

An LDO Primer

Part III: A Review on PSRR and Output Noise

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In Parts I and II of this article series, we discussed the factors that determine the dropout voltage, ground current, output current, regulation, stability and compensation of a linear regulator. These factors are intrinsic to the linear regulator.

For this third installment of the article series, we will focus on two key application-oriented parameters of the linear regulator that can be adjusted externally to the linear regulator: Power Supply Ripple Rejection (PSRR) and output noise. These parameters have been discussed before (see “References”). This article provides a practical and straightforward approach that is useful to design engineers of many experience and education levels.

Note: although “ripple” and “noise” are generally interchangeable, this article defines “ripple” as the fluctuation induced by an external disturbance coupled to the input of the linear regulator. “Noise” is the fluctuation intrinsic to the linear regulator itself. Therefore, “ripple” is used in the PSRR analysis section, and “noise” is used in the noise analysis section.

In review, there are three key elements in a linear regulator:

1. A pass element
2. A bandgap voltage reference (bandgap)
3. An error amplifier

PSRR

PSRR is defined as the linear regulator’s ability to eliminate output ripple caused by input variations. High PSRR values are desirable over the frequency range critical to the linear regulator (10Hz to 10MHz typical). Mathematically, PSRR is the *reverse* gain of the output ripple over the input ripple at a particular frequency. For LDOs, specifically, the PSRR is given as:

$$\text{PSRR} = 20\log(|A_V/A_{VO}|), \text{ expressed in dB} \quad (\text{Equation 1})$$

*where A_V is the open-loop gain of the feedback loop, and A_{VO} is the gain from V_{IN} to V_{OUT} when feedback loop is open.

The PSRR of a linear regulator is determined by three factors:

1. The PSRR of the bandgap voltage reference, whose output ripple affects the output ripple of the linear regulator up to the roll-off frequency of the bandgap.
2. The open-loop gain of the feedback loop (A_V), which is roughly equal to the open-loop gain of the error amplifier, up to the 0dB (unity gain) crossover frequency (Equation 1).
3. The open-loop gain from V_{IN} to V_{OUT} (A_{VO}), which is determined by the parasitic parameters of the pass element and values of external components (especially the output capacitor) along the V_{IN} to V_{OUT} path, starting from the 0dB crossover frequency (Equation 1).

The PSRR of the bandgap is a critical contributor to the PSRR of the linear regulator, up to the bandgap’s roll-off frequency, since any bandgap output ripple gets amplified by the error amplifier, which in turn propagates the amplified ripple through the pass element to V_{OUT} . There is no universally accepted theory to prove that one processing technology is superior to another for constructing high PSRR bandgap voltage references. In practice, PSRR values of bandgaps, based on both bipolar and CMOS technologies, are comparable.



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In addition to having a bandgap with high PSRR, it is a common practice to “bypass” its output ripple to the ground through a low-pass filter, before it reaches the error amplifier input. The low-pass filter is typically constructed with an internal resistor and an external capacitor. Its roll-off frequency should be as low as possible (100Hz typical), which enables it to filter out high frequency output ripple. This means the value of the RC should be high. Typically, the internal resistor has a very high value -- in the hundreds of KΩ range. The external capacitor usually has a relatively low value -- in the nF or even hundreds of pF range. This is because a capacitor that is too large negatively impacts the start-up response of the linear regulator (Figure 1, using a P-channel FET regulator as example).

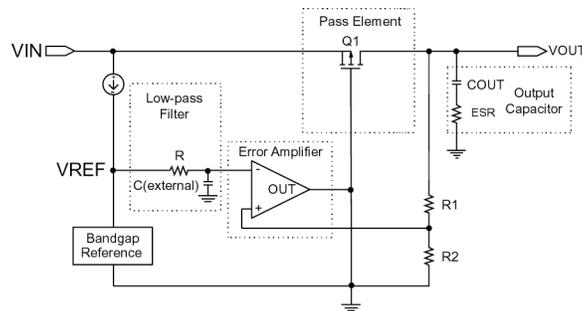


Figure 1. P-channel FET regulator with a low-pass filter and output capacitor.

The open-loop gain of the feedback loop (A_v) is the critical contributor to the PSRR of the linear regulator, above the roll-off frequency of the bandgap low-pass filter and up to the 0dB crossover frequency. There are two determining parameters:

1. The open-loop gain of the error amplifier, which is roughly equal to the open-loop gain of the feedback loop, up to the 0dB crossover frequency. As Equation 1 shows, the higher the open-loop gain of the error amplifier, the better the PSRR.
2. The structure of the pass element, which determines the 0dB crossover frequency (on first order approximation). It is desirable to have the 0dB crossover frequency as high as possible, from a PSRR performance standpoint.

In addition to increasing the open-loop gain of the error amplifier, it is a common practice to increase the 0dB crossover frequency to improve the PSRR. From application perspective, this is typically accomplished by manipulating the capacitance of the output capacitor.

Beyond the 0dB crossover frequency, the parasitic parameters of the internal and external components along the V_{IN} to V_{OUT} path, including the pass element and the output capacitor, start to dominate, with the capacitance of the output capacitor being most significant. Improving the PSRR in this frequency range is typically accomplished by increasing the capacitance of the output capacitor.

For the standard NPN regulator, in which dominant pole compensation is used, we established in Part II of this article series that the frequency of the dominant pole is given by:

$$f(P_{INT}) = 1/2\pi R_{INT}C_{INT} \quad \text{(Equation 2)}$$

*where R_{INT} and C_{INT} are the regulator's intrinsic resistance and capacitance

The addition of an output capacitor, which is not required for loop stability, “increases” the regulator's intrinsic capacitance C_{INT} . Equation 2 shows that the increased intrinsic capacitor moves the dominant pole to a lower frequency. This effectively decreases the 0dB crossover frequency, and reduces the PSRR between the new and old 0dB crossover points. As a result, although the added output capacitor filters out more ripple and therefore improves the PSRR beyond the 0dB crossover point, its impact on the overall PSRR below the 0dB crossover frequency is negative. As such, it is common practice to not add an output capacitor to the

standard NPN regulator to improve its PSRR performance, unless high PSRR values beyond the 0dB crossover frequency and low overall output noise are critical to the application (Figure 2).

Figure 2

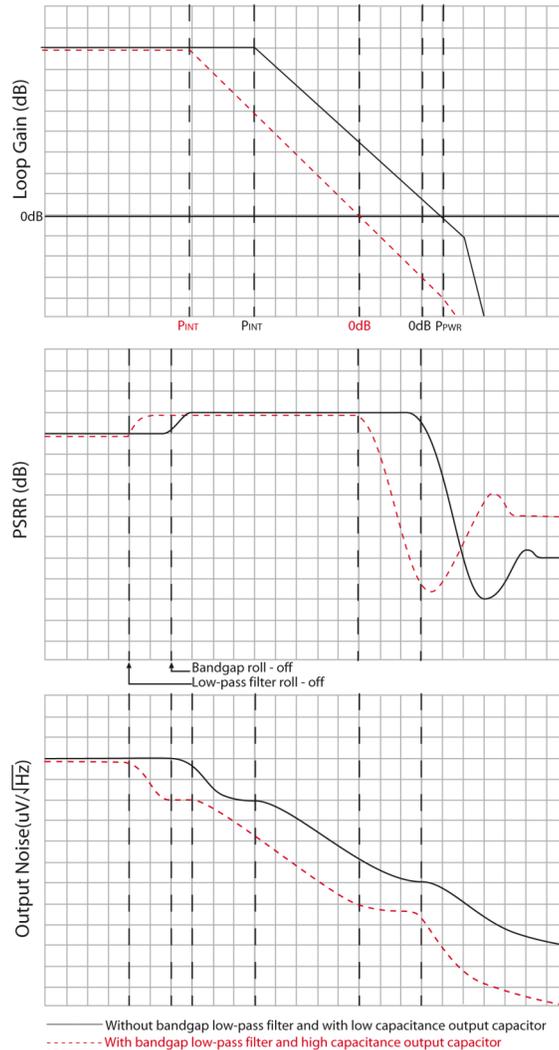


Figure 2. Standard NPN Regulator PSRR and Output Noise

Things are a little more complicated for the NPN pass transistor regulator, which also has an intrinsic dominant pole but requires an output capacitor for stability. Again, from Equation 2, we can see that increasing the capacitance of the output capacitor moves the dominant pole to a lower frequency, which decreases the 0dB crossover frequency.

However, as we also established in Part II of this article series, one of the functions of the output capacitor is to add a ZERO to keep the loop stable. The frequency of the ZERO is given by:

$$f(Z_{COMP}) = 1/(2\pi \times ESR \times C_{OUT}) \quad \text{(Equation 3)}$$

As we can see from Equation 3, increasing the capacitance of the output capacitor reduces the frequency of the ZERO, which actually increases the 0dB crossover frequency.

Therefore, in theory, whether the added capacitance increases or decreases the 0dB crossover frequency for the NPN pass transistor regulator cannot be easily determined, at least on first-order approximation. In practice, the added capacitance typically decreases the 0dB crossover

frequency because $f(P_{INT})$ drops faster than $f(ZERO)$ with an increase in the output capacitor. This effectively reduces the PSRR between the old and new 0dB crossover points. If improving the PSRR at a high frequency and reducing overall output noise are not critical, the common practice is to decrease the output capacitance in order to improve the PSRR (Figure 3).

Figure 3

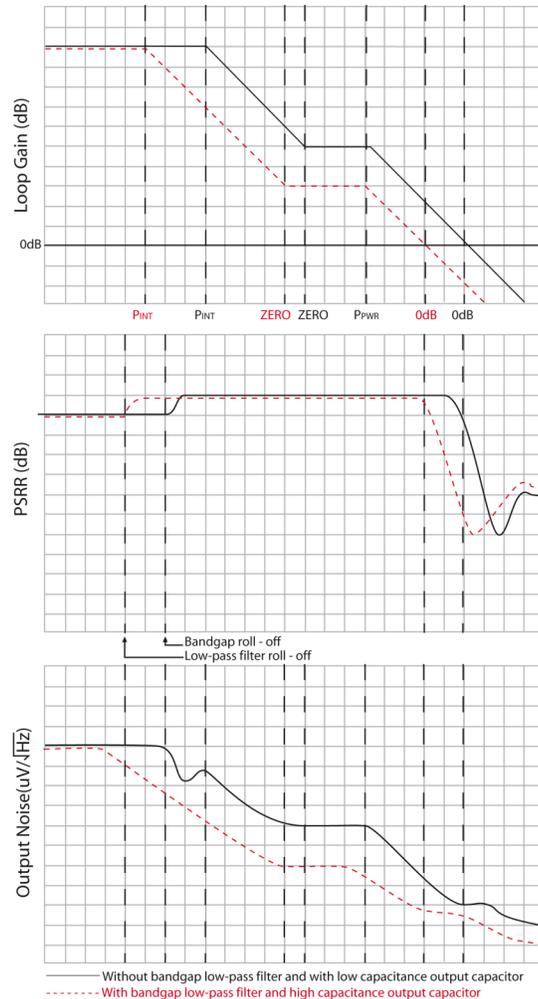


Figure 3. NPN Pass Transistor Regulator PSRR and Output Noise

The same conclusion is applicable to the N-channel FET regulator (Figure 6).

The PNP pass transistor regulator is different from the NPN-type regulators. In Part II of this article series, we established that the impedance of the load adds a low frequency first-order load pole (P_L) to the Bode Plot of the regulator, the frequency of which is given by:

$$f(P_L) = 1/(2\pi R_{LOAD} C_{OUT}) \quad \text{(Equation 4)}$$

As one can see from Equation 4, increasing the capacitance of the output capacitor decreases the frequency of the load pole, which effectively lowers the 0dB crossover frequency and decreases the PSRR between the old and new 0dB crossover point. Therefore, one way to improve the PSRR of the PNP pass transistor regulator is to do just the opposite – to actually decrease the capacitance of the output capacitor. However, this does increase the overall output noise (Figure 4).

Figure 4

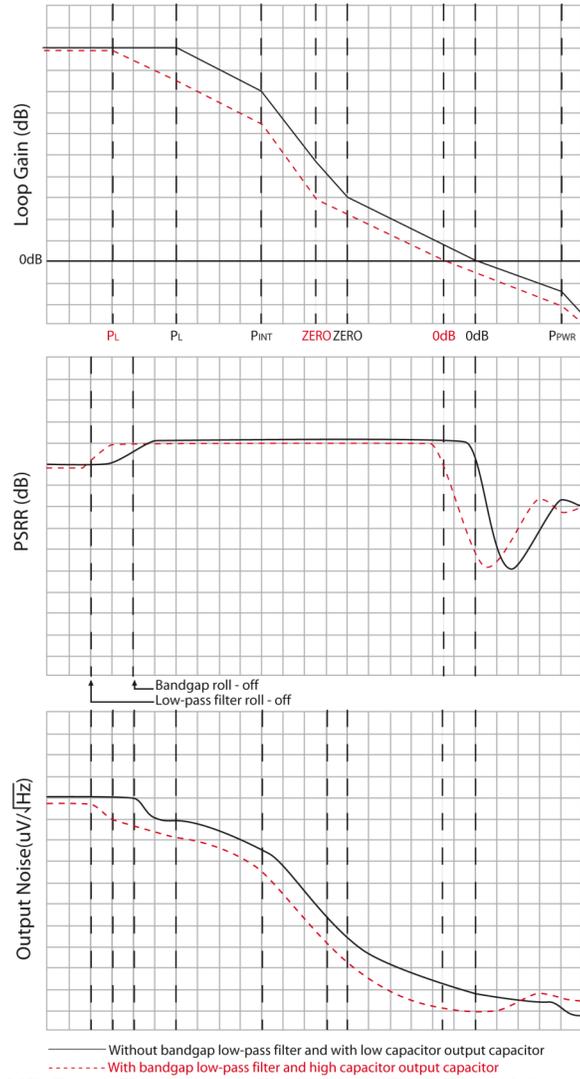


Figure 4. PNP Pass Transistor Regulator PSRR and Output Noise

The same analysis is applicable to the P-channel FET regulator (Figure 5).

Figure 5

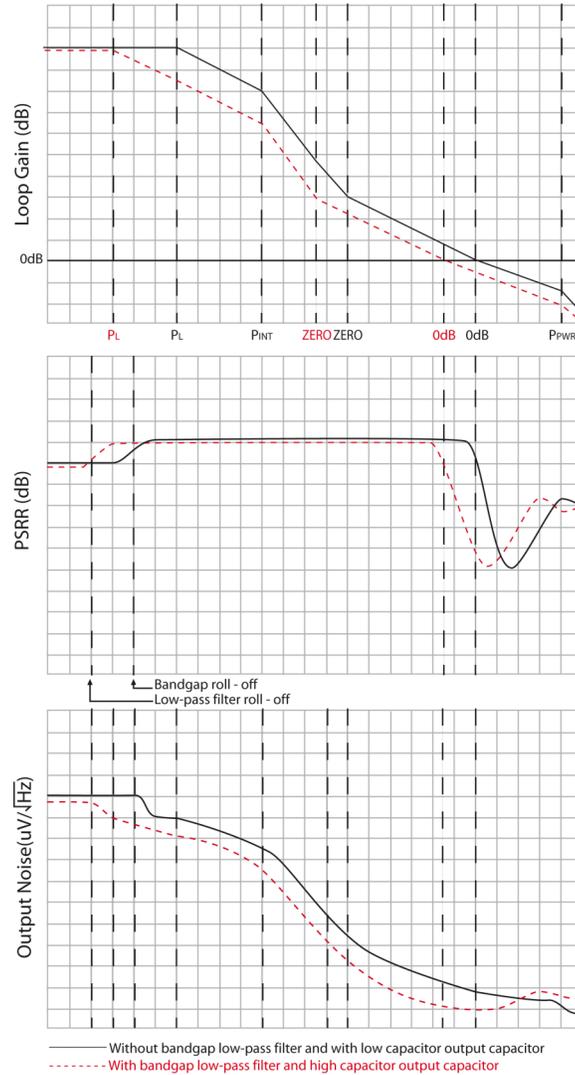


Figure 5. P-Channel FET Regulator PSRR and Output noise

Output Noise

The output noise of a linear regulator is illustrated by a “noise density” curve that shows the noise density [in the unit of $\mu\text{V}/\sqrt{\text{Hz}}$] vs. frequency. On most linear regulator datasheets, an overall output noise, expressed in μV_{rms} or mV_{rms} , is included. The overall output noise is the noise density integrated over a frequency range at which the linear regulator is sensitive.

The output noise of a linear regulator is amplified, self-generated noise, as opposed to the output ripple, which is induced by input disturbances. There are two primary sources of self-generated noise: the resistor divider and the bandgap. Both are inputs to the error amplifier. This means that the output noise is directly related to the open-loop gain of the error amplifier, which is essentially the open-loop gain of the feedback loop. Because of this, the output noise density curve looks very much like the loop gain curve of the Bode Plot developed in Part II of this article series. This is also the reason why the pass element is not a primary source of output noise, because its self-generated noise is not amplified through the feedback loop (Figure 1).

The resistor divider generates thermal related noise – the so called $4kTR$ noise, where k is the Boltzmann’s constant, T is the temperature expressed in Kelvin, and R is the impedance of the

resistor pair. It is obvious that, in order to reduce this noise, the R1 and R2 need to be small. However, smaller R1 and R2 values make the resistor divider consume more current, which reduces the efficiency of the linear regulator. Design trade-offs need to be made for each application.

One should always use a bandgap with low output noise below its roll-off frequency. Again, there is no universally accepted theory to prove that one processing technology is superior to another for designing low-noise bandgap voltage references. In practice, the output noise of bandgap designs, based upon both bipolar and CMOS technology, are comparable.

Since both the bandgap's input-induced output ripple and self-generated output noise manifest as output fluctuations with the same bandgap roll-off frequency, the same low-pass filter used to reduce its output ripple (to improve its PSRR) can also be utilized to reduce its output noise. The low-pass filter "bypasses" both the output ripple and output noise to the ground, to prevent them from propagating to the output of the linear regulator, down to its roll-off frequency.

Unfortunately, the similarity between improving the PSRR and reducing the output noise of a linear regulator stops here.

Because the noise density curve behaves like the loop gain curve and the overall output noise is an integral of the noise density over a certain frequency range, it is easy to see that, in order to reduce the overall output noise, it is actually desirable to have a lower open-loop gain and lower 0dB crossover frequency, just the opposite to what is required to improve the PSRR!

Because of the standard NPN regulator's high 0dB crossover frequency, its intrinsic output noise performance is not good. As we discussed in the PSRR section of this article, adding an output capacitor lowers the 0dB crossover frequency. As a result, although the added output capacitor does not improve the PSRR below the 0dB crossover frequency, it decreases the output noise below the 0dB crossover frequency, as well as above it. Therefore, if reducing the output noise is critical to the application, an output capacitor should be used (Figure 2).

For the NPN pass transistor regulator, the intrinsic output noise is lower than that of the standard NPN regulator since its 0dB crossover frequency is not as high. Again, as discussed in the PSRR section of this article, more output capacitance typically decreases the 0dB crossover frequency, which worsens the PSRR but reduces the overall output noise (Figure 3).

The same conclusion is also applicable to the N-channel FET regulator (Figure 6).

Figure 6

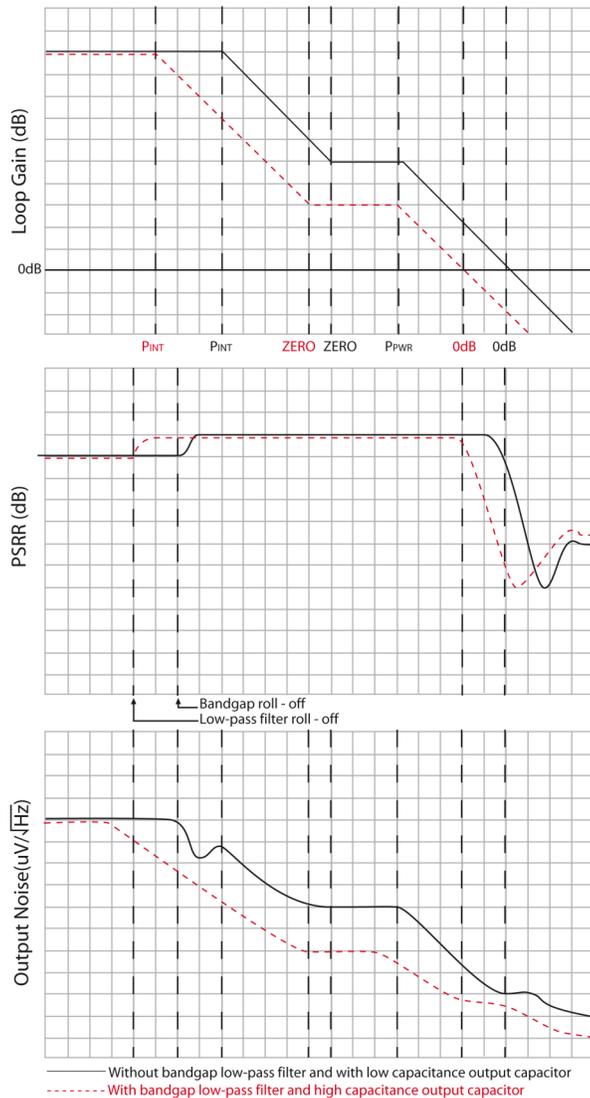


Figure 6. N-Channel FET Regulator PSRR and Output Noise

For the PNP pass transistor regulator, however, the opposite is true. First of all, it has lower 0dB crossover frequency than NPN-type regulators, which gives it low output noise. In addition, as we concluded from Equation 2, increasing the output capacitor decreases the 0dB crossover frequency, resulting in reduced overall output noise (Figure 4).

The same analysis is applicable to the P-channel FET regulator (Figure 5).

Conclusion

In a linear regulator, the PSRR and output noise performance of the bandgap voltage reference can be improved by adding a low-pass filter on its output to the error amplifier.

However, adding an output capacitor or increasing its value, which is the most effective way to improve the PSRR and overall output noise performance, produces opposite results for these two application-oriented parameters. Basically, the added or increased output capacitor reduces the 0dB crossover frequency. A higher 0dB crossover frequency improves the PSRR but increases the overall output noise, and a lower 0dB crossover frequency reduces the overall output noise

but decreases the PSRR. Good design trade-offs need to be made on a case-by-case basis at particular frequencies or frequency ranges, based upon application requirements.

Of course, the output capacitor must be sized for the resistive load, so there are limits in changing its capacitance value.

In addition, improving amplifier gain and control loop compensation also help improve PSRR and output noise. However, improving amplifier gain and control loop compensation are internal to the linear regulator design and not application-oriented. This places them outside the scope of this article.

PSRR and Output Noise Comparisons of Different Types of Linear Regulators

Regulator Type	Standard NPN (Darlington)	NPN Pass Transistor	PNP Pass Transistor	P-channel FET	N-channel FET
Bandgap PSRR	Comparable	Comparable	Comparable	Comparable	Comparable
Bandgap Noise	Comparable	Comparable	Comparable	Comparable	Comparable
Method to increase PSRR and reduce output noise for the bandgap	Low-pass filter on bandgap output	Low-pass filter on bandgap output	Low-pass filter on bandgap output	Low-pass filter on bandgap output	Low-pass filter on bandgap output
Intrinsic PSRR without bandgap (over frequency range)	High	Somewhat high	Fair	Fair	Somewhat high
Method to increase overall PSRR (minus bandgap)	Internal	Decrease the capacitance of the output capacitor			
Intrinsic Output Noise without bandgap (over frequency range)	High	Somewhat high	Fair	Fair	Somewhat high
Method to reduce overall output Noise (minus bandgap)	Add output capacitor	Increase the capacitance of the output capacitor	Increase the capacitance of the output capacitor	Increase the capacitance of the output capacitor	Increase the capacitance of the output capacitor

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