# Optimizing TPS6206x External Component Selection

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**ABSTRACT**

The TPS6206x internal compensation network is optimized for an LC output filter composed of a 1-µH inductor and a 10-µF ceramic capacitor. The device is designed to operate with nominal inductor values of 1 µH to 1.2 µH and with ceramic capacitor values of 10 µF to 22 µF. By selecting the proper feedforward capacitor, a wider range of output inductors and capacitors can be used with the TPS6206x. Adjusting these three components can optimize the device for smaller solution size, faster load-step response, lower output voltage ripple, increased output current, and/or increased control loop stability. This application report can be used with any of the TPS62060, TPS62065, or TPS62067 3-MHz, synchronous step-down converters.

## Reducing Solution Size

The output inductor is the largest component in the power supply, covering approximately 30% of the total area. Choosing an inductor with a smaller package has the greatest impact on the solution size. Table 1 shows different LC filter combinations that have been tested with the TPS62065. A stable design can be achieved with inductances as low as 0.56 µH.

Table 1 was generated with extensive laboratory testing of the various inductor and capacitor values. The corner frequency (Equation 1) of each LC combination is listed in each cell. Cells shaded white are recommended by the data sheet. The data sheet's recommendations produce a recommended corner frequency between 31 kHz and 50.3 kHz. Other LC combinations that yield corner frequencies within this range are shaded in green and can produce stable designs with an appropriate feedforward capacitor (Cff). Cells shaded in grey have produced stable designs in the laboratory (with a Cff), whereas cells shaded in blue are unstable and not recommended. The data in Table 1 is taken with a 5-V input and a 1.8-V output with a load current of 1.6 A.

$$\left( f\text{c} = \frac{1}{2\pi\sqrt{LC}} \right) \quad (1)$$

Lower inductances are typically available in smaller packages. However, the inductor saturation current typically decreases with decreasing volume. With lower inductances, the ripple current in the inductor is higher, resulting in higher peak currents that can saturate the inductor or trip the IC's current limit. The inductor must be selected carefully so its saturation current is higher than the peak inductor current. Also, it is important to note that as the inductor volume decreases, ac and dc losses generally increase due to an increase in ripple current and DCR. An increase in these losses reduces the efficiency of the converter.

**Table 1. TPS62065 Stability with Different LC Corner Frequencies**

| Inductance Value | Capacitance Value | | | | | |
|---|---|---|---|---|---|---|
| | 2.2 µF | 4.7 µF | 10 µF | 22 µF | 47 µF | 100 µF |
| | Corner Frequencies | | | | | |
| 0.56 µH | 143.4 kHz | 98.1 kHz | 67.3 kHz | 45.3 kHz | 31.0 kHz | 21.3 kHz |
| 0.68 µH | 130.1 kHz | 89.0 kHz | 61.0 kHz | 41.1 kHz | 28.2 kHz | 19.3 kHz |
| 1.0 µH | 107.3 kHz | 73.4 kHz | 50.3 kHz | 33.9 kHz | 23.2 kHz | 15.9 kHz |
| 1.2 µH | 98.0 kHz | 67.0 kHz | 45.9 kHz | 31.0 kHz | 21.2 kHz | 14.5 kHz |
| 1.5 µH | 87.6 kHz | 59.9 kHz | 41.1 kHz | 27.7 kHz | 19.0 kHz | 13.0 kHz |
| 1.8 µH | 80.0 kHz | 54.7 kHz | 37.5 kHz | 25.3 kHz | 17.3 kHz | 11.9 kHz |
| 2.2 µH | 72.3 kHz | 49.5 kHz | 33.9 kHz | 22.9 kHz | 15.7 kHz | 10.7 kHz |

**Legend:**

| | |
|---|---|
| | Recommended in data sheet |
| | Stable with Cff (outside recommended LC corner frequency range) |
| | Stable with Cff (within recommended LC corner frequency range) |
| | Unstable |

## Optimizing Load-Step Response

The load step response can be optimized for a lower voltage droop or for a faster response. During a load step, the output capacitor needs to supply the load with current until the regulator can increase its output current to react to the change. A larger capacitor is able to provide this current with a smaller amount of output voltage droop; however, a smaller capacitor increases the bandwidth of the device and provides a faster response. Figure 1 shows TPS62065 load-step responses using a (a) 2.2-µF and (b) 22-µF output capacitors with a 1-µH inductor. The response with the 22-µF capacitor has approximately 50% less voltage droop but is significantly slower.

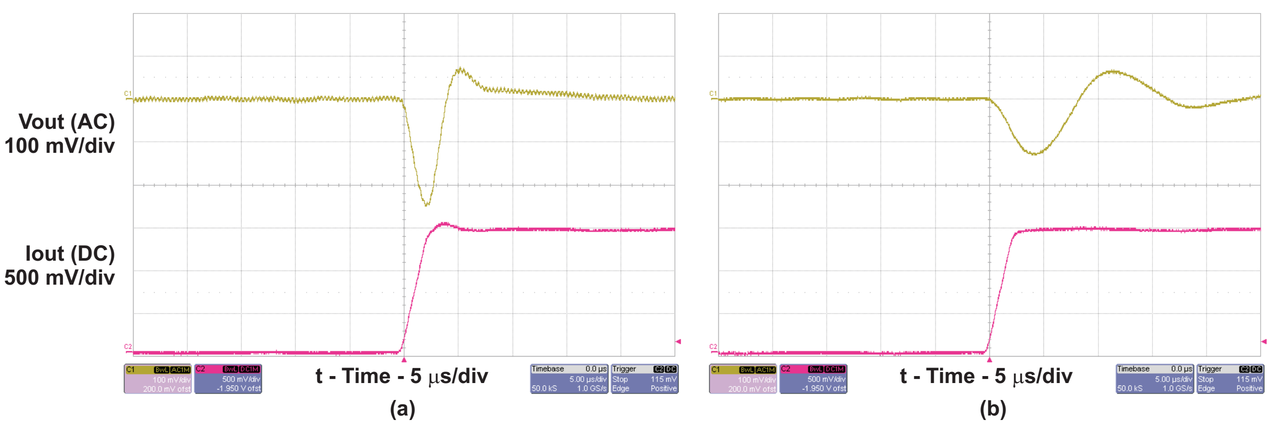



**Figure 1. TPS62065 Load-Step Response Using (a) 2.2-µF and (b) 22-µF Output Capacitors**

## Reducing Output Voltage Ripple

The output voltage ripple is given by $V_{ripple} = I_{ripple} \times Z_{Cap}$. A larger ceramic output capacitor has a lower impedance (Equation 2) at the switching frequency, reducing the output voltage ripple. Figure 2 shows the output voltage ripple with (a) 2.2-µF and (b) 22-µF output capacitors and a 0.68-µH inductor. Ignoring high-frequency spikes, the larger capacitor has about 30% less ripple.

$$\left( Z_{Cap} = ESR_{Cap} + \frac{1}{2\pi \times f_{sw} \times C_{Cap}} + 2\pi \times f_{sw} \times ESL \right) \tag{2}$$

Another way of reducing the output voltage ripple is to reduce the current ripple. The current ripple is inversely proportional to the inductance. Therefore, increasing the inductor value also reduces the voltage ripple.

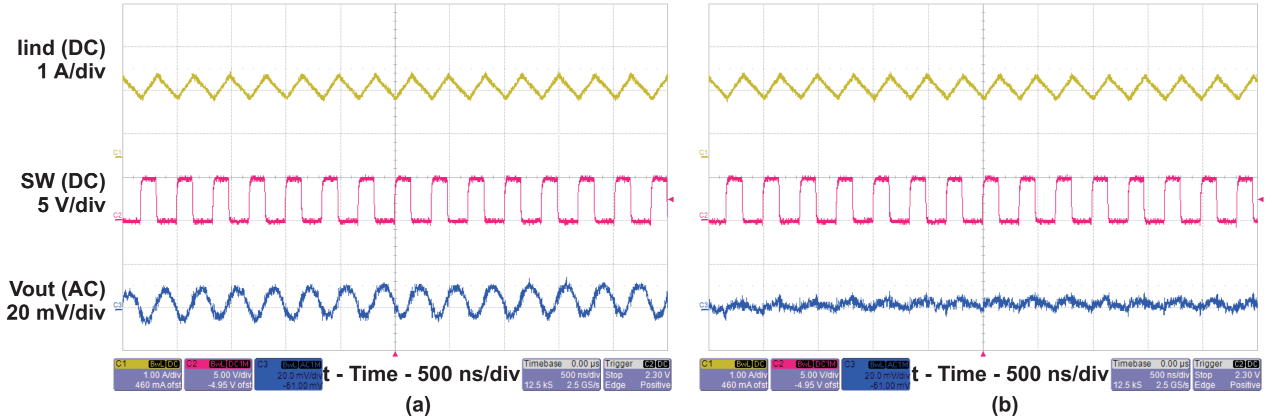



**Figure 2. Output Voltage Ripple With (a) 2.2-μF and (b) 47-μF Output Capacitors**

## Increasing Maximum Output Current

The peak inductor current can be calculated using

$$I_{Lmax} = I_{outmax} + \frac{\Delta I_L}{2},$$

$$\text{where: } \Delta I_L = V_{out} \times \frac{1 - \frac{V_{out}}{V_{in}}}{L \times f_{sw}} \tag{3}$$

For a TPS62065 design with a 5-V input, 1.8-V output, 2.75-A peak inductor current (the IC's current limit), and the recommended 1-μH inductor, $I_{outmax}$ = 2.56 A. Using a 2.2-μH inductor decreases the peak-to-peak output current ripple by 210 mA, allowing 2.66 A of output current.

## Feedforward Capacitor Selection

Figure 3 shows a typical TPS62065 application circuit. Along with resistors R1 and R2, the required feedforward capacitor (Cff) adds a zero and a pole to the closed-loop transfer function of the TPS6206x. This provides a phase boost that reaches a maximum at the geometric mean of the pole and zero frequencies. The application report *Optimizing Transient Response of Internally Compensated dc-dc Converters With Feedforward Capacitor* (SLVA289) details the process of empirically selecting a feedforward capacitor for an internally compensated converter.

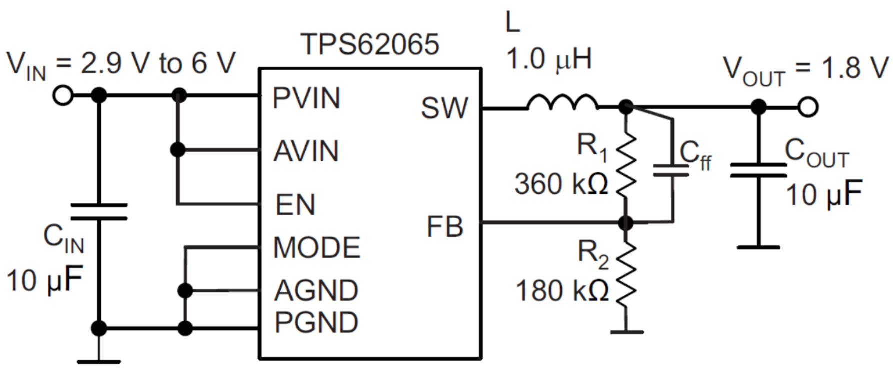



**Figure 3. Typical TPS62065 Application Circuit**

For optimum stability, Cff selection is a two-step process. First, the crossover frequency with an unpopulated Cff needs to be measured. Once the crossover frequency is determined, Equation 4 is used to calculate the Cff that provides the maximum phase boost at the crossover frequency.

$$Cff_{op} = \frac{1}{2\pi \times f_{noCff}} \times \sqrt{\frac{1}{R1} \times \left(\frac{1}{R1} + \frac{1}{R2}\right)} \quad (4)$$

Table 2 shows recommended Cff values and measured crossover frequencies and phase margins for different LC output filter combinations. This data was taken with a 5-V input, 1.8-V output, and 1.6 A of output current. Different operating conditions affect the loop response of the system. In each cell, the optimal feedforward capacitor (Cff), loop bandwidth, and phase margin are listed. Phase margins above 30 degrees are considered stable. However, some LC combinations with phase margins slightly less than 30 also were considered stable. In these cases, the phase remained close to 30 degrees at frequencies several decades higher than the crossover frequency.

**Table 2. TPS62065 Measured Stability Data, Vin = 5 V, Vout = 1.8 V, Iout = 1.6 A**

| Inductance Value | Capacitance Value | | | | | |
|---|---|---|---|---|---|---|
| | **2.2 µF** | **4.7 µF** | **10 µF** | **22 µF** | **47 µF** | **100 µF** |
| | **Cff, BW, PM** | | | | | |
| **0.56 µH** | 2.7 pF | 3.9 pF | 4.7 pF | 10.0 pF | 15.0 pF | 33.0 pF |
| | 396.5 kHz | 252.5 kHz | 193.2 kHz | 86.7 kHz | 63.5 kHz | 53.6 kHz |
| | 48.8° | 55.2° | 57.0° | 54.2° | 40.5° | 29.6° |
| **0.68 µH** | 2.7 pF | 3.9 pF | 5.6 pF | 10.0 pF | 15.0 pF | |
| | 402.4 kHz | 247.9 kHz | 204.6 kHz | 90.5 kHz | 62.1 kHz | |
| | 48.8° | 55.8° | 58.3° | 57.8° | 48.4° | |
| **1.0 µH** | 3.3 pF | 4.7 pF | 5.6 pF | 12.0 pF | 22.0 pF | |
| | 342.6 kHz | 227.1 kHz | 188.4 kHz | 88.3 kHz | 55.2 kHz | |
| | 52.7° | 55.6° | 54.8° | 45.2° | 29.8° | |
| **1.2 µH** | 3.9 pF | 5.6 pF | 8.2 pF | 15.0 pF | | |
| | 275.6 kHz | 177.5 kHz | 144.4 kHz | 73.6 kHz | | |
| | 51.0° | 50.1° | 49.5° | 29.8° | | |
| **1.5 µH** | 3.9 pF | 5.6 pF | 8.2 pF | 15.0 pF | | |
| | 248.5 kHz | 168.1 kHz | 133.0 kHz | 63.7 kHz | | |
| | 54.4° | 51.7° | 50.3° | 28.2° | | |
| **1.8 µH** | 4.7 pF | 6.8 pF | 8.2 pF | | | |
| | 230.9 kHz | 152.3 kHz | 117.0 kHz | | | |
| | 52.4° | 48.8° | 45.1° | | | |
| **2.2 µH** | 4.7 pF | 6.8 pF | 8.2 pF | | | |
| | 216 kHz | 148 kHz | 111 kHz | | | |
| | 52.4° | 48.8° | 44.8° | | | |
| **Legend:** | | | | | | |
| (gray) | Stable | | | | | |
| (blue) | Unstable | | | | | |

The inductors used to gather the stability data are listed in Table 3. The output capacitors were 6.3-V ceramic X5R. Due to the dc bias effect, the actual capacitances are lower than the values listed.

**Table 3. Inductors Used for Stability Data**

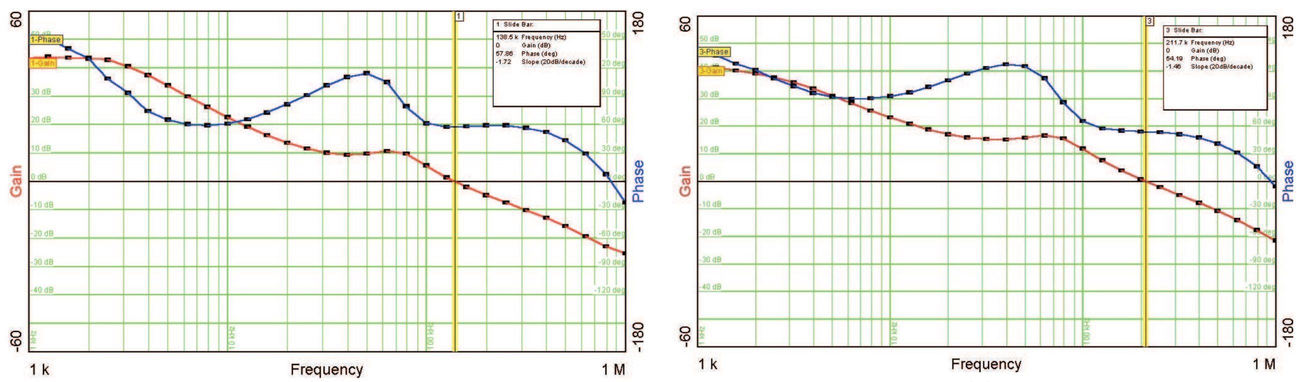
| Inductance (µH) | Description |
|---|---|
| 0.56 | Coilcraft LPS4018-561 |
| 0.68 | Coilcraft LPS4012-681 |
| 1.0 | Murata LQH44PN1R0NP0L |

**Table 3. Inductors Used for Stability Data (continued)**

| Inductance (µH) | Description |
|---|---|
| 1.2 | Coilcraft LPS5030-122 |
| 1.5 | Coilcraft LPS4012-152 |
| 1.8 | Coilcraft LPS5015-182 |
| 2.2 | Coilcraft LPS4018-222 |

## Optimizing Cff for Higher Bandwidth

At the expense of phase margin, a larger Cff can increase the bandwidth of the device. The feedforward capacitor can be increased as long as the phase margin is higher than 30 degrees. Figure 4 shows the closed-loop frequency responses with a 0.68-µH, 10-µF LC filter and a (a) 5.6-pF and (b) 47-pF Cff capacitor. With the larger capacitor, the loop bandwidth is increased by 73.2 kHz while the phase margin is decreased by 3.67 degrees.




(a) (b)

**Figure 4. Closed Loop Frequency Response With (a) 5.6-pF and (b) 47-pF Feedforward Capacitors**

The user must empirically measure power supply performance after modifying the external components. A large increase in feedforward capacitance increases ringing during load transients. The application report SLVA289 provides detailed information regarding the effects of varying the Cff value.

## Conclusion

By choosing the appropriate external components, a TPS6206x design can be optimized for smaller solution size, faster load-step response, lower output voltage ripple, increased output current, and/or increased control loop stability. Following the outlined empirical method, the feedforward capacitor is selected to ensure stability with the LC combination of the design.

## References

1. *Optimizing Transient Response of Internally Compensated dc-dc Converters With Feedforward Capacitor* application report (SLVA289)
2. *TPS62065/7, 3-MHz 2A Step Down Converter in 2x2 SON Package* datasheet (SLVS833)

## IMPORTANT NOTICE