Technical Article

Designing with Low-power Op Amps, Part 1: Power-saving Techniques for Op-amp Circuits

Daniel Miller

In recent years, the popularity of battery-powered electronics has made power consumption an increasing priority for analog circuit designers. With this in mind, this article is the first in a series that will cover the ins and outs of designing systems with low-power operational amplifiers (op amps).

In the first installment, I will discuss power-saving techniques for op-amp circuits, including picking an amplifier with a low quiescent current (I_Q) and increasing the load resistance of the feedback network.

Understanding power consumption in op-amp circuits

Let's begin by considering an example circuit where power may be a concern: a battery-powered sensor generating an analog, sinusoidal signal of 50 mV amplitude and 50 mV of offset at 1 kHz. The signal needs to be scaled up to a range of 0 V to 3 V for signal conditioning (Figure 1), while saving as much battery power as possible, and that will require a noninverting amplifier configuration with a gain of 30 V/V, as shown in Figure 2. How can you optimize the power consumption of this circuit?

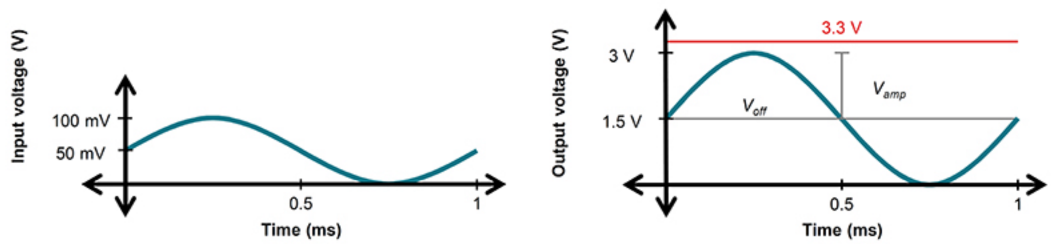

Figure 1. Input and output signals

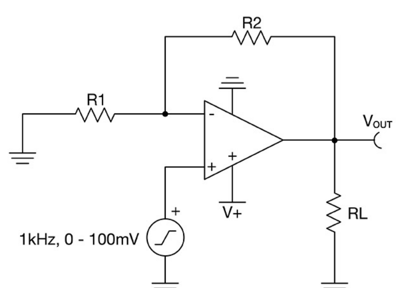

Figure 2. A sensor amplification circuit

Power consumption in an op-amp circuit consists of various factors: quiescent power, op amp output power, and load power. The quiescent power, $P_{Quiescent}$, is the power needed to keep the amplifier turned on and consists of the op amp's I_Q, which is listed in the product data sheet. The output power, P_{Output}, is the power dissipated in the op amp's output stage to drive the load. Finally, load power, P_{Load}, is the power dissipated by the load itself. My colleague, Thomas Kuehl, in his technical article, "Top questions on op-amp power dissipation – part 1," and a TI Precision Labs video, "Op Amps: Power and Temperature," define various equations for calculating power consumption for an op amp circuit.

In this example, we have a single-supply op amp with a sinusoidal output signal that has a DC voltage offset. So we will use the following equations to find the total, average power, $P_{total,avg}$. The supply voltage is represented by V_+. V_{off} is the DC offset of the output signal and V_{amp} is the output signal's amplitude. Finally, R_{Load} is the total load resistance of the op amp. Notice that the average total power is directly related to I_Q while inversely related to R_{Load}.

$$P_{total,avg} = P_{Quiescent} + P_{Output} + P_{Load} \quad (1)$$

$$P_{Quiescent} = V_+ \times I_Q \quad (2)$$

$$P_{Output} = \frac{(V_+ \times V_{off}) - \frac{{V_{amp}}^2}{2} - {V_{off}}^2}{R_{Load}} \quad (3)$$

$$P_{Load} = \frac{\frac{{V_{amp}}^2}{2} + {V_{off}}^2}{R_{Load}} \quad (4)$$

$$P_{total,avg} = (V_+ \times I_Q) + \frac{(V_+ \times V_{off}) - \frac{{V_{amp}}^2}{2} - {V_{off}}^2}{R_{Load}} + \frac{\frac{{V_{amp}}^2}{2} + {V_{off}}^2}{R_{Load}} \quad (5)$$

$$P_{total,avg} = (V_+ \times I_Q) + \frac{(V_+ \times V_{off})}{R_{Load}} \quad (6)$$

Picking a device with the right I_Q

Equations 5 and 6 have several terms and it's best to consider them one at a time. Selecting an amplifier with a low I_Q is the most straightforward strategy to lower the overall power consumption. There are, of course, some trade-offs in this process. For example, devices with a lower I_Q typically have lower bandwidth, greater noise and may be more difficult to stabilize. Subsequent installments of this series will address these topics in greater detail.

Because the I_Q of op amps can vary by orders of magnitude, it's worth taking the time to pick the right amplifier. TI offers circuit designers a broad selection range, as you can see in Table 1. For example, the TLV9042, OPA2333, OPA391 and other micropower devices deliver a good balance of power savings and other performance parameters. For applications that require the maximum power efficiency, the TLV8802 and other nanopower devices will be a good fit. You can search for devices with your specific parameters, such as those with ≤10 µA of I_Q, using our parametric search.

Table 1. Notable low-power devices

Typical specifications	TLV9042	OPA2333	OPA391	TLV8802
Supply voltage (V_S)	1.2 V-5.5 V	1.8 V-5.5 V	1.7 V-5.5 V	1.7 V-5.5 V
Bandwidth (GBW)	350 kHz	350 kHz	1 MHz	6 kHz
Typical I_Q per channel at 25°C	10 µA	17 µA	22 µA	320 nA
Maximum I_Q per channel at 25°C	13 µA	25 µA	28 µA	650 nA
Typical offset voltage (V_{os}) at 25°C	600 µV	2 µV	10 µV	550 µV
Input voltage noise density at 1 kHz (e_n)	66 nV/√Hz	55 nV/√Hz	55 nV/√Hz	450 nV/√Hz

Reducing the resistance of the load network

Now consider the rest of the terms in Equations 5 and 6. The V_{amp} terms cancel out with no effect on $P_{total,avg}$ and V_{off} is generally predetermined by the application. In other words, you often cannot use V_{off} to lower power consumption. Similarly, the V_+ rail voltage is typically set by the supply voltages available in the circuit. It may appear that the term R_{Load} is also predetermined by the application. However, this term includes any component that loads the output and not just the load resistor, R_L. In the case of the circuit shown in Figure 1, R_{Load} would include R_L and the feedback components, R_1 and R_2. Hence, R_{Load} would be defined by Equations 7 and 8.

$$R_{Load} = R_L \,||\, (R_1 + R_2) \qquad (7)$$

$$R_{Load} = \frac{R_L \times (R_1 + R_2)}{R_L + (R_1 + R_2)} \qquad (8)$$

By increasing the values of the feedback resistors, you can decrease the output power of the amplifier. This technique is especially effective when P_{output} dominates $P_{Quiescent}$, but has its limits. If the feedback resistors become significantly larger than R_L, then R_L will dominate R_{Load} such that the power consumption will cease to shrink. Large feedback resistors can also interact with the input capacitance of the amplifier to destabilize the circuit and generate significant noise.

To minimize the noise contribution of these components, it's a good idea to compare the thermal noise of the equivalent resistance seen at each of the op-amp's inputs (see Figure 3) to the amplifier's voltage noise spectral density. A rule of thumb is to ensure that the amplifier's input voltage noise density specification is at least three times greater than the voltage noise of the equivalent resistance as viewed from each of the amplifier's inputs.

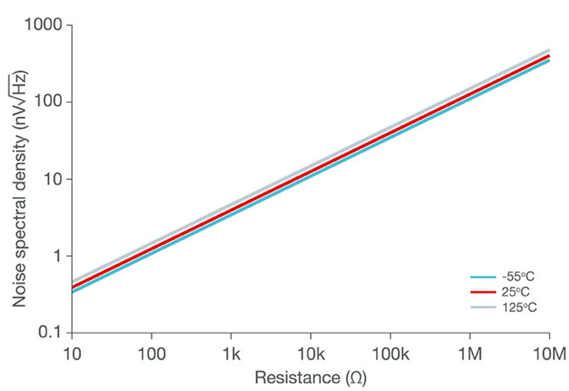

Figure 3. Resistor thermal noise

Real-world example

Using these low-power design techniques, let's return to the original problem: a battery-powered sensor generating an analog signal of 0 to 100 mV at 1 kHz needs a signal amplification of 30 V/V. Figure 4 compares two designs. The design on the left uses a typical 3.3-V supply, resistors not sized with power-savings in mind and the TLV9002 general-purpose op amp. The design on the right uses larger resistor values and the lower-power TLV9042 op amp. Notice that the noise spectral density of the equivalent resistance, approximately 9.667 kΩ, at the TLV9042's inverting input is more than three times smaller than the broadband noise of the amplifier in order to ensure that the noise of the op amp dominates any noise generated by the resistors.

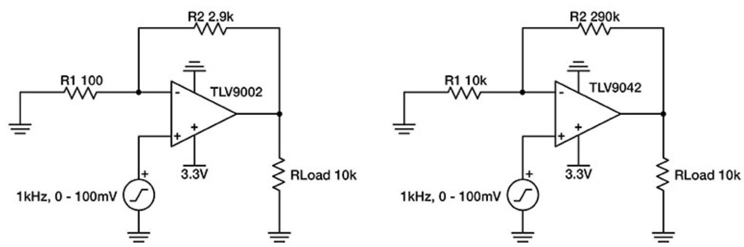

Figure 4. A typical design vs. a power-conscious design

Using the values from Figure 4, the design specifications and the applicable amplifier specifications, Equation 6 can be solved to give $P_{total,avg}$ for the TLV9002 design and the TLV9042 design. For your reading convenience, Equation 6 has been copied here as Equation 9. Equations 10 and 11 show the numeric values of $P_{total,avg}$ for the TLV9002 design and the TLV9042 design, respectively. Equations 12 and 13 show the results.

$$P_{total,avg} = (V_+ I_Q) + \frac{V_+ V_{off}}{R_{Load}} \quad (9)$$

$$P_{total,avg,TLV9002} = (3.3\ V \times 60\ \mu A) + \frac{(3.3\ V)(1.5V)}{10\ k\Omega\ ||\ (100\ \Omega + 2.9\ k\Omega)} \quad (10)$$

$$P_{total,avg,TLV9042} = (3.3\ V \times 10\ \mu A) + \frac{(3.3\ V)(1.5V)}{10k\Omega\ ||\ (10\ k\Omega + 290\ k\Omega)} \quad (11)$$

$$P_{total,avg,TLV9002} = 2.343\ mW \quad (12)$$

$$P_{total,avg,TLV9042} = 0.545\ mW \quad (13)$$

As can be seen from the last two equations, the TLV9002 design consumes more than four times the power of the TLV9042 design. This is a consequence of a higher amplifier I_Q, demonstrated in the left terms of Equations 10 and 11, along with smaller feedback resistors, as accounted for in the right terms of Equations 10 and 11. In the case where more I_Q and smaller feedback resistors are not needed, implementing the techniques described here can provide significant power savings.

Conclusion

I've covered the basics of designing amplifier circuits for low power consumption, including picking a device with low I_Q and increasing the values of the discrete resistors. In part 2 of this series, I'll take a look at when you can use low-power amplifiers with low voltage supply capabilities.

Additional resources

- Catch up on other installments in the "Designing with low-power op amps" series.
- Keep reading with the next installment in this series, "Designing with low-power op amps, part 2: Low-power op amps for low-supply-voltage applications."
- Learn how to work with op amps in TI Precision Labs - Op amps, a series of on-demand tutorials covering basic to advanced topics.