Application Report
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Optimizing the TPS62175 Output Filter

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ABSTRACT

The TPS62175 uses DCS-Control^{TM}, which combines the advantages of hysteretic, voltage mode and current mode control including an AC loop directly associated to the output voltage. This control loop takes information about output voltage changes and feeds it directly to a fast comparator stage, providing an immediate response to dynamic load changes. Use of this control topology allows for a wide range of inductor and output capacitor values to accomplish specific design goals. The designer is able to optimize many factors such as control loop stability, transient response, output voltage ripple, or maximum output current based on the needs of the application. This application report discusses how to choose the output filter for the TPS62175 in order to meet the requirements of a specific design.

1 Analyzing the Stability of the Design

The TPS62175 datasheet recommends inductance and capacitance ranges which support the majority of designs. If for some specific application requirement these ranges must be exceeded, certain tradeoffs must be made and the designer should consider many factors when choosing an inductor and output capacitor combination. For example, lower inductances save board space because they can be physically smaller due to fewer windings. However, this causes the peak switch current and output voltage ripple to increase. Larger voltage ripple can be lowered by using a higher output capacitance, if the design can tolerate the larger size and slower transient response.

The inductor and output capacitor values are also a key influence on stability. Regardless of what goals need to be met through optimizing the output filter, the design has to be stable. The LC filter forms a double pole in the control loop, which has a strong impact on the frequency response and system stability. Equation 1 calculates the corner frequency of the LC filter:

$$f_C = \frac{1}{2\pi\sqrt{LC_{out}}} \quad (1)$$

The closed loop crossover frequency of the control loop determines how fast the device responds to changes on the input and output. The control loop responds faster to load or line changes with higher crossover frequencies. The crossover frequency moves lower with lower corner frequencies and vice versa. If the corner frequency is too high, the crossover frequency also moves too high (too close to the switching frequency of typically 1 MHz) and instability results. Additional output capacitance solves this by moving the corner frequency lower.

Table 1 shows the stability of different LC combinations that have been tested with input voltages of 7.2 V, 12 V, and 24 V at a load current of 500 mA. All stability measurements were taken at 3.3-V_{out}. The measured crossover frequency of every LC combination at a 12-V input voltage is shown. To calculate the corner frequency, use the nominal inductor value and the nominal capacitor value de-rated by 50% to account for DC bias. Capacitors rated at 6.3-V were used for the 3.3-V output.

Nominal Inductance Value	Nominal Ceramic Capacitance Value (effective = 1/2 nominal)				
	10 µF	22 µF	47 µF	100 µF	200 µF
	Crossover Frequency at $12V_{in}$ (in kHz)				
4.7 µH	465	276	206	113	77
10 µH	215	171	129	76	50
22 µH	134	109	88	52	33
47 µH	101	70	54	31	19

	Recommended by the TPS62175 datasheet
	Stable at 7.2-V, 12-V, and 24-V input voltage
	Stable at 12-V and 24-V input voltages
	Unstable for all input voltages

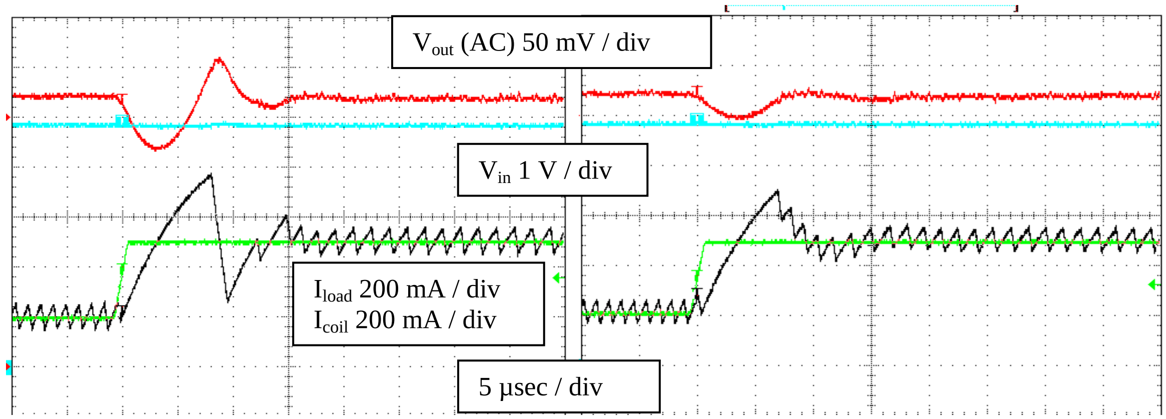
Table 1. TPS62175 Stability and Crossover Frequency

Table 1 shows those combinations recommended by the datasheet (colored in white) and additional combinations that are stable for all three input voltages tested (colored in green). Blue-colored cells contain combinations that were not stable at a 7.2-V input voltage and should only be used for higher input voltages. Typically, stability improves with increasing input voltage. Finally, yellow-colored cells indicate combinations that were never stable for any of the three input voltages tested.

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 or load transient response. For more information on control loop measurement procedures, see the application report *How to Measure Control Loop of TPS62130/40/50/60/70 DCS-Control™ Devices* (SLVA465A). For more information on determining the stability from the load-step response and Bode plot measurements, see the application report *Simplifying Stability Checks* (SLVA381A). Using these application reports, the LC filter combinations in Table 1 are determined to be stable because they have at least 30 degrees of phase before and at the crossover frequency, and they have less than three rings in the transient response. For the DCS-Control™ topology, phase margin at such high crossover frequencies is less meaningful and the transient response is the primary indicator of stability.

2 Optimizing Load Transient Response

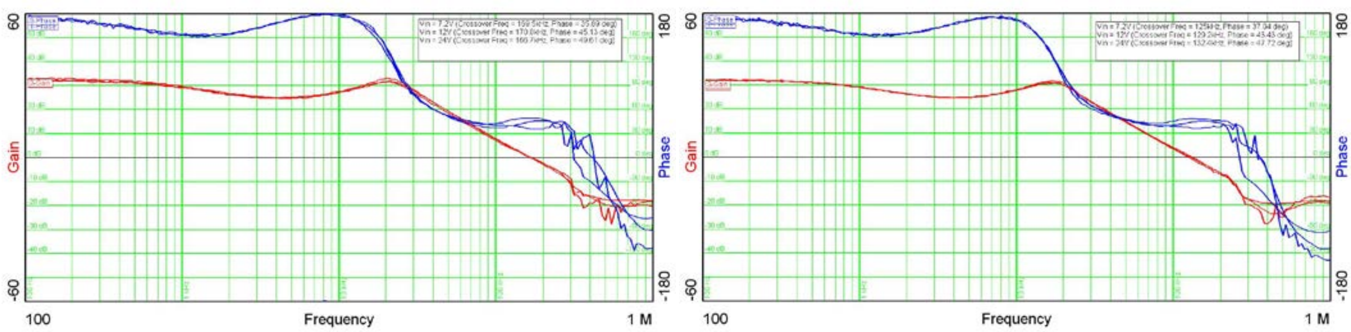
The transient (or load step) response can be optimized for a lower voltage drop or for a faster response. When the load is quickly increased (or stepped), the output capacitor supplies the load with current until the regulator reacts to the change and increases its output current. A larger output capacitor provides this current with a smaller amount of output voltage drop; however, a smaller capacitor increases the bandwidth of the device and provides faster response. Figure 1 shows the TPS62175 transient responses to a 200-mA to 500-mA load step using a (a) 22-µF and (b) 47-µF output capacitor with a 10-µH inductor at 3.3-V out at 4.75-V input voltage. The response with the 47-µF capacitor has approximately half the voltage drop. Note that because the inductor current (I_{coil}) is not linear, but curved, during the recovery of the output voltage, this indicates large signal affects (high-side MOSEFT $R_{(DS)ON}$, inductor DCR, and so on) are coming into play over the small signal control loop aspects. Thus, Figure 1a is not an indication of instability but rather shows the typical behavior at lower input voltages, such as 4.75 V.



(a) (b)

Figure 1. TPS62175 Load Transient Response Using a (a) 22-µF and (b) 47-µF Output Capacitor

Figure 2 shows the TPS62175 closed-loop frequency response at a load of 500 mA and 3.3-V_{out}. Both plots show a stable system for all three input voltages tested (7.2 V, 12 V, and 24 V).



(a) (b)

Figure 2. TPS62175 Closed-Loop Frequency Response Using a

(a) 22-µF and (b) 47-µF Output Capacitor

3 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. Worst case ripple occurs in power save mode when the load is at its lightest. At this operating point, each switching cycle transfers too much energy to the output such that the output voltage rises above its setpoint. This allows the device to enter a standby state with minimal power consumption and keep efficiency high at these light loads, but it also increases the output voltage ripple. The output voltage ripple in power save mode can be approximated as:

$$\Delta V_{out} \cong \frac{(V_{in} - V_{out}) \times V_{in} \times t_{on}^2}{2 \times L \times C_{out} \times V_{out}} \quad (2)$$

Where t_{on} is estimated from Equation 3:

$$t_{on} = \frac{V_{out}}{V_{in}} \times 1\mu s \quad (3)$$

Increasing either the output capacitance or inductance reduces the ripple in power save mode. Figure 3 shows the output voltage ripple for a 3.3-V_{out}, 12-V input voltage system at no load with both a single 22-µF output capacitor and two 22-µF output capacitors. The extra output capacitor reduces the ripple from 16.4 mV to 10 mV.

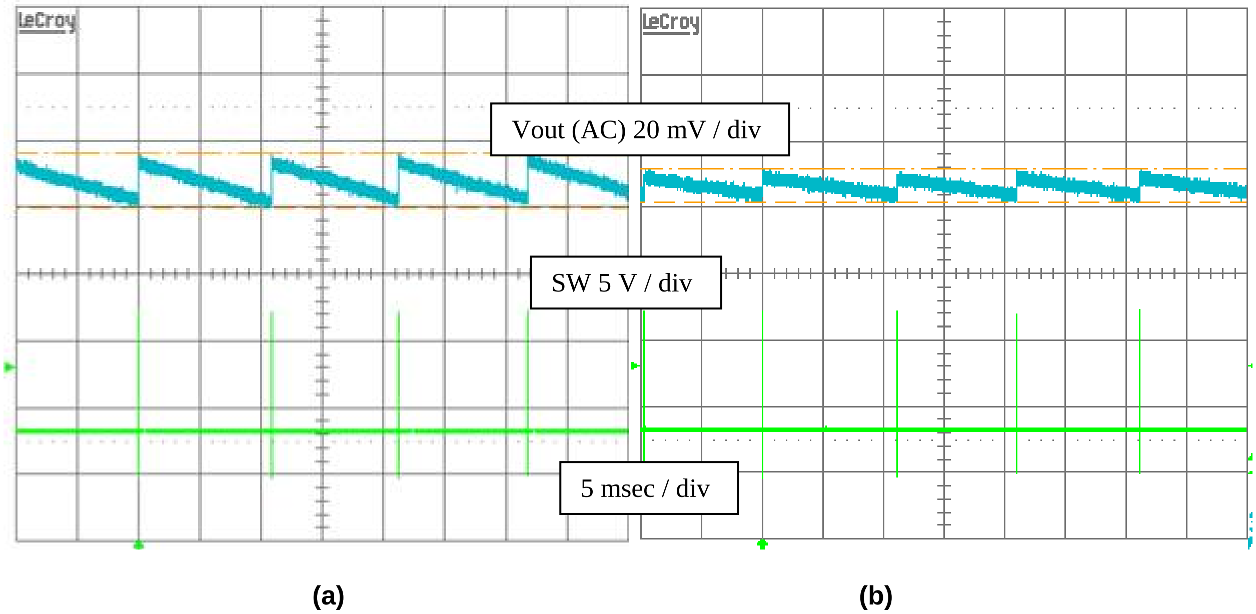


Figure 3. TPS62175 Output Voltage Ripple Using a (a) 22-µF and (b) 2 x 22-µF Output Capacitor

Note that the 3.3-V DC bias on these 6.3-V rated output capacitors substantially reduces the effective output capacitance, and when combined with device tolerances and propagation delays, the ripple increases above the result of Equation 2. Use Equation 2 as a guideline for estimating the required output capacitance, and then confirm with lab measurements.

The output voltage ripple in PWM mode is approximated using Equation 4. The same technique of increasing the inductance and output capacitance also reduces the ripple in PWM mode. The ripple in PWM mode is always lower than in power save mode.

$$\Delta V_{out} = \frac{\Delta I_L}{2\pi \times f_{sw} \times C_{out}} \quad (4)$$

$$\Delta I_L = \frac{(V_{in} - V_{out})}{L} \times \frac{V_{out}}{V_{in}} \times \frac{1}{f_{sw}} \quad (5)$$

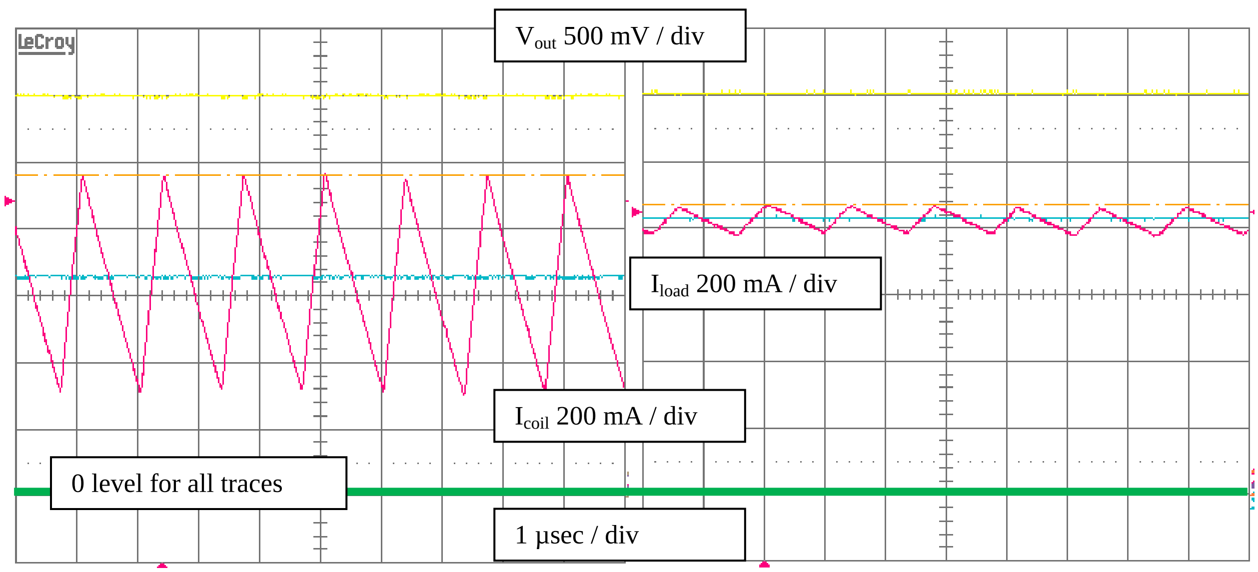
Where: f_{sw} is the switching frequency of typically 1 MHz.

4 Increasing Maximum Output Current

The TPS62175 contains a built-in current limiting circuit which needs to be accounted for when choosing an inductance. 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 inductance for a reliable power supply, the minimum high-side forward current limit value (0.8 A) must be used to determine the maximum allowable peak inductor current. Equation 5 and Equation 6 can be used to choose an inductance that meets the peak output current requirements:

$$I_{L\,max} = I_{out} + \frac{\Delta I_L}{2} \qquad (6)$$

Equation 5 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, with an input voltage of 12 V, the load is increased high enough to cause the device to enter current limit and reduce the output voltage to 3 V from its 3.3-V setpoint. Figure 4 shows the output voltage in yellow, load current in blue, and inductor current in red for two cases: (a) using a 4.7-µH inductor and (b) using a 47-µH inductor. Since the device always limits the peak current to the same 1-A typical, the output current delivered is higher for the larger inductance case. Specifically, the 47-µH circuit delivers 820 mA while the 4.7-µH circuit delivers only 650 mA of output current. Note that these are measured (typical) values, and they demonstrate that increasing the inductance provides higher output currents. However, the above equations should be used to account for worst case conditions and device tolerances when determining the maximum output current.



(a) (b)

Figure 4. TPS62175 Maximum Output Current Using a (a) 4.7-µH and (b) 47-µH Inductor

5 Conclusion

This application report has presented methods to analyze control loop stability, optimize transient response, minimize output voltage ripple, and increase maximum output current for the TPS62175 device. The methods presented in this application report and in the references show that a wider variety of external components can be used to achieve the desired power supply performance when the datasheet recommended output filters are not sufficient for the application. Using components outside of the datasheet recommendations has benefits and tradeoffs across all measures of performance, such as stability, transient response, output ripple, power save mode performance, efficiency, and so on. This application report discusses these tradeoffs and aids with the design of a TPS62175 power supply.

References

1. *Simplifying Stability Checks* (SLVA381A).
2. *How to Measure Control Loop of TPS62130/40/50/60/70 DCS-Control*^{TM} *Devices* (SLVA465A)
3. *TPS62175, 28V, 0.5A Step-Down Converter with Sleep Mode* (SLVSB35A)
4. *DCS-Control*^{TM} Landing Page: http://www.ti.com/ww/en/analog/tps621x/