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Capacitor Impedance and Resistance Measurements

PART II

By the Engineering Department, Aerovox Corporation

AT AUDIO AND RADIO FREQUENCIES

THE impedance of electronic circuit components may readily be measured at power-line, audio, and radio frequencies. A variety of instruments and methods makes this possible. For any impedance measurement, there will generally be available in each laboratory or shop a sufficient number of instruments to allow choice of method. This article will describe the most important instruments and methods from a practical point of view.

VOLTMETER-AMMETER METHOD

The simplest method of measuring impedance is an application of Ohm's Law for ac. A known voltage is applied across the unknown impedance, which may be either capacitive, inductive, or a combination of the two, and the resultant current through the impedance measured. The impedance value may then be calculated from Ohm's Law: $Z = E/I$, where Z is expressed in ohms, E in volts, and I in amperes. Apparatus required includes a source of alternating voltage of desired frequency, ac voltmeter, and ac ammeter (see Figure 1).

Impedances may be measured by this method over a wide range of frequencies. However, it is not advisable to employ test frequencies higher than about 50 kc., since at radio frequencies appreciable error is introduced by stray capacitances and skin resistance effects. Between 10 and 50 kc., greatest accuracy will be obtained with a vacuum-tube voltmeter and high-frequency type thermocouple ammeter.

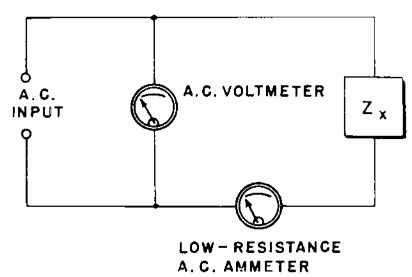

Figure 1

If the test-signal source is arranged to supply a continuously variable voltage to the test circuit, a wide range of impedance values may be covered. This is true because the input voltage may then be adjusted to pass a readable amount of current through any impedance. The test voltage may be obtained from the power line, a transformer secondary, or an oscillator. Test voltage may be adjusted by means of a potentiometer, attenuator, or variable auto-transformer (Variac).

The method of Figure 1 may be applied to yield direct indications of impedance in the following manner: It the signal voltage is always set to give the same ammeter reading (e.g., center scale), the voltmeter scale may be graduated directly in *ohms impedance*. In operation, the unknown impedance is connected into the circuit and the voltage raised from zero to the level required to deflect the ammeter to a reference point. The impedance is then indicated directly by the specially calibrated voltmeter dial.

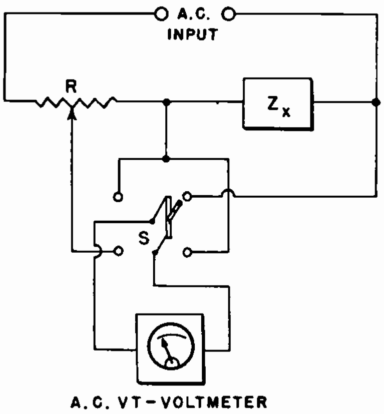

Figure 2

BRIDGE METHOD

Impedance of an inductor or capacitor may be calculated from reactive and resistive data obtained by bridge measurements. Reactance (X_C or X_L) is calculated from the inductance or capacitance indicated at balance, and resistance (as equivalent series resistance) from the power factor or dissipation factor indication:

(1)
$$Z = \sqrt{R^2 + X^2}$$
$$X_C = \frac{1}{\omega C}$$
$$X_L = \omega L$$

Any capacitance or inductance bridge set up for separate resistive and reactive balances will yield the figures needed for impedance determination by this method. Values of ω for common bridge frequencies are: 377 for 60 c.p.s., 754 for 120 c.p.s., 2513 for 400 c.p.s., 3141.6 for 500 c.p.s., and 6283 for 1000 c.p.s.

IMPEDANCE FROM R AND L

If the inductance (L) of a coil is known very closely and its dc resistance (R) is measured with a good dc bridge or ohmmeter, the approximate impedance it will offer at a frequency not higher than 10 kc. may be calculated from the L and R values so obtained:

(2)
$$Z = \sqrt{R^2 + (\omega L)^2}$$

At low frequencies, the resistive component will not differ greatly from the dc value measured with a dc bridge or ohmmeter. At frequencies beyond 10 kilocycles, however, skin effect will increase directly with frequency and the effective resistance will not be the same as the measured dc value. This method of impedance determination is accordingly not recommended for high frequencies.

The impedance of capacitors cannot be determined by this method, since the equivalent resistance of these units is not so easily measured as that of coils.

SERIES R-Z CIRCUIT

Both inductor and capacitor impedance may be measured at audio and power-line frequencies by means of the circuit shown in Figure 2. This is a well-known arrangement which is in use in numerous laboratories.

The unknown impedance, Z_X, is connected in series with a calibrated variable resistor, R, and a signal voltage of desired frequency forces a current through this combination. The current produces voltage drops (IR and IZ) across R and Z_X which may be read by switching the v.t. voltmeter first across the resistor and then the impedance by means of switch S. In order to obtain this action, the signal voltage must be high enough to force a current through the R-Z arm of the circuit.

If R is adjusted while the voltage drops are being read successively, a point will be found at which the voltage IR and the voltage IZ are identical. The meter deflection consequently will not change value as S is thrown from one position to the other. At this point, the unknown impedance (Z_X) is equal to the setting of R and may be read directly in ohms if the variable resistor is provided with a direct-reading dial.

This method allows rapid impedance measurements to be made, since the voltmeter reading will be the same for all impedance values within range of the variable resistor. The circuit is not practical at radio frequencies, however, since considerable error may be introduced by inductance in the resistor, skin effect, stray capacitances, and stray coupling. Its use is restricted to those audio frequencies commonly employed as bridge signals.

RADIO-FREQUENCY METHODS

Q-Meter. Reactive and equivalent resistive values may be obtained at radio frequencies by means of a standard Q-Meter, such as the Boonton 160-A instrument, and these values substituted in Equation (1) to determine r.f. impedance, when making capacitor

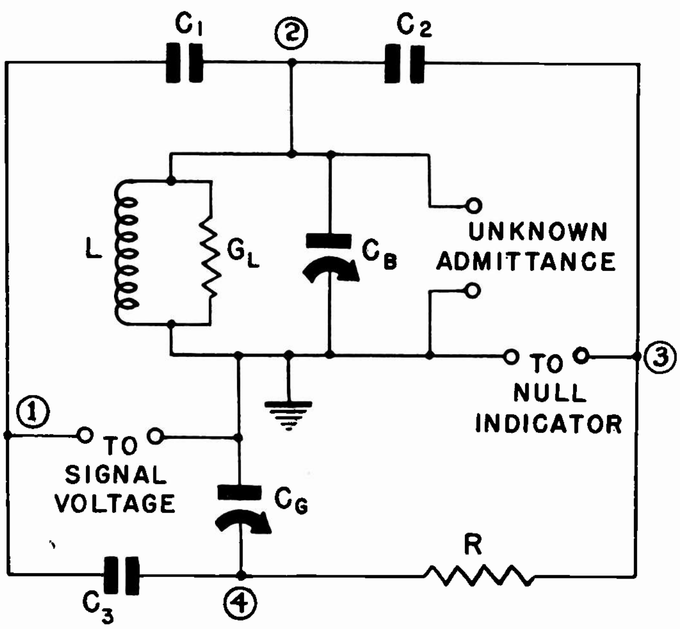

Figure 3

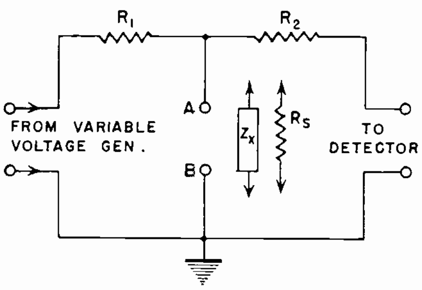

Figure 4

measurements, capacitances lower than 500 mmfd. being connected in parallel with the Q-Meter test circuit; capacitances higher than 500 mmfd. being connected in series with the test circuit. The preliminary Q-Meter readings are designated C_1 (capacitor dial) and Q_1 (Q-voltmeter scale). Subsequent readings with the sample capacitance connected into the circuit are designated C_2 and Q_2.

With the parallel-connected sample capacitor:

$$(3)\quad R_X = \frac{1.59 \times 10^8 C_1(Q_1-Q_2)}{f(C_2-C_1)^2 Q_1 Q_2} \text{ ohms}$$

and

$$(4)\quad X_X = \frac{1.59 \times 10^8}{f(C_2-C_1)} \text{ ohms}$$

With the series-connected sample capacitor:

$$(5)\quad R_X = \frac{1.59 \times 10^8 \left(\frac{C_1}{C_2}Q_1-Q_2\right)}{f C_1 Q_1 Q_2} \text{ ohms}$$

and

$$(6)\quad X_X = \frac{1.59 \times 10^8 (C_1-C_2)}{f C_1 C_2} \text{ ohms}$$

In (3), (4), (5) and (6) C is in mmfds. and f in kilocycles.

The values obtained by means of Equations (3) and (4) or (5) and (6) are substituted in Equation (1) to determine impedance.

When coils are checked on the Q-Meter:

$$(7)\quad R_X = \frac{1.59 \times 10^8}{f C_1 Q_1}\left(\frac{C_1}{C_1+\frac{C_2-4C_1}{3}}\right)^2 \text{ ohms}$$

$$(8)\quad X_X = \frac{15.9 \times 10^4 f C_1 (C_1-C_2)}{f^2 C_1 C_2 \left(C_1+\frac{C_2-4C_1}{3}\right)} \text{ ohms}$$

Equations (7) and (8) take into consideration the distributed capacitance of the coil, which is equal to $(C_2 - 4C_1)/3$. The values obtained by means of Equations (7) and (8) may be substituted in Equation (1) to determine the coil impedance at the test frequency.

Twin-T Impedance-Measuring Circuit. Resistive and reactive components for calculating inductor and capacitor impedance may be obtained at frequencies between 460 kc. and 30 Mc. by means of the Twin-T Impedance-Measuring Circuit manufactured by General Radio Co.

With this instrument, the parallel admittance components susceptance (B) and conductance (G), are obtained by means of a parallel-substitution method. For impedance calculation, these parallel components may be converted to series components, resistance (R) and reactance (X), as follows:

$$(9)\quad R_X = \frac{G}{B^2+G^2}$$

$$(10)\quad X_X = \frac{-B}{B^2+G^2}$$

B, G, R, and X are expressed in ohms.

Basic circuit of the Twin-T instrument is shown in Figure 3. The circuit embraces two T-networks (1-2-3 and 1-4-3), the transfer impedances are equal and opposite at null.

$$G_L - \omega R C_1 C_2\left(1+\frac{C_G}{C_3}\right) = 0$$

$$C_B + C_1 C_2\left[\left(\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}\right) - \frac{1}{\omega^2 L}\right] = 0$$

In operation, the circuit is first set to null by adjustment of variable capacitors C_B and C_G. The initial null settings of these two components are designated C_{B_1} and C_{G_1}. The unknown admittance is then connected to the terminals across C_B, and the two capacitors again adjusted for null. The final settings are designated C_{B_2} and C_{G_2}.

The unknown conductance and susceptance may then be calculated from the network values:

$$(11)\quad G_X = \frac{\omega^2 R C_1 C_2}{C_3}(C_{G_2} - C_{G_1}) \text{ ohms}$$

and

$$(12)\quad B_X = \omega(C_{B_1} - C_{B_2}) \text{ ohms}$$

A signal generator or spot-frequency r.f. oscillator supplies the T-network signal voltage and a radio receiver serves as the null detector.

Simple T-Network for Substitution Measurements. Figure 4 shows a well-known arrangement for impedance measurements by the substitution method. The circuit is a simple T-network.

The unknown impedance (Z_X) or a comparison resistor (R_S) may be connected between terminals A and B. The isolating resistors R_1 and R_2 are usually of the order of 1000 ohms each. The variable input voltage may conveniently be supplied by a signal generator with calibrated attenuator, and the detector may be a radio receiver with output voltage indicator.

In operation, R_S is connected to terminals A and B. The input voltage is then adjusted to give an arbitrary detector response. This voltage level is designated E_1. The unknown impedance (Z_X) is then connected between terminals A and B in place of R_S, and the input voltage readjusted to give the same detector response as before. This new voltage level is designated E_2. From the value of R_S and the ratio of the two test voltages the value of Z_X may be calculated directly in ohms, thus:

$$(13)\quad Z_X = \frac{E_1 R_S}{E_2} \text{ ohms}$$

This substitution method may be employed in the same manner at audio and power-line frequencies, provided the generator is an audio-frequency oscillator with calibrated attenuator (or v.t. voltmeter) and the detector is an audio amplifier with output-voltage indicator.

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