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Capacitor Quality Factors

By the Engineering Department, Aerovox Corporation

IF pure capacitance existed in natural isolation, only that important fundamental property would need be considered, together with maximum operating voltage, in selecting capacitors for any use. But since resistance and reactance are inherent in all practical capacitors, the amount and distribution of these components will, with capacitance, govern one or more factors whereby capacitor quality may be appraised with respect to specific applications. These factors will determine how good a capacitor will be in a certain circuit position and will explain certain peculiarities of capacitor operation.

Capacitor "quality factors" include leakage, dielectric strength, dielectric absorption, power factor, dissipation factor, Q and impedance, the latter three serving to show relationship between resistive and reactive components. Each of these may be determined quantitatively. Dielectric absorption, dielectric strength, and leakage are properties of the capacitor dielectric material. Power factor, dissipation factor, impedance, and Q take into consideration the magnitude of both resistive and reactive components, and appraise the total capacitor losses at a given operating frequency. The latter four factors are thus governed by the physical and chemical properties of the materials from which the capacitor is manufactured and the electrical and mechanical features of construction as well.

In order that capacitor quality factors may be more clearly understood,

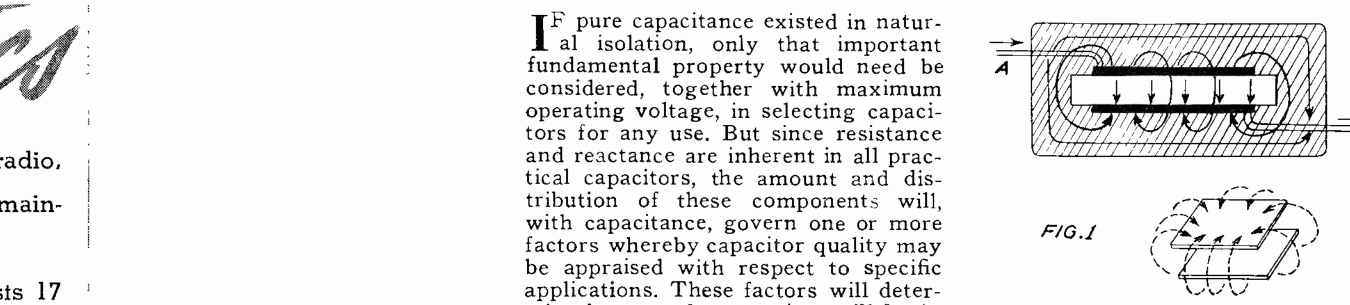


FIG. 1

it is intended in this article to describe the nature of each and to explain its importance in capacitor applications engineering.

LEAKAGE

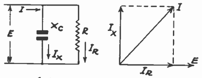
The strength of a direct current (not the charging current) which will flow steadily through a capacitor depends entirely upon the nature of the dielectric separating the capacitor plates and to some extent also upon that surrounding the plates. This assumes, of course, that uniform processing has been maintained. The ideal dielectric would offer infinite resistance and permit zero current flow, but this perfect condition does not obtain in nature. The best dielectric materials exhibit resistivity which, although extraordinarily high, influence capacitor quality.

Leakage currents through a capacitor take numerous paths. Figure 1 shows a two-plate capacitor molded in an insulating material, with several of the infinite current branches indicated by arrows. Current is conceived as entering the capacitor by way of lead A and leaving by way of lead B.

The main leakage current flows in an infinite number of paths through the dielectric between the plates. These paths are indicated by the vertical arrows. In addition to this current branch, there is an infinite number of paths through the molded case, these being indicated by the solid-line curved arrows. The longest paths are between the leads and are indicated by the long curved arrows. Shorter paths through the molded case extend from plate to plate, and are represented by the short curved arrows. The small dotted-line curved arrows indicate leakage paths along the surfaces and around the edges of the active dielectric.

All of these paths combine to yield the total leakage current. The path through the dielectric between plates is the most significant, since it is by comparison the shortest. The molding material is of high resistivity, and the current paths through it are several thousand times longer than those between plates. Nevertheless, these paths will be of lower resistance than those through the dielectric and thus will contribute most to leakage. In capacitors of other types, the long paths extend through oil, wax, or electrolytic filling compounds.

The main leakage path between plates will have characteristics governed by type and thickness of the dielectric material. At a given direct voltage applied across the capacitor, for example, leakage will be greater for paper than for mica, and will be lower for thick mica than for thin material of the same lot.



(A) FIG. 2 (B)

Except in the case of electrolytic capacitors, the dielectric characteristic is stated as insulation resistance rather than as leakage current. A.S.A. Specifications indicate, for example, that mica and ceramic capacitors shall show an insulation resistance greater than 7500 megohms at 100 volts dc, and that paper capacitors shall show a megohms-times-microfarads value of 500 to 6000 (depending upon type) at an applied voltage between 100 and 500 dc and test temperature of plus 25°C.

In current units, we give the following maximum leakage values for electrolytic capacitors tested at rated direct working voltages:

D.C. Voltage Rating	Maximum Leakage
400 v. or over	0.3 ma. plus 0.05 ma. per mfd.
300 v. to 399 v.	0.3 ma. plus 0.04 ma. per mfd.
200 v. to 299 v.	0.3 ma. plus 0.03 ma. per mfd.
100 v. to 199 v.	0.3 ma. plus 0.02 ma. per mfd.
0 v. to 99 v.	0.3 ma. plus 0.01 ma. per mfd.

Insulation resistance of a capacitor shows up as a resistance in parallel with the capacitance, as shown in Figure 2A. The corresponding vector diagram is given by Figure 2B. Leakage by ordinary conduction through this parallel resistance (the dielectric) can be of concern only at low frequencies and at dc. At the high frequencies at which capacitors are generally employed, parallel-resistance effects are inconsequential. This may easily be proved by working out the power factor equation (Figure 3C) for low and high frequencies.

Leakage and insulation resistance thus are important considerations when the capacitor is to be employed in direct-current service or in applications in which direct voltages are superimposed upon alternating voltages. And even in the latter case, it is the dc component which is of concern.

Lower insulation resistance may be tolerated in some circuit positions than in others. Coupling and tank capacitors, for example, should have the highest possible resistance, while bypass capacitors may show a much lower megohm - microfarad product without having their bypassing ability impaired.

DIELECTRIC ABSORPTION

The phenomena commonly ascribed to dielectric absorption alone are actually the combined effects of dielectric absorption and residual charges.

Dielectric absorption, also called *dielectric hysteresis* and *dielectric viscosity*, is an important factor because it gives rise to a power loss. Absorption is exhibited to some degree by all solid dielectrics used between capacitor plates, whether amorphous or crystalline, but is not shown by liquid and gaseous dielectrics.

The phenomenon of dielectric absorption is exhibited in the following manner: Charging current from a steady, unidirectional source continues to flow at a gradually decreasing rate into a capacitor of negligible series resistance for some time after the almost-instantaneous charge is completed. A steady value proportional to the capacitor parallel resistance is finally reached. The additional charge apparently is absorbed by the dielectric. Conversely, a capacitor does not discharge instantaneously upon application of a short circuit, but "drains" gradually after the capacitance proper ("geometric" capacitance) has been discharged.

A sudden discharge therefore cannot immediately remove all of the energy from a charged capacitor employing an absorbing dielectric material. When

CHART 1

(Values are for a 100 mmfd. capacitor at 1000 cycles per second)

R (R)	X ($\frac{1}{\omega C}$)	Z (R+jX)	P.F. ($\frac{R}{Z}$)	D ($\frac{R}{X}$)	Q ($\frac{X}{R}$)
0.001	1592	1592	628×10^{-9}	628×10^{-9}	1.592×10^{6}
0.01	1592	1592	628×10^{-8}	628×10^{-8}	1.592×10^{5}
0.1	1592	1592	628×10^{-7}	628×10^{-7}	1.592×10^{4}
1	1592	1592	628×10^{-6}	628×10^{-6}	1592
10	1592	1592.1	0.00628	0.00628	159.2
100	1592	1598	0.06265 *	0.06281 *	15.92
1000	1592	1884	0.530	0.628	1.592
10,000	1592	10,025	0.997	6.28	0.1592

*Note that power factor and dissipation factor values differ only in the fourth decimal place for the low values usually encountered in capacitors.

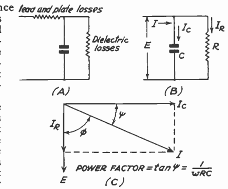


FIG. 3

an alternating or fluctuating voltage is applied to such a capacitor, dielectric absorption prevents all of the energy stored during the charging interval from being removed during the discharge interval. The "residual" energy thus left in the capacitor appears as a power loss.

The effect of dielectric absorption will vary with the frequency of the applied voltage and will cause the dielectric constant to vary somewhat with frequency.

DIELECTRIC STRENGTH

The ability of a capacitor to withstand the alternating or direct potentials, or both, in electric circuits depends upon the kind of dielectric employed and its thickness. This insulation property, termed *dielectric strength,* is stated in terms of the maximum voltage required to puncture, rupture, or otherwise break down the dielectric. The common term is volts per mil (1/1000") thickness.

The volts-per-mil rating varies with materials. A given thickness of one dielectric thus exhibits a value of dielectric strength several times higher than that of another dielectric. In order to make use of certain low-strength dielectrics at high operating voltages, it is common to place several sheets of these materials between each pair of capacitor plates. And complete capacitor sections are frequently connected in series, within a single case, to divide the total operating voltage among the individual sections.

Dielectric strength is rated in volts or kilovolts per mil thickness of the material and may be stated for ac or dc. It is the maximum voltage the material can withstand before puncture or rupture.

POWER FACTOR

Power factor takes into consideration the phase angle between current and voltage introduced by the practical capacitor and accordingly appraises total capacitor losses. These include dielectric losses (due to leakage, dielectric absorption, etc.) and ohmic losses due to capacitor plates, leads, etc. The former appear as resistance in parallel with the capacitance, while the latter show up as series resistance. Equivalent circuit of a capacitor with losses is given by Figure 3A.

Dielectric losses (parallel resistance) are indicated diagrammatically in Figure 3B. The effect of parallel resistance is to reduce phase angle between capacitor voltage and capacitor current to some value lower than the ideal 90-degree lead (Figure 3C). The difference between this practical angle and 90 degrees (phase difference) is ψ. The reactive current vector I_C equals ωCE.

Power factor is equal to the ratio of capacitor resistance to capacitor impedance (R/Z). It is thus equal numerically to the cosine of the phase angle (θ). It is also equal to the tan ψ = 1/(ωRC). The better the capacitor, the lower will be the power factor. Capacitor power factors are low in value, except in the case of some electrolytic types, the phase difference angle (ψ) being of the order of seconds and minutes rather than degrees.

Power factor of mica capacitors may be found by measurement as low as 0.01 percent, while that of electrolytics will reach several percent. A power factor of X percent indicates a loss of X percent of the total circuit k.v.a. in the resistive, rather than the reactive component of the capacitor.

The effect of series resistance upon capacitor power factor is always more important than that of parallel resistance but particularly so as the operating frequency is increased. A capacitor with series resistance only is represented by the diagram (Figure 4A). Vector relationships are given by Figure 4B.

Examination of the separate formulae given in Figures 3 and 4 respectively reveal that series resistance has a more deleterious effect upon power factor, as frequency increases, than does parallel resistance. Series resistance includes plate, terminal, joint, and lead resistance plus the high-frequency resistance introduced by skin-effect. These factors accordingly influence capacitor quality (insofar as it is indicated by power factor) to a much more marked degree than does leakage which is a manifestation of parallel resistance. Capacitors with low values of power factor are recommended for use in tuned circuits, wave filters, frequency discriminating networks, a.f.c. and a.v.c. systems, standardizing equipment, and the like. Radio-frequency applications are more exacting in this respect than are audio-frequency and dc services.

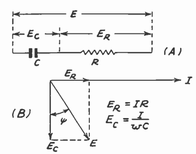
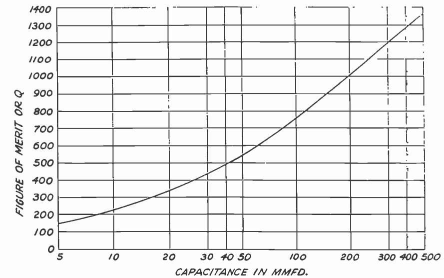


FIG. 4



A.S.A. MINIMUM PERMISSIBLE 1000-KC. Q VALUES

FIG. 5

DISSIPATION FACTOR

Dissipation factor is employed by some manufacturers of bridges and other test equipment, particularly when used for capacitor checking, in lieu of power factor. Dissipation factor is the ratio of resistance to reactance (R/X), which in the case of capacitors is ωCR. Dissipation factor is equal numerically to the cotangent of the phase angle, and for the small values encountered in capacitor quality testing is identical with power factor, or very nearly so.

Like power factor, the value of dissipation factor decreases with increasing capacitor quality (see Chart I).

Q

The factor of merit, Q, is the ratio of reactance to resistance (X/R) and indicates the comparative effectiveness of capacitor reactance with respect to resistance. Capacitor Q is equal numerically to 1/ωCR and increases as the effective series resistance of the capacitor decreases. A high Q value thus indicates high capacitor quality. For Q values greater than 10, Q is equal very closely to the reciprocal of the power factor, or of the dissipation factor.

Q measurements are very useful in determining capacitor quality at radio frequencies. Since skin effect is pronounced at these frequencies, virtually all of the resistance influencing capacitor Q is in series with the capacitance. Q at radio frequencies accordingly is influenced by all of those factors governing r.f. resistance—electrode, clamp, terminal, and lead resistance; quality of dielectric material within the field of capacitor electrodes; constitution of casing materials, and so on.

Since Q varies with frequency and capacitance, it is difficult to set up single high and low Q limits for all situations. A low Q value at one capacitance and frequency, for example, will not be so at other levels. The American Standards Association has offered the curve shown in Figure 5 for determining minimum permissible 1000-kc. Q values for capacitors rated between 5 and 500 mmfd.* (The Q value for capacitors rated higher than 500 mmfd. is recommended as higher than 1500).

IMPEDANCE

Since both reactance and resistance are presented by a practical capacitor, an impedance network results. Every capacitor accordingly introduces a certain amount of impedance in the circuit in which it is connected, and this value will vary with the frequency of the applied voltage. In a number of cases, the actual capacitor impedance at the operating frequency (or the principal operating frequency) is a more direct indication of capacitor performance in a circuit (and, to some extent, capacitor quality with regard to a specific application) than power factor, Q, dissipation factor, or leakage.

Capacitor impedance is of interest at both audio and radio frequencies and may be measured in both spectra by methods described in previous issues of the *Research Worker.*

*American War Standard. Fixed Mica Dielectric Capacitors. C75.3-1942. American Standards Assn., New York, N. Y.