Application Note

Design Considerations for Boost Converter With Pass-Through Mode

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Abstract

A boost converter supporting pass-through mode is a cost-effective design for applications in which the input voltage can exceed the required output voltage. Using the existing high-side FET rather than adding an additional bypass FET reduces product cost in pass-through mode. However, the inductor remains in the power stage circuit, forming an under-damped RLC network that can cause undershoot of the output voltage and ringing during load transients. Therefore, the effects of output voltage undershoot and recovery time must be evaluated. This application note provides analytical expressions for these effects and verifies the theoretical analysis through simulation and experimentation. This document also offers guidance for selecting components to meet transient requirements and notes that pass-through mode is suitable for most practical applications.

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1 Introduction

The boost converter with pass-through mode is used in applications where the supply voltage exceeds the target output (V_{o_target}). When the input voltage (V_{in}) exceeds the target output (V_{o_target}), the high-side FET turns on and the output voltage follows the input voltage.

Compared to the bypass topology, pass-through mode reuses the existing high-side FET. There is no need to add a bypass FET, thereby reducing costs. However, the inductor remains in the power stage circuit, causing output voltage undershoot and ringing during the load transient test. This application note contains the following:

1. Relationship between output impedance and transient response
2. Expressions for undershoot and recovery time
3. Simulation and experimental verification

2 Pass-Through Mode Steady-State and Transient Analysis

To better analyze the transient behavior in pass-through mode, the output impedance transfer function from load current (I_o) to output voltage (V_o) is shown below:

$$Z_O(s) = \frac{I_O}{V_O} = -\frac{sL + R_t}{s^2LC_O + sC_OR_t + 1} \quad (1)$$

where,

- I_o *(A)* = Load current
- V_o *(V)* = Output voltage
- *L(H)* = Inductor
- C_o*(F)* = Output capacitor
- R_t*(Ω)* = Circuit total resistance

The detailed circuit is shown below.

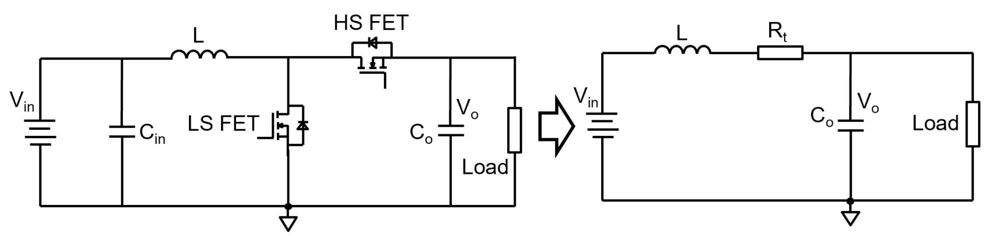

Figure 2-1. RLC Equivalent Circuit in Boost Pass-through Mode

This is a second-order system that includes a zero. The standard parameters for a second-order system are defined as follows:

Damping Ratio:

$$\xi = \frac{R_t}{2}\sqrt{\frac{C}{L}} \quad (2)$$

Undershoot %:

$$\sigma\% = e^{-\frac{\pi\xi}{\sqrt{1-\xi^2}}} \times 100\% \quad (3)$$

Natural Frequency:

$$\omega_n = \sqrt{\frac{1}{LC}} \quad (4)$$

Damp Frequency:

$$\omega_d = \omega_n\sqrt{1-\xi^2} \tag{5}$$

Phase Angle:

$$\varphi = cos^{-1}\xi \tag{6}$$

Recovery time:

$$t_s = (4\pi - \varphi)/\omega_d \tag{7}$$

For a second-order system with a zero, the zero affects the transient behavior. The undershoot and recovery time can be defined as follows:

$$\sigma_z\% = \sigma\%\frac{l}{|z|}e^{-\frac{\xi\theta}{\sqrt{1-\xi^2}}} \tag{8}$$

where,

- *l*: Length from zero point to the pole
- |*z*|: Amplitude of zero point
- *θ*: Phase angle between the zero point and pole

$$t_{sz} = t_s + \frac{1}{\xi\omega_n}\ln\frac{l}{|z|} \tag{9}$$

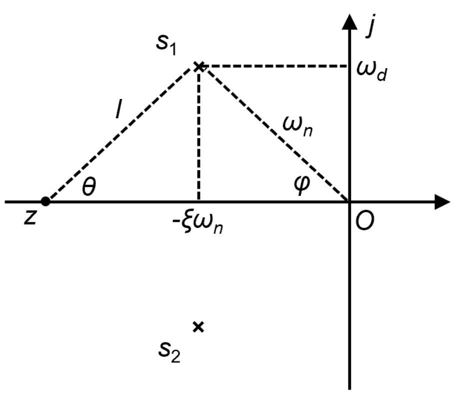

Figure 2-2. Zero–Pole Distribution of a Second-Order System

To better evaluate the transient behavior, the percentage of undershoot can be defined as follows:

$$Undershoot\% = \frac{\sigma_z}{V_O} \times 100\% \tag{10}$$

For the common DC/DC application, the undershoot% should be limited within ±5%.

When L=160nH, C_o=22µF, R_t=55mΩ, the MATLAB calculation and Simplis simulation transient results are shown in Figure 2-3 and Figure 2-4. The undershoot is 1.01 %, which satisfies the ±5% requirement. The calculation and simulation results are basically consistent.

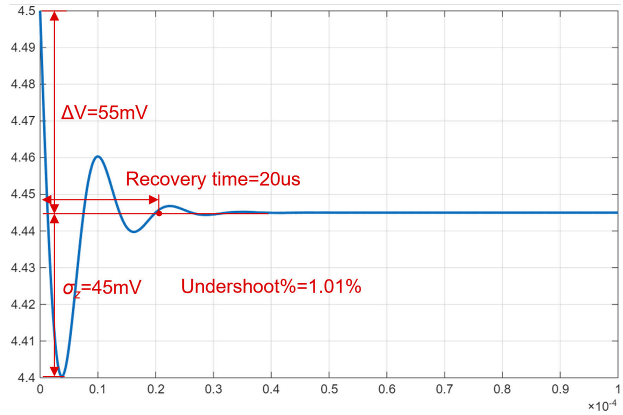

Figure 2-3. MATLAB Step-response Calculation Result

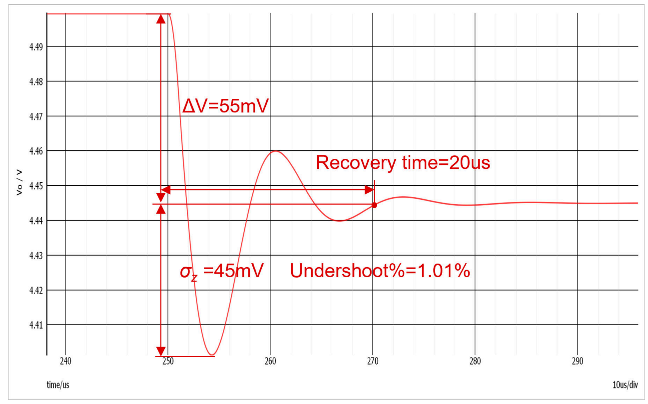

Figure 2-4. Simplis Step-response Simulation Result

3 Simulation Results

In pass-through mode, the boost converter's high-side FET is fully turned on when the input voltage (V_{in}) exceeds the target output voltage (V_{out_target}). In battery-powered applications, the battery can be modeled as a voltage source with internal resistance and capacitance. The high input capacitance provided by the battery can reduce the input voltage drop during a load transient test. The equivalent circuit is shown in Figure 2-1.

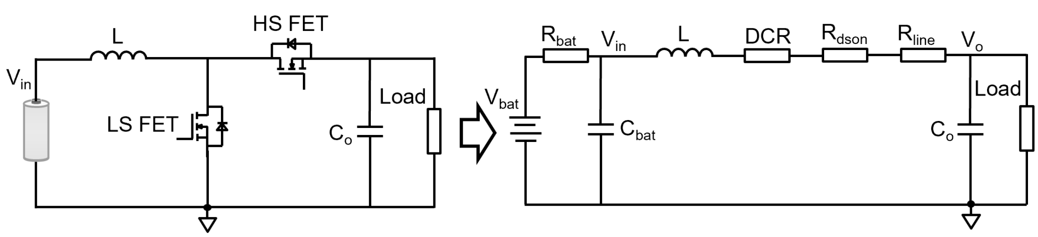

Figure 3-1. RLC Equivalent Circuit in Single Battery Application

The above circuit can be modeled as a series combination of the battery internal resistance (R_{bat}), inductor DC resistance (DCR), high-side FET on-resistance (R_{dson}), and PCB resistance (R_{line}). The steady-state relationship is as follows:

$$\Delta V = V_{in} - V_o = I_L(DCR + R_{dson} + R_{line}) \tag{11}$$

$$\Delta V_{in} = \Delta I_L R_{bat} \tag{12}$$

where,

- DCR: Inductor DC resistance
- R_{dson}: High side FET on-resistance
- R_{line}: PCB and line resistance
- R_{bat}: Battery internal resistance

Therefore, we can combine the above equations and use the following parameters for the simulation. Through these parameters, the RLC circuit model can be used to estimate the pass-through transient behavior. The simulation results are shown in Figure 3-2 and Figure 3-5.

Table 3-1. Circuit Parameters

PARAMETERS	VALUE
V_{in}	4.5V
V_{o_target}	3.3V
L	160nH/470nH

Table 3-1. Circuit Parameters (continued)

PARAMETERS	VALUE
C_{in}	2.2mF
C_o	11µF
R_{bat}	25mΩ
DCR	3/11mΩ
R_{dson}	18mΩ
R_{line}	10mΩ

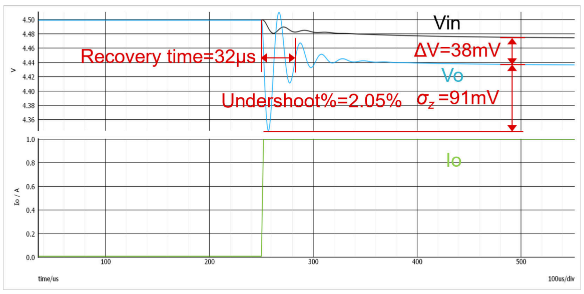

Figure 3-2. Transient Simulation, L=470nH, I_o=0 to 1A, 1A/µs

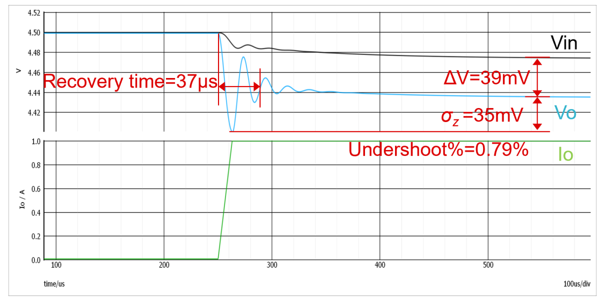

Figure 3-3. Transient Simulation, L=470nH, I_o=0 to 1A, 0.1A/µs

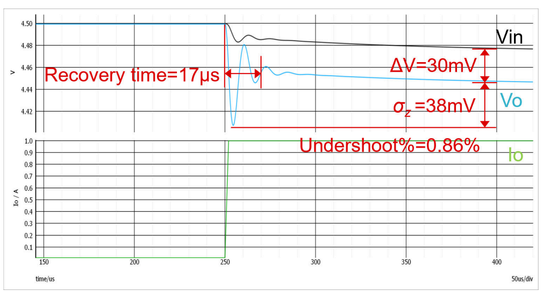

Figure 3-4. Transient Simulation, L=160nH, I_o=0 to 1A, 1A/µs

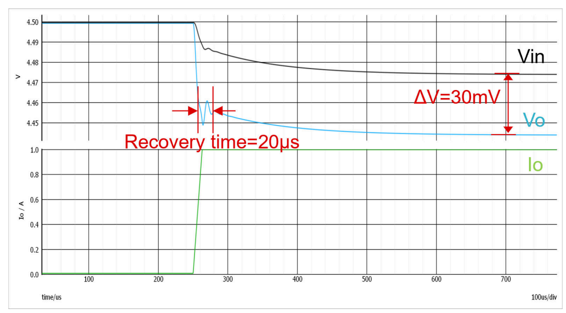

Figure 3-5. Transient Simulation, L=160nH, I_o=0 to 1A, 0.1A/µs

Table 3-2. Simulation Results Summary

Parameters	ΔV_{in}/mV		ΔV/mV		Undershoot%		Recovery Time/µs	
Inductor/nH	160	470	160	470	160	470	160	470
0-1A, 1A/µs	26	26	30	38	0.86%	2.05%	17	32
0-3A, 1A/µs	78	78	90	114	3.88%	5.43%	17	32
0-1A, 0.1A/µs	26	26	30	39	0%	0.79%	20	37
0-3A, 0.1A/µs	78	78	90	117	0%	2.44%	21	37

When the inductance is 160nH, due to the slow current change rate of 0.1A/µs, the σ_z of V_o is relatively small and does not exceed the steady value, so the undershoot%=0%.

Simulations were conducted under various operating conditions, including different inductances, currents, and transient response speeds. The results show that, in pass-through mode, both the undershoot of the output voltage and the recovery time meet the requirements of most applications in pass-through mode.

4 Test Results and Performance Curves

TPS61022 is a 0.5V-5.5V input, 2.2V-5V output synchronous boost converter. It supports the pass-through mode. To verify the accuracy of the theoretical calculations and simulations further, we selected this device for bench testing. The modified TPS61022EVM schematic is shown below.

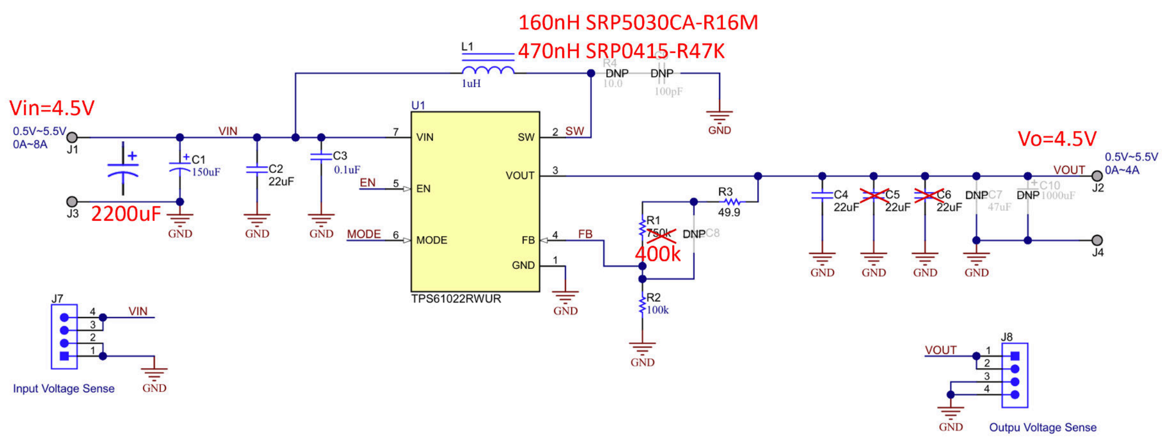

Figure 4-1. TPS61022EVM Schematic for Bench Test

Based on the simulation conditions, load transient tests were conducted in pass-through mode under the following specific conditions: V_{in}=4.5V, V_{out}=4.5V, L=470nH and 160nH, C_o=22µF (effective capacitance is 11µF), auto PFM mode. The bench test results are shown in Figure 4-2 to Figure 4-5.

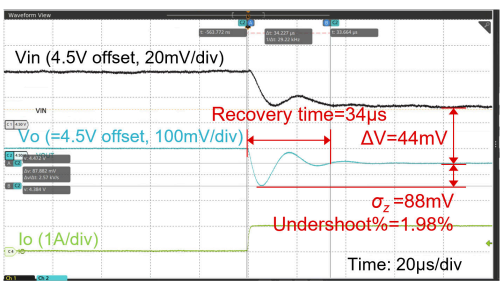

Figure 4-2. Load Transient in Pass-through Mode, I_o=0 to 1A, 1A/µs, L=470nH

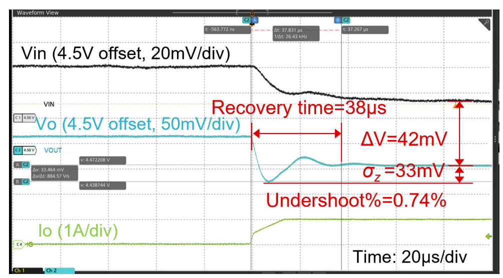

Figure 4-3. Load Transient in Pass-through Mode, I_o=0 to 1A, 0.1A/µs, L=470nH

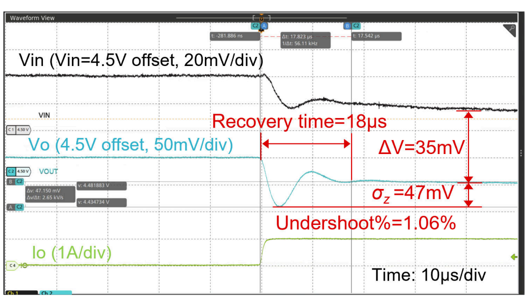

Figure 4-4. Load Transient in Pass-through Mode, I_o=0 to 1A, 1A/µs, L=160nH

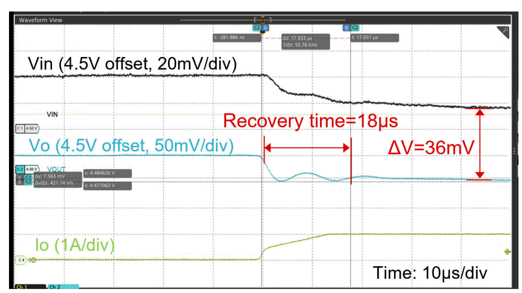

Figure 4-5. Load Transient in Pass-through Mode, I_o=0 to 1A, 0.1A/µs, L=160nH

Table 4-1. TPS61022EVM Bench Test Results Summary

Parameters	ΔV_{in}/mV		ΔV/mV		Undershoot%		Recovery time/µs	
Inductor/nH	160	470	160	470	160	470	160	470
0-1A, 1A/µs	26	25	35	44	1.06%	1.98%	18	34
0-3A, 1A/µs	78	79	80	106	2.3%	5.71%	19	37
0-1A, 0.1A/µs	26	25	36	42	0%	0.74%	18	38
0-3A, 0.1A/µs	80	81	79	103	0%	0.88%	21	37

When the inductance is 160nH, due to the slow current change rate of 0.1A/µs, the σ_z of V_o is relatively small and does not exceed the steady value, so the undershoot% = 0%.

According to Table 4-1, most of the test conditions can meet the requirements of undershoot% and recovery time. And compared with Table 3-2, the simulation and bench test results are basically consistent. Therefore, for most applications, the transient response of the pass-through mode meets the requirements and offers cost advantages.

In addition, the ΔVin and ΔV reflect the steady-state response and are related to the DCR, Rdson, and the PCB resistance of the board. Undershoot% and recovery time are related to the inductor, transient slew rate and amplitude.

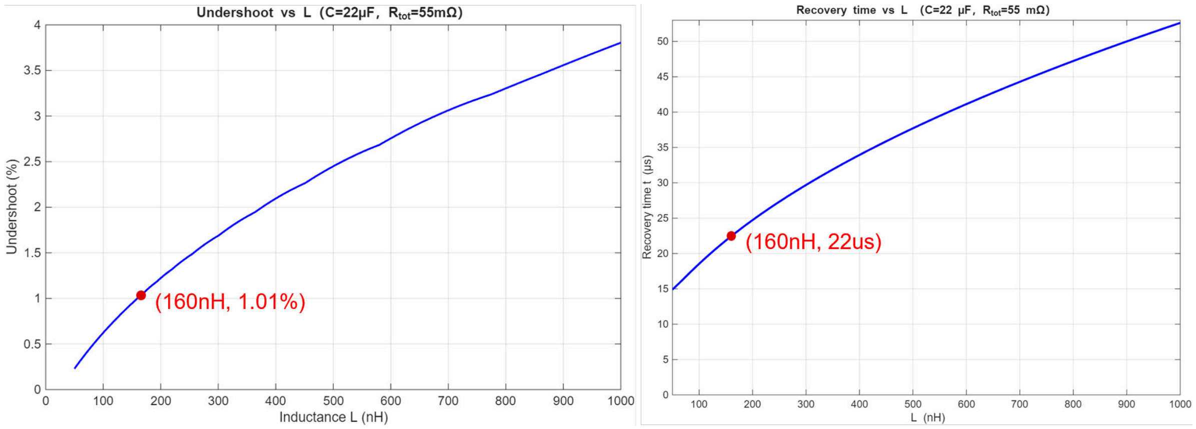

Figure 4-6. Undershoot% and Recovery Time versus Inductance

5 Summary

This application note provides a systematic analysis of the performance of the TPS61022EVM in pass-through mode and draws the following conclusions:

1. ΔV_{in} and ΔV_o are determined solely by DC resistance loss in the power path (R_{bat}, DCR, R_{dson}, R_{line}) and are independent of LC.
2. ΔV_{in}, ΔV_o, and V_o undershoot are all proportional to the load transient amplitude, which confirms the linearity of the RLC system model. In actual applications, undershoot for 0-3A is around three times greater than for 0-1A.
3. Transient performance is related to the LC network, transient slew rate, and the transient amplitude. Bench test results show that the output undershoot can be kept within ±5% under typical conditions. This meets the requirements of most practical applications.

In general, pass-through mode is easy to implement and cost-effective. This mode is widely used in various boost converters.

6 References

- Texas Instruments, *TPS61022 8-A Boost Converter with 0.5-V Ultra-low Input Voltage*, data sheet
- Texas Instruments, *TPS61022 Evaluation Module User's Guide*, EVM user's guide
- Texas Instruments, *Choosing the Boost with Bypass or Pass Through*, application note

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