Application Report
SLVA466–December 2011

Using a Feedforward Capacitor to Improve Stability and Bandwidth of TPS62130/40/50/60/70

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ABSTRACT

A common method to improve the stability and bandwidth of a power supply is to use a feedforward capacitor, which is a capacitor placed across the high-side feedback resistor. This capacitor adds a zero and a pole ($f_Z < f_P$) to the control loop, which can be strategically placed to improve the phase margin and bandwidth. This improvement can be measured in both the transient response and bode plot of the new circuit. This application report details two design strategies for placing the pole and zero at the optimal frequency to improve transient response and circuit stability for the TPS62130/40/50/60/70 DCS-Control™ devices. Additional information may be found in the TI application report *Optimizing the TPS62130/40/50/60/70 Output Filter*.

1 Adding Extra Capacitance

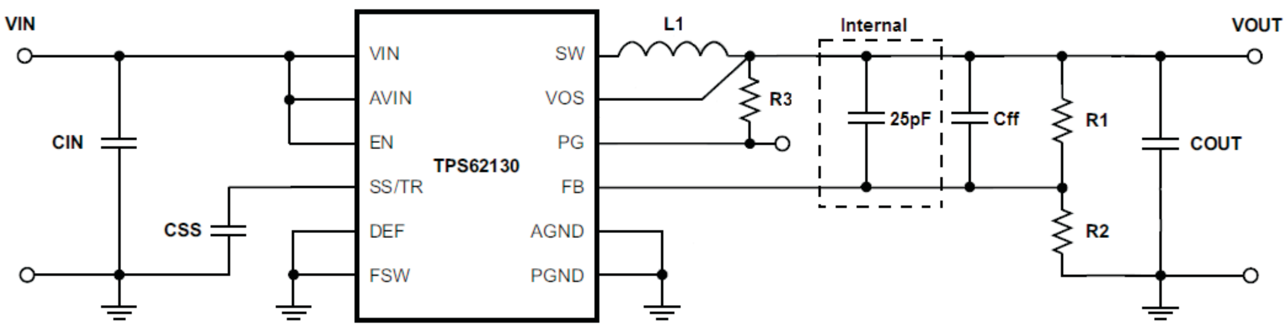

Figure 1. Simplified Schematic With Internal and External Feedforward Capacitors Shown

The traditional method of designing with a feedforward capacitor is to add an external capacitor (Cff) in parallel with the high-side feedback resistor, R1 in Figure 1. The capacitor value is chosen based on the values of the feedback resistors to place the geometric mean of the pole and zero at the unity gain crossover frequency. The application report *Optimizing Transient Response of Internally Compensated dc-dc Converters With Feedforward Capacitor* (SLVA289) presents an equation to calculate the optimal feedforward capacitor. Because the TPS6213x/4x/5x/6x/7x family of integrated circuits has an internal 25-pF feedforward capacitor, the equation must be modified as shown in Equation 1.

$$C_{ff} = \frac{1}{2\pi f_{CO}} \sqrt{\frac{1}{R_1}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)} - 25\ \text{pF} \tag{1}$$

Where f_{CO} is the unity gain crossover frequency of the control loop without the external feedforward capacitor installed and R1 and R2 are the high-side and low-side feedback resistors, respectively. Figure 1 shows the locations of the feedback resistors and feedforward capacitor. This capacitor value places the geometric mean of the zero and pole at f_{CO}, which provides the best phase margin boost. The actual frequencies of the zero and pole are calculated using Equation 2 and Equation 3. Note that the pole is always at a higher frequency than the zero because R_1 is always larger than $R_1//R_2$.

$$f_Z = \frac{1}{2\pi\ R_1 C_{ff}} \tag{2}$$

DCS-Control is a trademark of Texas Instruments.

$$f_P = \frac{1}{2\pi \ (R_1 \, // \, R_2) C_{ff}} \tag{3}$$

As an example, take a 12-Vin, 3.3-Vout TPS62130 design with a 4.7-µH inductor, 200-µF output capacitor, R_1 as 10 kΩ, and R_2 as 3.16 kΩ. First, the loop gain without the feedforward capacitor needs to be measured to find the unity gain crossover frequency. The application report *How to Measure Control Loop of TPS62130/40/50/60/70 DCS-Control™ Devices* (SLVA465) explains how to take a loop measurement on the DCS-Control™ topology and Figure 2 shows the results. The crossover frequency is 33.62 kHz, so Equation 1 is used to calculate that 941 pF of extra capacitance is needed. Figure 3 shows the new loop response with an added 1000-pF Cff compared with the response without the external Cff.

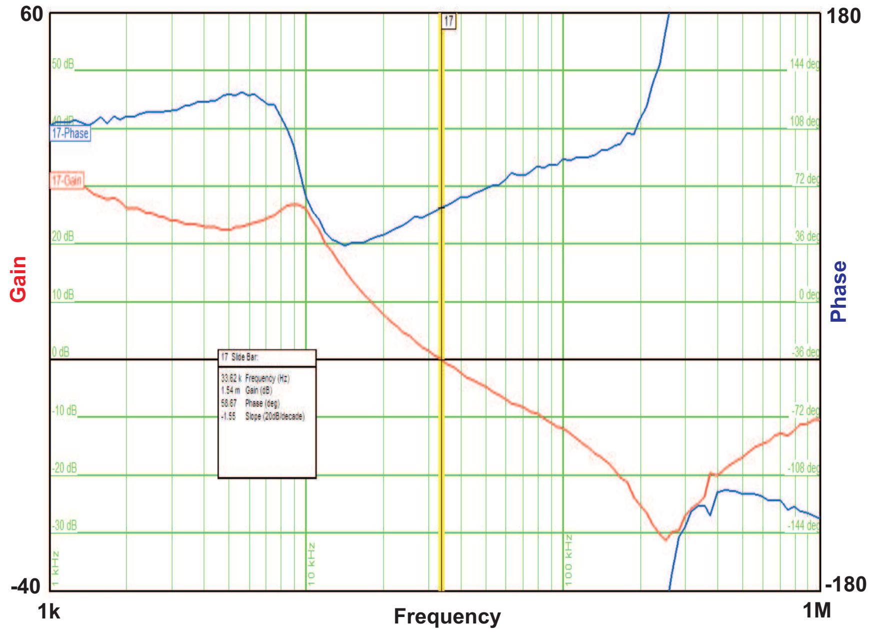

Figure 2. Measuring the Gain Crossover Frequency Without a Feedforward Capacitor

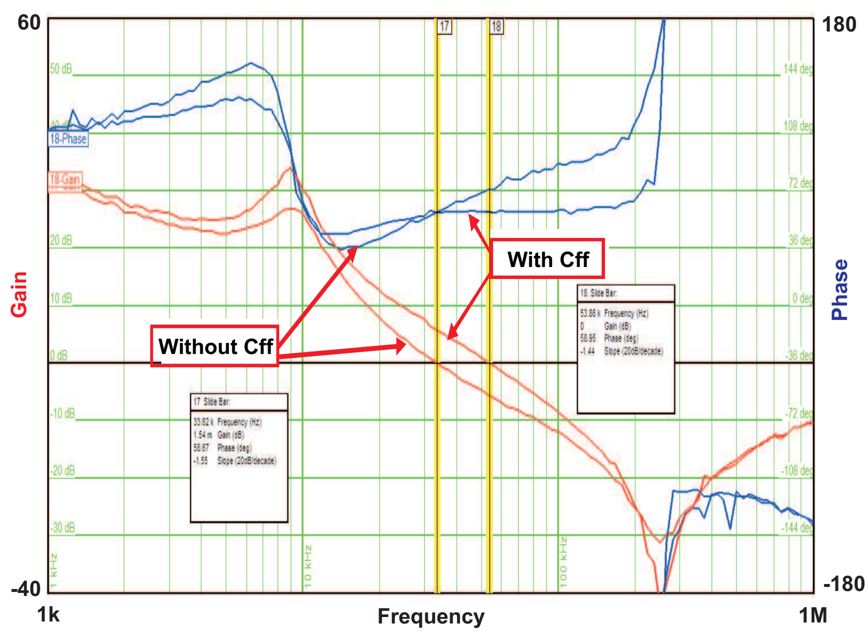

Figure 3. Loop Gain With and Without Feedforward Capacitor

Figure 4 shows the load transient response before and after adding the additional Cff. The increase in loop bandwidth due to the Cff is seen in the bode plot, whereas the transient response shows the tangible benefit of the gain in bandwidth. The transient response is faster and the voltage undershoot is less with the external Cff. In addition, no ringing occurs in the output voltage because the phase is not allowed to dip as low due to the added zero. Note that with the external Cff, the load regulation is reduced somewhat as shown by the different final values of the output voltage in Figure 4. This effect is more pronounced for smaller external Cff values. For this reason, adjusting the resistors and using only the internal 25-pF Cff is the preferred method of loop response optimization as discussed in the next section.

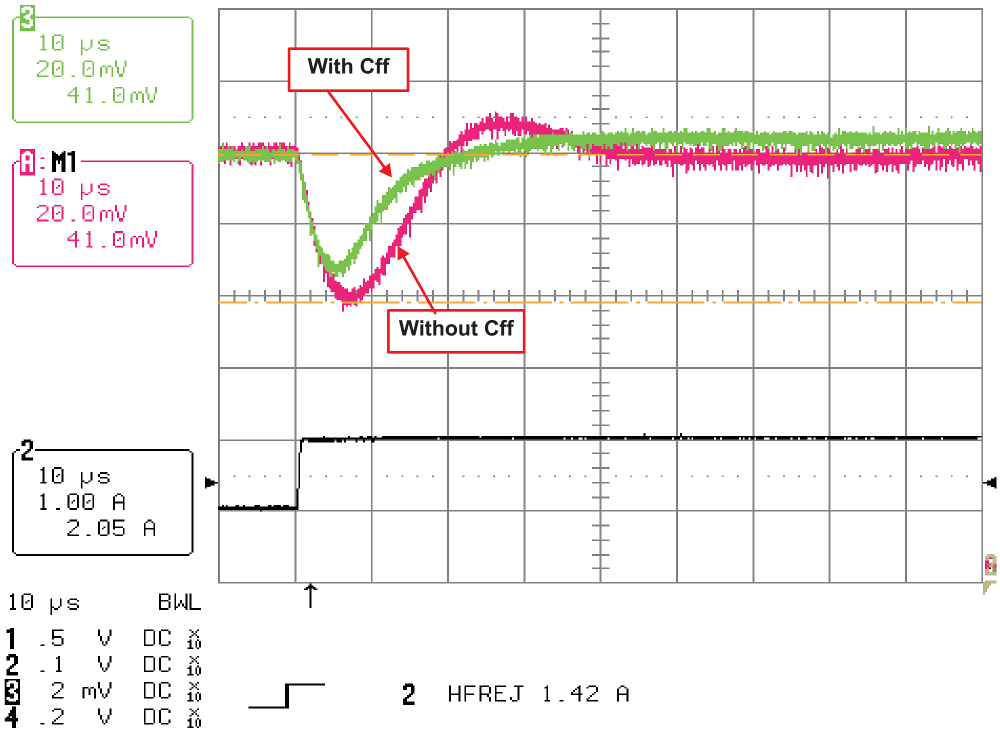

Figure 4. Load Transient Response With and Without Feedforward Capacitor

2 Choosing Feedback Resistors Based on Internal Cff

The second and preferred method of designing a TPS62130/40/50/60/70 power supply with a feedforward capacitor is to choose the feedback resistors based on the internal 25-pF feedforward capacitor. This method is unique to this family of devices because of the internal capacitor. The benefit of using this method is the ability to eliminate one component from the circuit to reduce production costs while keeping superior load regulation in practice.

The first step is to measure the control loop with resistors that place the zero due to the internal feedforward capacitor at a frequency higher than the gain crossover point. Because the feedforward capacitor does not have an effect at frequencies higher than 100 kHz (see Section 3), choose R_1 such that the frequency of the zero is at least greater than 100 kHz. To completely eliminate the effect of the zero's phase response, the zero must be placed one decade above the gain crossover frequency. Therefore, placing the zero at 1 MHz is sufficient for all gain crossover frequencies. Using Equation 2, an appropriate high-side resistor can be calculated as shown by the following equations.

$$R_1 = \frac{1}{2\pi(1\ \text{MHz})(25\ \text{pF})} \approx 6.34\ \text{k}\Omega \tag{4}$$

Therefore, using a 6.34-kΩ resistor is sufficient for any LC combination. R_2 can be chosen for the desired output voltage using Equation 5.

$$R_2 = \frac{R_1 \times V_{REF}}{V_{OUT} - V_{REF}} \tag{5}$$

For example, for a desired output of 3.3 V, R_2 is calculated as:

$$R_2 = \frac{6.34\ \text{k}\Omega \times 0.8\ \text{V}}{3.3\ \text{V} - 0.8\ \text{V}} \approx 2.05\ \text{k}\Omega \tag{6}$$

From Equation 2 and Equation 3, the zero and pole are placed at 1 MHz and 4.194 MHz, respectively. The control loop gain can then be measured to find the unity gain crossover frequency without any effect from the internal Cff. The following equations then can be used to calculate R_1 and R_2 to reposition the geometric mean of the pole and zero to the crossover point, with Cff equal to 25 pF.

$$R_1 = \frac{1}{2\pi C_{ff} f_{CO}} \sqrt{\frac{V_{OUT}}{V_{REF}}} \tag{7}$$

$$R_2 = \frac{R_1 \times V_{REF}}{V_{OUT} - V_{REF}} \tag{8}$$

Continuing with the previous example, for a 3.3-V output and a crossover frequency of 30.3 kHz, R_1 and R_2 are calculated to be 432 kΩ and 137 kΩ, respectively. Figure 5 shows the increased loop bandwidth and phase with the new resistor values. This causes the improved transient response in Figure 6, which also has no ringing and excellent load regulation.

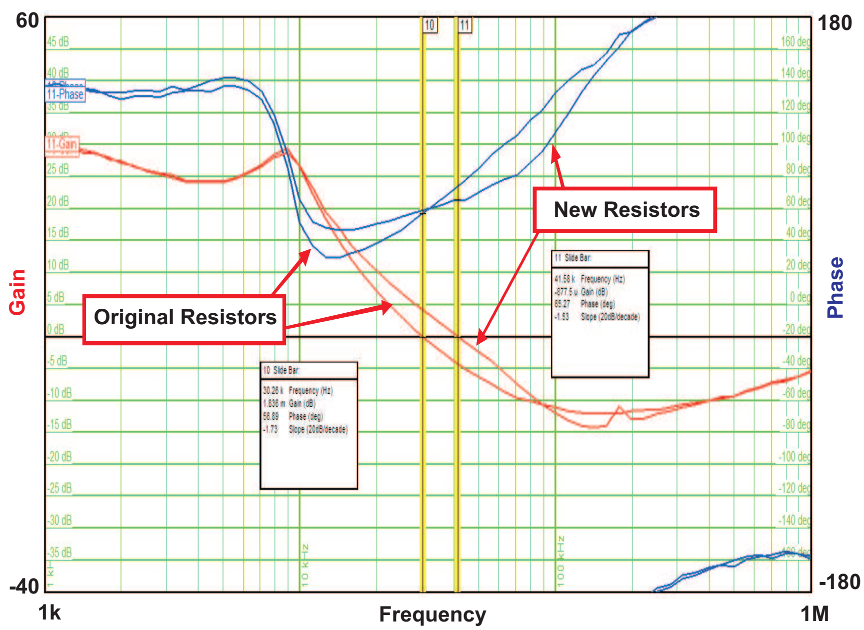

Figure 5. Loop Gain Before and After Optimizing Resistors

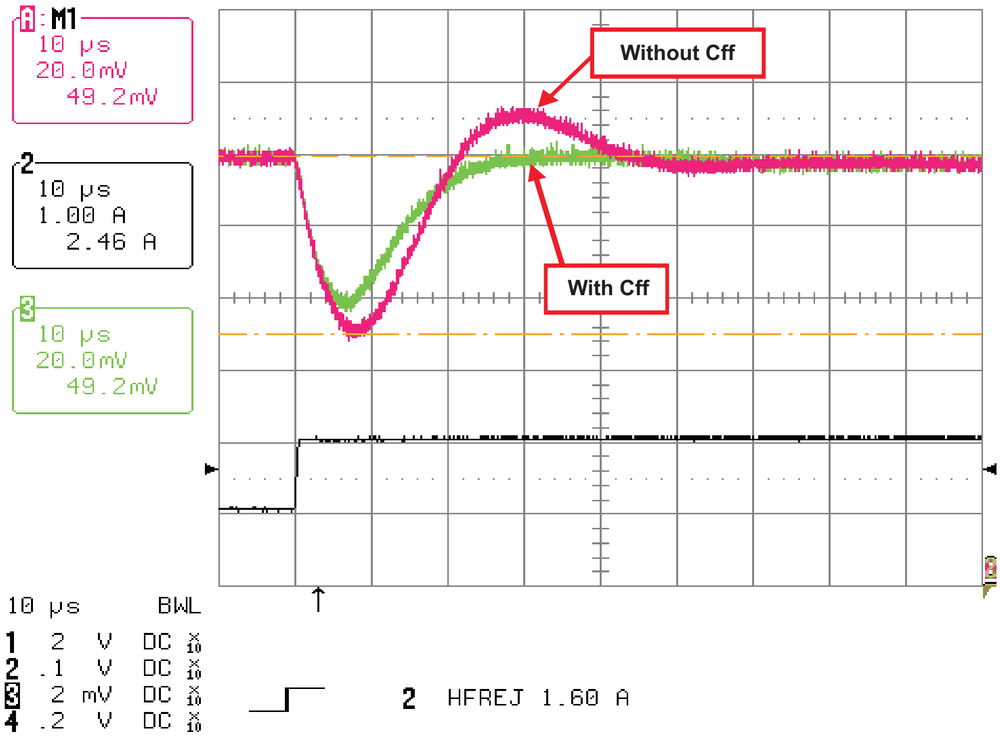

Figure 6. Load Transient Response Before and After Optimizing Resistors

3 Feedforward Capacitor for Gain Crossover Frequencies Above 100 kHz

At loop bandwidths above 100 kHz, the feedforward capacitor has limited or no effect on the response. This is a characteristic of the DCS-Control™ topology as implemented on the TPS62130/40/50/60/70. Figure 7 and Figure 8 show the results of optimizing the feedback resistors for the recommended 2.2-µH inductor and 22-µF output capacitor, which has a unity gain crossover frequency of 298.5 kHz. The lack of any significant change in the bode plot and load transient shows that the Cff has no effect.

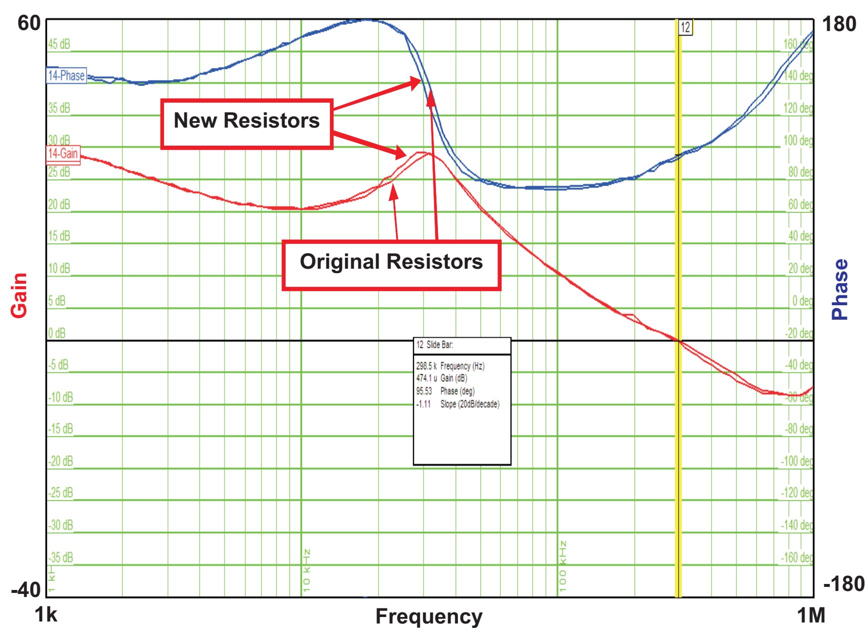

Figure 7. Loop Gain for 2.2-µH Inductor and 22-µF Capacitor

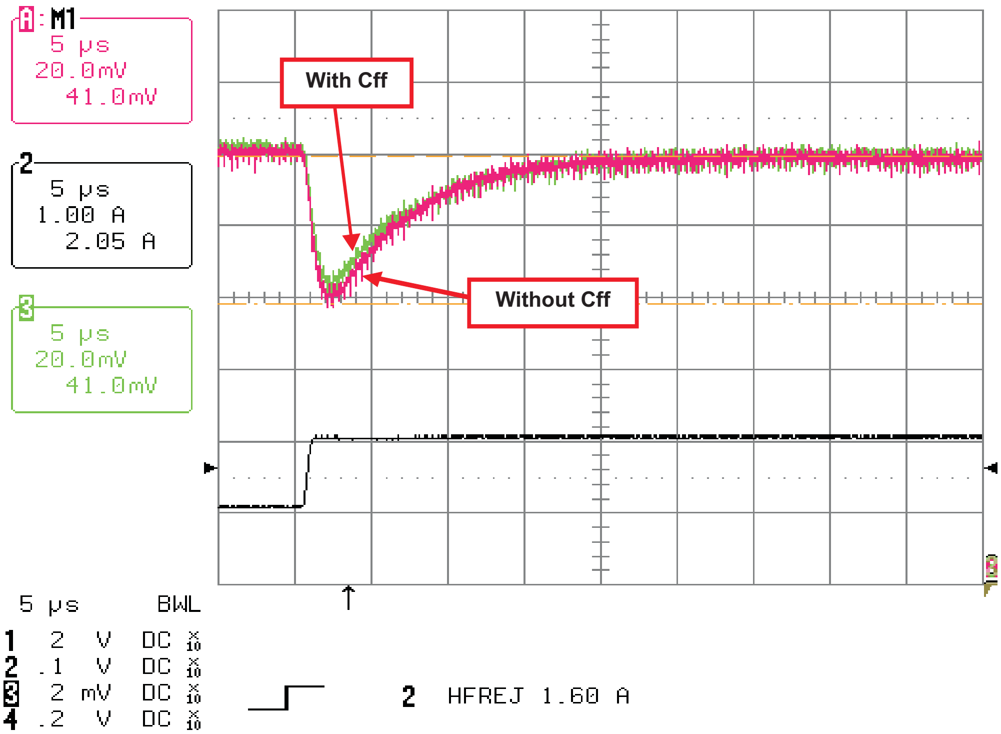

Figure 8. Load Transient Response for 2.2-µH Inductor and 22-µF Capacitor

4 Conclusion

This application report presents methods of improving the load transient response of the TPS62130/40/50/60/70 family of devices by using a feedforward capacitor. Either adding an external capacitor or adjusting the feedback resistors are two ways to improve the loop response for loop bandwidths below 100 kHz. For most designs, adjusting the feedback resistors to take advantage of the internal 25-pF Cff provides the best response without any extra components or negative performance effects.

5 References

1. *Optimizing the TPS62130/40/50/60/70 Output Filter* application report (SLVA463)
2. *How to Measure Control Loop of TPS62130/40/50/60/70 DCS-Control™ Devices* application report (SLVA465)
3. *TPS62130, 3-17V 3A Step-Down Converter in 3x3 QFN Package* data sheet (SLVSAG7)
4. *Optimizing Transient Response of Internally Compensated dc-dc Converters With Feedforward Capacitor* application report (SLVA289)