Design Considerations for DC-DC Converters in Fast-Input Slew Rate Applications

Mahmoud Harmouch, Ashish Khandelwal, Ankur Verma — *Mixed Signal Automotive*

ABSTRACT

This application report describes the ways to optimize the design of DC-DC converters (TPS54040-Q1, TPS54060-Q1, TPS54140-Q1, TPS54160-Q1, TPS54240-Q1, TPS54260-Q1, TPS57040-Q1, TPS57060-Q1, TPS57140-Q1, and TPS57160-Q1) in applications with fast transition at the input voltage on the rising and falling edges. First, the issues faced under such a scenario are analyzed. Then, design considerations are provided so that the application circuit operates according to device specifications (see Section 4 for a list of device data sheets).

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1 Application Solution During Fast Rising Input Transient

The topics covered in this application report apply to any DC-DC converters in the TPS540x0-Q1, TPS541x0-Q1, TPS542x0-Q1, TPS570x0-Q1, and TPS571x0-Q1 family of devices. For the purposes of this report, use the following example: the input voltage transitions from a low level of approximately 5 V to a high voltage level of approximately 40 V which means a rapid transition of approximately 35 V occurs at the input voltage, V_I. The TPS57140-Q1 device has a minimum on-time of 170 ns. The minimum on-time is limited by many factors such as bond wire and PCB parasitics, propagation delay, and others. However, the system design parameters can be selected in a way that the minimum on-time is no longer a restriction for fast input-voltage transients.

If the system design parameters are not carefully selected, then the output voltage can experience an overshoot because of the minimum on-time limitation that can reach the overvoltage-protection (OVP) threshold of the device.

To ensure that device does not reach the OVP threshold during an input voltage transient, the following condition must be satisfied at a given output voltage and switching frequency across the entire V_I operating range.

$$\frac{V_O}{V_I} > t_{on(min)} \times f_{SW} \tag{1}$$

where

- V_O is the output voltage of the converter.
- $t_{on(min)}$ is the maximum limit of the minimum on-time listed in the data sheet.
- f_{SW} is the switching frequency.

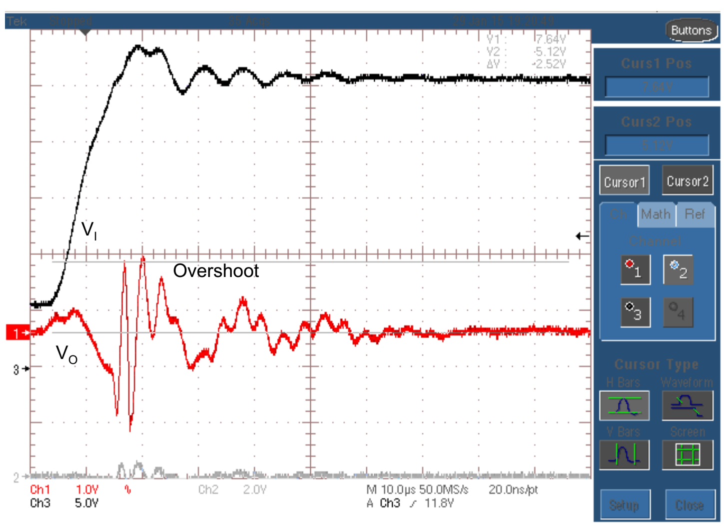
Use the following values for this example: f_{SW} = 2 MHz, $t_{on(min)}$ = 170 ns, and V_O = 3.3 V.

Use Equation 2 to calculate the maximum allowed value for V_I.

$$V_I < \frac{V_O}{t_{on(min)} \times f_{SW}} \tag{2}$$

Equation 2 results in V_I < 9.7 V.

In this case, if the V_I transient goes above 9.7 V, an overshoot occurs at V_O because of a violation of the specification for the minimum on-time which may cause the converter to reach the OVP threshold.



NOTE: V_O is AC-coupled in this scope capture.

Figure 1. Output Voltage Overshoot (Channel 1) With Fast Input-Voltage Transient (Channel 3)

Figure 1 shows the effect when the output voltage (V_O) experiences an overshoot during the rising transition. This overshoot, if high, could reach the OVP threshold of the device.

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To avoid a V_O overshoot during the rising V_I transition, either lower the switching frequency of the converter or increase the bandwidth of the voltage loop.

1.1 Lowering the Converter Switching Frequency

One method to avoid a V_O overshoot during the rising V_I transition is lowering the switching frequency of the converter. If the switching frequency is lowered, then the input voltage changes accordingly as shown in Equation 3.

$$V_I < \frac{V_O}{t_{on(min)} \times f_{SW}} \tag{3}$$

For example, when f_{SW} = 500 kHz, $t_{on(min)}$ = 170 ns, and V_O = 3.3 V, the maximum allow V_I value is calculated as 38.8 V. Therefore, if the V_I transient goes above 38.8 V, an overshoot will occur at V_O because the minimum on-time limitation can reach the OVP threshold of the device.

1.2 Increasing the Voltage-Loop Bandwidth

Another method to avoid a V_O overshoot during the rising V_I transition is increasing the bandwidth of the voltage loop. Increasing the bandwidth of the voltage loop allows the converter to respond quickly to the sudden change in the input voltage. As soon as the converter receives this information, the power FET quickly turns off and stops charging the output capacitor.

For example, when V_I = 35 V (5- to 40-V change), V_O = 3.3 V, inductance (L) = 10 µH, and $t_{on(min)}$ = 170 ns, the inductor ripple current is calculated as 620 mA using Equation 4.

$$\Delta I_L = \frac{V_I - V_O}{L} t_{on} \tag{4}$$

This inductor ripple current charges the output capacitor ($C_{(OUT)}$) and leads to an overshoot at the output voltage. Use Equation 5 to calculate the change in the output voltage (ΔV_O).

$$\Delta V_O = \Delta I_L \frac{\text{charge time}}{C_{(OUT)}} \tag{5}$$

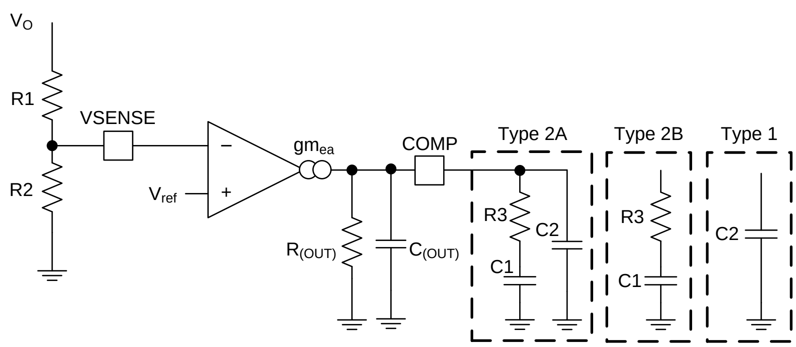

Figure 2. Types of Frequency Compensation (TPS57140-Q1)

If the required change in the output voltage must be within ±4% (0.04 × 3.3 V = 0.132 V), the charging time can be calculated as 9.94 µs (with $C_{(OUT)}$ = 47 µF).

The loop response, if lower than 9.94 µs in this example, can help compensate for the overshoot in the output voltage. Using the standard bandwidth versus response time, use Equation 6 to calculate the bandwidth which, for this example, results in 35.2 kHz.

$$BW = \frac{0.35}{t_{res}} \tag{6}$$

where

- BW is the bandwidth.
- t_{res} is the response time.

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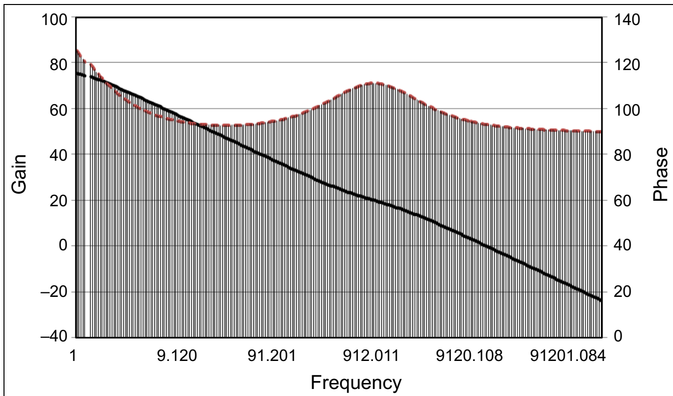
If values of the compensation network are changed to achieve a bandwidth of 35.2 kHz, the overshoot can be controlled to be within ±4% of V_O. Use the design calculator tool (www.ti.com/tool/tps54-57xx0-calc) for the TPS54xx0-Q1 and TPS57xx0-Q1 to calculate the crossover frequency for the selected R3 and C1 values.

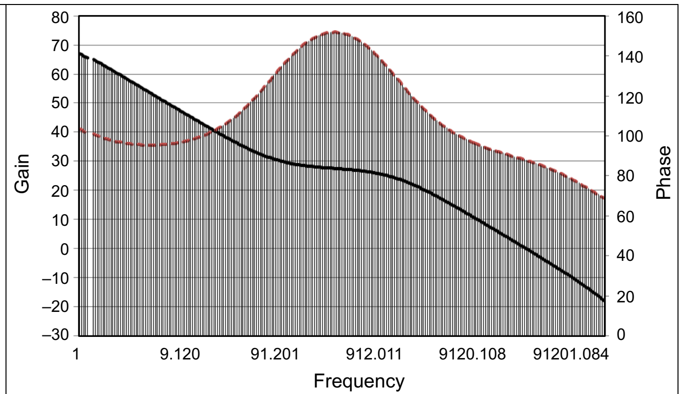
With the following values, R3 = 100 kΩ and C1 = 2.2 nF, the crossover frequency is calculated as 14.45 kHz (see Figure 3).

By changing the value of R3 to 243 kΩ and C1 to 6.8 nF, the crossover frequency can be increased to approximately 35 kHz (see Figure 4). Increasing the crossover frequency helps limit the overshoot voltage at the output.



Crossover frequency = 14.45 kHz

Figure 3. Gain and Phase Plots for Power Stage and Error Amplifier



Crossover frequency = 35.2 kHz

Figure 4. Gain and Phase Plots for Power Stage and Error Amplifier

2 Application Issue during fast falling input transient

During the fast input falling edge, if the slew rate of the input is higher than a particular value, the internal LDO regulator of the device resets because of the power-supply rejection-ratio (PSRR) limitation. The PSRR is a measurement of the power supply of the circuit expressed as a ratio of the output ripple to input power supply ripple.

Equation 7 shows the basic equation to calculate PSRR.

$$PSRR = 20 \log \frac{V_{I(rip)}}{V_{O(rip)}}$$

where

- $V_{I(rip)}$ is the input voltage ripple
- $V_{O(rip)}$ is the output voltage ripple (7)

The fast transition corresponds to higher frequencies. The bandgap noise that is internal to the LDO regulator becomes a limiting factor in the rejection of high frequency components. Using the TPS57140-Q1 design simulation and bench test measurement, the resulting slew-rate value was 1.2 V/µs. If the slew rate is higher than this value, the device is disabled and regenerates a soft start. Higher ESR of the input capacitor negatively affects the slew rate of the input voltage and the duration of this rate because of high current transient across the ESR according to ESR × C × dV/dt. Therefore, the use of a low-ESR ceramic capacitor is recommended.

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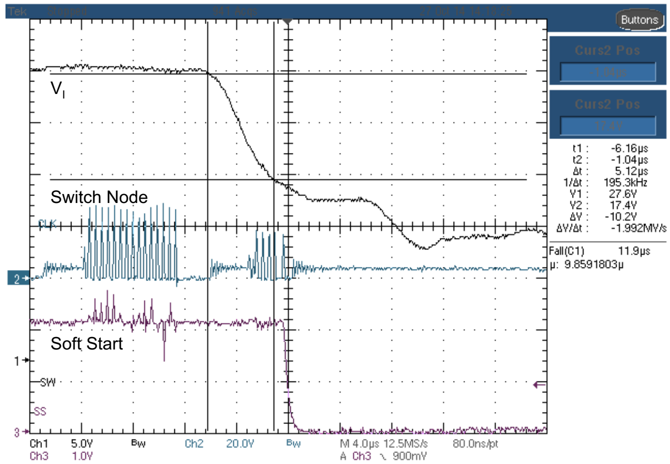

Figure 5. Disabling the Device With Fast-Falling Input Transient

3 Conclusion

In conclusion, a fast-rising input transient can be avoided by either increasing the voltage-loop bandwidth or reducing the switching frequency of the converter. A fast-falling input transient can be avoided by selecting a low-ESR ceramic input capacitor.

4 Related Documentation

For related documentation, see the following:

- TPS54040-Q1 *0.5-A 42-V STEP-DOWN SWIFT™ DC/DC CONVERTER WITH Eco-mode™*, SLVSA26
- TPS54060-Q1 *0.5-A 60-V STEP-DOWN SWIFT™ DC/DC CONVERTER WITH Eco-mode™*, SLVSA25
- TPS54140-Q1 *1.5-A 42-V STEP-DOWN SWIFT™ DC/DC CONVERTER WITH Eco-mode™ CONTROL*, SLVSA24
- TPS54160-Q1 *1.5-A 60-V STEP-DOWN SWIFT™ DC-DC CONVERTER WITH Eco-mode™ CONTROL*, SLVS922
- TPS54240-Q1 *3.5-V to 42-V STEP-DOWN SWIFT™ DC/DC CONVERTER WITH Eco-mode™ CONTROL SCHEME*, SLVSAQ4
- *TPS54260-Q1 3.5-V to 60-V Step-Down Converter With Eco-Mode™*, SLVSAH8
- *TPS57040-Q1 0.5-A 42-V Step-Down SWIFT™ DC-DC Converter With Eco-mode™*, SLVSAP4
- TPS57060-Q1 *0.5-A 60-V STEP-DOWN SWIFT™ DC/DC CONVERTER WITH Eco-mode™*, SLVSAP2
- TPS57140-Q1 *1.5-A 42-V STEP-DOWN SWIFT™ DC/DC CONVERTER WITH Eco-mode™ CONTROL*, SLVSAP3
- *TPS57160-Q1 1.5-A 60-V Step-Down SWIFT™ DC-DC Converter With Eco-mode™ Control*, SLVSAP1

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