

Second-Stage LC Filter Design

by Dr. Ray Ridley

Power supply output voltages are dropping with each new generation of Integrated Circuits (ICs). Anticipated current level reductions have not materialized, and the problem of switching power supply noise is pervasive. Reducing noise with a conventional single-stage filter seldom works. The inductor is already large, and dropping the noise an order of magnitude just isn't feasible. For this reason, many designers add a second "noise" filter at the output of their power supply. The filter typically consists of an additional small inductance, and a small, high-quality capacitor. This seemingly intuitive approach can often lead to an unstable system. The mistake is in designing with large components followed by small components.

Designing a single-stage filter is straightforward. The inductor is selected to give about 20% current ripple, and the capacitor is chosen with sufficiently low ESR to meet the output ripple requirements. The output holdup and step-load requirements also impact the choice of capacitor.

The resonance of a single-stage filter is typically not a critical concern. It is inside the feedback loop bandwidth (either current-mode or voltage-mode control) and its peaking and resonance effects are eliminated by the feedback. *Figure 1* shows a typical single-stage filter designed for a point-of-

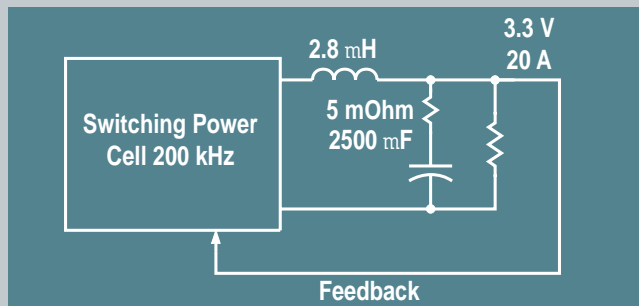
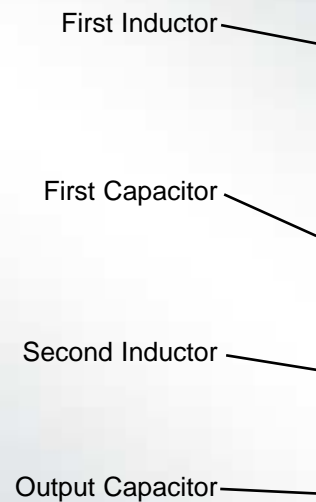


Fig. 1: Point-of-Load Buck Converter with Single-Stage Filter

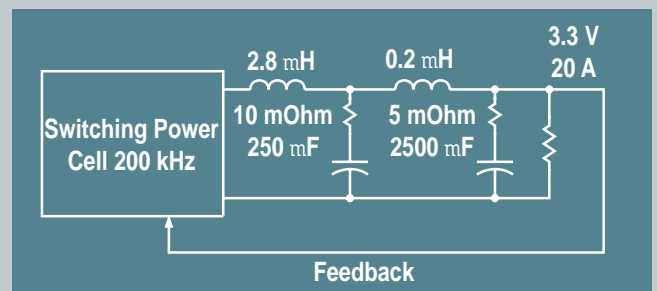


Fig. 2: Point-of-Load Buck Converter with Two-Stage Filter

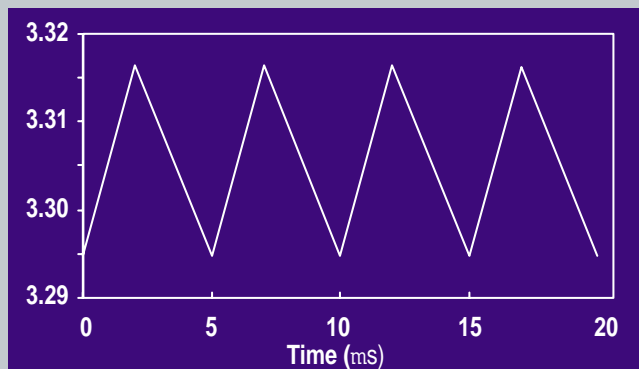


Fig. 1a: Output Voltage Ripple of the Circuit of Fig. 1

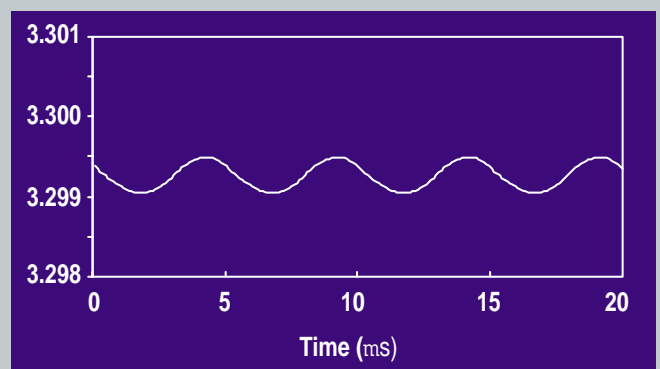


Fig. 2a: Output Voltage Ripple of the Circuit of Fig. 2



load converter, and *Figure 1a* shows the output voltage ripple with this filter.

Figure 2 shows a two-stage filter. This is used to reduce the ripple without substantially increasing the volume of power components needed. A two-stage filter is far more effective than a single stage, because components can be smaller for the same amount of attenuation. In fact, with this design, adding only 10% more capacitance and inductance gives more than 30 times reduction in output ripple, as shown in *Figure 2a*. Notice that the scale of *Figure 2a* is enlarged— 3 mV full scale, compared to 30 mV full scale for the ripple of the single-stage filter.

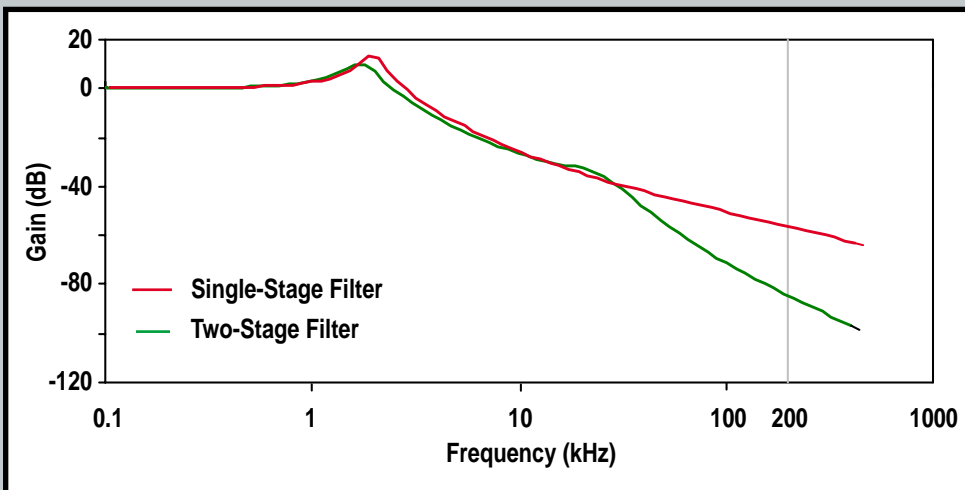


Fig. 3: Output Filter Transfer Functions

Figure 3 shows what happens to the filter transfer function with two stages. It still has a low frequency resonance close to the single stage resonance, and this will be controlled by the feedback loop. The second filter resonance for this example is at 22 kHz. You can see from the transfer functions that the additional attenuation is more than 28 dB at the switching frequency. Furthermore, the additional phase delay (not shown here) is less than 15 degrees at 10 kHz, so stability is not significantly affected.

The second filter resonance that you get with a two-stage filter must be placed very carefully— beyond the control loop crossover to avoid stability problems, but at a low enough frequency to attenuate both the switching frequency ripple and the high frequency noise. This presents a challenge to the designer. Furthermore, the design of the filter must be robust and stable under worst case conditions of line, load, and any extra capacitance the user may add.

Most two-stage filters are designed in as an afterthought. The converter is finished, but the noise is too high, and there is only room and time to put some small components on the board. This works when the converter is tested on the bench, but when placed in the application, load bypass capacitors can significantly change the filter characteristics, reducing the second resonance to a frequency where it causes instability. To understand a better way to do it, let's look at the analysis of the two-stage filter system.

Analyzing the Filter

It is important to know how the components of the two-stage filter interact. Recognize that the inductors of the two-stage filter are very different in size— the first inductor is largest, in order to constrain the ripple currents in the power semi-conductors. Select it on this basis, as you would for a single-stage design.

There are two pairs of poles for this filter. They determine the location and characteristics of the resonant frequencies shown in *Figure 3*. These poles are given by:

$$\Delta(s) = \left[1 + \frac{s}{\omega_l Q_l} + \frac{s^2}{\omega_l^2} \right] \left[1 + \frac{s}{\omega_h Q_h} + \frac{s^2}{\omega_h^2} \right]$$

There are two resonances— a low frequency resonance, and a high frequency resonance. The first resonant frequency is calculated from the circuit of *Figure 4*.

$$\omega_l = \frac{1}{\sqrt{LC_p}}$$

where C_p is the parallel combination of capacitors:

$$C_p = C_1 + C_2$$

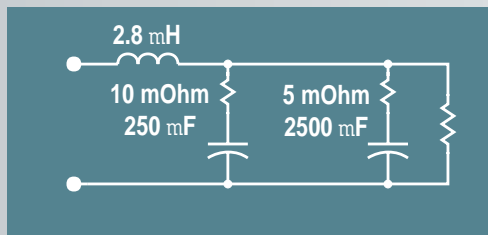


Fig. 4: Low-frequency circuit for calculating first resonance

In other words, we add the capacitor values together to get the first resonance formed with the big inductor.

This resonant frequency won't move much with capacitive loading. There is usually sufficient capacitance in the filter that any load capacitance won't significantly change the value. Even with a 2:1 change, the filter resonance would only move by 40%, and stability will not be a problem.

The Q of the first resonance is not very interesting. We'll close a control loop around it, and use the feedback to cancel the filter peaking effects.

The second filter frequency is given by the circuit of Figure 5.

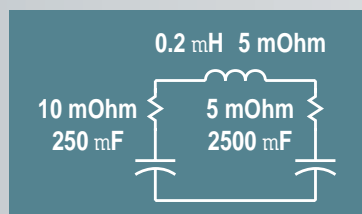


Fig. 5: High-frequency circuit for calculating second resonance

$$\omega_h = \frac{1}{\sqrt{L_2 C_s}}$$

where C_s is the series combination of capacitors given by:

$$C_s = \frac{1}{\left(\frac{1}{C_1} + \frac{1}{C_2}\right)}$$

this expression is dominated by the smaller of the two capacitors. This creates an interesting design choice.

If the output capacitor, C_2 is smaller, the second resonance is very sensitive to any capacitive loading by the application. In fact, load capacitance can make the system unstable.

If the first capacitor, C_1 , is smaller, the second resonance is insensitive to capacitive loading, and system stability can be maintained with significant load capacitance. This is the proper way to design two-stage filters.

In most applications the second filter resonance is placed beyond the crossover frequency of the feedback loop. (We'll examine in a future issue of Switching Power Magazine whether that can be changed for some converters— an interesting possibility brought up recently by one of our readers.) We must control this resonance very careful, by fixing the resonant frequency, and then by controlling the peaking with damping elements. This is similar to input filter design. We don't directly damp the resonances with a control loop, so we must damp them with resistive components.

The Q of the second filter is given by:

$$Q_h = \frac{1}{\omega_h C_s (R_1 + R_2 + R_3)}$$

For good design, the Q of the second stage filter should be one or less. It is usually necessary to compromise the attenuation of the filter to achieve this. Increasing the inductor resistance, R_3 ,

would allow us to damp the two-stage filter without sacrificing attenuation, but this increases the dissipation of the filter. For the filter design of Figure 2, the ESRs of all three reactive elements contribute to the filter damping.

With this analysis, it's easy to design the second filter. The smaller capacitor has to be carefully selected to carry the full ripple current from the inductor. In some power supplies, this entails using a different type of capacitor. Even though it is ten times smaller in capacitance for the example in this article, the ESR has to be a similar value to the output capacitor. For commercial applications, this often leads to film capacitors for the first stage, and electrolytic or tantalum capacitors on the output.

Industry Application

Since this filter technique was first developed, many companies have adopted it as the standard way to design. This is the technique used by IBM in the design of all load regulators for their mainframes described in this magazine. The photograph in this article shows three 2-kW converters. Two of them are mounted next to each other, and the third is shown on its side to reveal the hidden components. The main inductor is a large EE core, with a single bus bar through each window. These bus bars mount to the first capacitor, which is a low-ESR film type.

A second, smaller EE core is clamped around the bus bars to form the second inductor, and the output of this feeds a bank of electrolytic capacitors. The EE core construction with bus bars forms a very low-capacitance inductor for each of the filter stages, and helps with both differential-mode, and common-mode filtering.

If your power supply is too noisy, but there is not much space to increase filter components, a two-stage filter is the only practical solution. Follow the design rules in this article and you can have it all— low noise output, small filter components, stable operation, and immunity from capacitive loading.

Design Rule #1: Don't think of the filter as "Main filter followed by Noise filter", that can get your design in trouble. It's an integral filter which you won't separate that way when you design it properly.

Design Rule #2: Make the first capacitor the smaller of the two. Then you'll have a second filter resonance which is fixed—it won't be affected by capacitive loading. Typically, the first capacitor will be 2-20 times smaller than the output capacitor

Design Rule #3: Make the second inductor much smaller than the first— typically about 10% of the main inductor value.

Design Rule #4: Put the second filter resonance about 3 times higher than the loop crossover frequency.

Design Rule #5: Damp the second filter resonance properly. That means carefully choosing the ESR of the second inductor and the filter capacitors.