ESR Testing

—Can it be trusted?

ESR testing can be a real time-saver for screening incoming capacitors. But look out for factors that can undermine results.

Rick Price

In recent years, equivalent series resistance (ESR) testing has become popular among designers as a fast, repeatable, non-destructive screening test for metallized film capacitors. ESR testing is typically used to determine the quality of the termination joints between the capacitor and its leads — a key ingredient in reliability. Most designers believe that the lower the ESR of a capacitor, the less its chance of failure and, hence, the greater its reliability. Theoretically, this is true. In actual practice, however, it may not always be the case.

Certain factors in the ESR equation must be scrutinized carefully to avoid invalid or confusing test results. Capacitors with the "same" capacitance value can, in fact, exhibit a variety of ESR values for reasons other than defects. So, to determine ESR accurately and validate capacitor reliability, it's important to fully understand the capacitor components that can affect ESR measurements.

Basically, there are three types of losses in a metallized film capacitor (Fig. 1): metal losses (R_S), leakage (insulation resistance) losses (R_{IR}), and dielectric losses (R_{DIE}). The following formula (leaving out extensive derivations) shows how these losses are related to a capacitor's ESR.

$$\mathrm{ESR} = R_S + \frac{1}{R_{IR}\,(2\Pi fC)^2} + \frac{DF_{DIE}}{2\Pi fC}$$

Metal losses (R_S) are the sum of the losses in a capacitor's leads, termination junctions, and capacitor plates. The R_{IR} losses result from leakage currents within a capacitor. And R_{DIE} is caused by molecular polarization dielectric absorption factors of the particular material.

One thing becomes clear from the equation — the measured ESR is dependent upon both test frequency and capacitance. At low frequencies, the insulation resistance leakage losses (second term) prevail due to the magnitude of the equation's values. Then, as frequency increases, first the dielectric losses (third term) and then the metal losses (first term) become predominant. So, since the intent of ESR measurements is to determine the integrity of a capacitor's termination junctions, the test frequency must be set high enough so that the metal losses become the predominant component in the total measured ESR. But it also must be low enough to avoid a resistive "skin" effect, which would produce misleading ESR measurements.

Under these conditions, a compromise test frequency of 100 kHz is generally used to measure the ESR of capacitors of all values. At 100

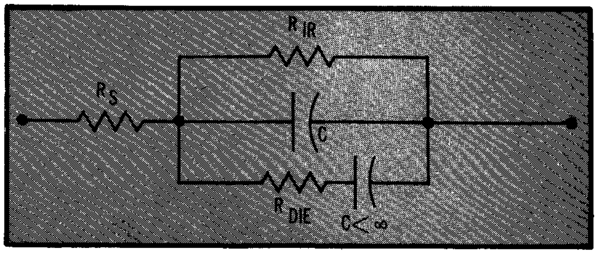


Fig. 1. In this simplified model of a film capacitor, R_S represents metal losses (sum of lead, termination junction, and electrode plate losses), R_{IR} represents leakage current losses through the capacitor's insulation resistance, and R_{DIE} is the resistance of the capacitor's dielectric.

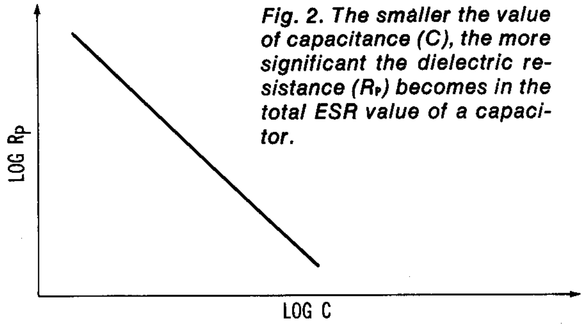


Fig. 2. The smaller the value of capacitance (C), the more significant the dielectric resistance (R_P) becomes in the total ESR value of a capacitor.

kHz, the second term in the ESR equation approaches zero and, therefore, can be ignored. (The insulation loss could have an effect on the equation if it were very low, but this type of defect is screened out by other tests.) 100 kHz is not the best test frequency at which to measure the ESR of all capacitance values but as a fixed common reference point, it provides the best compromise.

With the middle term dropped from the ESR equation, the equation can be simplified further by replacing the third term with R_P, representing the dielectric losses in parallel with C (Fig. 1). Thus,

$$ESR = R_S + R_P$$

where R_S = sum of the metal losses and
R_P = parallel resistance (dissipation factor [DF] of dielectric).

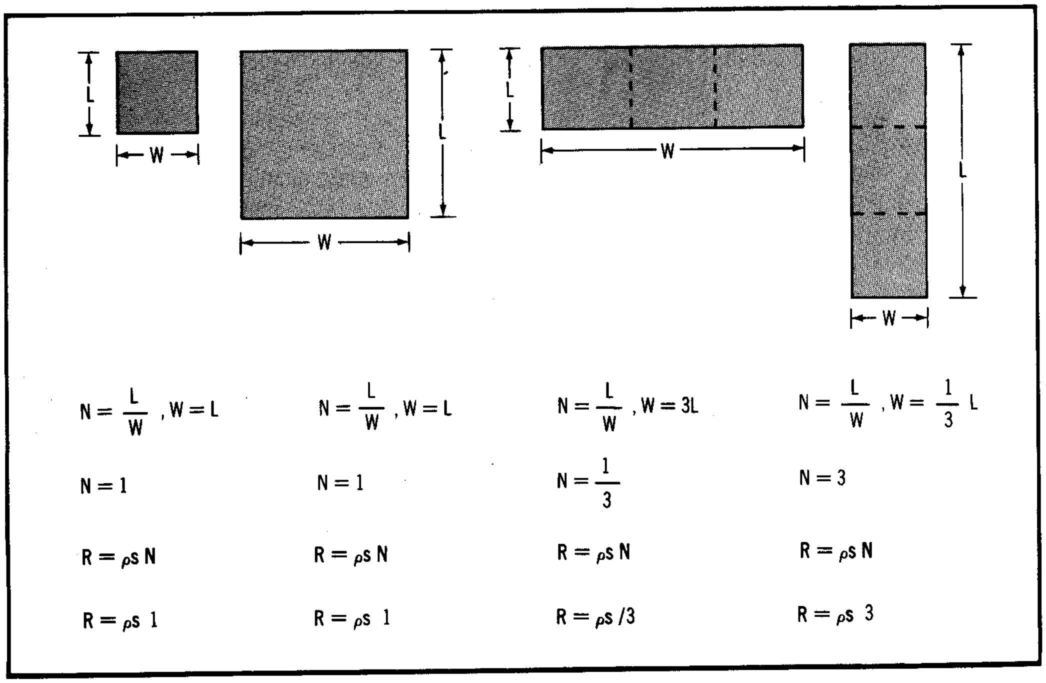
But, depending upon how this equation is interpreted, it can be misleading. To understand exactly what is being tested, it's necessary to fully understand R_P and R_S.

Capacitors, of course, are not rated at an absolute value but, rather, at some nominal value plus or minus a specified tolerance. Tolerances usually range from ±0.5% to ±50%, depending upon the specific application. Thus, the ESR values of a group of capacitors with the same capacitance value could, according to the ESR equation, vary by as much as the capacitance tolerance. Such variation depends on the nominal capacitance value of the group of capacitors and the dissipation factor (DF) inherent to the dielectric material used. The smaller the nominal value, the more predominant the dielectric resistance is in determining the total ESR (Fig. 2) — if the inherent DF of the dielectric material is high enough to make the value of R_p a significant figure in the total ESR value. A larger nominal capacitance value obviously reduces the significance of the dielectric resistance.

So, in the case of capacitors whose capacitance values are the same, the capacitors with the lowest ESR values are not necessarily the units with the best lead-to-capacitor terminations. On the contrary, they could be weak sisters hiding behind either of these scenarios: (1) the low ESR units may be made of dielectric material with an inherently lower DF than the rest of the group, or (2) they may simply be units whose capacitance values are on the high side of the nominal value, thus triggering a low total ESR value.

Metal resistance (R_S), the other component of the governing ESR equation, is a composite of lead, electrode plate, and termination junction resistance. A complication arises here with re-

Fig. 3. It's common practice to represent a resistor's aspect ratio (L/W) as the number of squares (N) in the resistor. A square is a unit that has an equal number ratio of parallel to series resistive elements, so the resistances of any squares of the same size, material and thickness are equal. The use of squares simplifies determining the effects of adding to or subtracting from the length of a resistor.



gard to the electrode plate resistance. You can't compute it simply by finding the number of squares of metallization and then multiplying by the ohms-per-square constant for the given metallization. In ESR testing, the ac component makes the use of ohms per square insufficient. You need a different approach.

An applicable formula developed by TRW produces a value for "total effective resistance" of two plates in a capacitor. The formula takes into consideration both the sheet and the bulk resistivity of the metallization.

$R_{plate} = 2N\rho_s/3$ (Total effective resistance of two plates in a capacitor)

where $N = \frac{L}{W}$ (Number of squares of metallization) and

ρs = sheet resistivity (ohms/square constant of the metallization — usually 0.5 to 2.5 ohms)

This total effective resistance factor is applied to the value representing the number of metallized squares in an unrolled capacitor electrode plate (Fig. 3).

Figure 3 illustrates another unsettling revelation about capacitors whose capacitance values are accepted as "the same." In such a group, those capacitors with the lowest ESR values are, again, not necessarily those with the most reliable lead-to-capacitor terminations. The glitter of their low ESRs could result, instead, from (1) smaller lead-to-lead lengths, L, which make the plate resistance smaller, or (2) capacitance values on the high side of the nominal value, which increase the effective width, W, of the electrode plate. The latter results in more resistance in parallel, which decreases the effective plate resistance.

The connection connection

There's still more shaky ground under the ESR foundation. The essential validity of the establishing equation for capacitor plate resistance rests on the assumption that perfect connections have been formed along the entire length of the winding, W, and the coating on the end of the winding (Fig. 4). This is, however, a pollyannish assumption.

Suppose the end of the lead is attached in such a way that it passes through the coating on the end of the winding. The result — disconnection of that area of the metallization from the main current path, thereby causing the charging current to pass along the turns of the winding in that area rather than through them. This would replace a parallel set of resistances with a series set of resistances and cause an increase in the total ESR. Note that this increase belongs to the termination junction resistance — the very objective of screening in ESR testing. Anytime a lead is connected to a capacitor, there is some damage done to the coating-metallization interface. The extent of this damage is determined by variables such as the size and shape of the lead, the method of attachment (welding or soldering), and the size and shape of the capacitor, among others.

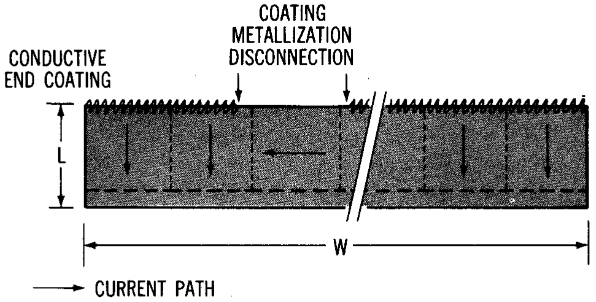


Fig. 4. Any defects in coating at the end of a capacitor's winding can result in an increase in total ESR.

Lead attachment is not the only circumstance that can introduce high resistances into ESR measurements. Severe mechanical, thermal, and/or electrical stress, or exposure to excessive moisture can also cause a high resistance to develop between the coating and the winding.

Scratches in the metallization — rare but possible — are another cause of increased ESR. Fortunately, today's more sophisticated manufacturing techniques and testing procedures can detect and eliminate this type of defect, which once was virtually undetectable.

The law of lead resistance

The last remaining resistance of any consequence is lead wire resistance. With proper test precautions, its contribution to total ESR can be ignored except in testing higher capacitance units, in which lead resistance and end coating resistance are the dominant factors in total ESR.

The diameter of the lead is the prime determinant of lead resistance. Because lead diameter is varied in accord with capacitance value, lead resistance is indirectly tied to capacitance value. Physical considerations play their role here; obviously, you don't attach a thin, flimsy lead onto a large capacitor or a thick, stubby lead on a tiny capacitor. Thus, production realities dictate the following: lead resistance of a capacitor decreases as capacitance value and, consequently, lead diameter increase.

Weigh all the factors

Figure 5 gives you a handle on how to weigh the influences affecting capacitor ESR. For low capacitance values, the resistance due to the inherent dissipation factor of the dielectric material is the most significant value in total

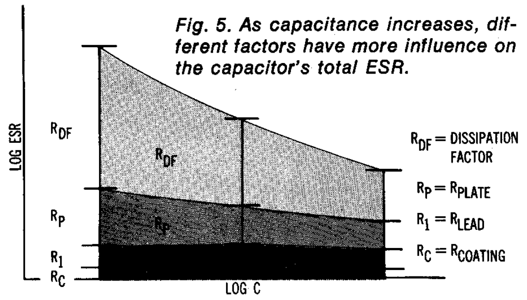


Fig. 5. As capacitance increases, different factors have more influence on the capacitor's total ESR.

ESR of a capacitor. As the capacitance value is increased, first the plate resistance, then the lead resistance, and finally the end coating resistance is the dominant factor affecting total ESR.

The bottom line on ESR

Since capacitors with the same capacitance value reflect a variety of ESR values for reasons other than actual defects, what is the final verdict on ESR testing as a useful screening procedure? It's apparent that secondary testing is advisable. Parameters such as capacitance value and insulation resistance need verification as being within design specifications. That done, the remaining capacitors can be sorted by ESR testing, and the high resistance units discarded.

How to define "high" is the remaining question. Keep in mind that, depending on the particular application, higher than normal resistances are not necessarily detrimental to capacitor performance. Certainly, when you're dealing with a high-current, high-performance application, keeping resistance as low as possible is necessary to suppress the I^2R heating effects that can degrade the capacitor. But in most low-current, low-stress applications, capacitors could exhibit a range of ESR values and still operate dependably.

The upshot is that ESR screening can validate capacitor reliability only if all the components that affect the ESR rating are submitted to scrutiny. The working principle is to set the maximum allowable ESR value of a given capacitor according to its specific design construction and specified application. This will ensure an ESR ceiling low enough to flunk defective units, yet high enough to avoid the uneconomical rejection of good capacitors.

When can you depend on an ESR comparison? For openers, only when (1) the capacitors being compared are constructed of the same type and dimensioned material, and (2) they have the same nominal capacitance value. Given these two contingencies, there's still room for healthy skepticism because of the inverse relationship between capacitance value and ESR. ⊕

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