

# How Output Capacitor Reduction Affects Load Transient in TPS563231 with D-CAP3 Control

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## ABSTRACT

Load-transient performance of the power supply is vital to the stable operation of digital systems like set-top boxes, wireless routers, digital TVs, and so forth. TI's proprietary D-CAP3 control mode supports a fast transient response with low-ESR output capacitors. When considering output performance, cost, and size, output capacitance is a critical design parameter. To help easily achieve a design trade-off, this application report introduces a method to evaluate how output capacitor reduction affects the load transient in a D-CAP3 buck converter.

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## 1 Introduction

In digital circuits, power ripples have huge influences on valid timing. Thus, the load transient performance of a power supply is vital to the stable operation of digital systems like set-top boxes, wireless routers, digital TVs, and so forth.

TI's proprietary D-CAP3 control mode supports low-ESR output capacitors, such as specialty polymer capacitors and multi-layer ceramic capacitors, without complex external compensation circuits. The fast transient response of the D-CAP3 control mode can reduce the number of output capacitors. In an actual buck converter design, output capacitance is a critical design parameter that considers the trade-off between output performance, cost, and size. To help easily achieve a design trade-off, this application report introduces a method to evaluate how output capacitor reduction affects load transient in the D-CAP3 buck converter.

## 2 Overall Control Block Diagram and Transfer Function of DCAP3

Figure 1 shows the simplified schematic for the D-CAP3 buck converter.

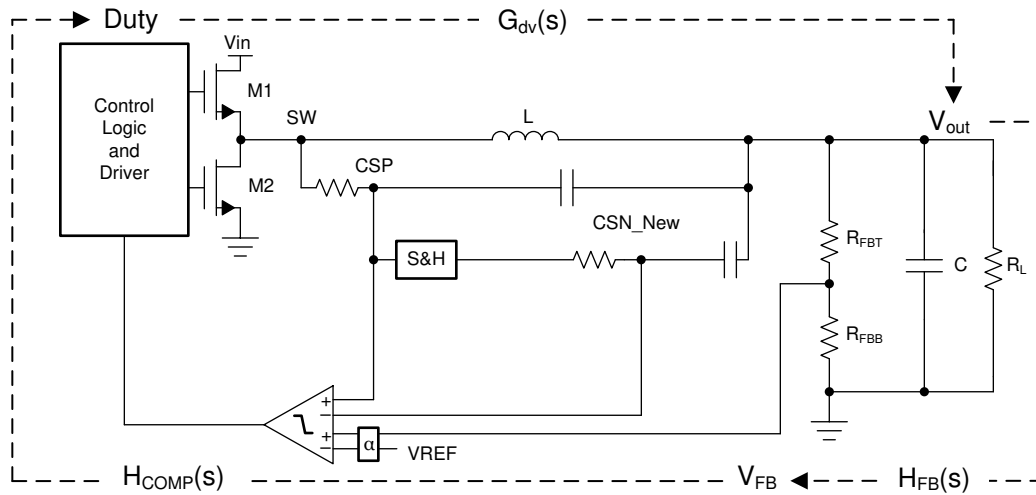


Figure 1. Simplified Schematic for the D-CAP3 Buck Converter

Equation 1 shows a simplified open-loop transfer function.

$$G_{\text{open}}(s) = G_{\text{dv}}(s)H_{\text{FB}}(s)H_{\text{COMP}}(s) \quad (1)$$

Where  $G_{\text{dv}}(s)$  is the transfer function from Duty to  $V_{\text{out}}$ ,  $H_{\text{FB}}(s)$  is the transfer function of the feedback divider network from  $V_{\text{out}}$  to  $V_{\text{FB}}$ .  $H_{\text{COMP}}(s)$  is the transfer function of the comparator, and has the ripple injection circuit from  $V_{\text{FB}}$  to Duty. Equation 2 and Equation 3 list the expressions.

$$G_{\text{dv}}(s) = \frac{V_{\text{in}}}{1 + 2\delta \frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

where

$$\delta = \frac{\sqrt{L/C}}{2R_L}, \omega_0 = \sqrt{\frac{1}{LC}} \quad (2)$$

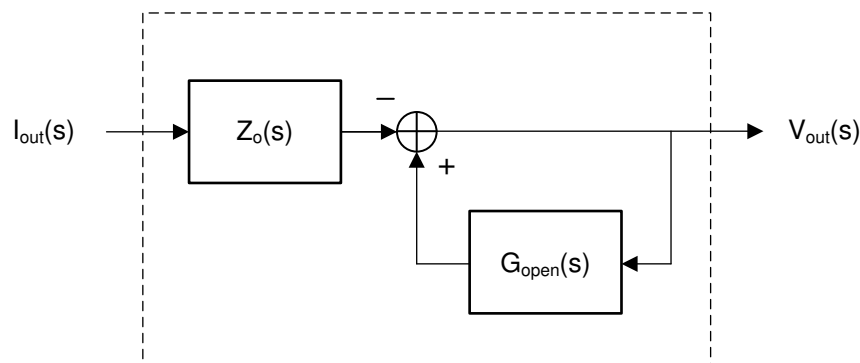
$$H_{\text{FB}}(s) = \frac{R_{\text{FBB}}}{R_{\text{FBT}} + R_{\text{FBB}}} \quad (3)$$

$$H_{\text{COMP}}(s) = \frac{A_{\text{cp}}}{V_{\text{in}}}(1 + sT_c) \quad (4)$$

In Equation 4,  $T_c$  and  $A_{\text{cp}}$  are internal parameters that are determined by ripple injection circuits.

### 3 Load-Transient Function Derivation on Time Domain

The bode diagram of transfer function  $G_{open}(s)$  is commonly used in loop-performance prediction. The straightforward method of analyzing load-transient performance is getting the  $V_{out}$  response function on  $I_{out}$  excitation.



**Figure 2. Transfer Function Flow of Load Transient Analysis**

Figure 2 shows the transfer function flow of load-transient analysis on a s-domain. As expressed in Equation 5,  $Z_o(s)$  is the direct-output impedance of the buck converter.

$$Z_o(s) = \frac{Ls}{1 + 2\delta \frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2} \quad (5)$$

According to the function flow, actual output impedance can be derived as:

$$Z_{iv}(s) = \frac{Z_o(s)}{G_{open}(s) - 1} \quad (6)$$

Thus, Equation 7 can express the  $V_{out}$  response function on  $I_{out}$  excitation. Equation 8 expressed the load transient function on time domain as follows:

$$V_{out}(s) = Z_{iv}(s)I_{out}(s) \quad (7)$$

$$V_{out}(t) = L^{-1}[V_{out}(s)] \quad (8)$$

To figure out how output capacitor reduction affects the load transient, the capacitor value needs to be kept as analytic, while others can be numerical. Here, the TPS563231EVM-032 board is used as the example. Table 1 lists related specifications.

**Table 1. TPS563231EVM-032 Specifications**

Input Voltage	12 V
Output Voltage	3.3 V
Load Current	1 A to 3 A transient
Output Inductor	3.3 $\mu$ H
Feedback Resistor	45.3 k $\Omega$ / 10 k $\Omega$
$T_c$ (approximate)	6 $\mu$
$A_{cp}$ (Approximate)	-35

Equation 6 can be rewritten as Equation 9 with the values from Table 1:

$$Z_{iv}(s) = -\frac{s}{Cs^2 + 12.42s + 2.22 \times 10^6} \quad (9)$$

Although the switching converter cannot respond to a transient action that occurs within one on-off period, step-response is still a simple and effective analysis method. Assuming  $I_{out}(s)$  is a step transient from 1 A to 3 A, it is expressed as:

$$V_{\text{out}}(s) = \frac{2}{s} Z_{\text{iv}}(s) \quad (10)$$

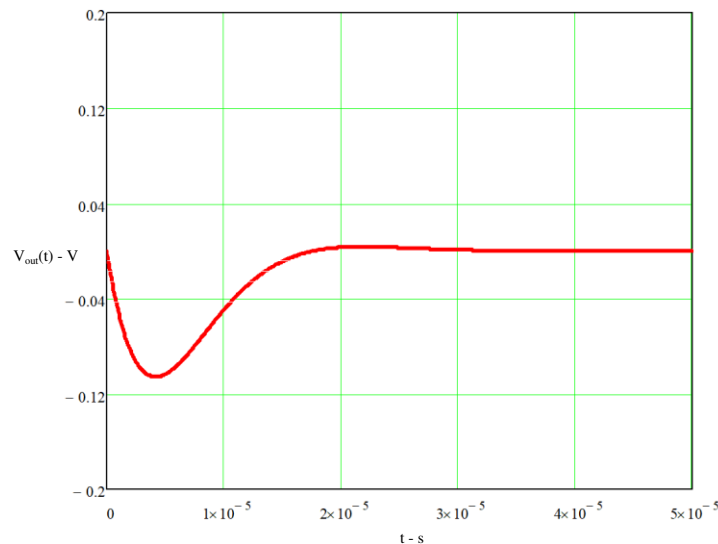
Using [Table 1](#) values in [Equation 10](#), and using an inverse-Laplace transform, the load-transient function on time domain can be rewritten as:

$$V_{\text{out}}(t) = \frac{ke^{\alpha t}(\text{Sin}[\omega t])}{\omega}$$

where

$$\bullet \quad k = -\frac{1}{C}, \alpha = -\frac{6.21}{C}, \omega = \sqrt{\frac{2.15 \times 10^6}{C} - \frac{38.56}{C^2}} \quad (11)$$

From [Equation 11](#), the load-transient waveform can be drawn on time domain:



**Figure 3. Load-Transient Waveform Drawing from Equation 11**

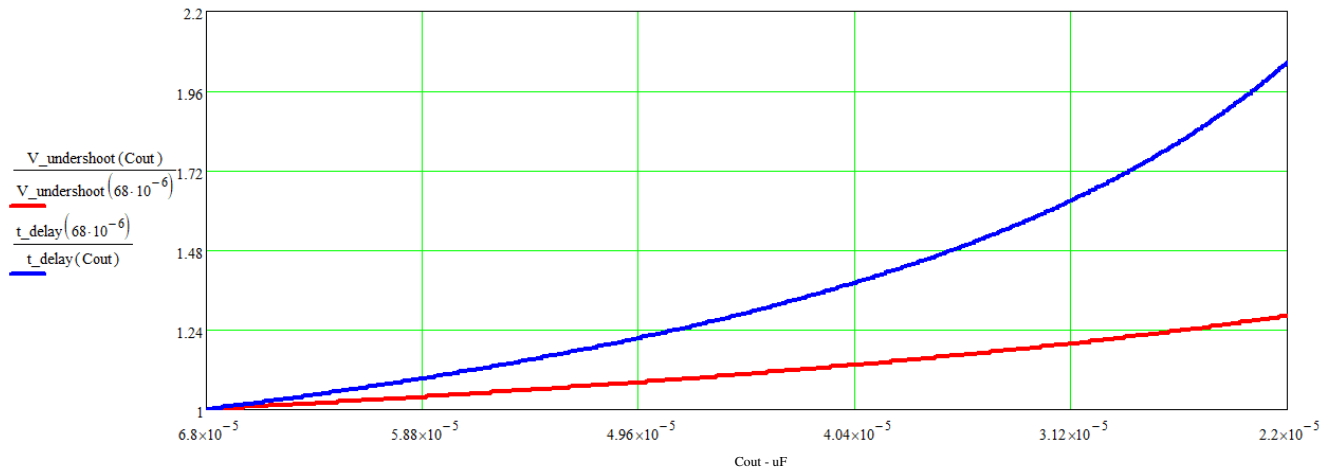
#### 4 Load-Transient Prediction

Although [Equation 11](#) illustrates the time domain function of the load-transient waveform with an output capacitor as the analytic parameter, a more direct function can be derived from [Equation 11](#). This function, [Equation 12](#), shows relevance between load-transient performance and the overshoot, or undershoot, voltage function of the output capacitor:

$$V_{\text{undershoot}} = f(C_{\text{out}}) \quad (12)$$

Finding the minimum values in [Equation 11](#) is a simple way to get the undershoot voltage function in this case. This is done by getting the derivative, with respect to time, and bringing it back with the results complicated, but still as an analytic.

As shown in [Figure 4](#), curves from the results of [Equation 12](#) offer a simple method to understand how, in a reasonable output capacitor range, output capacitor reduction affects load transient in the D-CAP3 buck converter.

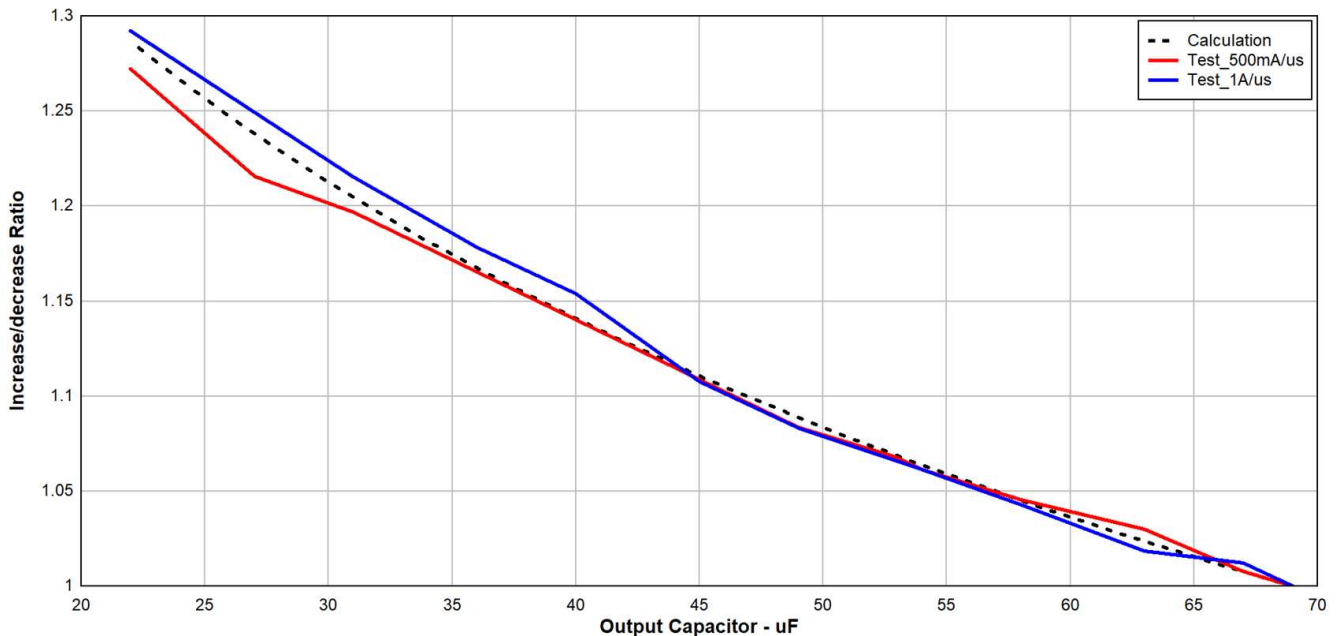


**Figure 4. Load-Transient Performance Variation When Output Capacitor Reduces**

Figure 4 shows the predicted undershoot voltage increase when the output capacitor decreases from 69  $\mu\text{F}$  to 22  $\mu\text{F}$ . The red curve shows the undershoot voltage increase ratio, while the blue shows capacitor decrease ratio as a reference. The curves reveal that, in a reasonable output capacitor range, undershoot voltage changes much less than the output capacitor does.

## 5 Simulation and Testing Verification

Figure 5 shows the simulation and testing results compared with the previous calculations:



**Figure 5. Calculation and Testing Results on Transient Performance**

Two load-transient slew rates, 500m A/ $\mu\text{s}$  and 1 A/ $\mu\text{s}$ , are applied in testing. When the output capacitor changes from 69  $\mu\text{F}$  to 22  $\mu\text{F}$ , the undershoot voltage increase is less than 30%, which is consistent with the calculation result.

## 6 Conclusion

This application report introduces a method to evaluate how output capacitor reduction affects the load transient in TPS563231. When the open-loop transfer function of the TPS563231 is achieved, the relevance between load-transient performance, and the output capacitor, can be derived as an overshoot or undershoot voltage function. This is done by using an inverse Laplace transform. Calculation results are acceptable when compared with test results on the TPS563231EVM-032 board. Both the calculation and testing reveals that, on a reasonable range of output capacitor values, undershoot voltage changes much less than the output capacitor does.

## 7 References

- Texas Instruments, [Accuracy-Enhanced Ramp-Generation Design for D-CAP3 Modulation Application Report](#)
- Texas Instruments, [TPS563231EVM-032 3-A, Synchronous Step-down Converter Evaluation Module User's Guide](#)

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