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APPLICATION NOTE 5686

PASSIVE COMPONENTS AREN'T REALLY SO PASSIVE (PART 2): RESISTORS

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Abstract: Passive components don't draw power but even resistors can, and modify signals in unexpected ways. A resistor's reaction to temperature, voltage, and signal frequency can often catch the inexperienced engineer by surprise. Tolerances may not be as they seem and simple resistors may provide nonlinear signal response, introducing harmonics where there were none.

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Capacitors, resistors, inductors, connectors, and even the PCB are called passive because they don't have gain or control power like semiconductors or other active devices. But these apparently passive components can, and do, change the signal in unexpected ways because they all contain parasitic portions. In [Part 1](#) of this series on “passives” we talked about capacitors. Now in Part 2 we look at resistors. Indeed, resistors are simple, benign, passive devices—right? Wrong. As we will see, resistors really do some unexpected things. In [Part 3](#) we discuss how PCB flaws and errors that are usually hidden, or at least disguised, can introduce passive errors into IC performance.

The Simple Resistor, Really Ain't that Simple

How many times have we walked down a street and seen concrete that is lumpy, bumpy, and horrible. It reveals someone's inexperience and overconfidence because pouring concrete looked so simple. Resistors have the same basic issue: they seem simple until one looks closely. There is a superb book on resistors ¹ and the authors Dr. Zandman et al. have the same lament, “This work [book] attempts to demonstrate that

the design and fabrication of resistive components require the application of particularly complex physical phenomena and are no longer based on the traditional empirical methods generally associated with the 'kitchen recipe' approach."²

Ahhh, the kitchen. While cooking, so many of our mothers use to say, "a little of this and a pinch of that." Fine for cookies, but this kitchen-recipe approach to manufacturing resistors is a serious issue. There are vendors that prioritize price over quality. Other vendors accept a large variation in tolerances as if they were formulating batches using a kitchen recipe. A little difference in food can add variety and interest, but the kitchen recipe has no place in manufacturing of close tolerance parts.

The late Dr. Zandman, inventor of a zero-tempco resistor and founder of Vishay Intertechnology, certainly underscores his work with mathematics and material science. His book delineates the formulas and reasons behind the many variations in resistors. He devotes three wonderful chapters to Ohm's law, first to Ohm's law itself and its limitations, then to reversible and irreversible phenomena associated with the law. Reversible conditions include a rise in temperature that changes the resistance, but the resistance returns to the starting point when the temperature is reduced. An irreversible effect means that the resistor's change becomes permanent like those caused by diffusion or oxidation.

Set Tolerances to Match the Application

Let's admit an important fact at the outset: resistors introduce error. Our initial reaction may be to ignore resistor inaccuracy as "too small to matter." After all, a pinch of salt in an Olympic-sized swimming pool does not make it salt water. True, but adding a ton of salt would be a different issue. Obviously, an application dictates the acceptable error. The more precision required, the tighter the component tolerances must be. Knowing this, we should define what magnitude of error is acceptable.

We will examine an example system with 12-bit resolution, one-half the least significant bit (LSB) is one part in 8192, or 0.012%, or 122 parts per million (ppm).³ A quick look at Digi-Key[®] and Mouser[®] catalogs finds thousands of 1% tolerance resistors with typically a $\pm 100\text{ppm}/^\circ\text{C}$ temperature coefficient (tempco). Consequently, barely more than a 1°C temperature change causes more than one LSB deviation. Not so good. So let's try 0.1% tolerance resistors with a $\pm 25\text{ppm}/^\circ\text{C}$, which means if the temperature changes 5°C , our error is one LSB. Remember that this is just one resistor and most systems have many resistors.

We can draw some important conclusions from this example. To bracket the resolution numbers:

- A. For 8-bit (1 part in 256) resolution, one-half LSB is 0.195% or 1953ppm; and
- B. At 16-bit resolution (1 part in 65536), one-half LSB is 0.0015% or 15ppm.

Clearly the need for smaller tolerances and tempco is more important at higher resolutions.

That is actually true for many systems, but there are two extreme cases to note. First, a completely open-loop use, such as an arbitrary waveform generator, needs the DAC output and amplifier to have nearly perfect linearity. Second, a system with a feedback loop, such as a mechanical movement generated in a process controller, has servo action that is always driving the action toward the center to null out any error. As long as the servo is directed in the proper direction (the system is, by definition, monotonic), small nonlinearity errors will be ignored.

Resistor Parasitic Components

Figure 1 illustrates the parasitic components that are present with resistors. Inside the dotted Resistor box is the resistor. The inductors and capacitors on either side are the PC board (PCB) connections and traces. The R is what we want; the additional factors inside that box are unavoidable parasitics. To illustrate the effects of these parasitics, we drive the left side of the resistor with a low-impedance signal generator. That will swap out the left capacitor to ground, C_G

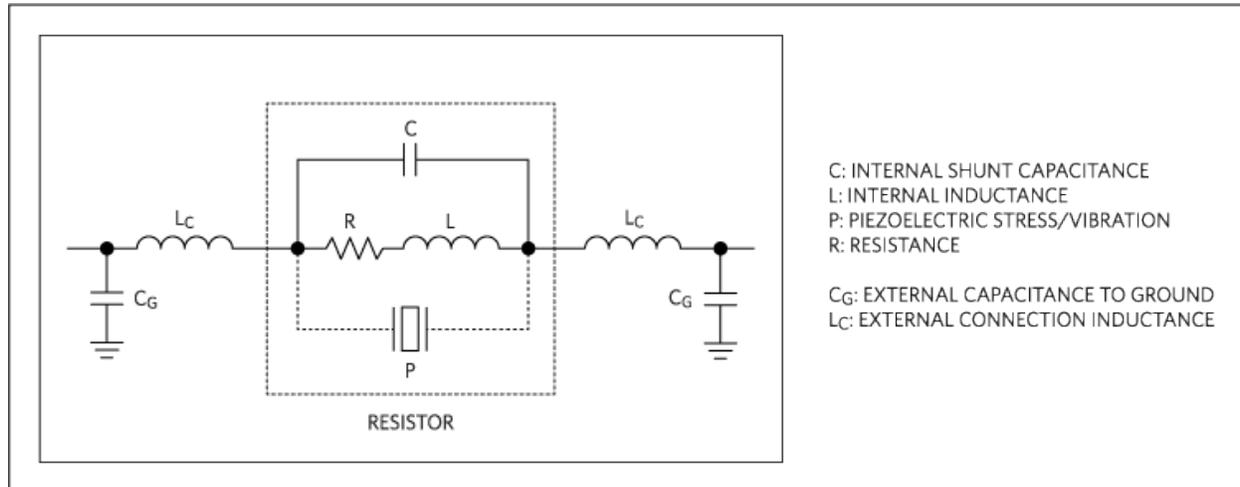


Figure 1. We may only want a resistor, the R above, but we also have all the other unavoidable parasitic components. We can minimize some parasitics, but they are always present.

To the right of the resistor we see the composite of all the network components. A frequency sweep of a sine wave shows the dominant RC high-frequency rolloff caused by resistor R and the right-side capacitor, C_G . The series inductors cause additional, but minor, high-frequency attenuation. Capacitor C and inductor L inside the resistor cause a minor frequency peaking. Yes, each of the parasitic components is small. Still, we need to consider them when designing circuits so we can decide whether or not to ignore them. For example, at audio frequencies we can choose to disregard the parasitics, but at radio frequencies we may have to adjust for them.

The piezoelectric element, P , is interesting as it influences performance during stress and vibration. (It also could represent a magnetostriction response to a magnetic field.) Stress can change the resistance depending on the resistor chemistry, and vibration can be converted into small AC voltages, which then add to the electrical noise. The solder stress is probably dominant and is important especially with surface-mount parts. Older designs with through-hole resistors allowed the leads to twist to absorb and mitigate most of the stress. Surface-mount parts, however, are held against a relatively rigid PCB. As the solder solidifies, these parts capture the change in thermal expansion between the resistor and PCB. To minimize the stress we must carefully follow the manufacturer's recommendations for solder time/temperature profile.

Let's now talk briefly about wire-wound resistors, often chosen because they have very low temperature coefficients (tempcos). These resistors also have an important, unique characteristic: its structure can react to magnetic fields. Because they are essentially a coil of wire, they magnify a magnetic field that a single conductor might pick up. As a coil, they also have more inductance than other types of resistors. We have seen circuits with transformers, inductors, and wire-wound resistors cross talk over small magnet fields. To mitigate these effects, careful layout, rotating components 90 degrees, increasing the spacing, and shielding may be necessary.

Finally, do not forget our friend Seebeck. Any dissimilar metal connections such as at the solder-to-board interface can cause small temperature-dependant offset voltages.

Manufacturing Tolerance, Power Rating, and Temperature Coefficient

Two other parameters, manufacturing tolerance and power rating (wattage), also impact resistor operation. In our last article⁴ on capacitors we explained how sorting and binning can distort manufacturing tolerances. This can also happen with some kinds of resistors. As a general rule, binning can cause performance problems for both manufacturers and customers if there is a process shift and then there is a large demand for the most precise item. A manufacturer can always ship more precise parts in place of low-precision parts, but the reverse is not true. For example, a 5% tolerance resistor could actually contain resistors with a tolerance between -5% to -2% and +2% to +5%. This is clearly not the full range between -5% through +5% that one might expect. If not enough high-precision devices are binned or if the customers only want the high-precision parts, then the manufacturer faces parts shortages.

Power rating is simple, right? Voltage times the current ($V \times I$) tells you what wattage rating to choose so the resistor does not burn up from self-heating. Right? No, wrong (or, maybe)? The answer, of course, depends on the application. A series resistor to limit current in a light-emitting diode (LED) can be a plain “vanilla” circuit where little additional concern is necessary. If the resistor has a negative tempco the resistance is reduced as the temperature increases. This, in turn, causes the resistor to draw more current at higher temperature, and that can contribute to overheating. At the other extreme, bias and modulation currents are critical in radio and laser communications systems.

Many systems including radio and laser communications systems need to remain stable over the operational temperature extremes. Centering the feedback loop over temperature and voltage changes requires deeper study. How much power is dissipated and how each of the components reacts, including the resistor, are important. In such circuits the laser must be cooled to keep it on frequency; the heat of the surrounding components (self-heating) must also be removed. What do you do? There are questions to ask and answer before your design goes any further.

- Is there air flow across the circuit?
- What is the temperature of the air at the critical circuit (not just the air entering the enclosure)?
- Was the air heated by another circuit?
- Many times the air is first routed to the circuit boards and then exits through the power supply. Now does the power-supply voltage change with temperature?
- Are there other systems racked together in the same enclosure?
- Are there fans? How does dust and dirt collect, and what happens if one or more fans fail?

Most resistors have a negative tempco, meaning that the resistance is reduced at higher temperatures. This also means that the resistor draws more power when heated. Each of us needs to carefully read a resistor's data sheet because the different chemistries and manufacturers may have different ways of specifying the tempco. The tempco curves can be just about any shape and they may be specified by the

“box method,” which is common for integrated circuits⁵ (ICs). Even a factory-trimmed part with thousands of transistors will show a family of curves over temperature and process variation. Simulation and correlation allow us to define a box that contains all the possible curves. The box “x axis” is the total operating temperature and the “y axis” the total magnitude of the error. Statistically we guarantee that the error of all

the parts is within the box, but we do not know the shape of the curve for any individual part.⁶ Specialized resistors called thermistors can have negative (NTC) or positive (PTC) tempcos, and the curves tend to be very nonlinear.

Basic Chemistry and Voltage Coefficient of Resistance (VCR)

What is inside IC resistors, i.e., the chemistry, is very important for understanding resistance. Designers and process engineers need to understand how chemistry in the manufacturing process affects resistor performance.⁷

In chemistry there are two broad classifications for things made of one or more chemicals. A compound is two or more chemicals that react to make something new. A mixture is multiple mixed chemicals that retain their original properties. Remember that the resistors with color bands on a brown shell are carbon composition resistors, CC. The CC resistors are mixtures and some of the contact points inside form semiconductors. They change resistance with heating, cooling, vibration, and applied voltage.

The high-voltage vacuum tubes (“valves” in the U.K.) remembered from our past history (and that still “resonate” for some audiophiles today) created “resistor distortion”⁸ that some people actually find pleasant. The distortion is caused by a voltage coefficient of resistance (VCR), a reduction in resistance value with an increase in voltage. In an audio system with a sine-wave signal of 75V peak-to-peak (V_{P-P}), biased at 50V, the resistor that sets gain will be at a higher resistance (gain) on the lower half of the sine wave and have a lower resistance and gain on the positive peak. This adds second-harmonic errors to the signal. This “resistor distortion” is soft and smooth in the onset of distortion, which, as mentioned above, some find pleasant. For most resistors the voltage-coefficient error only becomes measurable over 25V. Today most circuits are lower voltage so the resistor distortion tends to be ignored.

VCR is an important characteristic of high-voltage thick-film resistors.⁹ Typical thick-film ink consists of conductive material suspended in an insulating matrix. As the voltage across the ink is increased, new conducting paths are opened. The result is a drop in resistance. This means that the VCR is always negative in value. Thick-film resistors can be used as series-protection resistors in electrocardiogram (ECG) input circuits. These resistors help protect the ECG input from the 3kV to 5kV from defibrillator pulses.¹⁰

Obviously, we want the resistors to maintain their value and survive multiple voltage pulses. There are resistors with a VCR of < -1ppm to 5ppm over a large working voltage. With ECG, the humidity and the temperature performance of the resistor are critical. The resistor also must dissipate the heat energy of the defibrillator pulses.

Thus, while the IC designer does not define the internal chemistry of a circuitry, it is important to understand how chemistry affects the tolerance and tempco of the part. Once again, this speaks to the importance of studying the data sheet.

Thermal, White, or Johnson Noise

Thermal noise, also called Johnson noise, is present in all passive resistive elements and is caused by the random thermal motion of electrons. The thermal noise level is unaffected by DC current.

Resistors always generate noise, even when floating outside a closed circuit. This is white noise, which has a uniform spectral density and increases with temperature and resistance. Because some resistors are made of semiconductors, they can have other types of noise, such as shot, avalanche, flicker (1/f), and

popcorn noise¹¹ There is a free Thermal Noise Calculator and a User's Guide that further explain the different noise types.¹²

Conclusion

Good engineering is about the details and we are fortunate to be standing on the shoulders of engineering “giants.” Pioneering engineers like Dr. Zandman have struggled while researching physics and materials science, executing the careful work that produced the understanding that we rely on every day. As he observed, the seemingly small insignificant factors in an IC are many times taken for granted. This is certainly true for resistors that seem to be benign and passive, until their performance in a circuit startles us awake. That little resistor, in fact, dominates the circuit’s error budget. Tempco and manufacturing tolerance are just the start. That passive resistor can change value with voltage and actually lowpass filter a signal. The effect is unexpected and surprising until we look closely and realize that there is more to a resistor. Ultimately, the resistor that we tried to ignore is just following the laws of physics and we need to pay it special attention.

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