Understanding noise in linear regulators

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Types of noise in analog circuits may include thermal, flicker, and shot noise, among others. In an LDO application, noise is sometimes confused with power supply ripple rejection (PSRR). Many times the two are lumped together and loosely called "noise" just because both cause unwanted signals on the output. This is incorrect. PSRR refers to the amount of ripple on the output coming from ripple on the input. Noise, on the other hand, is purely a physical phenomenon that occurs with transistors and resistors (capacitors are noise-free) on a very fundamental level.

Noise in an LDO is indicated in two fashions. One is spectral noise density, a curve that shows noise ($\mu V/\sqrt{Hz}$) versus frequency. The other is integrated output noise, also commonly called output noise voltage (in μV_{rms}); it is simply the spectral noise density integrated over a certain frequency range and can therefore be thought of as the total noise in a specified frequency range. Since the output noise voltage is represented by a single number, it is very useful for comparison purposes.

Typically, noise in an LDO is specified as output-referred noise (noise occurs throughout the LDO but eventually must be referred to the output). The typical approach to finding the output-referred noise of an LDO is first to refer all noise contributors to the input of the LDO differential amplifier. To *refer* means to divide each individual noise contributor by the gain that exists between it and the op amp input (assuming the noise contributor is located downstream on the signal path). The next step is now to refer the total input-referred noise to the output by multiplying by the closed-loop gain of the feedback network. The closed-loop gain of an LDO is simply

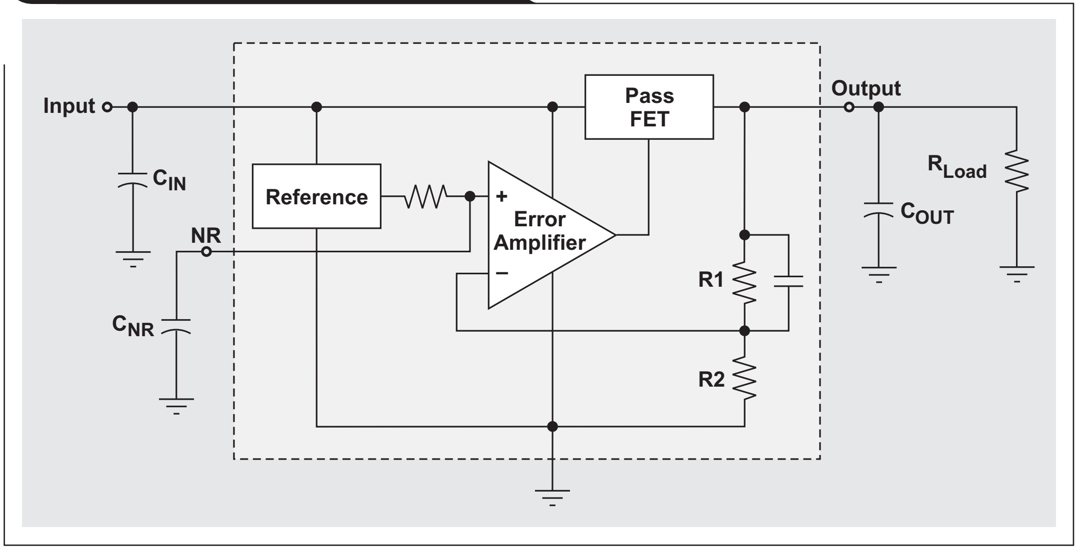
$$A_{CL(DC)} = \frac{V_{OUT}}{V_{BG}},$$

where V_{BG} is the internal bandgap reference. In many cases V_{BG} is about 1.2 V (although some LDOs have sub-bandgap references and thus a V_{BG} of less than 1.2 V). An LDO with an output voltage of 3.0 V will have almost twice the output noise voltage of a 1.5-V LDO; therefore it's very important when comparing noise on various LDOs always to compare those with identical output voltages. When this isn't possible, an approximation can be made by simply taking into account the ratio of the two output voltages. For example, when comparing the noise voltage of a 3.0-V LDO to that of a 1.5-V LDO, either multiply the noise voltage of the 1.5-V LDO by 2 or divide the noise voltage of the 3.0-V LDO by 2.

The simplified block diagram in Figure 1 shows the primary noise sources in an LDO-the bandgap, the resistor divider, and the input stage of the op amp. The effects of some of these noise sources can be reduced if the latter are properly understood.

The dominant source of noise in an LDO is usually the bandgap. In most cases this is solved by adding a large low-pass filter (LPF) to the bandgap output so that none of the noise makes it into the gain stage. (This same filter

Figure 1. Simplified LDO block diagram



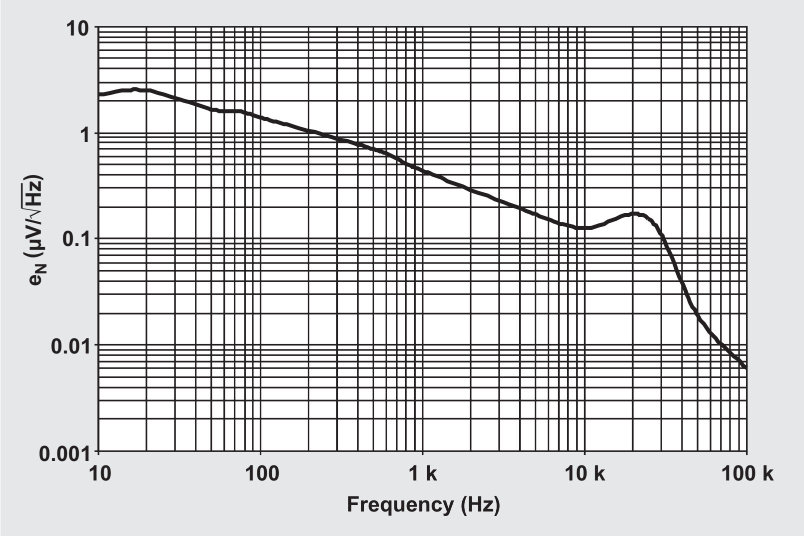
is also used to improve PSRR.) Typically this LPF is formed with a large internal resistor and an external capacitor. In most cases the cutoff frequency of this filter is set somewhere between 1 and 500 Hz, therefore filtering out nearly all of the noise coming from the bandgap. In many cases the down side of using too large an RC filter is that the time to charge the filtered bandgap increases drastically, which significantly slows down the output startup. This can be solved by using a low-noise, high-PSRR LDO with a fast-charge circuit such as the TPS793/4/5/6xx or one from the TPS799xx family. Even with a fairly large noise reduction capacitor of 0.01 µF, these LDOs are still able to start up in only 50 to 100 µs.

Another source of noise in an LDO is the resistor divider network. This noise is known as thermal noise and is equal to 4kTR (sometimes called 4kTR noise), where k is Boltzmann's constant, T is temperature in Kelvin, and R is the resistance. The resistor divider is tied to the input of the LDO differential amplifier, so this noise is amplified by the closed-loop gain of the LDO. When calculating this noise source, you can simply use the parallel combination of R1 and R2 since the op amp input sees them as being virtually in parallel. Therefore, to reduce this noise source, the most important thing to remember is that smaller feedback resistors create less thermal noise. Of course, the disadvantage of using smaller resistors is that they burn more current through the feedback divider; but if noise is of prime importance, then this sacrifice must be made.

The other source of noise is the internal LDO differential amplifier, which is usually designed in such a way that the input stage has a large amount of gain—more specifically, transconductance (g_m). This is done so that any noise coming from devices in the signal path located after the input stage have their noise attenuated by the gain of the input stage when they are referred back to the input. There is nothing outside of the internal circuitry that can be done to reduce this noise source.

Many people are surprised that the huge power pass FET, which usually takes up at least half of the total die area in an LDO, isn't a primary noise contributor. The reason for this is the lack of gain. All of the primary noise sources (bandgap, resistor divider, and op amp input stage) are connected to the input of the differential amplifier and thus are not attenuated by any internal gain. Remember that the procedure for finding output noise is first to refer each noise contributor to the op amp input; so to find the noise from the pass FET you would first divide its noise contribution by the open-loop gain that exists between it and the op amp input. This gain is typically quite large; therefore, the noise contribution from the pass FET is usually negligible.

Figure 2. Spectral noise density example



Also somewhat surprising is that neither the output capacitor, the load current, nor even the input voltage has any direct effect on the output noise, at least to a first order. However, load current and output capacitance do have an indirect second-order effect. As mentioned previously, output noise is calculated by multiplying the input-referred noise by the closed-loop gain. The closed-loop gain isn't constant at V_{OUT}/V_{BG} over the entire frequency range, and of course it eventually rolls off at high frequencies. A fundamental rule of feedback analysis is that low phase margin will cause peaking in the closed-loop gain near the unity-gain frequency. Since the closed-loop gain amplifies the noise, this peaking increases the noise in that frequency range even more, thus increasing the total output noise. This effect can often be seen in spectral noise density plots like the one in Figure 2.

High load currents and low output capacitance contribute to output noise because they both make the LDO less stable, which reduces the phase margin. This phase margin reduction increases the closed-loop gain peaking, which in turn increases the output noise. Another significant effect is that many times a higher equivalent series resistance (ESR) capacitor will actually reduce noise. This is because a larger ESR creates a lower-frequency zero, which many times may improve the LDO stability. Finally, note that the peaking effect explains why, as previously mentioned, the output noise voltage of a 3.0-V regulator usually isn't quite twice as much as that of a 1.5-V regulator. A 3.0-V regulator tends to be a bit more stable than a 1.5-V regulator due to its lower feedback factor. This improved stability increases the phase margin, reducing the closed-loop peaking and thus the output noise voltage.

One final trick sometimes used to reduce noise is to add a capacitor across the top resistor in the resistor feedback divider. This works because at high frequencies the capacitor begins to reduce the closed-loop gain and thus the noise, so that the system begins to look like a unity-gain feedback configuration providing no noise gain. The tradeoff is that this could potentially slow down start-up time significantly, since the capacitor would have to be charged by the current in the resistor divider. The TPS799xx implements this technique via an internal capacitor and also includes a fast-charge circuit.

In summary, there are many ways to reduce noise in an LDO application. The most important is to start with a low-noise, high-PSRR LDO optimized for low-noise applications such as one from the TPS793/4/5/6xx family or the low-I_q TPS799xx family. The second way is to use as large a noise-reduction capacitor as is feasible for startup while keeping in mind that there's a point where increasing this capacitance will offer no further improvement. Finally, use small resistances for the resistor divider network (if the LDO is an adjustable version) and a small capacitor across the top resistor, if possible. Some less obvious improvements are to optimize the output capacitor along with the load current for the highest phase margin to reduce closed-loop peaking. Many times, stability can be optimized by using the stability plots provided in some LDO data sheets.

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