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# Capacitor Impedance and Resistance Measurements

## PART I

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### AT RADIO FREQUENCIES

THE capacitor is a simple two-terminal impedance. Its equivalent single-mesh network includes series resistive, reactive, capacitive, and inductive components. Capacitance and capacitive reactance are the parameters of primary concern in capacitor applications. Resistance and inductance are inherent in the mechanical structure and act respectively to limit Q and establish a resonant frequency.

In most electronic applications, the capacitor is employed for by-passing and coupling. Its capacitance accordingly is chosen for low reactance at a given operating frequency. In a typical by-passing application, for example, a 0.1-mfd. capacitor shunts the 300-ohm cathode resistor of a tube operated at 1000 kc. The reactive path, in this instance, is approximately 1.7 ohms against the 300-ohm resistive path. In fewer electronic applications, the capacitor becomes a part of a tuned circuit, and in such applications effective series resistance (which acts to broaden the selectivity curve) and capacitor resonant frequency must be taken into account.

Capacitor Q is directly proportional to the effective series reactance and inversely proportional to the effective series resistance ($Q = X_S/R_S$), and is now widely employed in determining quality of capacitors intended for radio-frequency applications. In several respects, as will be explained later, however, it appears that a measurement of capacitor impedance would determine more directly the efficacy of the capacitor at a given operating frequency. Methods of making capacitor impedance measurements at audio and radio frequencies will be outlined.

Resonant frequency of a capacitor, with respect to the normal operating frequency, will govern the efficacy of the capacitor for blocking and by-passing. A capacitor exhibits capacitive reactance at all frequencies lower than its resonant frequency, and inductive reactance at frequencies higher than resonance. At resonance the two reactances cancel, leaving the equivalent series resistance as the only impeding agent. At this point, the capacitor will be most effective for blocking and by-passing since it now offers the lowest practicable impedance.

Ordinarily, it will be of no consequence whether the reactance of a coupling or by-passing capacitor is inductive or capacitive at a given operating frequency as long as the reactive path it supplies is considerably lower in value than the circuit element it shunts (by-passing), or as long as the lowest possible impedance is offered at the operating frequency (coupling). However, inductive reactance varies directly with frequency and at some operating frequency higher than the resonant point, becomes prohibitive for by-passing or coupling. The phase shift introduced is important in many cases.

### NATURE OF CAPACITOR IMPEDANCE

A certain amount of inductance is inherent in the capacitor structure and is due to leads, contact members, and the capacitor plates themselves. The inductive reactance introduced into the capacitor network combines with the capacitive reactance and series resistance to determine the impedance of the system.

Assuming series resistive and reactive components, the network schematic and vector diagrams of Figure 1 apply. In a circuit of this type, inductive reactance is lower than capacitive reactance below resonance, and is higher above resonance. The total reactance (jX) in this circuit is:

$$(1) \qquad jX = j(X_L - X_C)$$

The impedance (the vector sum of R and X, regardless of character) is then:

$$(2) \qquad Z = R + jX = R + j(X_L - X_C)$$

The vector diagrams, (Figures 1-B and 1-C), assume the theoretical condition in which reactive voltage is 90 degrees ahead or behind resistive voltage. Thus, the resistive voltage drop (IR) will be in phase with I (Figure 1-B), and IX (the voltage drop across the capacitive reactance) is 90 degrees behind I; while in the other case (Figure 1-C) IR is again in phase with I, while IX (the voltage drop across the inductive reactance) is 90 degrees ahead of I.

Figure 1-B will apply strictly to the condition below resonance, i.e., when capacitive reactance is predominant; Figure 1-C above resonance, i.e., when inductive reactance predominates.

Current flowing through the network at any frequency will be, in terms of the voltage E impressed across the network:

$$I = \frac{E}{\sqrt{R^2+\left(2\pi fL-\frac{1}{2\pi fC}\right)^2}} \qquad (3)$$

It is this current which flows through the by-pass or coupling path provided by the capacitor. It is easily seen that at the resonant frequency, $X_L = X_C$, but the two reactive components are opposite in sign, and R accordingly remains as the sole current-limiting factor.

The resonant point of a capacitor may be determined by checking the capacitor impedance at a number of frequencies in succession, these test frequencies being spaced as closely as practicable. The lowest impedance indication will then be obtained at the resonant frequency of the capacitor.

## NATURE OF EQUIVALENT SERIES RESISTANCE

Capacitor resistance may be regarded as equal to any inphase voltage component divided by the current. When high-frequency voltages are impressed across the capacitor impedance mesh, the resulting resistance values will be somewhat larger than the dc or ohmic value, because of skin effect. It is then to be expected that the R factor will increase in magnitude as the operating frequency rises.

The effective resistance depends upon several factors, such as lead length, lead surface area, lead conductivity, clamp and fixture surface area and conductivity, area and conductivity of the capacitor plates, joint resistance, contact resistance, proximity of the capacitor case material, and operating frequency. It is extremely difficult, if not impracticable, to predict r.f. resistance from a given set of dimensions and characteristics.

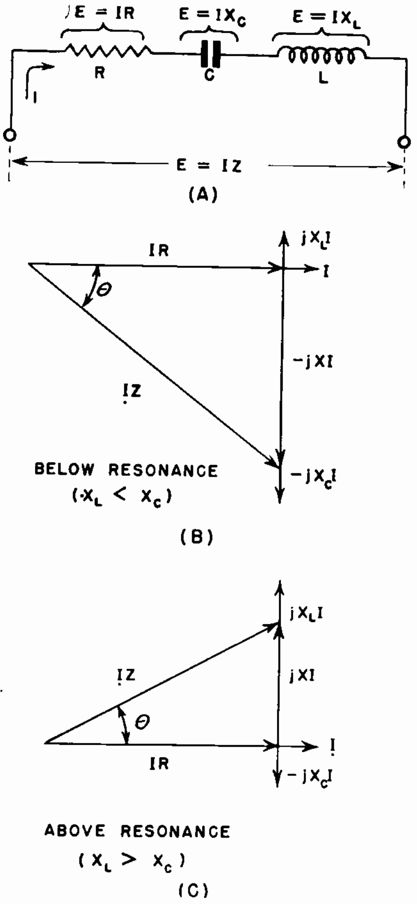

Figure 1

From fundamental relationships, effective resistance is proportional to Q and reactance and may be calculated from these measured quantities:

$$R = \frac{1}{X_C Q} \qquad (4)$$

For standard capacitances, a table may be set up showing equivalent series resistance values corresponding to various Q values at specified measurement frequencies.

## METHODS OF MEASURING CAPACITOR IMPEDANCE

For measuring the radio-frequency impedance of capacitors by the substitution method, the arrangement shown in Figure 2 is recommended. The measurement circuit is a simple T-network which has the advantages that it is easily manipulated and affords a common ground between generator, measurement circuit, and detector. The arrangement consists of a stable r.f. oscillator, such as a signal generator; a voltmeter and attenuator for determining the output voltage of the oscillator; a measurement circuit, consisting of the non-inductive isolating resistors ($R_1$ and $R_2$) and terminal posts (A and B); an r.f. detector, such as a sensitive radio receiver; and an output voltmeter actuated by the detector.

If the signal is modulated, the detector indicating device will be a regular ac output voltmeter operated by the last audio stage of the receiver. If the signal is unmodulated, this indicator will have to be operated by the average rectified signal carrier voltage, and will take the form of a direct current instrument operated by one or more of the tubes between (or including) the antenna stage and second detector. Communications type superheterodyne receivers are usually provided with such a carrier intensity indicator (S-meter).

Since the oscillator output voltage will be of the order of microvolts or millivolts, it is not likely that a standard v.t. voltmeter will be applicable as the r.f. voltmeter. It is preferable, therefore, that the r.f. oscillator be provided with an accurately calibrated attenuator which will indicate r.f. output voltage in lieu of the r.f. voltmeter shown in Figure 2.

The isolating resistors, $R_1$ and $R_2$, are non-inductive. Small carbon resistors, of 1-watt size, are entirely satisfactory, since these components do not enter into the impedance calculation and accordingly need not be critically matched nor of close tolerance. These resistors may be 1000 ohms each.

The terminals A and B receive the capacitor under test (C in Figure 2) or the low-value (10 ohm) non-inductive "setting-up resistor", $R_3$. The latter must be a non-inductive unit of the best accuracy.

In use, the circuit is first set up by inserting $R_3$ into terminals A and B and adjusting the r.f. oscillator output voltage for a given deflection of the receiver output meter. The r.f. voltage at this point may be called $E_1$. $R_3$ is then replaced by connecting the capacitor whose impedance is to be measured to terminals A and B. The oscillator output voltage is then re-adjusted to give the same deflection of the receiver output meter as before. This second value of r.f. voltage may then be termed $E_2$. Both $E_1$ and $E_2$ may then be taken directly from the calibrated attenuator of the oscillator.

From the data obtained, the capacitor impedance may be calculated according to the following equation:

$$Z_C = \frac{E_1 R_3}{E_2} \qquad (5)$$

The same arrangement of apparatus as shown in Figure 2 may be employed at lower frequencies, such as those in the audio and power range. The r.f. oscillator will be replaced by an a.f. instrument with a voltage-calibrated attenuator or accurate output voltmeter, a multi-stage audio amplifier will take the place of the radio receiver, and the final output voltmeter will be operated directly by the last amplifier stage.

The Figure 2 system has the decided advantage that, at radio or audio frequencies, the capacitor impedance may be compared directly with the impedance of a short length of heavy wire at a given operating frequency. Obviously, the best obtainable by-pass or coupling path would be provided by a short length of heavy wire. If the impedance of such a wire is measured at a given operating frequency according to equation 5, a ratio may then be set up between this "best" impedance and any capacitor impedance value to express the efficacy of the capacitor.

For best results, both oscillator and detector (Figure 2) must be adequately shielded. Shortest and heaviest possible leads must be employed throughout, and it is desirable that the measuring circuit, comprising the T-network, be independently shielded.

A circuit widely used for capacitor impedance measurements at audio frequencies is given in Figure 3. In this arrangement an a.f. voltage, delivered by an oscillator or the power line, is applied to the capacitor under test and a calibrated variable resistor (R) connected in series. Separate voltage drops accordingly develop across the capacitor and resistor. These voltages are read on the scale of the high-impedance v.t. voltmeter: across the resistor when switch S is in the *left-hand* position, and across the capacitor when S is in the *right-hand* position.

The capacitor voltage drop will be equal to the alternating current flowing through the series R-C circuit multiplied by the capacitor impedance ($E=IZ$). It follows that when the capacitor impedance is equal to the resistance of R, the same voltage will be developed across R and C and the meter will not change reading as switch S is thrown from one position to the other. At that point, the resistance of R will also indicate the impedance of C.

Operation of the circuit is exceedingly straightforward. Switch S is thrown from right to left, while the v.t. voltmeter deflection is observed, and resistor R is adjusted until a point is reached at which the meter indication does not change as the switch is thrown. The resistance setting of R may then be determined either by reading a calibrated OHMS dial attached to R, or by measuring the ohmic value at the critical setting by means of an accurate resistance bridge or ohmmeter.

For a given input voltage to the circuit, the voltmeter deflection will always be the same regardless of the magnitude of the impedance detected.

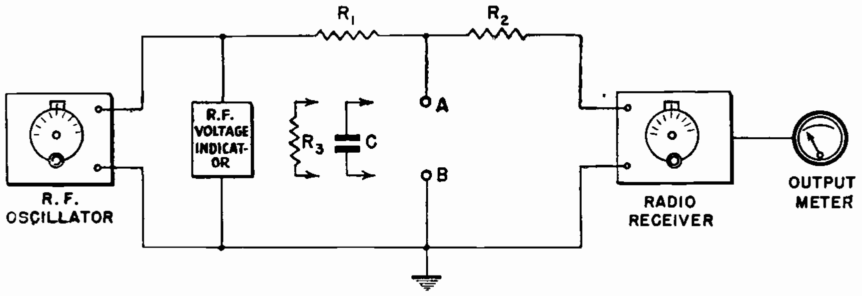

Figure 2

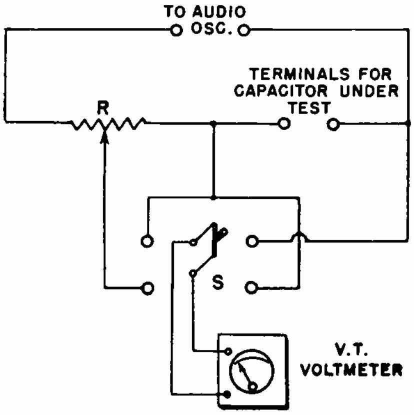

Figure 3

This further simplifies manipulation of the setup.

## SUGGESTED METHOD FOR MEASURING EQUIVALENT SERIES RESISTANCE

When employing the test equipment of Figure 2, test capacitor C might be connected to terminals A and B in series with an inductor of known r.f. resistance. The measurements might then be made at the resonant frequency of this resulting series resonant circuit.

Since all inductive and capacitive reactances cancel at resonance, any impedance value obtained would actually be an indication of the *total* equivalent resistance. The equivalent series resistance of the coil being known beforehand, it appears that that of the capacitor might be ascertained by subtracting the coil resistance from the apparent impedance value obtained in the measurement.

Present available means for determining the equivalent series resistance of coils are much more accurate and reliable than those for determining the same capacitor parameter. It seems reasonable, therefore, that the coil resistance might readily be determined beforehand. For example, the coil Q might be measured at the impedance test (resonant) frequency, by means of a standard Q-Meter, and equation 4 employed to determine R.

It is believed that all capacitor impedance measurements might thus be converted into measurements of equivalent series resistance. The measurements might be made at *any* frequency by selecting an inductor capable of resonating the test capacitance at that frequency.

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