Author: Yuval Hernik
Tel: +972-54-3000191
E-mail: Yuval.Hernik@vishaypg.com

Reading Between the Lines in Resistor Datasheets

Don't believe everything you read. That rule applies not only to your daily news sources but also to component datasheets. In a perfect world, all datasheets would be based on terms that have the same meaning for every supplier. But they're not. Many datasheets should come with a warning label to the effect that terms like "tolerance" and "TCR" are being used loosely.

As an engineer, you need a healthy skepticism that allows you to decipher incomplete and misleading specifications. The need is particularly urgent given the increasing number of counterfeit sources of "precision" resistors that unscrupulous suppliers may try to disguise on datasheets with superfluous text, figures, marketing fluff, and half-truths with respect to specifications. The problem is not necessarily that data is being withheld, but that it's being mixed up in a confusing way. As elsewhere in life, the devil is in the details.

Realizing that design engineers are under great pressure to quickly assimilate the information in datasheets, we have prepared this article with the goal of offering a strategy that can help any person to reach the fundamentals in a precision resistor datasheet within a few minutes. To this end, we look at the key terms that turn up in these documents and review what they really mean.

Tolerance

Tolerance has many meanings, ranging from purchase tolerance (initial tolerance) to end-of-life tolerance (total error budget). The last thing you need know in the component selection process is the part's initial tolerance. The first thing you need to know is the required *end-of-life tolerance* of the design. You need to evaluate all the components for their expected changes after all of the stresses and exposures they might experience over the planned life of the equipment.

Every component must have an error budget assigned to it which, if exceeded, will cause the equipment to fall out of its performance specification, or possibly fail. In addition to initial tolerance, the error budget includes allowable shifts through shelf life, assembly, TCR, shock, vibration, humidity exposure, thermal shock, thermal EMF, load-life drift, ESD, radiation, and harmonic distortion (harmonic distortion is a measure of a component's conformance to Ohm's law as a predictor of reliability.) You then need to select a particular resistor technology with the least amount of change through all the stresses, add up all the expected ΔRs, and subtract these from the end-of-life tolerance limit to arrive at the purchase tolerance. The Bill of Materials

(BOM) then specifies the resistor model by resistance, tolerance, and possibly by TCR (usually typical or restricted to a narrow temperature range). Although not delineated on the BOM, each delta-R limit for the specified resistor technology is critical to the application.

This is why precision resistors with the same resistance, tolerance, and TCR but of different technologies are not interchangeable: because their changes through service life are not the same. Substitution on the basis of these alone could jeopardize performance and mission success. Only the OEM engineer who did the error budget analysis can determine a suitable substitute. Unfortunately, today we see more and more attempts by certain electronic manufacturing services to replace precision resistors with cheaper solutions that put system performance at risk.

To be considered as substitutes, all performance characteristics through all stresses and exposures must be completely and exactly defined in specific detail to be sure they qualify without reducing reliability or shortening equipment life.

Particularly for high-precision circuits using high reliability and tight tolerance resistors, it is not enough for the manufacturer to measure the resistors before shipment. Its equipment must be calibrated and traceable to the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards). Its measurements must also have a guard band that confines measurement error to the specified tolerance and applies this to 100% of the resistors. Also, the OEM must be assured that the resistors are within tolerance when received—not just "finessed" into a measured tolerance long enough to be listed as good for shipment (but not long after). Unfortunately many OEMs' incoming inspection checks are not sufficiently calibrated to measure tight tolerance resistors, so they must depend upon the suppliers' honesty. In addition, some companies have purchased components shipped directly to the production floor, bypassing incoming inspection completely. If the application is important, the supplier must be accessible for qualification inspection and periodic Q.A. audits.

The end customer must also evaluate whether a tolerance offered by a manufacturer is really practical. For example, some surface mount thin film chip resistors are offered in very tight tolerances for very low resistance values. That's impressive on the datasheet but not compatible with assembly processes. As these resistors are mounted on the board there is a resistance change due to solder heat. The solder terminations melt, flow, and re-solidify with changed resistance values. For low-value resistors the amount of resistance change is much greater than the specified tolerance. Having paid a premium price for an impractically tight tolerance, the customer ends up with looser-tolerance resistors once they're assembled on the PCB.

Temperature Coefficient of Resistance (TCR)

TCR is an area of particular concern because it is often misrepresented or incompletely defined. It is also a characteristic that influences circuit performance from the very first day of operation. Additionally, TCR is often used as an indication of a resistor's overall level of performance. It is assumed, and is generally true, that the lower the TCR, the more precise the resistor. So, if the TCR is not completely and accurately defined, that assumption is invalid and the use of that resistor invalidates all the accuracy, stability and reliability assessments made by the designer.

The TCR stated on datasheets comes from resistance measurements made after the resistors have stabilized at a specified temperature which defines the limits of a given temperature range, typically for 30 minutes at each temperature. In actual operation, resistors of different physical bodies have different thermal response times and, unlike the measurement conditions, the resistors in the circuit may all be operating at different temperatures from each other and from the ambient temperature. Different operating power levels, different proximities to other components, and other environmental factors will cause resistors to operate at different temperatures.

Industry protocols dictate standard measurement procedures. Typically, resistance measurements are made at a reference temperature, a lower temperature, and a higher temperature, and the TCR is defined as the delta-R/Rref in the cold range and the delta-R/Rref in the hot range. For military range applications, these would be 25°C, −55°C, and +125 °C, respectively. The TCR defined as ΔR/R vs ΔT, based on only two measurements (+25°C to −55°C, or +25°C to +125°C), assumes a linear TCR even though the ΔR/R = f(T) is a parabola. The characteristic TCR curve only appears to be linear since its basis is two measurements each in the hot range and the cold range, and two points always define a straight line even if they're actually points are on a curve. In fact the instantaneous TCR between these two temperature measurement end points could be much higher. So never assume that TCR is going to be the same over different temperature ranges, unless you're using Bulk Metal® Foil technology, which has such a low TCR that it is essentially linear over the full military temperature range.

Through various manipulations of temperature during production or materials doping during element development, that characteristic TCR curve may be rotated either clockwise or counter-clockwise (pivoted around the 25°C reference point). What the datasheet doesn't say is that the rotation that produces the lower TCR in one range also worsens the TCR in other temperature ranges. So you need to avoid being distracted by the TCR in the narrow range if this causes you to overlook the deterioration of the TCR in the other ranges. Unless the datasheet shows the complete TCR curve over the entire temperature range; you cannot tell what it is between the end test points and over temperature ranges other than the narrowly-focused partial temperature range.

In short, you need to know that the TCR of the resistors you're designing with is fully specified over all temperature ranges. Datasheets that do not delineate an important detail in one characteristic must be taken as suspect in all details. Further, the stress/strain balance throughout the entire temperature and power application ranges of precision resistors is such that it can exceed the elastic limit (Hooke's law) for any material used and therefore influence whether the performance criteria are repeatable and reliable. Resistor manufacturers never mention if the resistor is a Hookian body or not.

TCR Tracking

Some circuits require constant ratios among a number of resistors but not the absolute stability of each individual resistor. For example, the accuracy of an operational amplifier depends on the accuracy and stability of the *ratios* of the input, feedback, and bias resistors; if all resistors move together to maintain the constant ratio, the op amp accuracy remains constant. The resistor manufacturer may test resistors and select a set with a good TCR match to achieve the required ratio stability over a defined temperature range. But this neglects the power-induced divergence of resistance values through service life.

As described above, the TCRs of all the resistors are measured after the resistors are all stabilized at each desired temperature; then sets are selected for their proximate similarity of TCRs. However, in actual application the resistors do not all dissipate the same power, are not all in identical local temperature environments, and are not all at the same internal operating temperature. Therefore, the ratio changes are related to each resistor's absolute TCR in addition to their matched TCRs. For example, imagine a design where resistors with a ±10 ppm/°C absolute (independent) TCR need to be matched to within 2 ppm/°C of each other. If they all experience a 90°C increase in ambient temperature, one would expect that their ratio would change by 90°C x 2 ppm/°C = 180 ppm or 0.018%. But if one resistor is running at 100°C there is an additional error equal to the absolute TCR of 10 ppm/°C times the 10°C temperature difference for an additional error of 100 ppm for a total ratio error of 280 ppm, or 0.028%, which is far too much error for any precision application.

Using a set of Z-1 Foil Bulk Metal Foil resistors with ±0.2 ppm/°C TCR tracking in that same application would result in a much tighter ratio match over these temperatures. One resistor with a +0.2 ppm/°C TCR at 90°C would change +18 ppm (+0.0018%), the other with −0.2ppm/°C at 100°C would change −20 ppm (−0.0020%) for a total ratio change of 38 ppm (0.0038%) compared to 0.028% for the thin film resistor example. The error in the thin film matched TCR set is more than 7 times greater than the natural unmatched foil set with inherently low TCR. Moreover, resistors with inherently low TCRs will provide excellent TCR tracking even when the resistors are on different boards in different equipment at different locations.

For any important precision application in which the resistors might be at different internal operating temperatures, it is essential that the resistors have very low absolute TCRs, not just tightly matched (or relative) TCRs. Again, you need to have all the detailed specifications in addition to the promoted specifications (absolute TCR in this case as well as TCR match or track).

Last but not least: there is a common rule of thumb in the industry that says that the absolute TCR of each resistor shouldn't be more than 3 times the TCR tracking among the resistors of the set.

Moisture Resistance

Both MIL-PRF-55182 and MIL-PRF-55342 military resistor specifications include moisture resistance tests. MIL-PRF-55342 has no power applied during its moisture test while MIL-PRF-55182 has power applied at 100% of rated power. But this doesn't tell the whole story. Every epoxy and every plastic encapsulant absorbs moisture. Resistors experience temperature variations, humidity variations, and pressure variations. This draws moisture into the resistor. It might not be enough moisture to register a significant resistance change under static measurement, but the application may have serious consequences under various environmental conditions.

When the resistor is running very hot the moisture is driven out. But when the resistor is running at low DC power in the presence of moisture, the conditions are ripe for etching and catastrophic failure. There's not enough power (which translates into heat) to drive the moisture out, but there is still an electric field established across the resistance element. There are also impurities drawn into the resistor from the encapsulation materials and possibly some residual impurities remaining from production. In the presence of moisture these impurities can be deposited upon and etch parts of the resistance element. This phenomenon can open thin film resistors in just a few hours of operation.

The potential for etching is not an insignificant matter because designers try to run precision resistors at the lowest possible power for the smallest possible long-term load-life resistance change. The best power conditions for load-life stability are the worst power conditions for DC applications in high-humidity environments. Bulk Metal Foil resistors are subject to the same phenomenon as thin films but their resistive elements are hundreds of times thicker than thin film resistors and, therefore, require hundreds of times more chemistry to do the equivalent damage.

In this situation, be aware that the moisture resistance tests cited in the datasheets may not represent actual operating conditions and may not provide adequate warning of catastrophic failure.

Reliability/Stability

Every resistor technology has a range in which it operates at its best performance and reliability. But because of competitive pressures manufacturers extend their offerings to the highest value they can produce and sell. In every technology these extended range products do not perform with the same stability and reliability as their lower optimal resistance ranges. For best reliability one would be advised to avoid using the top third of resistance values offered in any one specific model and size by any manufacturer. A manufacturer may supply load-life or other data for his product and imply that it is representative of his product or technology. However, users must carefully evaluate that data to be sure it represents the full range of values supplied by the manufacturer. Otherwise, one might find that his circuit does not perform as planned because the performance of the actual values used is nowhere near the performance implied by the manufacturer's carefully selected samples in his limited range of best performing values. Also, one must beware of data presented on a few samples of only ten or twenty units. Such "representative" data is statistically insignificant. To be truly significant the data must come from many large lots of continuing tests over long periods of time, from many manufacturing lots, and include the full range of values offered.

Any designer of precision circuits for critical applications should demand specific data from his suppliers to be certain that the resistors are exactly what are needed. As much as possible the data should cover the resistance values required by the circuit and one should not assume that all resistors of a particular style, configuration, or technology have the same implied reliability.

Inductance/Frequency Performance and Noise

Precision wirewound resistors have both inductance and capacitance. The insulated wire is wound with many turns in layers around a plastic or ceramic bobbin. The bobbin has several separate sections known as "pi" sections. Typically the wire is wound in one direction in the first pi section then fed over a notch into the next section and wound in the opposite direction. This “reverse pi” winding is meant to reduce the inductance. In some cases the wire is taped down midway through the first pi, reverse-wound, and then duplicated in the next pi section to further reduce the inductance. The manufacturer then labels these resistors as “low inductance” but no claims are made for any specific inductance level because different resistor configurations, size, and resistance values use different wire diameters of different resistivity, and different length.

This inexact classification for inductance is hardly an adequate basis upon which to depend for any high-speed or high-frequency applications. Moreover, wirewound resistors are primarily inductive only in very low values, about 100 Ω and below. Above that, wirewound resistors are primarily capacitive. By focusing on their “non-inductive” winding techniques, manufacturers distract designers from the fact that the reactance in higher value resistors is primarily capacitive. For a manufacturer to give the exact amount of capacitance—or even an approximate amount—is extremely rare, almost non-existent.

Bulk Metal Foil resistors of equal or better precision have 0.1 µH maximum inductance and 0.5 pF maximum capacitance, as uniquely specified on their datasheets.

ESD

Every data sheet for precision resistors should include an ESD (electrostatic discharge) warning. Never ignore this warning, because ESD is always present and, like Murphy's Law, waiting to strike at the least opportune moment. Some users say that they do not worry about ESD because they use bipolar semiconductors or other circuit protection. This belief is a misconception, because 1500 V ESD can damage the thin film resistive layer, yet static charges can even be much higher than this. Always follow ESD-approved handling and installation procedures.

Conclusion

Resistor datasheets contain masses of information that aren’t always complete. This is why you might sometimes feel like you should send datasheets to the legal department to read the fine print. Although the first-page data is deliberately made very attractive, don’t rely on it to make design decisions without reading and understanding the rest of the datasheet. Many manufacturers supply samples so you can test the resistor before committing to use it. Take full advantage of these. There’s no substitute for testing a resistor in your circuit environment and verifying that you’ve got the right device.

Further information about Vishay Foil Resistors products is available at:
www.vishayfoilresistors.com

Follow Vishay Foil Resistors at: **http://twitter.com/FoilResistor**

For more information about this product group, please contact us at: **foil@vishaypg.com**