RESISTOR MEASUREMENTS

This month, Bob Botos of Hewlett-Packard describes the affect of parasitic reactances on resistor performance

Of the three classes of circuit components, resistors probably cause the least measurement difficulties, partially because it is often practical to measure them with a d.c. test signal applied. In contrast, inductors and capacitors by their very nature must always experience a.c. test excitation.

Manufactured discrete resistors embrace many materials and technologies. Some of the most common are wire-wound types, usually with metal-alloy windings; composition types, made with a baked mixture of carbon powder, filler and binder; and film types, generally formed by sputtering, sintering or evaporating films of carbon, metals or oxides onto a form.

The resistance of many other circuit elements also affect measurements. Such factors as switch-contact resistance, the incremental resistance of semiconductors, and leakage and insulation resistance all require measurement techniques that take into account both the resistive magnitude and the first-order dependency factors. However, this discussion is limited to discrete resistor elements ranging in value from milliohms to teraohms; commercial resistors with such values are available.

Resistors made with carbon rate as the most popular group, primarily because of their low cost. They come in two basic forms: carbon-composition (slug) types with moulded, pressed or extruded bulk construction, and carbon-film types that use a mixture of carbon or graphite and resin, deposited on a rod of ceramic or glass. Resistance values range from 10Ω to 22 MΩ for slug types; special glass-sealed carbon-film units have values ranging into the teraohm region.

Pure carbon exhibits a negative temperature coefficient (TC) of resistance, but carbon-composition slug type resistors can have TCs between ±0.05%/°C. For carbon-film devices, coefficients are negative and can reach −0.15%/°C; the TC generally become more negative with increased resistance. Voltage coefficients range to −0.02%/V.

Fig 1

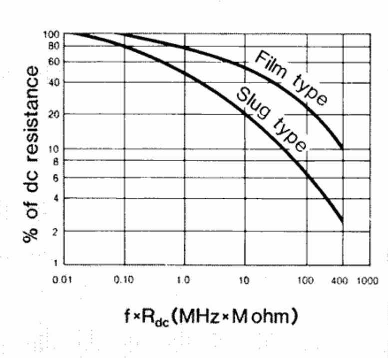


Fig 2

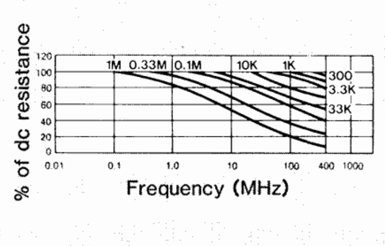


Fig 3

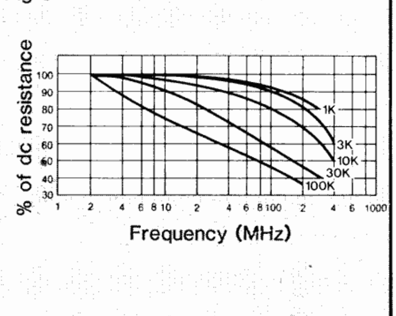


Fig. 1: frequency dependence of carbon-composition resistors

Fig. 2: frequency dependence of carbon film resistors

Fig. 3: high-voltage, high-wattage deposited carbon resistors show a more pronounced frequency dependence

The resistance of all carbon-element resistors is frequency dependent; for both film and slug types, it decreases as frequency increases. This Boella Effect results primarily from shunting by distributed capacitance produced by the many conducting particles of carbon held in contact by the resistor's dielectric binder.

Carbon-film resistors have considerably less capacitance than those with slug construction. High-frequency 1/2W film resistors normally display 0.2 to 0.5 pF of shunt capacitance, depending on the manufacturer and the resistor's size and configuration. Fig. 1 shows the relative frequency dependencies of carbon-film and slug resistors, while Fig. 2 depicts the response of specific-value carbon-film types. Consider both sets of curves only as examples; consult individual resistor specification sheets if more detailed information is required.

A second major type of resistor—wire-wound—divides into two general classes: high-precision and general-purpose power types. The high-precision units generally use one of two winding techniques to reduce their inherently inductive nature:

1) The pi-section fabrication technique utilises a bobbin (form) with the winding space divided into an even number of sections. As the wire is wound onto the bobbin, the winding direction is reversed in alternate sections, resulting in minimised inductance.
2) The Ayrton-Perry technique uses an even number of single-layer windings, with alternate layers wound in opposite directions.

Common values for high-precision wire-wound resistors range from

Equivalent series resistance (ESR) is a recently coined term for effective resistance and is now used extensively in component evaluation. It can apply to a battery, a capacitor or almost any other circuit component. In essence, ESR is the magnitude of a circuit component's real vector as modelled with a series equivalent circuit.

Using Fig. A1 and assigning reactance designators to the inductance and capacitance results in the following expression for equivalent series *impedance:*

$$Z = j\omega L + \frac{R(1/j\omega C)}{R + (1/j\omega C)}$$

Simplifying this expression into real and imaginary parts results in

$$Z = \frac{R}{1 + \omega^2R^2C^2} + j\frac{\omega L - \omega CR^2 + \omega^3LC^2R^2}{1 + \omega^2R^2C^2}$$

The real part is ESR; note that it depends on frequency. Here, controlled by the magnitude of shunt capacitance, frequency can be a second-order component-dependency factor.

A word of caution: Note that the equivalent circuit of Fig. A1 embodies only one possible representation of a resistor; such models depend on resistors' physical composition and predominant parasitics. Fig. A1 could represent a carbon-composition unit, where the shunting capacitance is the predominant parasitic and the series inductance is minimal.

Based on these guidelines, the general frequency-related characteristics of such a circuit component appear in Fig. A1. If instead of being a 1W carbon-composition unit, the resistor of Fig. A1 were a poorly designed wire-wound unit with 1mH of inductance, its characteristics would vary with frequency in a different manner, producing two interesting features:

- The impedance Z equals the ESR at two frequencies—d.c. and the resistor's self-resonant frequency (f_r).
- If any shunt capacitance exists, ESR decreases as the frequency increases.

If you recall that ESR is the "resistance" that an instrument generally measures, it should thus come as no surprise when the indicated resistance differs considerably from the nominal or effective value.

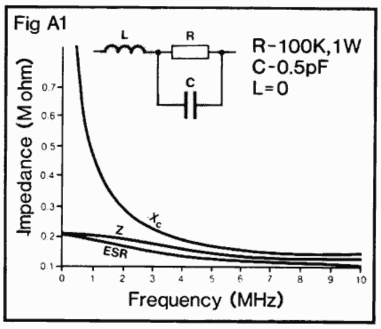


Fig. A1: practical resistors usually exhibit at least two parasitics—series L and shunt C

Fig. A1 also shows typical characteristics of a 100kΩ, 1W carbon-composition resistor; lead inductance is negligible but shunt capacitance has a noticeable effect

0·1Ω to 10 MΩ, with resistance accuracies to ±0.02%.

Because their resistance-wire element usually takes the form of a single-layer solenoid, general-purpose wire-wound resistors exhibit inductance in the range of 0.03 to 2.5 μH for 1/4W units, 0.2 to 33 μH for 1/2W units and 0.4 to 56 μH for 2 and 4W units. Inductance usually increases with increased resistance (because higher resistance devices require more turns). Inductance is, of course, a second-order dependency factor in resistance measurements.

Another second-order factor, which, like inductance, increases a wire-wound unit's effective resistance with increasing frequency, is skin effect. However, this factor doesn't make a noteworthy contribution below the microwave region. As for the quantitative effect of inductance, considering a worst-case value of 56 μH at 1 MHz yields a reactance of 350Ω. For a nominal 8-kΩ resistor, this parasitic could significantly affect the resistance measurement.

Depending on the resistance-wire material used, wire-wound resistors can have positive, negative or near-zero TCs. Units with pure-metal windings generally have positive TCs, while zero-TC units are made of alloys of constantan and manganin. Most common wire-wound resistors have TCs between 0.03 and 0·08%/°C.

Carbon-element and wire-wound resistors can't by themselves serve all needs. Notable for their low TCs (typically to 0.005%/°C) and excellent high-frequency performance, metal-film resistors fill an important niche. Their principal parasitic is capacitance, which generally runs from 0.2 to 0.6 pF. Resistance values range from 100Ω to 5 MΩ for general-purpose metal-film types.

Problems compound when too many "highs" characterise resistor requirements. For example, in some deposited-carbon units rated for high-voltage (750V) and high-wattage (2W) service at high frequencies, the resistance of even relatively low-R units drops with frequency (Fig. 3). Clearly, it isn't a simple matter to achieve specific effective resistance values under the combined requirements of high voltage, high wattage and high frequency.

Measuring resistors

Generally, resistance measurements are based on Ohm's Law: A test signal of known voltage or current is applied to the device under test (DUT), and the resulting current or voltage is measured and processed to yield an indication of the resistance's magnitude.

Test signals can be either a.c. or d.c. Note, though, that the application of d.c. automatically negates any concern that parasitic reactances will affect the indicated value. On the other hand, when an a.c. test signal is used, you can usually consider the resulting indicated value to represent the equivalent series resistance. Frequency then becomes a second-order factor, whose effects depend entirely on the extent of resistor parasitics.

You can model any resistor with significant parasitics in both equivalent series and parallel circuits, making use of lumped values. One modelling technique might prove mathematically more convenient than the other, so it often becomes necessary to convert from one to the other (Fig. 4).

Unless the design of an a.c. measurement setup takes into account a resistor's complex nature, the indicated value will represent the vector sum of the resistance's real and imaginary parts; such an indicated value exaggerates the frequency dependence. Some instruments that

A review of key points

Real-world resistors have both real and reactive natures. Consequently, they have effective and indicated values.

True resistance can be measured at d.c., but the result of such a measurement is the "true" value only under those specifically defined test-parameter and environmental conditions. Any "true-value" measurement presupposes that all measurement loss factors have been accounted for.

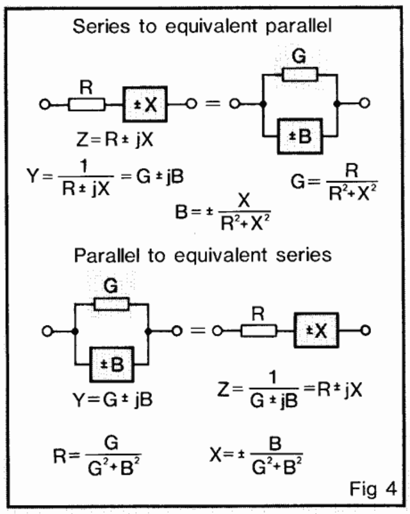
Resistance can be expressed as either a series or parallel equivalent value; the relative magnitudes of these values depend on the degree or reactance associated with the device.

Special considerations should govern the measurement of extremely low and extremely high resistance values. For low values, use of the 4-terminal technique with constant-current sourcing is necessary. High-value measurements require constant-voltage sourcing, primarily because of the impracticality of using constant-current sourcing in this case. Environmental radiated interference causes measurement instabilities that can be remedied by proper shielding and/or guarding.

The real part of a complex resistance can itself depend on frequency, as the definition of equivalent series resistance shows.

remedy this impedance-based indicated value incorporate a form of synchronous detection (Fig. 5); here, the synchronous detector yields an output voltage proportional only to the real part (R) of the DUT.

To understand the synchronous detector's significance, note that the voltage drop across the DUT is composed of both real and imaginary components: $V_{DUT} = V_R + jV_X$. Also, recall that the associated reactance produces a phase shift between the applied test signal and the resulting current. A voltage across a relatively reactance-free reference resistor (R_{REF}) serves as the synchronous detector's reference signal; the detector then yields an output proportional only to the voltage across the DUT that is in phase with V_R, its real part. Consequently, synchronous detection minimises the effect of both DUT



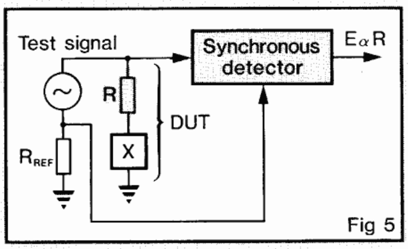


Fig. 4: converting between parallel and series representations can often simplify analysis

Fig. 5: synchronous detection permits separate measurement of the real part (R) of DUT impedance

reactance and reactance in the circuitry.

To achieve any substantial degree of precision, you must measure low resistance using the 4-terminal technique and constant-current sourcing. These two provisions combine to virtually eliminate lead-resistance effects. Forms of synchronous detection, coupled with these techniques, are today yielding a.c. measurements at progressively higher frequencies. (Even though synchronous detection permits measurement of only the real part of a resistance, recall that this real part is nevertheless frequency dependent.)

Assuming the use of 4-terminal connections, it's necessary to exercise several precautions when connecting the terminals to a DUT:

1) Be sure to observe correct phasing of source and sense terminals (HIGHs together and LOWs together).
2) While it is irrelevant whether you make the current-source or the voltage-sense terminals the inner members at the connection point, remember that the indicated value will characterise the region between the exact points to which the voltage-sense terminals are attached.
3) For extremely low-value DUTs, twisting voltage leads together and current leads together minimises errors caused by mutually induced EMFs.

Any factor affecting the voltage drop sensed across the DUT will influence the measurement precision of low-value resistances. Several second-order dependency factors might be responsible for errors:

1) Thermal EMFs generated by the contact of dissimilar metals—often, using beryllium-copper alloys helps minimise these thermal EMFs.
2) Contact resistance of voltage-sense leads—gold, silver and mercury are commonly used for their high conductivity, but contact cleanliness and pressure also can contribute significantly to decreasing resistance.
3) Lead length between the resistor and the actual contact point—for low-value precision wire-lead resistors of 10Ω or less, government and industry generally specify that the voltage test be applied 3/8±1/16 in. from the end of the body.
4) The accuracy tolerance of the measuring instrument—when correlating measurements, even between two instruments of the same model, remember that the worst-case difference is the arithmetic sum of the individual tolerances.

High resistance values are generally measured with constant-voltage sourcing and current detection, because the current-sourcing technique usually used for low-resistance measurements exhibits prohibitive voltage-compliance requirements for high resistances. For example, 1 mA of current through a 10-MΩ resistor requires a voltage compliance of 10,000V.

Several other limitations govern high-R measurements, including voltage sensitivity, RFI or EMI effects and the formation of parallel resistance paths as a result of surface contamination.

Next month's article will discuss capacitance measurements