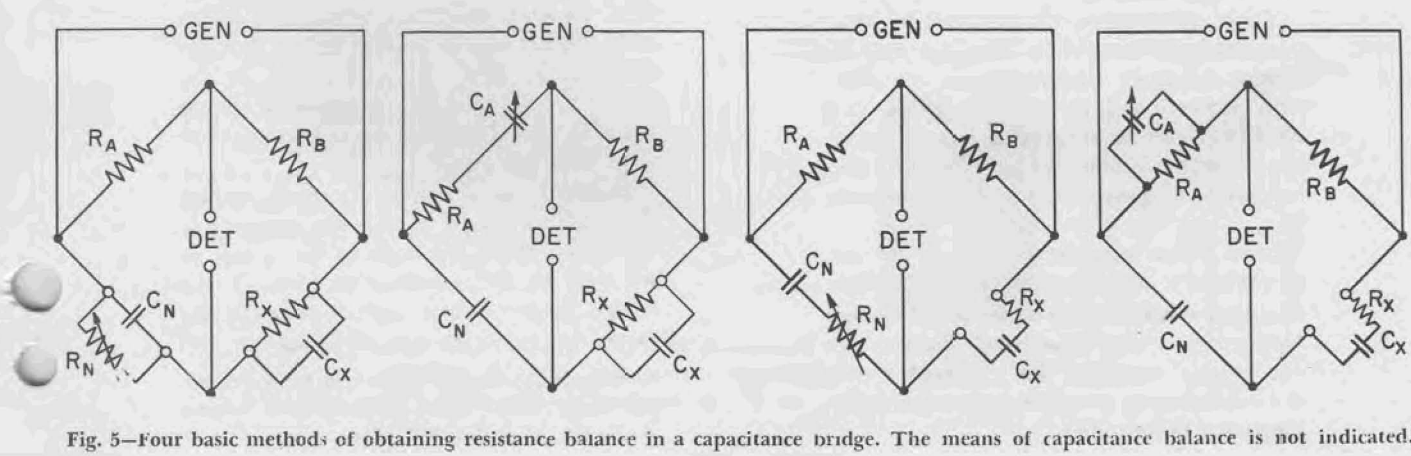


Fig. 5—Four basic methods of obtaining resistance balance in a capacitance bridge. The means of capacitance balance is not indicated.

erator and one side of the detector are all at ground potential. Capacitance is read directly from the settings of capacitor C_B. Conductance is

$$G_x = \omega^2 C1\,(C2)\,R\,\frac{\Delta C_G}{C\,3} = k\omega^2\,(\Delta C_G)$$

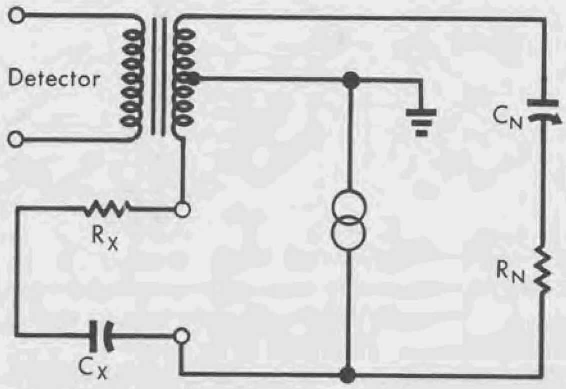


Fig. 6—Transformer bridge, in which the transformer replaces the usual ratio arms.

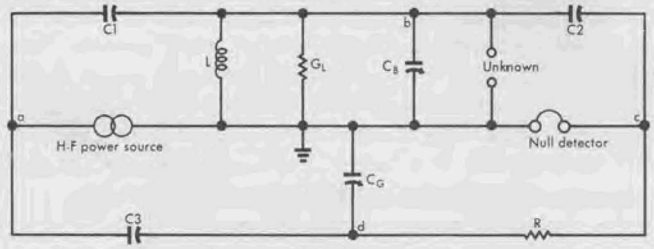


Fig. 7—Parallel-T circuit for measuring impedance.

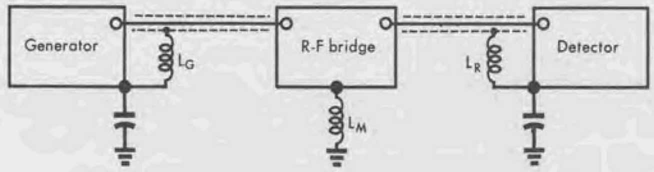


Fig. 8—Effects of small series inductances in interconnecting leads.

GENERATORS AND DETECTORS

Generators—Important considerations in selecting a power source for a-c bridge measurements are good frequency stability, adequate power output and low harmonic content. Most general-purpose oscillators meet these requirements. At radio frequencies, however, we need to add the requirement of adequate shielding to avoid direct coupling between generator and detector or between generator and unknown.

Detectors—For maximum precision, it is necessary to obtain a virtually complete null balance. The desired characteristics of a bridge detector are:

1. High sensitivity, preferably the ability to detect a few microvolts.
2. High selectivity to reject harmonics, noise and other interfering signals. This is particularly important in the measurement of iron-cored coils and other non-linear elements.
3. Quasi-logarithmic response to obviate the necessity for gain adjustments during the balancing procedure.

These requirements are best met by some combination of amplifier, filter and null indicator. At audio frequencies, an amplifier, with either fixed or tunable filters, and either a meter or earphones, is satisfactory. With visual indicators, such a system can also be used at frequencies up to several megacycles.

From a few hundred kc to some 40 mc, well-shielded radio receivers make excellent detectors, while at very-high and ultra-high frequencies, where broadband receivers are not usually available, the preferred system is a heterodyning oscillator, mixer and fixed-frequency IF amplifier.

CONNECTIONS

Shielding—Generator and detector must be shielded sufficiently so that there is no direct coupling between them or between generator and bridge or unknown impedance. Adequate ground connections and shielded generator and detector leads are necessary but are particularly important at high frequencies. At audio and low-radio frequencies, electrostatic shielding of the leads is usually all that is necessary. Above a few megacycles, coaxial leads must be used; these must be grounded securely to the detector, generator and bridge shields to provide a completely shielded system, and to eliminate common impedances between generator and detector. These can cause large errors at high frequencies, as shown in Fig. 8. The voltage drop in L_G causes current to flow around the loop consisting of the cable sheath, the ground lead, L_M and the generator capacitance to ground. Similarly, current flows in the right-hand loop that includes L_R. The voltage applied to the detector has, therefore, two components, one from the bridge and the other from the drop across L_R. At the null point, the bridge is out of balance by the amount necessary to make the vector sum of the bridge voltage and the extraneous voltage equal to zero. Complete coaxial connections will avoid this error.

Residual Impedances—Residual impedances are unwanted impedances inherent in the device to be measured, in the bridge itself and in their interconnections. In the bridge, these residuals limit its accuracy and range. In the unknown, they obscure and

1. "Impedance Bridges Assembled from Laboratory Parts", I. G. Easton, available from General Radio Co., West Concord, Mass.

modify the main characteristic that we want to measure. In the interconnections, they produce errors in the measurement.

The effects of bridge residuals can be minimized by shielding, by proper design of the bridge circuit, by the use of a shielded transformer between bridge and generator and detector and by the use of a substitution method of measurement. Bridge residuals are the concern of the bridge designer and manufacturer and have been discussed extensively in the literature.[1]

Connecting the Unknown—When present in the unknown impedance and its connecting leads, residuals affect both the choice of a method of measurement and the accuracy. This concerns the relative magnitudes of the residual impedances and the quantity to be measured. The most important residuals are: (1) distributed (or effective shunt) capacitance associated with inductors and (2) inductance in series with capacitors.

For example, a 1-henry standard inductor will have an effective shunt capacitance of some 100 MMF, so that its resonant frequency is near 16.5 kc. At 1 kc, the inductor will measure nearly 1.01 henries. Any accurate measurement of this inductor therefore must be made at a low frequency, 100 cps or below, and we must be careful not to add any significant capacitance by the method of connection to the bridge.

At the other extreme let us consider a coil whose inductance at 1000 cps is 10 microhenries. We want to measure it at 20 mc, and we connect it to a radio-frequency bridge with two leads of No. 12 wire, 2 inches long and ½ inch between centers. What the bridge sees is then the capacitance of the leads (about 0.6 MMF) in parallel with the coil to be measured and the inductance of the leads in series with it (approximately 0.025 microhenry). While the latter is negligible compared to the unknown, lead capacitance will produce an error of nearly 10 percent.

The remedies for these conditions depend primarily on the frequency range in which the measurement is made. At audio frequencies, a 3-terminal or guarded measurement eliminates the effects of lead capacitance, as will a transformer bridge. At radio frequencies, the usual procedure is to measure the impedance of the leads and to calculate their effect. For acceptance tests and limit testing, a test fixture. which provides a standard environment, is generally used (Fig. 9).

Guard Circuit—Whenever the impedance to be measured has appreciable capacitance from its terminals to ground, a guard circuit can eliminate effects of the unwanted residual impedances.

Fig. 10 shows a Schering Bridge with a capacitor connected having stray impedances C1 and C2 to ground from both its terminals. The guard circuit provides two impedances Z_{G1} and Z_{G2}. These are adjusted by successive balancing until terminal 3 is at the same potential as terminals 1 and 2. Both ends of C1 are then at the same potential, and so C1 has no effect. C2 is part of the guard circuit impedance and does not affect the balance. Hence, the capacitance measured is that of Cx alone.

The guard circuit permits accurate measurement of the capacitance and dissipation factor between two terminals of a 3-terminal network. One of the most important applications of such a measurement is in determining the properties of dielectric materials under controlled changes in environment. A guard electrode often is employed to eliminate effects of variable lead parameters as temperature or other conditions are changed.

Transformer Bridge—The transformer bridge, Fig. 6, offers a considerably simpler method of eliminating the effects of lead capacitance. Capacitance to ground from the unknown capacitor appears across either the oscillator, where it has no effect on the measured capacitance, or over part of the transformer winding, whose impedance is so low that shunting values in the thousands of micromicrofarads do not affect it.

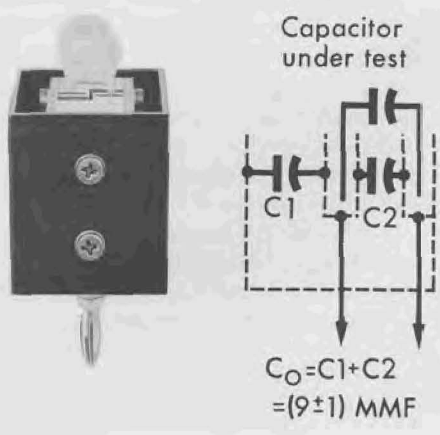


Fig. 9—Standard Test Jig for measuring disc-ceramic capacitors at radio frequencies. Capacitor leads are completely enclosed by jig terminals.

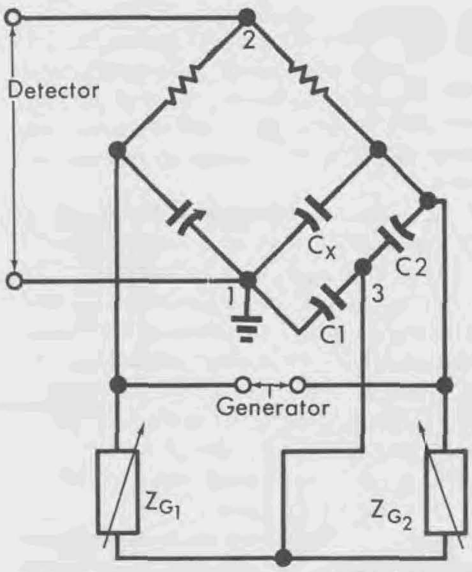


Fig.10—Bridge network and guard circuit with 3-terminal unknown capacitance connected.

Either the guarded bridge or the transformer bridge is a satisfactory solution to the lead-capacitance problem.

Substitution Methods—Substitution methods of measurement can be used to advantage with all a-c bridges. In this method, the unknown is measured in terms of the difference between two settings of a calibrated resistance or reactance. For instance, as shown in Fig. 11, an unknown capacitance is connected in parallel with an adjustable calibrated capacitor in the previously balanced bridge; the calibrated element is then readjusted until the bridge is again in balance.

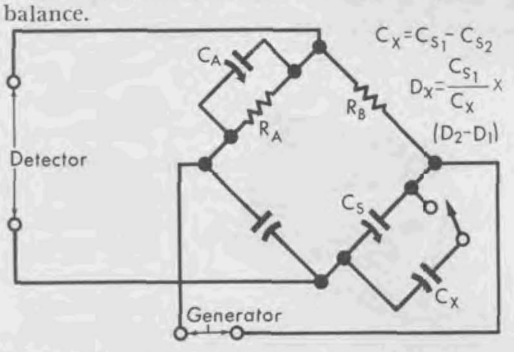


Fig. 11—Measurement by parallel substitution.

Increased accuracy results from the fact that the measurement is solely in terms of the difference between two settings of a calibrated precision capacitor, the bridge circuit functioning only as an indicator of identical conditions. The bridge circuit does, however, enter into determination of dissipation factor, which is balanced by capacitor C_A.

The series substitution method of Fig. 12 is used to make resistance and reactance dials direct reading in ohms and is particularly useful for radio-frequency measurements.

2. This statement refers to the 4-arm bridge with two complex arms. If three or more arms are complex, the degree of dependency is expressed in a somewhat more complicated fashion.

Sliding Balance—In any alternating-current bridge, there are two conditions that must be satisfied simultaneously to obtain a true null balance. For maximum convenience, it is desirable that the two adjustments be independent so that varying one element does not affect the balance of the other. Otherwise, the condition commonly known as a "sliding zero" occurs. It is characterized by the fact that balance must be approached by comparing a number of successive adjustments for minimum. The degree of dependency of the two components of balance (i.e., the amount of "sliding") depends only on the storage factor Q of the unknown impedance.[2] The higher the Q of the unknown impedance, the less pronounced is the sliding effect.

It can be shown that truly independent balances are obtained only when the two adjustments for balance are made in the same arm, or when one adjustment is made in each com-

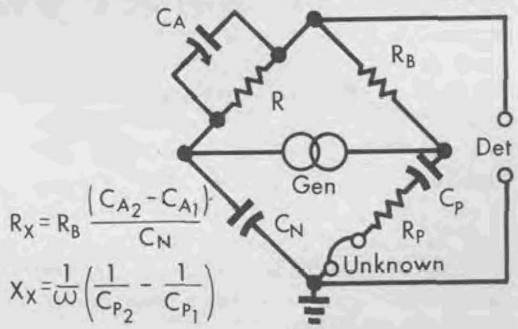


Fig. 12—Series substitution method.

plex arm. An example of the first method is the Owen bridge, while the series substitution bridge devised by Sinclair[3] illustrates the second.

Range Extension—The element to be measured may often be beyond the range of the available bridge. A successful procedure is to modify the unknown, rather than the bridge, by connection of a known capacitor in series or in parallel with it. The measurement is then made first, with the unknown connected and then with the unknown disconnected. A simple computation will then give the value of the unknown impedance.

A bridge designed primarily for one type of measurement can often be easily adapted for another type. The bridge of Fig. 5d is correctly called a capacitance bridge, but one can measure a large inductance on it by connecting the inductor in series with a known capacitor and calculating the inductance from the change in effective capacitance.

Similarly, a high resistance can be measured by connecting it in parallel with a known capacitor and observing the change in dissipation factor.

SELECTING A BRIDGE

Among all the bridge circuits and bridges available, how does one choose the bridge best suited to his needs? Obviously, there is not always a complete free-

3. D. B. Sinclair, "A Radio-Frequency Bridge for Impedance Measurements from 400 Kilocycles to 60 Megacycles", Proc. IRE, *Nov. 1940, pp. 497-503.*

dom of choice; a bridge already available in the laboratory must often be used, but even here, it is helpful to consider the characteristics of available bridges in light of the known characteristics of the thing to be measured.

1. Capacitance Bridge—The series and parallel-resistance bridges are ordinarily used at power, audio and ultrasonic frequencies, although they can be made to operate satisfactorily up through the standard

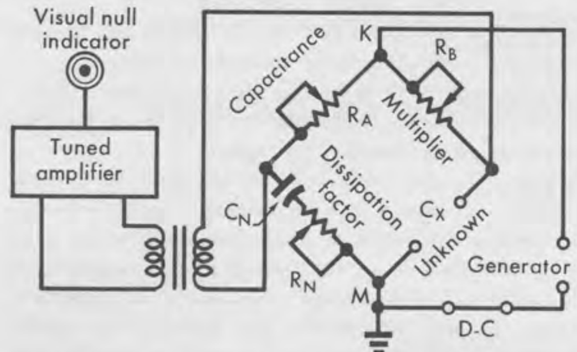


Fig. 13—Series-Resistance Capacitance Bridge.

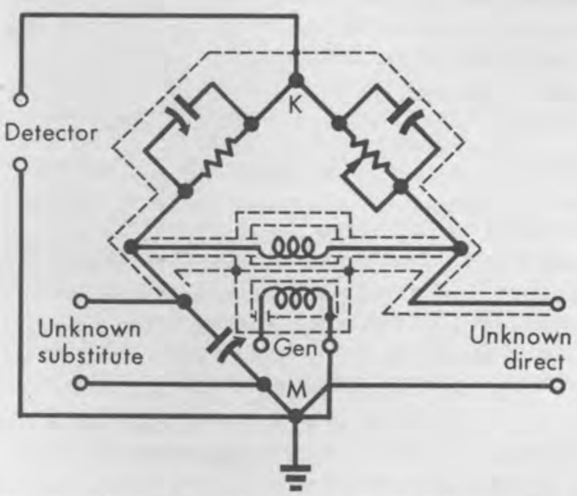


Fig. 14—Schering Precision Bridge. Dashed lines indicate shields.

broadcast band if residual impedances are kept low. Most multi-purpose impedance bridges, where accuracies of the order of 1 percent are adequate, use these circuits, usually with arm R_A adjustable in order to balance the magnitude of C_X, Fig. 5b.

The series-resistance circuit is used in capacitance test bridges, like that of Fig. 13. It operates at 60 and 120 cycles, has a nominal accuracy of 1 percent and is used widely to measure electrolytic and paper capacitors to EIA specifications. Since there is no d-c path through the N and X arms, a polarizing voltage can be applied to the unknown capacitor. A disadvantage of this circuit is its sliding balance, which is most evident when losses in unknown capacitor are high.

2. The Schering Bridge—The Schering circuit shown in Fig. 14 has many advantages. Both the capacitance and loss balances are made with variable capacitors, which are more stable and have lower residual impedances than any other type of variable element. This bridge is used for precise standardization measurements, for dielectric measurements where accurate loss determination is important and for high-voltage measurements of capacitance. For high-voltage use, the generator is usually connected across points K and M, so that most of the applied voltage appears across the standard and unknown capacitors, whose impedances are usually much higher than those of the resistive arms.

3. Transformer Bridge—The basic circuit of Fig. 6, because of its freedom from the effects of ground capacitance, is inherently well suited to the measurement of direct, or 3-terminal capacitance. One commercial form of this bridge, shown in Fig. 15, was designed primarily for standardizing aircraft fuel-gage calibrators. The unique feature of this bridge is the T-network used in the standard side to obtain a direct indication of dissipation factor. The direct impedance

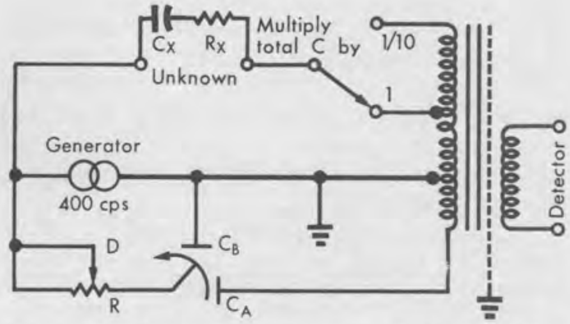


Fig. 15—Transformer-Type Capacitance bridge for 400 cycle operation.

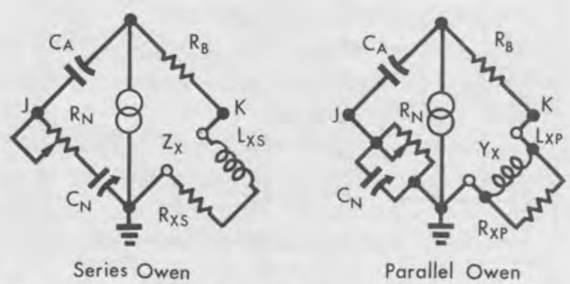


Fig. 16—Owen Bridges for precise measurement of inductance at audio frequencies.

of this network balances out the direct impedance of the unknown. The balance equations are $C_X = C_A(M)$, $D_X = \omega R(C_A + C_B)$

By means of a differential-type capacitor, the sum $(C_A + C_B)$ is kept constant, so that R is proportional to D_X and the resistor dial can be calibrated directly in dissipation factor at the measurement frequency of 400 cycles. This bridge has a range from 5 MMF to 0.011 MF, with an accuracy of 0.1 percent.

4. Inductance Bridge—While the inductance counterparts of the series- and parallel-resistance capacitance bridges are sometimes used, the Hay, Owen and Maxwell bridges are usually preferred. Of these, the Owen bridge (Fig. 16) is one of the most satisfactory.

The unknown inductance is measured in terms of a fixed standard capacitor C_A and the bridge is balanced by means of decade resistor R_N and decade capacitor C_N. R_B is switched in decade values to cover the total range of 0.0001 microhenry to 1111 henries.

$$L_X = C_A R_B R_N \qquad G_X = \frac{1}{C_A R_B} C_N$$

High resolution for the inductance balance is one of this bridge's desirable characteristics; inductance standards can be compared to a high degree of precision. This is accomplished by use of a 6-dial decade resistor for R_N. The two balance controls are independent and d-c bias can be applied to the unknown.

5. The Radio-Frequency Bridge—At low radio frequencies, up to a few hundred megacycles, lumped-element bridges can still be used. One type, widely used for the measurement of antennas, is the series substitution bridge of Sinclair, shown in Fig. 17. At radio frequencies, the variable air capacitor is the most reliable and stable circuit element available and its residual impedances can be kept very low.

Bridge residuals are rendered innocuous in this circuit by thorough shielding and use of a substitution method. R_X and X_X are determined by the change in settings of capacitors C_A and C_P.

$$R_X = \left(\frac{R_B}{C_N}\right)(C_{A_2} - C_{A_1}) \qquad X_X = \frac{1}{\omega}\left(\frac{1}{C_{P_2}} - \frac{1}{C_{P_1}}\right)$$

where the subscripts 1 and 2 denote initial and final balances respectively.

The dials of both capacitors C_A and C_P can be made direct reading in ohms. The reactance dial is calibrated at a convenient reference frequency. At

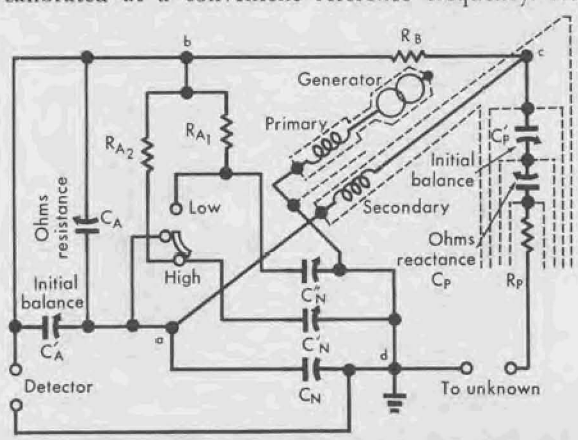


Fig. 17—Radio-Frequency Bridge using series substitution method of measurement.

other frequencies its indication is multiplied by the ratio of reference to operating frequency. The unknown reactance can be either positive or negative, i.e., either a capacitor or an inductor. This bridge is the standard device for antenna measurements in the range from 400 kc to 60 mc.

LIMIT BRIDGES AND COMPARATORS

For acceptance tests and production-line testing, the limit bridge provides a go-no-go indication. Visual indication is widely used, but automatic accept-reject mechanisms can be made to operate from the bridge unbalance voltage. Almost any bridge with a visual-type null indicator can be calibrated for limit testing. To do this, the bridge is first balanced with a sample that is exactly on the desired value. The bridge is then unbalanced by the desired maximum tolerance, and either the detector sensitivity or the generator voltage is adjusted to give a satisfactory deflection of the detector. This can be marked with a mask or even a pencil line.

THE Z-Y BRIDGE

The Z-Y bridge[4] was designed to provide a truly universal audio-frequency instrument, and, in particular, to relieve the engineer of the frustration he experiences when he finds that the impedance he wants to measure is outside the range of the available bridge. The Z-Y bridge can be balanced for any impedance connected to its terminals from short circuit to open circuit, real or imaginary, positive or negative. Impedances up to 1000 ohms are measured as impedances, i.e., in ohms resistance and ohms reactance. Higher impedances are measured as admittances, with the answer in micromhos conductance and susceptance.

The basic circuit is the familiar RC bridge but a substitution method is used in which the difference in two settings of the controls measures the complex components of the unknown. Separate balance controls are provided for the initial balance so that the main dials read directly, without substitution.

In the simplified circuit shown in Fig. 18, the series rheostats provide the R balance for impedance and the B balance for admittance, while the parallel rheostats provide the G balance for admittance and the X balance for impedance. R and G readings are independent of frequency, while X and B readings are direct at any of three reference frequencies—100 cps, 1 kc and 10 kc as selected by a switch that changes certain bridge components.

4. *I. G. Easton and H. W. Lamson, "The Type 1603-A Z-Y Bridge", GENERAL RADIO EXPERIMENTER, Vol. 30, No. 2, July 1955.*

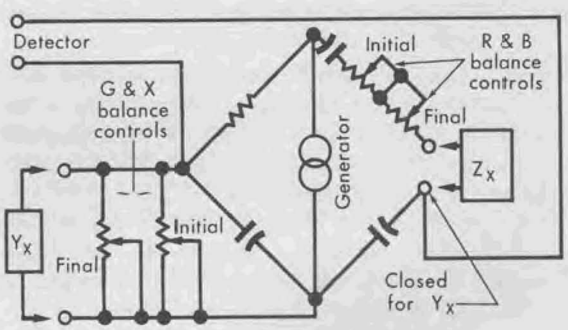


Fig. 18—Simple schematic of Z-Y bridge.

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