Using TPS5410/20/30/31/50 With Aluminum/Ceramic Output Capacitors

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ABSTRACT

As internally compensated devices, the wide input step-down SWIFT™ DC/DC converters, including TPS5410/5420/5430/5431/5450, have the advantages of less external part count and reduced design complexity, as well as limited output capacitor selection. By adding a few external components into the standard circuitry, these devices generally work well with aluminum/ceramic output capacitors. This application report shows the step-by-step design procedures when using aluminum/ceramic output capacitors with the wide input SWIFT™ DC/DC converters. Two design examples are provided to better understand both procedures.

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1 Introduction

The internally compensated wide input SWIFT™ product family was specifically designed for high-performance applications using high-quality output capacitors such as POSCAP™ (solid electrolytic capacitors with polymerized organic semiconductor), OS-CON™ (aluminum solid capacitors with organic semiconductive electrolyte), tantalum, and super-low-impedance aluminum capacitors, etc. Adopted from the TPS5430EVM-136 3-A, SWIFT™ Regulator Evaluation Module User's Guide (SLVU149), Figure 1 shows the schematic of TPS5430EVM-136 using 10TPB220M (POSCAP) and Figure 2 shows the measured loop-response characteristics at Vin=10.8 V and 5-V/3-A output. Additional details in this user's guide illustrate the performance of the design using POSCAP.

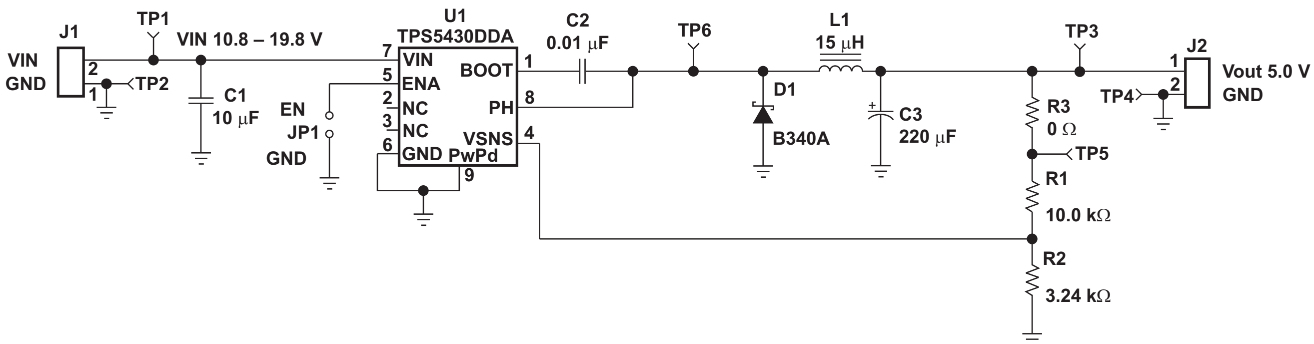

Figure 1. TPS5430EVM-136 Schematic

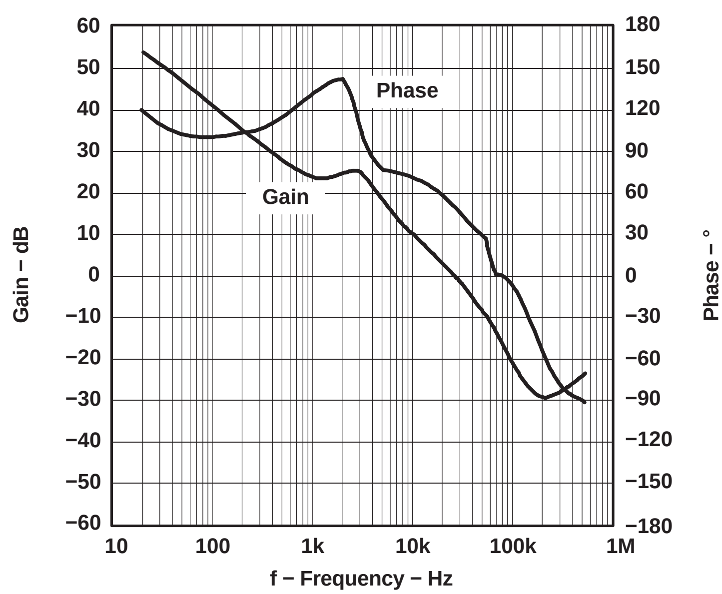

Figure 2. Measured Loop Response for TPS5430EVM-136, Vin=10.8 V

The ESR (equivalent series resistance) value of output capacitors plays an important role in the system stability of step-down DC/DC converters because of the resulting ESR zero in the power-stage frequency response. The ESR zero, which could be as low as 1 kHz for aluminum capacitors and as high as 5 MHz for ceramic capacitors, impacts both the gain response and the phase response. This makes it difficult for the fixed internal compensation network to work with a broad range of various aluminum/ceramic output capacitors. However, this does not preclude applications with aluminum/ceramic output capacitors. By simply adding two or three more external small resistors and capacitors, which are usually referred as RC networks, flexible designs generally can be done.

The basic idea of the external RC networks is to re-shape the frequency response so that the system stability is improved. For advanced users, see Appendix A, *Related RC Networks and Their Transfer Functions*.

Two design procedures are discussed in this application report: one is for applications using aluminum output capacitors and the other is for applications using ceramic output capacitors. For other design procedures, including the use of an output inductor, see the application sections of relevant data sheets. This application report focuses only on designing the additional RC network.

2 Design Procedure for Aluminum Output Capacitors

Figure 3 shows a TPS5430 application circuit using an aluminum output capacitor. Compared to Figure 1, a typical TPS5430 design, Figure 3 shows that two external components C12 and R7 have been added. Using application circuit 1 as an example, the following design procedure shows how to select component values for C12 and R7.

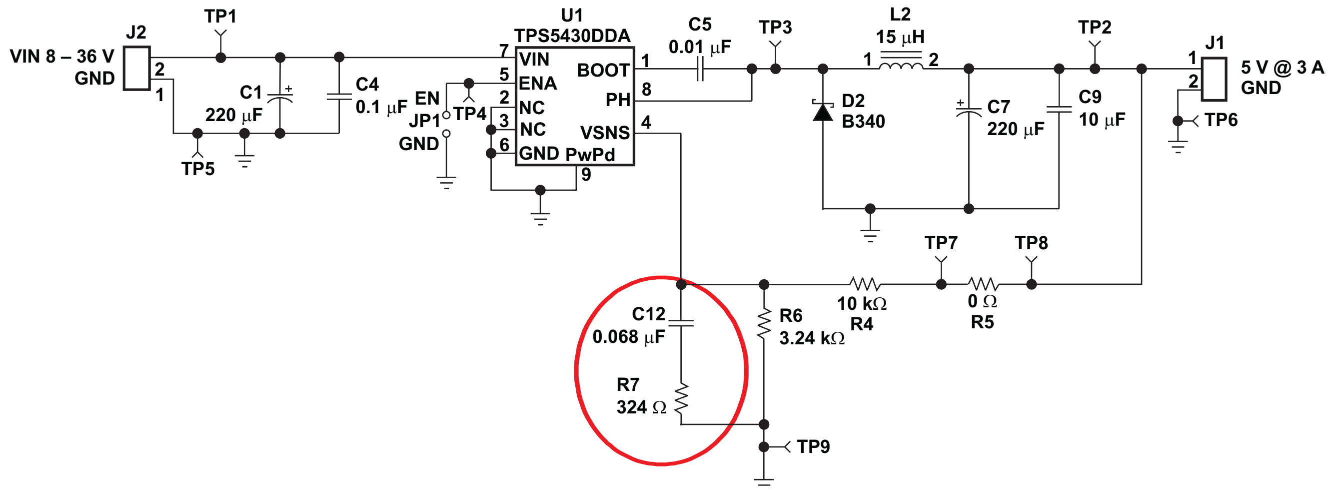

Figure 3. Application Circuit 1 Using Aluminum Output Capacitor

2.1 Design Parameters

- Input voltage range (Vin): 8 V - 36 V
- Output voltage (Vo): 5 V
- Output current rating (Io): 3 A
- Operating switching frequency (fs): 500 kHz

Following the routine design practice, DR125-150 from Coiltronics is selected as L2.

2.2 Aluminum Output Capacitors

In order for users to obtain good performance from the aluminum output capacitors they select, the following guidelines are recommended:

1. The resonant frequency f_{LC} in Equation (1) of the output filter should be no more than 5 kHz

$$f_{LC} = \frac{1}{2\pi \times \sqrt{Lo \times Co}} \quad (1)$$

Where Lo is the output inductance and Co is the output capacitance

So

$$Co \geq Co, min = \frac{1}{(2\pi \times 5k)^2 \times Lo} \quad (2)$$

2. The equivalent maximum ESR of the aluminum output capacitors Resr should yield an output ripple less that 5% of the output voltage which means the Resr should be less than the ESRmax defined in Equation (3)

$$ESR\,max = \frac{Vo \times 5\%}{Iopp} \quad (3)$$

Where

$$Iopp = \frac{(Vin,max - Vo)}{f s \times Lo} \times \frac{Vo}{Vin,max} \tag{4}$$

In this design, Lo = L2 = 15 µH, Vin,max = 36 V, fs = 500 kHz, then

$$Co \geq Co,min = \frac{1}{(2\pi \times 5k)^2 \times 15\ \mu H} = 67.5\ \mu F \tag{5}$$

$$Iopp = \frac{(36-5)}{500k \times 15\mu} \times \frac{5}{36} = 0.574\ A \tag{6}$$

$$ESR\,max = \frac{5 \times 5\%}{0.574} = 435\ m\Omega \tag{7}$$

Therefore, aluminum capacitors with greater than 67.5 µF equivalent capacitance and less than 435 mΩ of total ESR should yield good performance. The design example uses EEVFK0J221P with a maximum ESR of 360 mΩ from Panasonic for C7. C9 is a 10-µF ceramic bypass capacitor.

2.2.1 C12 and R7 Calculation

Perform the following steps to determine the values of C12 and R7:

1. Calculate the resonant frequency f_{LC} of the output filter by Equation 1 and the ESR zero fz0 of the output capacitor by Equation 8

$$f\,z0 = \frac{1}{2\pi \times Co \times Resr} \tag{8}$$

In this case, Lo = L2 = 15 µH, Co = C7 = 220 µH, Resr = 360 mΩ, therefore

$$f_{LC} = \frac{1}{2\pi \times \sqrt{15\mu \times 220\mu}} = 2.77\ kHz \tag{9}$$

$$f\,z0 = \frac{1}{2\pi \times 220\mu \times 360m} = 2.01\ kHz \tag{10}$$

2. Select the output voltage divider.

The output voltage Vo is set by the resistor divider of R4 and R6. R4 should be fixed at 10 kΩ. Calculate R6 value for 5-V output voltage using Equation 11:

$$R6 = \frac{R4 \times 1.221}{Vo - 1.221} \tag{11}$$

R6 is then 3.24 kΩ.

3. Calculate C12 and R7

As shown in Appendix A, *Related RC Networks and Their Transfer Functions*, the network composed of R4, R6, C12, and R7 has one pole fp1 and one zero fz2. Determine the pole and zero by the following equations:

$$f\,p1 = maximum\left(0.3k \times \frac{f\,z0 \times Vo}{f_{LC}} Hz, 1\ kHz\right) \tag{12}$$

$$f\,z2 = minimum\ (7.5 \times f\,p1,\ 10\ kHz) \tag{13}$$

Then, C12 and R7 can be calculated by Equation 14 and Equation 15,

$$C12 = \frac{1}{2\pi \times f\,p1 \times (R4\,//\,R6)} \tag{14}$$

$$R7 = \frac{1}{2\pi \times f\,z2 \times C12} \tag{15}$$

Where R4//R6 is the equivalent resistance when R4 and R6 are in parallel

For this design,

$$f\,p1 = \text{maximum}\left(0.3k \times \frac{2.01k \times 5}{2.77\ k}\text{Hz}, 1\ \text{kHz}\right) = \text{maximum}(1.09\ \text{kHz},\ 1\ \text{kHz}) = 1.09\ \text{kHz}$$

$$f\,z2 = \text{minimum}(7.5 \times 1.09\ \text{kHz},\ 10\ \text{kHz}) = \text{minimum}(8.17\ \text{kHz},\ 10\ \text{kHz}) = 8.17\ \text{Hz} \quad (16)$$

Then

$$C12 = \frac{1}{2\pi \times 1.09k \times 2.45k} = 0.06\ \mu F \quad (17)$$

$$R7 = \frac{1}{2\pi \times 8.17k \times 0.06\ \mu} = 325\ \Omega \quad (18)$$

Select the next highest standard value for C12 and the closest standard value for R7, respectively; then, C12 is 0.068 µF and R7 is 324 Ω.

2.3 Bill of Materials

Table 1 is the bill of materials for the key components in application circuit 1.

Table 1. Bill of Materials for Application Circuit 1

Count	RefDes	Value	Description	Size	Part Number	MFR
1	C1	220 µF	Capacitor, Aluminum, 220-µF, 50-V, 20%	0.457 × 0.406	EEVFK1H221P	Panasonic
1	C4	0.1 µF	Capacitor, Ceramic, 50-V, X7R, 10%	0603	Std	TDK
1	C5	0.01 µF	Capacitor, Ceramic, 50-V, X7R, 10%	0603	Std	TDK
1	C7	220 µF	Capacitor, Aluminum, 6.3-V, 220- µF, 20%, 360-mΩ	0.260 × 0.276 inch	EEVFK0J221P	Panasonic
1	C9	10 µF	Capacitor, Ceramic, 10-µF, 16-V, X5R, 20%	1210	Std	TDK
1	C12	0.068 µF	Capacitor, Ceramic, 50-V, X7R, 10%	0603	Std	TDK
1	D2		Diode, Schottky, 3-A, 40-V	SMC	B340	Motorola
1	L2	15 µH	Inductor, SMT,4.27-A, 29.8-mΩ	0.492 sq inch	DR125-150	Coiltronics
1	R4	10.0kΩ	Resistor, Chip, 1/16-W, 1%	0603	Std	Std
1	R5	0Ω	Resistor, Chip, 1/16-W, 1%	0603	Std	Std
1	R6	3.24kΩ	Resistor, Chip, 1/16-W, 1%	0603	Std	Std
1	R7	324Ω	Resistor, Chip, 1/16-W, 1%	0603	Std	Std
1	U1		IC, Switching Step-Down Regulator, 5.5-V - 36-V, 3-A	SO8 [DDA]	TPS5430DDA	TI

2.4 Performance Graphs

To illustrate how well the application circuit 1 operates, Figure 4 shows the loop responses for Vin = 12 V and Vin = 36 V. Figure 5 shows the output ripple, and Figure 6 shows the transient response.

2.5 Tips

To fine tune the values of C12 and R7 manually, keep in mind that decreasing C12 results in higher crossover frequency which means faster transient response and increasing R7 will boost the phase margin which means better system stability.

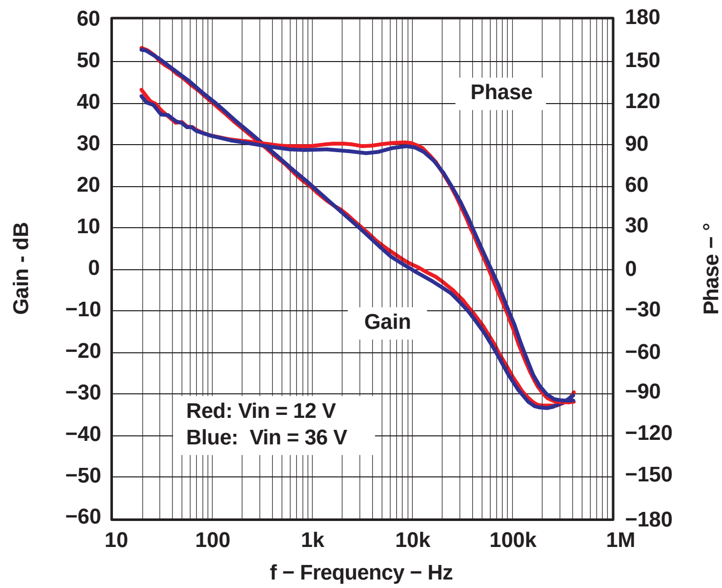

Figure 4. Measured Loop Responses for Application Circuit 1, Io = 3 A

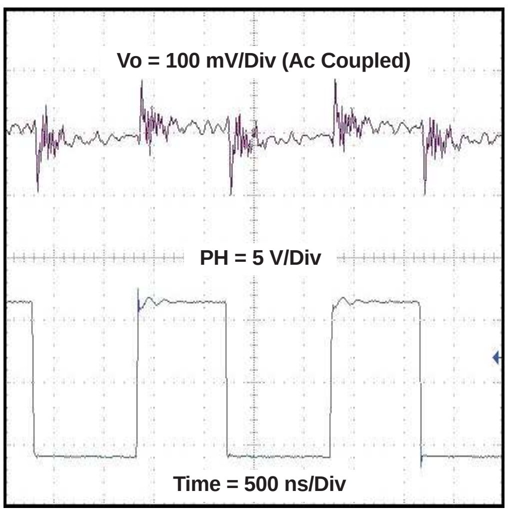

Figure 5. Measured Output Ripple for Application Circuit 1, Vin = 12 V and Vo = 5 V/3 A

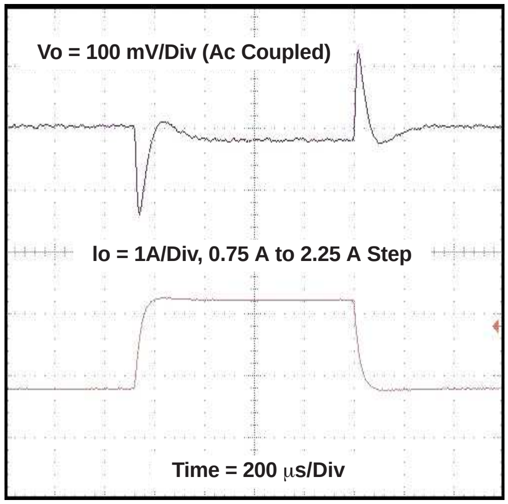

Figure 6. Measured Load Transient Response for Application Circuit 1, Vin = 12 V

3 Design Procedure for Ceramic Output Capacitors

Figure 7 shows application circuit 2, similar to application circuit 1 shown in Figure 3, but this circuit uses ceramic rather than aluminum output capacitors. The only differences between the two circuits are the output capacitors C7 and C9 and the external RC network C11, C12, C13 and R7. Using application circuit 2 as the example, the following design procedure shows how to select component values for C11, C12, C13 and R7.

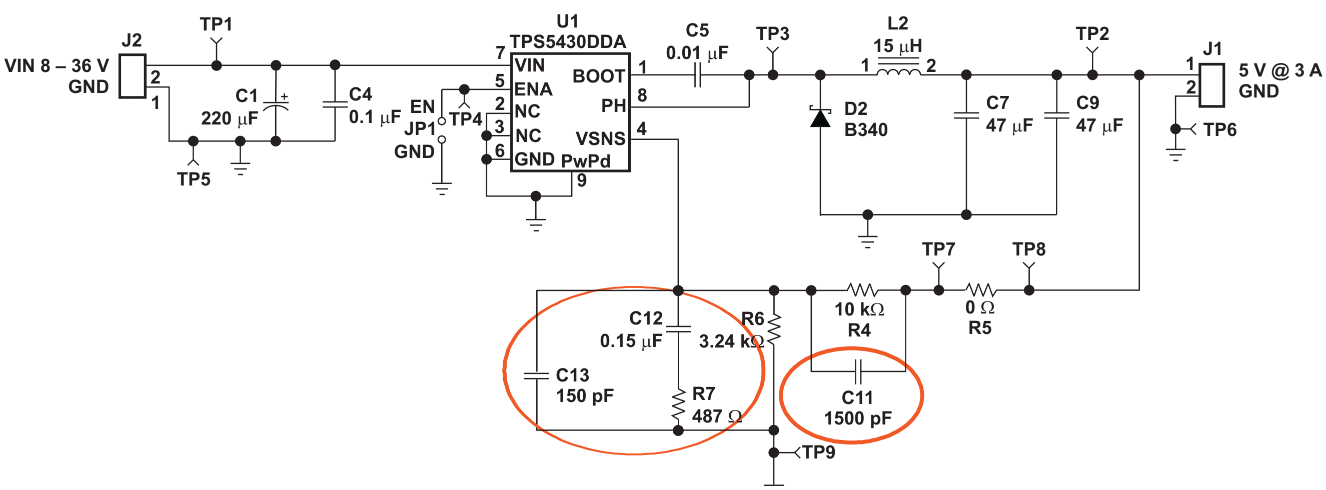

Figure 7. Application Circuit 2 Using Ceramic Output Capacitors

3.1 Design Parameters

- Input voltage range (Vin): 8 V - 36 V
- Output voltage (Vo): 5 V
- Output current rating (Io): 3 A
- Operating switching frequency (fs): 500 kHz

Following routine design practice, DR125-150 from Coiltronics is selected for L2.

3.2 Ceramic Output Capacitors

In order for users to obtain good performance from the ceramic output capacitors they select, it is recommended that the resonant frequency f_{LC} of the output filter is no more than 6 kHz, i.e.,

$$Co \geq Co, min = \frac{1}{(2\pi \times 6k)^2 \times Lo} \tag{19}$$

In this example, Lo = L2 = 15 µH, then

$$Co \geq Co, min = \frac{1}{(2\pi \times 6k)^2 \times 15\ \mu H} = 46.9\ \mu F \tag{20}$$

Therefore, ceramic capacitors with more than 46.9 µF equivalent capacitance should yield good performance. The design example uses C4532X5R1A476M from TDK as C7 and C9.

3.2.1 C11, C12, C13 and R7 Calculation

Perform the following the steps to determine the values of C11, C12, and R7:

1. Calculate the resonant frequency f_{LC} of the output filter by Equation 1. In this case, Lo = L2 = 15 µH, Co = C7//C9 = 94 µF, then

$$f_{LC} = \frac{1}{2\pi \times \sqrt{15\mu \times 94\mu}} = 4.24\ kHz \tag{21}$$

2. Select the output voltage divider.

   As mentioned previously, R4 should be fixed at 10 kΩ; R6 is calculated to be 3.24 kΩ for a 5-V output voltage using Equation 11.

3. Calculate C11, C12, and R7

   As shown in Appendix A, *Related RC Networks and Their Transfer Functions*, the network, composed of R4, R6, C11, C12, and R7, has two poles fp1 and fp4 and two zeros fz2 and fz3. Determine the poles and zeros by the following equations:

$$f\,p1 = 0.5\ M \times \frac{Vo}{f_{LC}} \tag{22}$$

$$f\,z2 = 0.7 \times f_{LC} \tag{23}$$

$$f\,z3 = 2.3 \times f_{LC} \tag{24}$$

   fz4 is usually located at too high a frequency to be concerned with. Then, C11, C12, and R7 can be calculated by Equation 25, Equation 26, and Equation 27.

$$C12 = \frac{1}{2\pi \times f\,p1 \times (R4\ //\ R6)} \tag{25}$$

$$R7 = \frac{1}{2\pi \times f\,z2 \times C12} \tag{26}$$

$$C11 = \frac{1}{2\pi \times f\,z3 \times R4} \tag{27}$$

Where R4//R6 is the equivalent resistance when R4 and R6 are in parallel

For this design,

$$f\,p1 = 0.5\ M \times \frac{5}{4.24k} = 589.62\ Hz$$

$$f\,z2 = 0.7 \times 4.24k = 2.97\ kHz$$

$$f\,z3 = 2.3 \times 4.24k = 9.75\ kHz \tag{28}$$

Then,

$$C12 = \frac{1}{2\pi \times 589.62 \times 2.45k} = 0.11\ \mu F$$

$$R7 = \frac{1}{2\pi \times 2.97k \times 0.11\mu} = 487\ \Omega$$

$$C11 = \frac{1}{2\pi \times 9.75k \times 10k} = 1633\ pF \qquad (29)$$

Select the next highest standard value for C12 and the closest standard value for C11 and R7, respectively; then, C11 is 1500 pF, C12 is 0.15 µF, and R7 is 487 Ω.

C13 is recommended to improve the load regulation performance. Since C13 is effectively in parallel with C11 to determine the location of fp4, C13 should be much smaller than C11 to be negligible. C13 must be less than the 1/10 value of C11. In this example, 150pF works well.

3.3 Bill of Materials

Table 2 is the bill of materials for the key components in application circuit 2.

Table 2. Bill of Materials for Application Circuit 2

Count	RefDes	Value	Description	Size	Part Number	MFR
1	C1	220 µF	Capacitor, Aluminum, 220-µF, 50-V, 20%	0.457 × 0.406	EEVFK1H221P	Panasonic
1	C4	0.1 µF	Capacitor, Ceramic, 50-V, X7R, 10%	0603	Std	TDK
1	C5	0.01 µF	Capacitor, Ceramic, 50-V, X7R, 10%	0603	Std	TDK
2	C7, C9	47 µF	Capacitor, Ceramic, 10-V, X5R, 20%	1812	C4532X5R1A476M	TDK
1	C11	1500 pF	Capacitor, Ceramic, 50-V, X7R, 10%	0603	Std	TDK
1	C12	0.15 µF	Capacitor, Ceramic, 50-V, X7R, 10%	0603	Std	TDK
1	C13	150 pF	Capacitor, Ceramic, 50-V, X7R, 10%	0603	Std	TDK
1	D2		Diode, Schottky, 3-A, 40-V	SMC	B340	Motorola
1	L2	15 µH	Inductor, SMT,4.27-A, 29.8-mΩ	0.492 sq inch	DR125-150	Coiltronics
1	R4	10.0kΩ	Resistor, Chip, 1/16-W, 1%	0603	Std	Std
1	R5	0Ω	Resistor, Chip, 1/16-W, 1%	0603	Std	Std
1	R6	3.24 kΩ	Resistor, Chip, 1/16-W, 1%	0603	Std	Std
1	R7	487Ω	Resistor, Chip, 1/16-W, 1%	0603	Std	Std
1	U1		IC, Switching Step-Down Regulator, 5.5-V - 36-V, 3A	SO8 [DDA]	TPS5430DDA	TI

3.4 Performance Graphs

To illustrate how well the application circuit 2 operates, Figure 8 shows the loop responses for Vin = 12 V and Vin = 36 V. Figure 9 shows the output ripple, and Figure 10 shows the transient response.

3.5 Tips

The capacitance for MLCC (multilayer ceramic chip) capacitors not only depends on the temperature and operating hours, but also depends on the applied DC bias voltage. The actual capacitance could drop to less than 60% of the nominal capacitance at the rated voltage, depending on the dielectric, the case size, and the nominal capacitance [1] [2] [3]. Because the capacitance change may affect the performance and stability of the corresponding circuit, it is important to examine the capacitors under the actual operation conditions and verify the actual capacitance. The foregoing design procedure is based on nominal values. If the actual capacitance reduces by more than 25% of the nominal value in the application, the foregoing calculations should be based on the actual capacitance, but not the nominal capacitance.

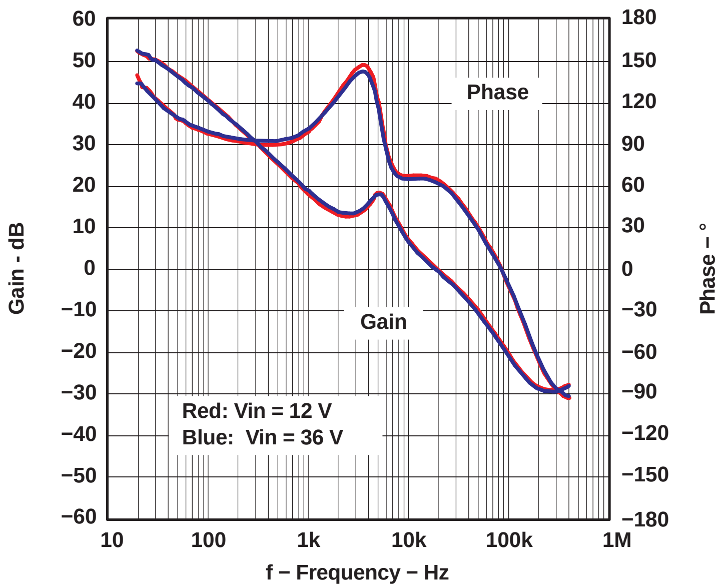

Figure 8. Measured Loop Responses for Application Circuit 2, Io = 3 A

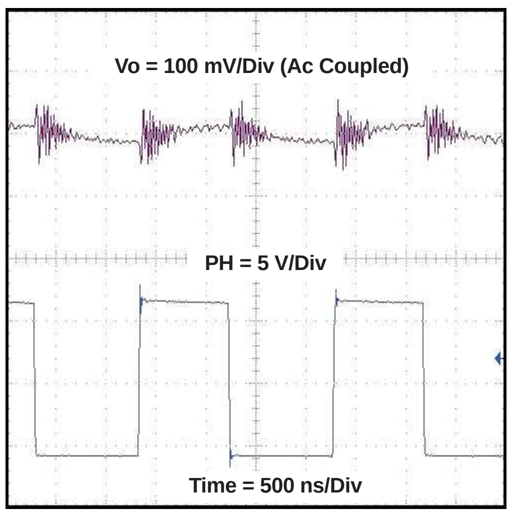

Figure 9. Measured Output Ripple for Application Circuit 2, Vin = 12 V and Vo = 5 V/3 A

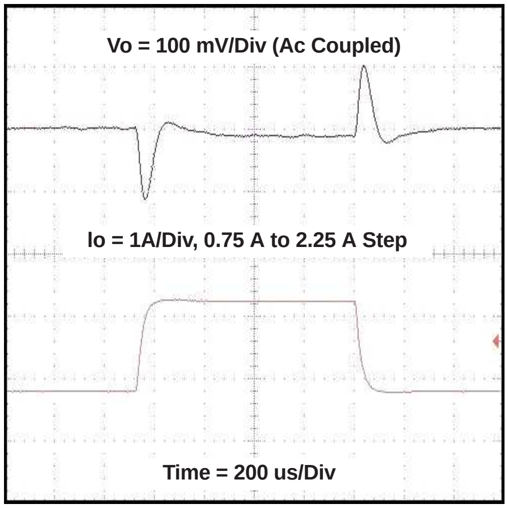

Figure 10. Measured Load Transient Response for Application Circuit 2, Vin = 12 V

4 Conclusion

The design procedures described in this application report have shown that it is easy to design with aluminum/ceramic output capacitors using the wide input step-down SWIFT™ DC/DC converters. The experimental measurements also have illustrated the feasibility of the design procedures.

Appendix A Related RC Networks and Their Simplified Transfer Functions

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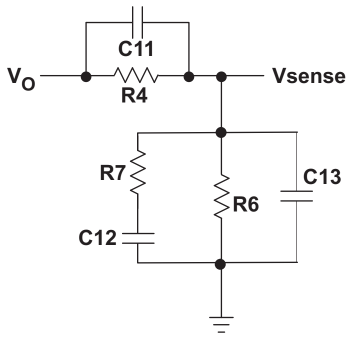
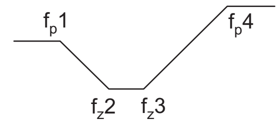
<td>
</td>
<td>$$\frac{Vsense(s)}{Vo(s)} = \frac{R6}{R4 + R6} \times \frac{(1 + s \times C11 \times R4) \times (1 + s \times C12 \times R7)}{[1 + s \times (C11 + C13) \times (R6 // R7)] \times [1 + s \times C12 \times (R4 // R6 + R7)]}$$</td>
<td>

$$f\,p1 = \frac{1}{2\pi \times C12 \times [(R4 // R6) + R7]}$$
$$f\,z2 = \frac{1}{2\pi \times C12 \times R7}$$
$$f\,z3 = \frac{1}{2\pi \times C11 \times R4}$$
$$f\,p4 = \frac{1}{2\pi \times (C11 + C13) \times (R6 // R7)}$$</td>
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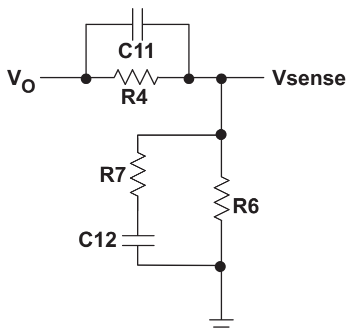
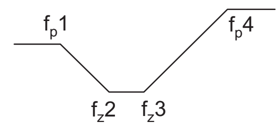
<td>
</td>
<td>$$\frac{Vsense(s)}{Vo(s)} = \frac{R6}{R4 + R6} \times \frac{(1 + s \times C11 \times R4) \times (1 + s \times C12 \times R7)}{[1 + s \times C11 \times (R6 // R7)] \times [1 + s \times C12 \times (R4 // R6 + R7)]}$$</td>
<td>

$$f\,p1 = \frac{1}{2\pi \times C12 \times [(R4 // R6) + R7]}$$
$$f\,z2 = \frac{1}{2\pi \times C12 \times R7}$$
$$f\,z3 = \frac{1}{2\pi \times C11 \times R4}$$
$$f\,p4 = \frac{1}{2\pi \times C11 \times (R6 // R7)}$$</td>
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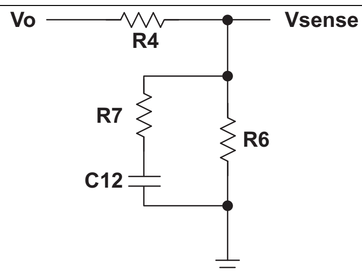
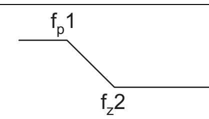
<td>
</td>
<td>$$\frac{Vsense(s)}{Vo(s)} = \frac{R6}{R4 + R6} \times \frac{(1 + s \times C12 \times R7)}{[1 + s \times C12 \times (R4 // R6 + R7)]}$$</td>
<td>

$$f\,p1 = \frac{1}{2\pi \times C12 \times [(R4 // R6) + R7]}$$
$$f\,z2 = \frac{1}{2\pi \times C12 \times R7}$$</td>
</tr>
</table>

Appendix B References

1. George M. Harayda, Akira Omi, and Axel Yamamoto, *Improve Your Designs with Large Capacitance Value Multi-Layer Ceramic Chip (MLCC) Capacitors*, Panasonic Industrial Company.
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