What's All This "Error Budget" Stuff, Anyhow?

Bob Pease | Jun 07, 2006

I was just on the phone explaining how to do an "error budget" analysis on some fairly simple circuits to a young engineer. Later, I mentioned this while I was visiting with my friend Martin, and he said he had been quite surprised when he found that many engineers in Europe were quite unfamiliar with the concept of an "error budget." How can you design a good circuit without being aware of which components will hurt your accuracy?

When I was a kid engineer back in 1962, my boss George Philbrick gave me a book on differential amplifiers by Dr. R. David Middlebrook, and he asked me to do a book review. I studied the book, and it was full of hundreds of partial differential equations. If you wanted the output of a circuit with 14 components, you could see a complete analysis of how each component would affect the output offset and gain. Each equation filled up a whole page. It did this several times.

Yet it didn't offer any insights into what's important. I mean, is b × d(R1) more important than R1 × d(b)? In retrospect, I'm glad I didn't submit any critique of that book. I woulda done more harm than good. Such a mess! Even now, it would be hard to write a critique on a book that was so true, but so unhelpful.

Things are much simpler now that people are mostly (but not entirely) designing with op amps. The best thing is that the output offset and dc gain and ac gain errors are largely orthogonal. An "operational" amplifier does perform, largely, an " operation" based on what task you ask it to perform when you "program it" with Rs and Cs. If the offset varies, the gain does not, and vice versa. We all agree that it's very helpful that you can compute what the performance will be with almost no interaction. No partial derivatives.

Now, let's take a look at a couple of applications—real circuits—and their tolerances within an error budget. Here is an amplifier to magnify the I × R drop of current through a 0.1-Ω resistor and bring it back down to ground. Figure 1 shows a conventional differential amplifier, with the common mode up at +12 V. The gain of −20 will bring the 1.0 A × 0.1Ω signal down to a ground level. If the current is 0.1 A, the output will be 0.2 V, "small-scale." A full-scale current of 1 A will bring the output up to 2.0 V, which is suitable to send to a detector or analogto-digital converter.

Let's select an op amp like the LMC6482B, with low offset voltage less than 1.0 mV. (There are other versions of this amplifier with less than 0.35 mV, but let's select an intermediate model.) This 1 mV does cause 21 mV of output error. This op amp has less than 20 pA of IB at all temperatures, so at least that's negligible. (Bipolar op amps might have small IB errors, but you'd have to check it.)

Now let's see what the resistors add. Assuming all Rs have a 1% tolerance, the gain of (2.0 V per A) has a tolerance of ±3%. This would cause ±60 mV at full scale, but only ±6 mV at "small scale" (0.1 A). This may be acceptable.

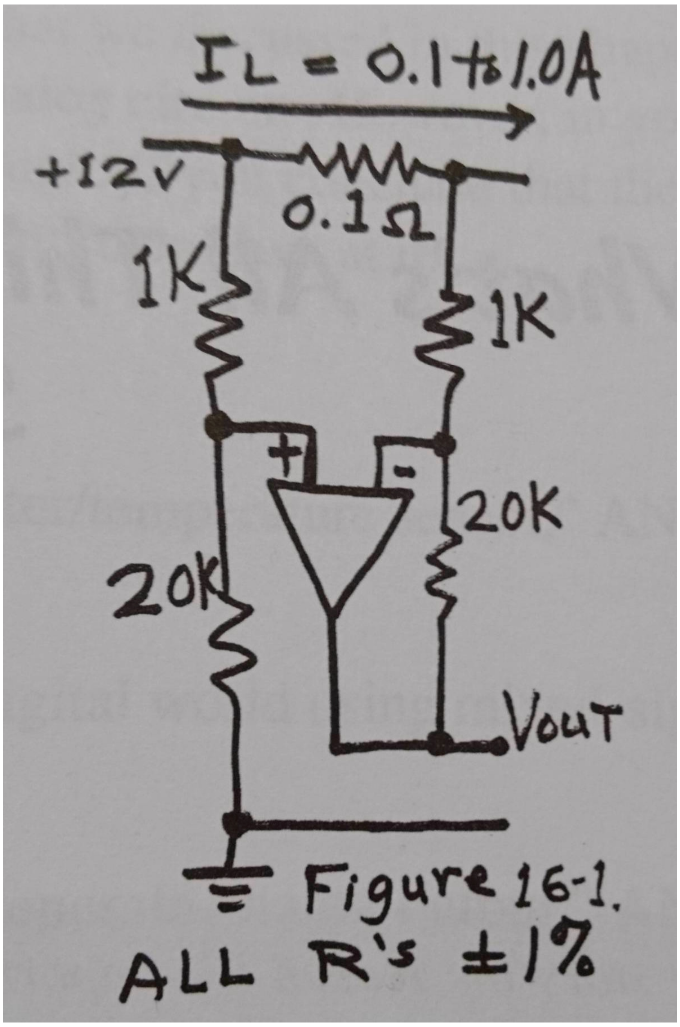

Figure 1

Then let's consider the common-mode errors. If R4 has a 1% tolerance, and it has 11.4 V across it, the 1% tolerance could cause a 114-mV error. By symmetry, a 1% error of each of R1, R2, R3 can cause another 114 mV! Added together, the common mode could cause an output error of 456 mV! That's about ±1/4 of full scale—even for small signals. That doesn't look so good to me!

It's true that if adjacent 1-kΩ resistors are inserted, they're likely to match within ±1/2% so the probable error between the pair might cause ±60 mV, and the ±1/2% matching between the 20 kΩ would cause another 60 mV. That added to the 21 mV from the VOS would add to 141 mV.

Some textbooks teach you that you should add these errors arithmetically to 141 mV. Others point out that they could be added in an RMS way, so that 60 + 60 + 21 mV = 87 mV. Typically, this might be true. But the worst case of 141 or 456 mV might be more realistic. I mean, if you're going to build 1000 circuits, and most of them are better than 141 mV, what are you going to do with the 400 circuits that are worse than 141 mV? And, that's still 7% of full-scale....

You could go shopping for 0.1% resistors, but they aren't cheap. You could put in a trim-pot to trim the error to (no offset error) for small signals. But as you may have noticed, a trim-pot has to be properly trimmed. And if that pot is accessible, it could someday be mistrimmed, and it would have to be corrected, in some awkward calibration cycle. Most people want to avoid that trim-pot. Before we decide that this 141 mV is unacceptable, let's look at another circuit.

Figure 2 shows an alternative circuit with the same gain, 2.0 V per A, using a PN4250 or 2N4250, a high-beta pnp transistor. What does the error budget look like? The same op amp causes just 20 mV of output error. The 1% resistor tolerances cause the same gain error, 60 mV at full scale, or 6 mV at "small scale." The newly added transistor adds (?1/3%) max from its alpha, or less than 7 mV, at full scale.

What is the offset error due to common-mode rejection ratio (CMRR), or due to resistor mismatch? Nothing. Zero. The transistor doesn't care about the voltage across it. There are no resistors with 12 V across them.

So the offset error is ±20 mV, due primarily to the amplifier's VOS (which could be reduced), not ±400 mV. This little circuit has greatly reduced errors compared to Figure 1, even if Figure 1 had a couple bucks of 0.1% resistors. This may be acceptable. Even the offset errors could be reduced to 7 mV by selecting the LMC6482A.

So we have seen that circuits with similar functions can have completely different "error budgets." I love to recommend amplifiers with high CMRR. But depending on cheap 1% resistors can hurt your "error budget" a lot more than you'd suspect.

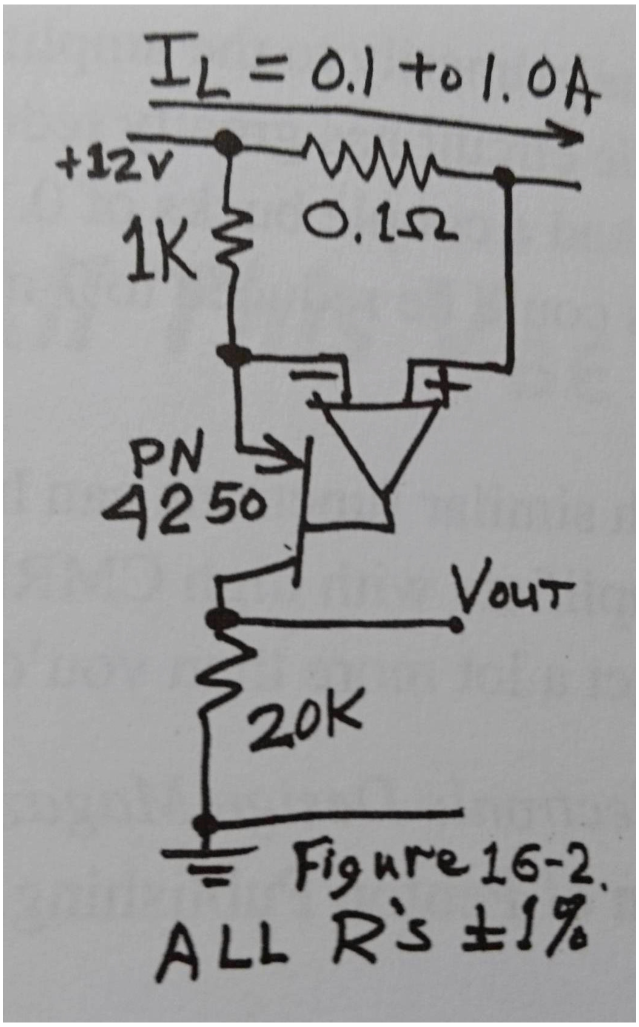

Figure 2