Application Report

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Optimizing the TPS62130/40/50/60/70 Output Filter

Matt Guibord

Battery Power Applications

ABSTRACT

The TPS6213x/4x/5x/6x/7x family of devices uses a variation of the inherently stable hysteretic control called DCS-Control™, though this topology is not itself inherently stable. However, use of this control topology does allow for a wider range of inductor and output capacitor values than traditional voltage mode control buck converters. This allows more lenience in choosing inductor and output capacitor values to accomplish specific design goals, such as transient response, loop stability, maximum output current, or output voltage ripple, based on an application's needs. This application report discusses how to choose the output filter for any of the TPS62130, TPS62140, TPS62150, TPS62160, or TPS62170 high Vin buck converters in order to meet the specific requirements of a design.

1 Choosing an LC Combination

The designer must consider many factors when choosing an inductor and output capacitor combination for any switching regulator. For example, lower inductances can be physically smaller due to fewer windings, which can save board space; however, this causes the peak switch current and output voltage ripple to increase. Larger voltage ripple can be offset by using a higher capacitance at the cost of larger size and slower transient response.

Stability is also a key factor that the inductor and capacitor values affect. The LC filter forms a double pole in the control loop, which has a strong impact on the frequency response and system stability. Table 1 shows the stability of different LC combinations that have been tested in the laboratory with an input voltage of 12 V and a load current of 1 A at an output voltage of 3.3 V with the device running in high frequency mode. Although the stable combinations in the table satisfy the requirements for control loop stability, certain combinations may not work in every system due to other measures of performance, such as output voltage ripple, load transient response, or maximum output current.

Table 1. Stability vs Effective LC Corner Frequency

Nominal Inductance Value	Nominal Ceramic Capacitance Value (effective = 1/2 nominal)								
	4.7 µF	10.0 µF	22 µF	47 µF	100 µF	200 µF	400 µF	800 µF	1600 µF
	Effective Corner Frequencies								
0.47 µH	151.4 kHz	103.8 kHz	70.0 kHz	47.9 kHz	32.8 kHz	23.2 kHz	16.4 kHz	11.6 kHz	8.2 kHz
1.00 µH	103.8 kHz	71.2 kHz	48.0 kHz	32.8 kHz	22.5 kHz	15.9 kHz	11.3 kHz	8.0 kHz	5.6 kHz
2.2 µH	70.0 kHz	48.0 kHz	32.4 kHz	22.1 kHz	15.2 kHz	10.7 kHz	7.6 kHz	5.4 kHz	3.8 kHz
3.3 µH	57.2 kHz	39.2 kHz	26.4 kHz	18.1 kHz	12.4 kHz	8.8 kHz	6.2 kHz	4.4 kHz	3.1 kHz
4.7 µH	47.9 kHz	32.8 kHz	22.1 kHz	15.1 kHz	10.4 kHz	7.3 kHz	5.2 kHz	3.7 kHz	2.6 kHz
10.0 µH	32.8 kHz	22.5 kHz	15.2 kHz	10.4 kHz	7.1 kHz	5.0 kHz	3.6 kHz	2.5 kHz	1.8 kHz

	Recommended for TPS6213x/4x/5x/6x/7x
	Recommended for TPS6213x/4x/5x only
	Stable without Cff (within recommended LC corner frequency range)
	Stable without Cff (outside recommended LC corner frequency range)
	Unstable

Table 1 shows control loop stability versus effective corner frequency and indicates the corresponding nominal inductance and capacitance. The white and blue cells are within the data sheet's recommended LC range and are thus stable. While the white cells are recommended for all TPS6213x/4x/5x/6x/7x devices, the blue cells are recommended for the TPS6213x/4x/5x devices only. The green cells are within the data sheet's recommended LC corner frequency range and have been found to be stable. The gray cells are outside the data sheet's recommended range, but have been tested and were found to be stable. The yellow cells have been tested and were determined to be unstable by containing more than three rings in their load transient response, which indicates low phase margin (see SLVA381).

The corner frequencies listed are based on the effective inductance and capacitance, but the nominal values are indicated in the table. The effective capacitance takes the dc bias effect of ceramic capacitors into account. All of the capacitors used had X5R dielectric and were rated for 6.3 V. By a rough metric for capacitance versus dc voltage, the effective capacitance at a 3.3-V bias is about half the nominal capacitance. The inductors chosen had saturation currents large enough such that the effective inductance is approximately equal to the nominal inductance. The 1-µH to 4.7-µH inductors were from the Coilcraft XFL4020 series and the 0.47- µH inductor was a Vishay IHLP-1616BZ-01.

2 Optimizing Load Transient Response

The load transient response describes the controller’s ability to recover from sudden changes in output current, such as those caused by a processor changing states. The amount of voltage deviation and the time that the controller takes to recover are the main measures of a controller’s load transient performance.

The response time of the controller is directly related to the bandwidth of the control loop. A higher bandwidth allows the controller to respond faster. Because the control loop compensation is fixed inside the integrated circuit, the bandwidth is primarily impacted by the corner frequency of the LC filter, which forms a double pole in the control loop. The corner frequency of the filter is given as:

$$f_{LC} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Higher LC corner frequencies allow for higher control loop bandwidths. To increase the LC corner frequency, decrease the product of the inductance and capacitance.

Secondly, the amount of voltage deviation that occurs during a change in load must be restricted to keep the power supply voltage within the requirements of the system. This can especially pose a problem for processors that may operate incorrectly at low voltages. Two main things determine the amount of voltage deviation: the output capacitance and control loop bandwidth. From the equation I = C × dV/dt, the output voltage deviation in response to a load step is defined as:

$$V_{DEV} = V_{OUT}(t_2) - V_{OUT}(t_1) = \frac{1}{C}\int_{t_1}^{t_2}\left[i_L(t) - i_{Load}(t)\right]dt \tag{2}$$

Where t_1 is the time the load step begins, and t_2 is the time that the average inductor current equals the new load current (see Figure 1). The time between t_1 and t_2 is an initial time period during which the output capacitor must supply the extra load current, and therefore, the capacitor voltage must decrease. From Equation 2, the most obvious way to reduce this initial deviation is to use a larger capacitance. It is worth noting that a larger capacitance will have a negative impact on the controller’s response time. Figure 2 shows the effect of a larger output capacitor on voltage deviation and settling time. Plot (a) shows the transient load response with a 2.2-µH inductor and 10-µF capacitor. Plot (b) shows the transient load response with the same inductor and a 100-µF capacitor. The 10-µF capacitor has a voltage deviation of about 50 mV, whereas the 100-µF capacitor has a deviation of about 30 mV. The downside of using the larger capacitor is that the settling time of the output voltage is about twice as long as the smaller capacitance. Figure 3 shows the control loop bandwidth for each circuit as measured by the method presented in SLVA465. As expected, the (b) circuit has a lower bandwidth which translates to a longer response time.

At time t_2, when the average inductor current is equal to the new load current, the controller begins to supply the extra current rather than the output capacitor. At this time, the voltage has deviated by its maximum amount from the desired value, and the controller begins to recharge the output capacitor. Therefore, another way to reduce the amount of voltage deviation is to decrease the amount of time that the controller takes to respond and thus reduce the time between t_1 and t_2. This is accomplished by increasing the bandwidth of the controller by decreasing the inductance. If the crossover frequency of the control loop is less than 100 kHz, then a feedforward capacitor can also be used to improve the bandwidth of the system and decrease the response time (see SLVA466).

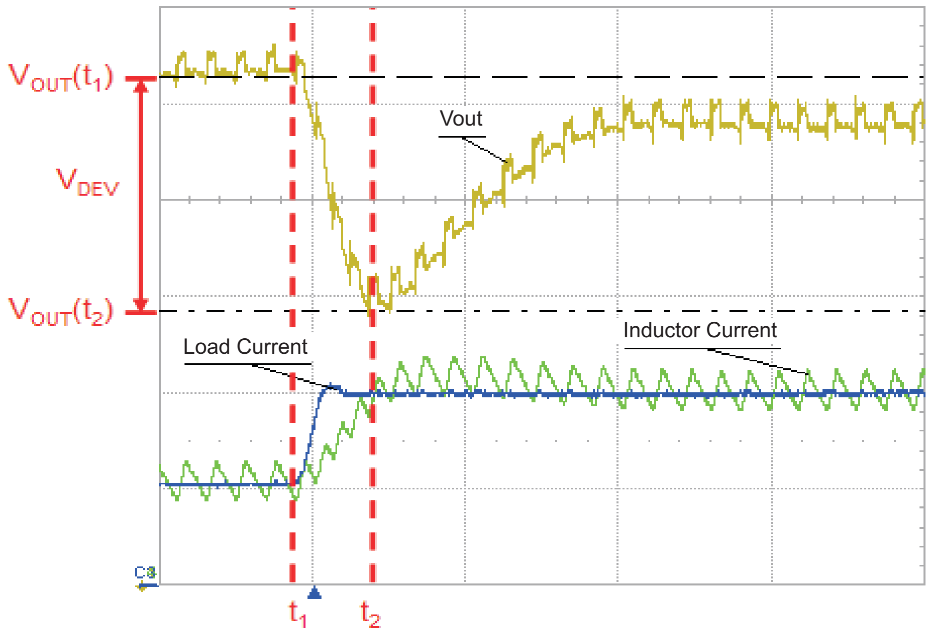


Figure 1. Load Transient Response of the TPS62130

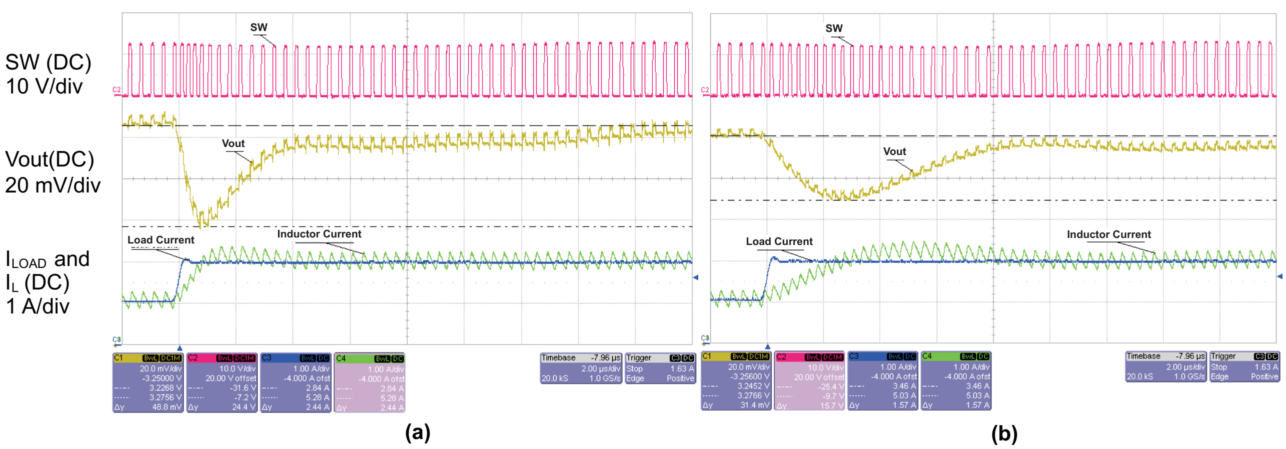
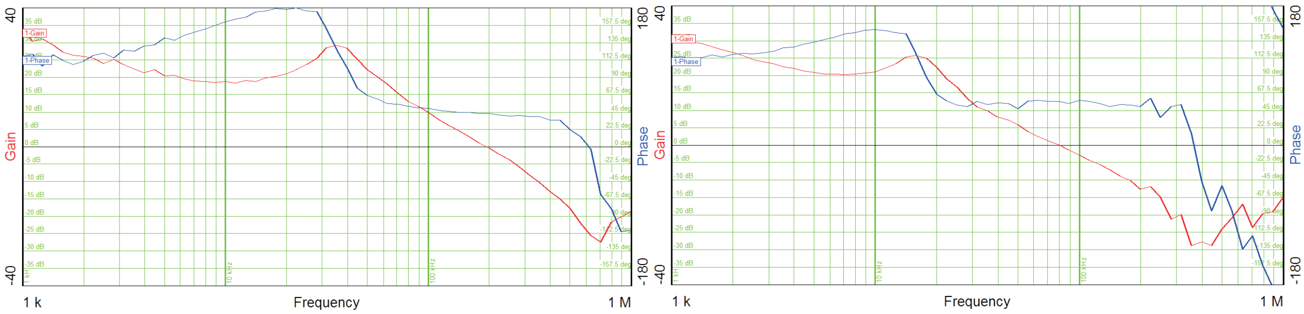


Figure 2. Load Transient With 2.2-µH Inductor and (a) 10-µF and (b) 100-µF Capacitor



(a) (b)

Figure 3. Control Loop Gain With 2.2-µH Inductor and (a) 10-µF and (b) 100-µF Capacitor

3 Increasing Maximum Output Current

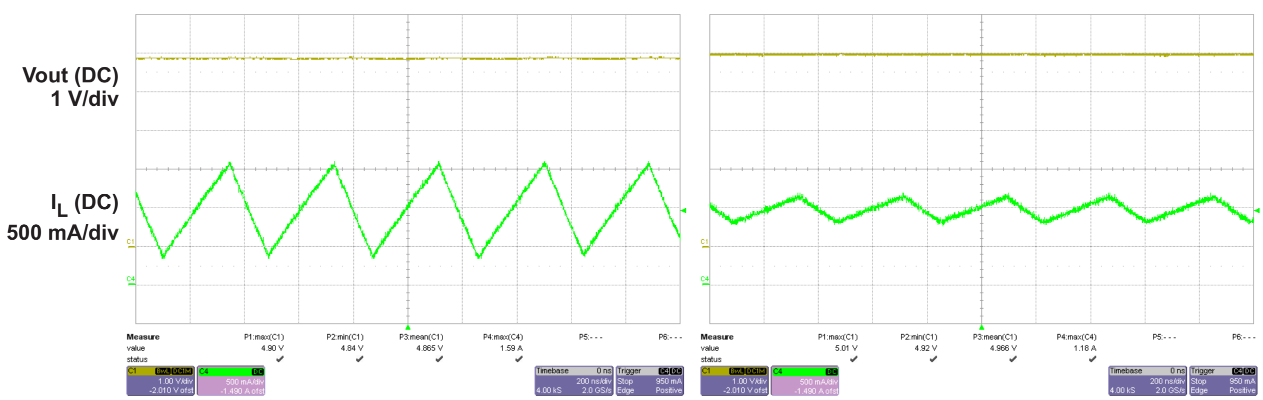
The TPS6213x/4x/5x/6x/7x family of devices has a built-in current limiter which needs to be accounted for when choosing an inductor. In order for the device to regulate properly, the peak inductor current needs to be less than the high-side MOSFET forward current limit as stated in the data sheet. When choosing an inductor for a reliable power supply, the minimum high-side forward current limit must be used to determine the maximum peak inductor current. Equation 3 and Equation 4 can be used to choose an inductor that meets the peak output current requirements:

$$I_{Lmax} = I_{out} + \frac{\Delta I_L}{2} \tag{3}$$

Where

$$\Delta I_L = \frac{V_{out} \cdot \left(1 - \frac{V_{out}}{V_{in}}\right)}{L \cdot f_{sw}} \tag{4}$$

Equation 4 shows that the peak inductor current is inversely proportional to inductance. Thus, in order to decrease the peak inductor current, a larger inductance must be used. For example, for an input voltage of 8 V and a load of 1 A at 5 V, a 0.47-µH inductor has a peak inductor current of 1.8 A with the TPS62150's high-frequency setting of 2.5 MHz. The TPS62150 has a minimum current limit of 1.4 A which prevents the 0.47-µH inductor from ramping up to the peak current of 1.8 A. As a result, the device is no longer able to regulate the output voltage to its desired value. If the recommended 2.2-µH inductor is used instead, the peak inductor current is calculated at just under 1.2 A, which is below the minimum specified current limit. Figure 4 shows the results of using a 0.47-µH inductor versus the recommended 2.2-µH inductor. In the case of the 0.47-µH inductor, the output voltage has fallen 100 mV from the 5-V setpoint which accounts for an error of 2 percent.



(a) (b)

Figure 4. TPS62150 Output Voltage Regulation With (a) 0.47-µH and (b) 2.2-µH Inductor

4 Reducing Output Voltage Ripple

Output voltage ripple can pose a problem to processors that have tight voltage tolerances and systems that are sensitive to power supply noise. The output voltage ripple can be approximated by the following equations:

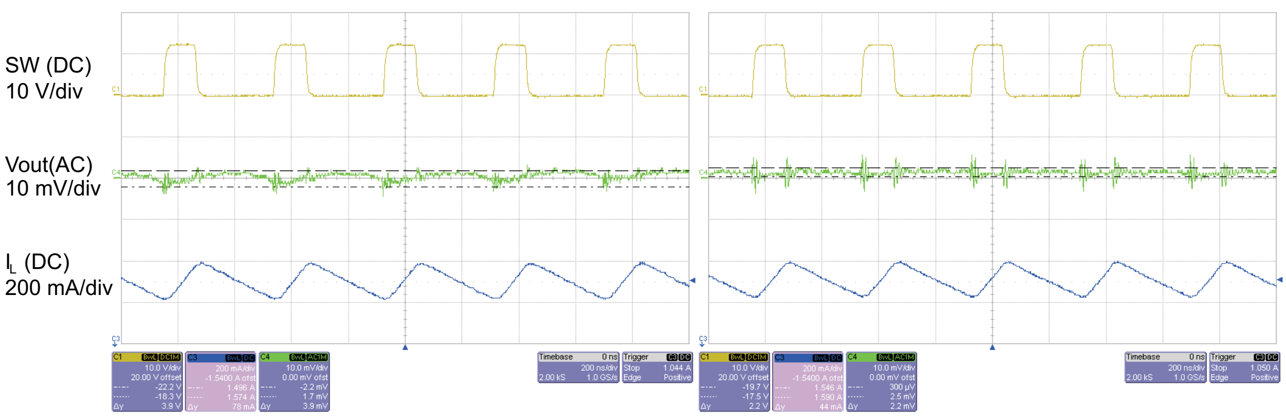
$$\Delta V_{out} = \Delta I_L \times Z_C \tag{5}$$

$$Z_C = R_{ESR} - \frac{j}{2\pi \times f_{sw} \times C} + j \times 2\pi \times f_{sw} \times L_{ESL} = R_{ESR} + j\left(2\pi \times f_{sw} \times L_{ESL} - \frac{1}{2\pi \times f_{sw} \times C}\right) \tag{6}$$

$$|Z_C| = \sqrt{R_{ESR}^2 + \left(2\pi \times f_{sw} \times L_{ESL} - \frac{1}{2\pi \times f_{sw} \times C}\right)^2} \tag{7}$$

From Equation 5, there are two ways to reduce the output voltage ripple. One way is to reduce the amount of ripple current through the inductor, however the more common way is to reduce the magnitude of the impedance of the capacitor at the switching frequency, shown in Equation 7. Because a ceramic capacitor has very low ESR and a relatively high resonant frequency, the most effective way to reduce the output voltage ripple is to use a larger capacitance. Although effective, at some point, increasing the capacitance begins to have a negligible effect due to the impedance from the ESR and ESL. Note that ESL varies based on the physical geometry of the capacitor, and therefore, manufacturer data sheets must be consulted when choosing a capacitor to ensure low impedance at the switching frequency. Placing multiple capacitors in parallel of large and small values is frequently done to achieve low impedance across a wide frequency range.

Figure 5 shows the output voltage ripple when using a 4.7-µH inductor with a 10-µF and a 100-µF output capacitor. The amount of ripple voltage has decreased with the larger capacitance as expected



(a) (b)

Figure 5. Output Voltage Ripple With 4.7-µH Inductor and (a) 10-µF and (b) 100-µF Capacitors

5 Conclusion

This application report has presented methods to ensure stability, improve the load transient response and output voltage ripple, and achieve higher load currents with the TPS6213x/4x/5x/6x/7x family of devices. The methods presented in this application report, as well as in the references, allow for a wide variety of external components to be used to achieve the desired power supply performance. The benefits and tradeoffs associated with designing the output filter, as discussed in this document, can aid with the design of a TPS6213x/4x/5x/6x/7x power supply.

6 References

1. *Using a Feedforward Capacitor to Improve Stability and Bandwidth of TPS62130/40/50/60/70* application report (SLVA466)
2. *How to Measure Control Loop of TPS62130/40/50/60/70 DCS-Control™ Devices* application report (SLVA465)
3. *Simplifying Stability Checks* application report (SLVA381)
4. *TPS62130, 3-V to 17-V, 3-A, 3-MHz Step-Down Converter in 3x3 QFN Package* data sheet (SLVSAG7)

Revision History

Changes from Original (December 2011) to A Revision	Page
• Changed value in *Stability vs Effective LC Corner Frequency* table. In the cell associated with 10 µF and 0.47 µH, the value is now 103.8 kHz, was 10 kHz.	1

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

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