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tech tips

Understanding ESR in Capacitors

The need to test equivalent series resistance (ESR) increases daily because more electrolytic capacitors are finding their way into circuits where resistance causes problems. The patented ESR test provides a new test for this capacitor failure, which reads the series resistance directly in ohms. This Tech Tip answers the most common questions about ESR.

1. What Is ESR?

Every capacitor has some ESR. ESR is the electrical resistances in series with the capacitor plates. This includes the resistance of the metal leads and plates and the connections between them. An aluminum electrolytic capacitor also has resistance in the wet electrolyte solution, and in the layer of aluminum oxide which contains high levels of water (called the "hydrated oxide").
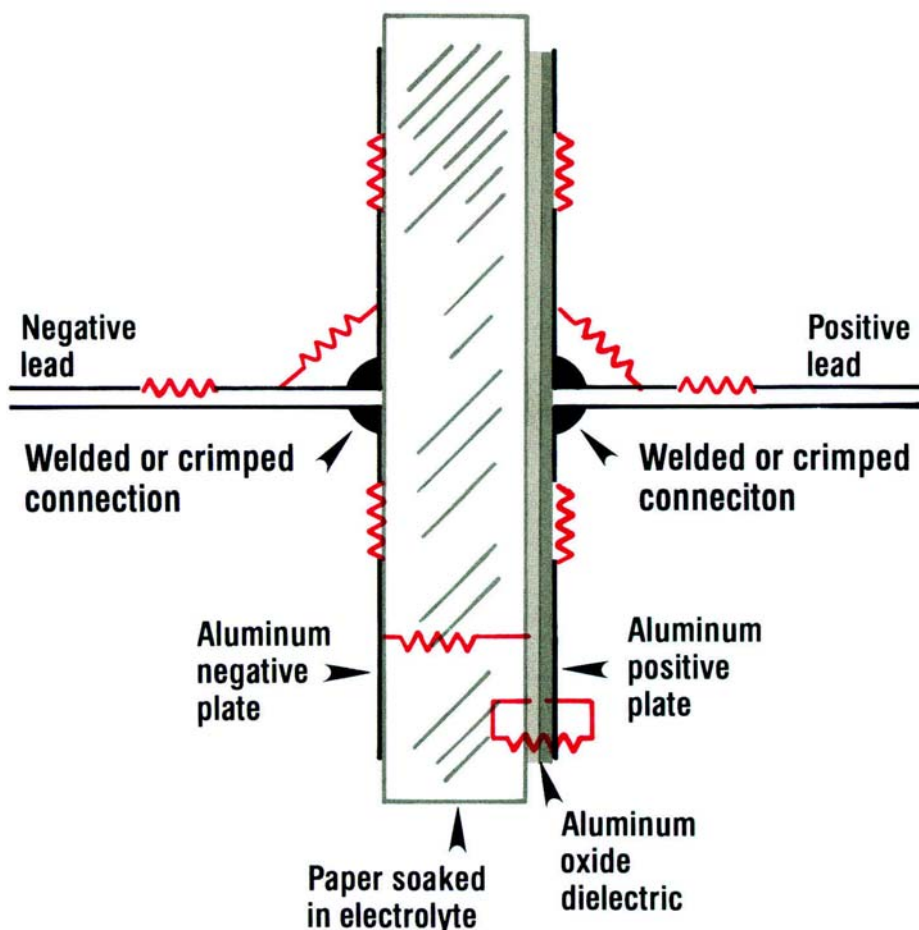
2. What Causes ESR To Change?

First, we can ignore the resistance contributed by the metal leads and plates, because it's so small. There are two common causes of high ESR: 1) Bad electrical connections, and 2) Drying of the electrolyte solution. Electrical connection problems can happen in old or new capacitors, while drying is usually only a problem in old ones.

Connection problems happen because the leads coming into the capacitor cannot be made of aluminum, since aluminum cannot be soldered. The electrical connection between the aluminum plates and the copper leads calls for a weld or a mechanical crimp. Problems with either method produces high series resistance.

Drying problems occur because of the importance of water in the electrolyte solution. The solution soaks the paper spacer between the two aluminum plates. The water carries the electrical charge from the negative aluminum plate to the surface of the insulating oxide on the positive plate. The oxide forms the capacitor's dielectric and the negative charge on the surface of the oxide forms the negative capacitor plate. As the water evaporates, the electrical resistance increases.

3. Is ESR responsible for leakage?

No, leakage is a PARALLEL resistance path which connects the two plates. ESR is just the opposite, since it's all the resistance EXCEPT for the leakage path. If ESR is large enough, it can reduce the leakage current.

Fig. 1: The equivalent series resistance (ESR) is the combination of all electrical resistances, including the leads, plates, connections, and water in the electrolyte.
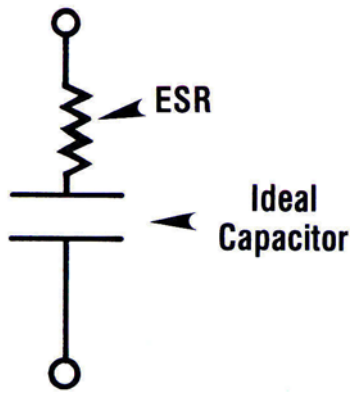
Fig. 2: In effect, all of the ESR components add to equal one resistor placed in series with an ideal capacitor.

ESR has little effect if it's smaller than the Xc. At the frequency where the ESR becomes equal to Xc, the value of the capacitor is effectively cut in half. When the ESR is much larger than the Xc, it becomes the dominant part of the two series components, which prevents the circuit from seeing the capacitor at all.

ESR vs. **Power:** Equivalent series resistance can also cause problems at low operating frequencies if the capacitor must handle high levels of current. This often occurs in high current power supplies, such as those used to power banks of digital logic circuits. Consider, for example, a 20,000 µF capacitor used to filter a 5 ampere, 60 Hz power supply. The capacitor must alternately charge to the voltage supplied by the rectifier, and then discharge into the circuit load during the time the rectifier isn't conducting. This 5

4. Why does ESR affect some circuits worse than others?

Two types of circuits are more severely affected by ESR than others; those using high frequencies or high currents. Circuits which don't have either condition can tolerate much higher levels of ESR.

ESR vs. Frequency: First, let's see how ESR affects circuits with a high operating frequency. A typical example is the DC blocking capacitor at the output of the audio amplifier shown in the schematic in Fig. 3. The graph in Fig. 4 shows how the output power changes with output frequency for two 100 µF capacitors, one with no ESR and one with 6 ohms.

Notice that the output at 60 Hz is nearly the same for both capacitors. The good capacitor produces 1.7 watts, and the bad one produces 1.3 watts. This shows that the capacitor with the high ESR will still work well as a power supply filter. But, notice the results at 1000 Hz. The good capacitor allows 10 watts to pass to the speaker, while the bad capacitor restricts the power to only 5.6 watts. The differences become even more pronounced at higher frequencies.
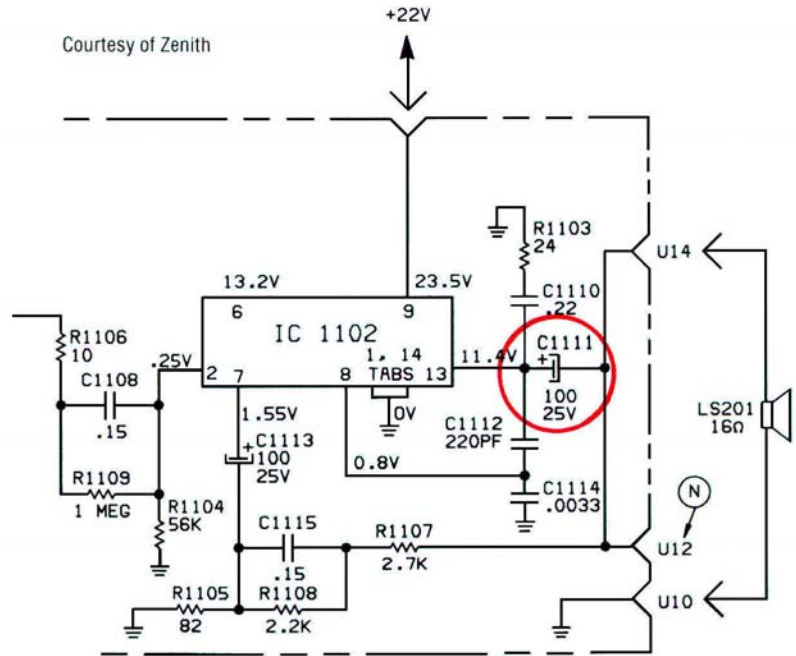
The reason for this effect is the relationship between the series resistance and the capacitive reactance (Xc) of the capacitor. Remember that the Xc of a perfect capacitor can be thought of as its electrical resistance at a certain frequency. Xc is large at low frequencies (infinite at DC) and lower as the frequency increases. The capacitor should act as a dead short to higher frequencies.

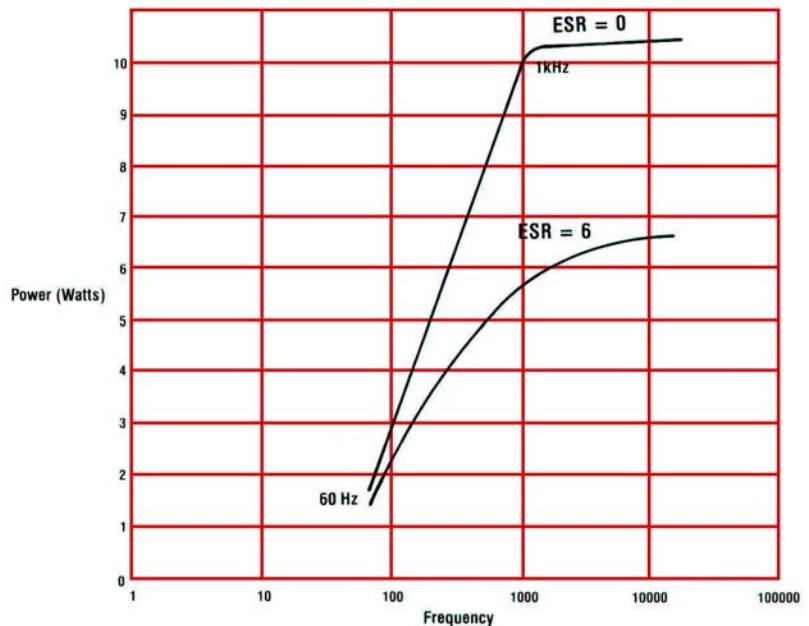Series resistance causes a voltage divider action between the Xc and the ESR. The

**Fig. 3: A typical audio output stage with a series DC blocking capacitor can be affected by high ESR.**

Fig. 4: The output from the circuit in Fig. 3 with a good capacitor and one with 6 ohms of ESR. Notice that this capacitor would still serve as a power supply filter, since there is virtually no difference at 60 or 120 Hz.

amps of "ripple current" alternately passes in and out of the capacitor.

If the capacitor has an ESR of only 0.5 ohms, Ohm's Law tells us that this generates 12.5 watts of heat inside the capacitor. This heat causes the capacitor to quickly dry out and fail. Also, the series resistance can reduce the filtering. For example, a resistance of 0.5 ohms in a 5 volt TTL power supply may cause ripple as high as 2 volts. This equates to 40 percent ripple, which will cause most digital circuits to perform incorrectly.

High frequency power supplies (such as switchers or flyback-powered TV circuits) involve both high operating frequencies and high currents. ESR is even more of a problem in these circuits.
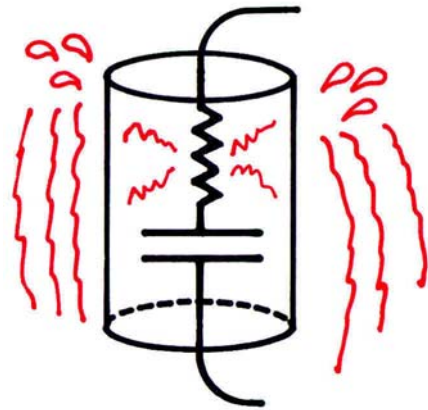
Fig. 5: If a capacitor with high ESR is used to filter a high current supply, internal heating may result. The higher temperatures may cause the capacitor to dry out or rupture.

5. Should I throw a capacitor with high ESR away if it doesn't affect the circuit?

Generally, yes. Although high ESR may not affect some circuits, it's still a signal that something isn't right inside the capacitor. Either the connections are coming loose, or else the electrolyte is drying out. If the problem continues to worsen, it will eventually cause a circuit failure.

6. Why does ESR only apply to electrolytics over 1 µF?

High levels of ESR on smaller value capacitors will cause them to read low on the value test. ESR on a good electrolytic capacitor, however, is so low that it won't affect the value test. Therefore, it must be measured separately.

7. Why is ESR so difficult to detect?

The circuits that measure ESR must be able to ignore other capacitor parameters, including the capacitive reactance at a given frequency. It would be handy if we could just reach inside with a DC ohmmeter and measure the resistance in series with each metal plate. We can't do that, because the capacitor blocks any attempt to measure with DC. Therefore, we must use an AC signal to isolate a DC failure mode.

8. How do the Z METER circuits detect ESR?

The Sencore engineers struggled with this problem for a long time before coming up with a good answer. We finally found that waveshaping theory supplied an answer.

First, let's see how an ideal capacitor should react if we apply a voltage to it from a power supply with a known output impedance.

The capacitor should immediately begin charging at the R/C time constant made up of the capacitance value and the output impedance of the supply. The voltage should begin at zero, and then build in the normal fashion until fully charged (generally in 5 time-constants) as Fig. 6 shows. If we charge and discharge this capacitor repeatedly, we end up with a sawtooth waveform.

Now, consider what happens if we place a resistor in series with the capacitor and observe the charging curve on the side of the resistor farthest from the capacitor. At the instant voltage is applied, the capacitor acts like a short circuit. Fig. 7 shows how the voltage at the resistor instantly rises to a DC level based on the ratio of the power supply impedance and the resistor's value. The capacitor then begins to charge through the combined resistance of the
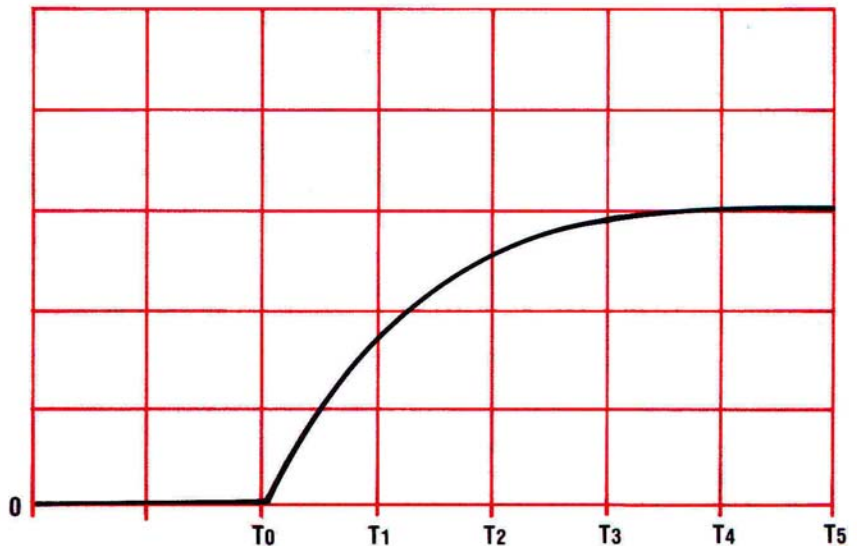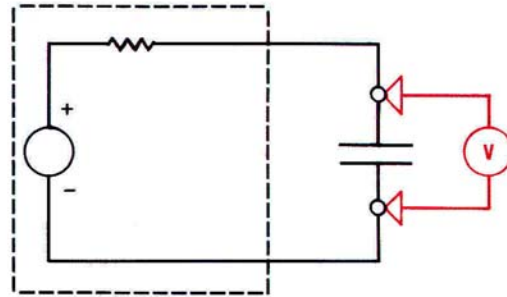
Fig. 6: When current is applied to a normal capacitor, it begins recharging from zero, building in voltage according to the normal R-C charging curve.
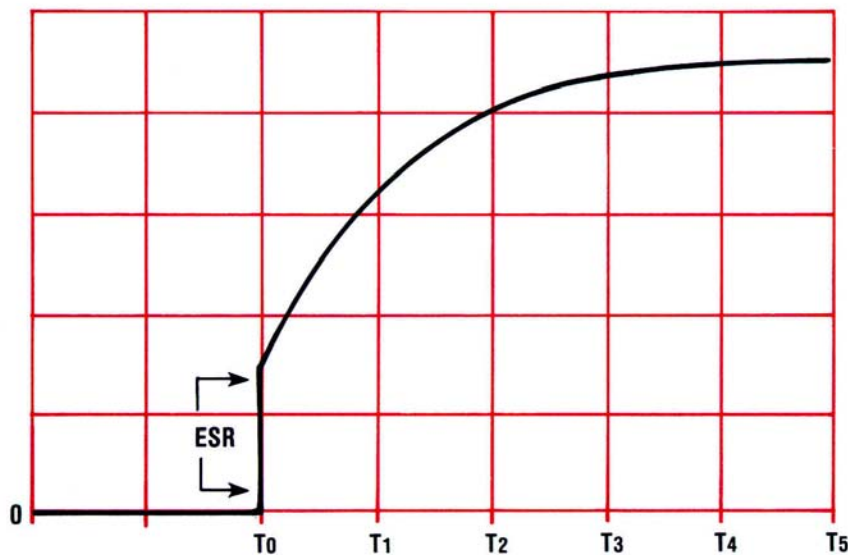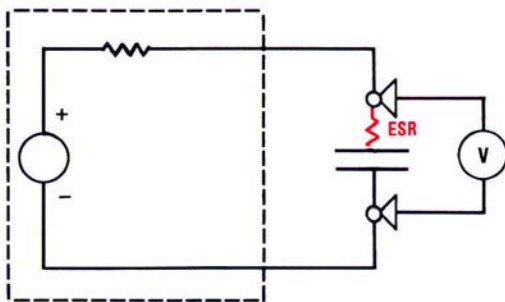
Fig. 7: When there is series resistance, the charging voltage instantly rises to a voltage /eve/ (proportional to the resistance in the capacitor and the output impedance of the power supply) before beginning the normal R-C curve.

power supply and the series resistor. The larger the series resistance, the higher step before the charging curve. If we discharge the capacitor and repeat the process, we learn that the waveshape changes from a sawtooth to a trapezoidal waveform.

The Z METERs simply charge the capacitor, while measuring the rise in voltage during the first microsecond after applying the voltage. The instantaneous voltage step calculates directly to resistance using normal voltage-dividing formulas. Sencore has been granted a patent on this test.

9. How does the Z METER ESR test relate to frequency?

A number of customers have been told that ESR must be tested at a particular frequency. This is not the case, because true ESR does not depend on frequency. ESR represents pure resistive losses, and resistance has the same impedance at any frequency. The Z METER only measures resistance.

The confusion appears to come from formulas which attempt to convert the **"D"** (dissipation factor) reading from an AC impedance bridge to an ESR value. ESR, however, is only one of the many capacitor imperfections that causes poor D readings. D also includes the effects of leakage resistance, equivalent series inductance, dielectric absorption, dielectric stress, and losses (such as water molecule resonance) in the dielectric. Most of these other losses are frequency selective, so any attempt to calculate ESR from D will make it seem that ESR varies with frequency.