Application Note

Large Duty Cycle Operation of D-CAP3 Converters

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ABSTRACT

Most buck converters have a limited duty cycle. In order to obtain a larger duty cycle to support rated output at a lower input voltage, some converters reduce its frequency when the duty cycle is high. However, for those converters with D-CAP3™ (Constant On-time) control, it achieves this target through extending the on-time, which is the On-Time Extension (OTE) operation. This application note presents a detailed introduction to this large duty feature based on TPS56837, including the implementation of large duty, the performance and advantages of OTE in D-CAP3™ control mode.

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Trademarks

D-CAP3™ is a trademark of Texas Instruments.
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1 Introduction

For D-CAP3™ converters, some of them don't have large duty feature and its max duty is decided by the minimum off-time and frequency. Some converters such as TPS568230 can expand their on-time multiple times to support a larger duty cycle, which is introduced in the application note *Large Duty Cycle Operation With the TPS568230*. The other converters such as TPS56837 are able to extend the on-time smoothly. This application note will describe this feature of TPS56837 in detail.

The TPS56837 is a high-efficiency, easy-to-use, synchronous buck converter with a wide input voltage range of 4.5-V to 28-V, and supports up to 8-A continuous output current at output voltages between 0.6-V and 13-V. The TPS56837 includes an on-time extension feature which can support large duty cycle operation up to 98%.

2 D-CAP3 Control Architecture

The D-CAP3™ mode control architecture has an internal compensation circuit and combines Adaptive On-Time control (AOT control) for pseudo-fixed frequency operation.

2.1 Adaptive On-Time Control

Adaptive on-time control is a non-linear control architecture for buck regulators. At the beginning of each switching cycle, the high-side MOSFET is turned on. This MOSFET is turned off after an internal one shot timer expires. The ON time duration is set proportional to the output voltage, V_{OUT}, and inversely proportional to the converter input voltage, V_{IN}, to maintain a pseudo-fixed frequency over the input voltage operating range. The ON timer is reset and the high-side MOSFET is turned on again when the feedback voltage falls below the reference voltage.

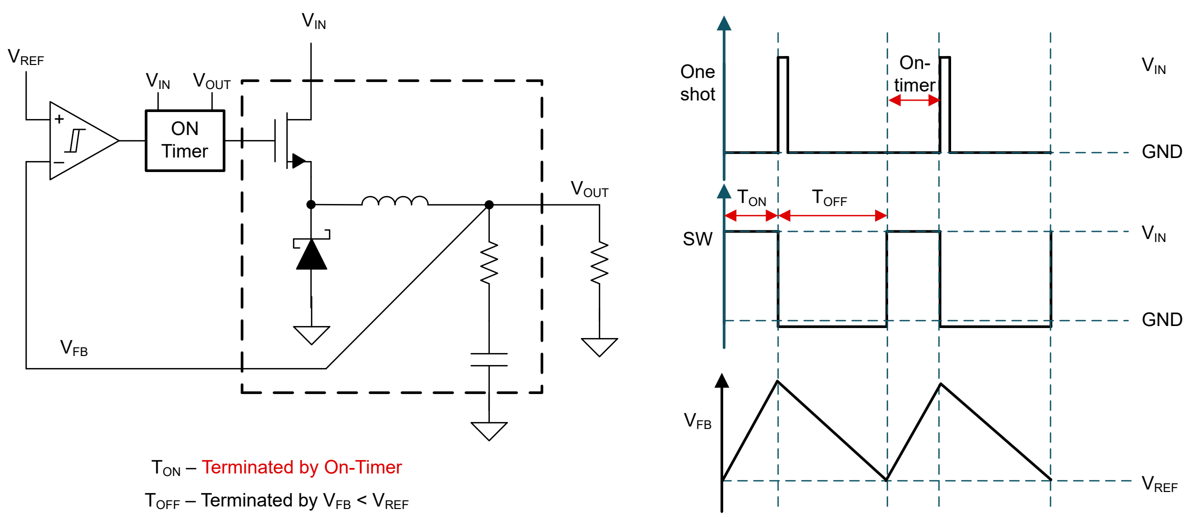


Figure 2-1. Adaptive On-Time Control (AOT Control)

In ACOT control, the pseudo-fixed frequency is designed with the calculations in Equation 1 and Equation 2.

$$T_{ON} = D \times T_{SW} = \frac{V_{OUT}}{V_{IN} \times F_{SW}} \tag{1}$$

$$F_{SW} = \frac{1}{T_{SW}} \tag{2}$$

Based on Equation 1, if T_{ON} is adjusted with V_{OUT} and V_{IN}, the switching frequency F_{SW} will be constant. For the TPS56837 device, the switching frequency F_{SW}, is selectable at 500 kHz, 800 kHz , or 1.2 MHz.

2.2 D-CAP3 Control

Figure 2-2 shows the detailed control block diagram of D-CAP3™ converters.

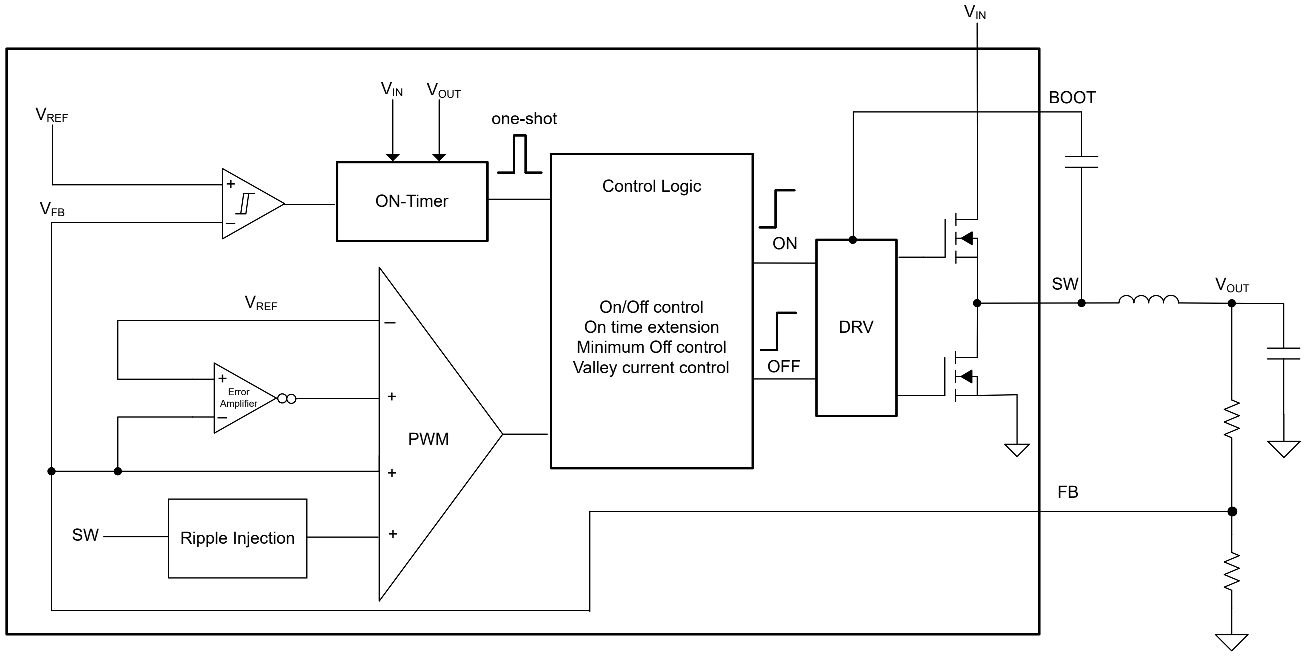


Figure 2-2. Detail D-CAP3 Control Block Diagram

To improve loop stability with virtually no ripple on the output voltage, an additional ripple injection circuit is added. Also an included error amplifier improves the output voltage accuracy.

In the control block of the D-CAP3™ device, the boot capacitor needs to be charged during low-side MOSFET on, in the meanwhile, the inductor valley current is monitored by measuring the SW node voltage during this off-time, which both lead a minimum off time requirement.

As we know, most of the High-side MOSFETs are N-MOS and need a voltage higher than Vin for Gate driver to keep the High-side MOS on, and the voltage is provided by BOOT capacitor. This capacitor is charged during off-time, thus the off-time has a minimum value to ensure the charges of BOOT capacitor are enough.

For D-CAP3™ converters, when the one-shot timer is expired, the high-side MOSFET is turned off and the low-side MOSFET is turned on. The turning on process of the low-side MOSFET causes the SW ringing. When measuring the SW node voltage, a blanking time needs to be included to let the internal SW node ringing dissipate. This time delay results in the minimum off time for the high-side MOSFET.

3 Large Duty Cycle Operation

3.1 Min Off-Time Performance of Buck Converters

The duty cycle increases as the input voltage comes close to the output voltage and the off-time of the high-side switch gets smaller. When the off-time reaches the minimum value, it could not decrease any more, and keeps the minimum value even if the input voltage continues to drop.

Figure 3-1 shows waveforms during normal operation. The on time begins when FB voltage is below internal reference and the off time begins when one-shot pulse comes after a constant on-time timer. The min off-time signal starts the timer once the off-time begins and holds for a constant minimum off-time value shown in the data sheet. If the off-time is longer than the min off-time, the signal won't works.

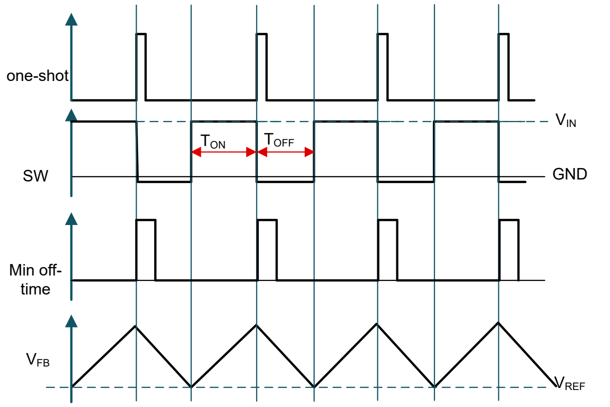


Figure 3-1. Normal Operation without Min off-time Triggered

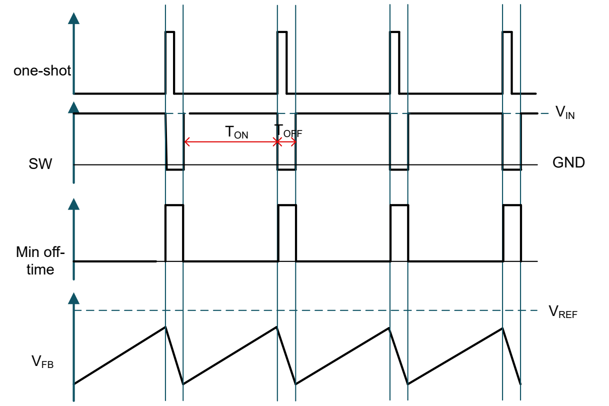


Figure 3-2. Operation with Min off-time Triggered

Figure 3-2 indicates the operation of converter when the min off-time is triggered. After the off-time decided by the loop is shorter than minimum off-time, even though the FB voltage is less than reference voltage, the off-time no longer follows the V_{FB} comparator but just operates the constant min value while the on-time is still decided by the one-shot circuit and proportional to the V_{OUT}/V_{IN}. With such two limitation, the output voltage would finally fall under the rated reference value and reaches another balance.

Without on-time extension function, it is obvious that the duty cycle is fixed when min off-time is triggered. Based on Equation 3, since Toff has a minimum value, it follows that the duty cycle, D, has a maximum value. If the F_{SW} is fixed, a smaller $T_{OFF(min)}$, means a larger duty cycle can be supported. Alternatively, if the $T_{OFF(min)}$ is fixed, a larger duty cycle can be supported with a smaller F_{SW}.

$$D = \frac{T_{ON}}{T_{SW}} = 1 - \frac{T_{OFF}}{T_{SW}} = 1 - F_{SW} \times T_{OFF} \quad (3)$$

3.2 On-Time Extension Function

To support higher duty cycle operation, the TPS56837 includes an On-Time Extension function. This function operates by increasing the High-side FET On-Time beyond that during normal operation, thus lowering the operating frequency and allowing large duty cycles to be maintained.

From application note *Large Duty Cycle Operation With the TPS568230*, we can know that TPS568230 extends its on-time through twice or trice one shot trigger signal. However, different with the OTE of TPS568230, TPS56837 is using an advanced one shot circuit to expand its on-timer.

The On-Time Extension function is implemented following Figure 3-3 flow chart.

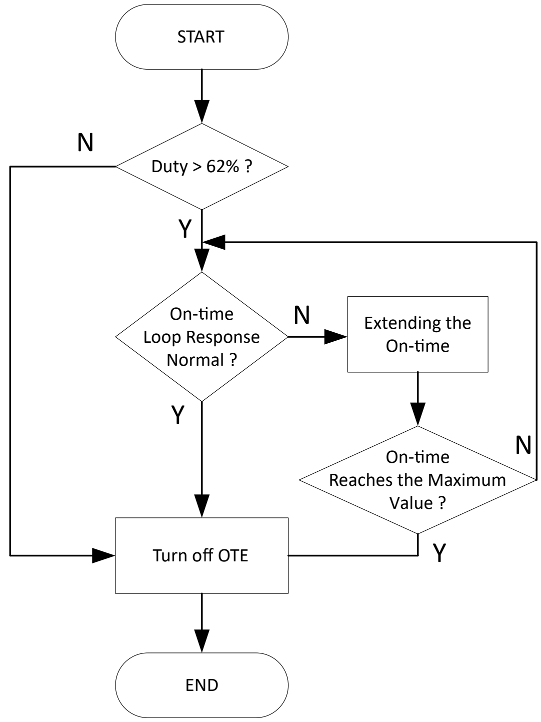


Figure 3-3. Flow Chart of On-Time Extension Function

Large duty cycle operation of TPS56837 only happens during on-time. When the duty cycle is larger than 62%, the device starts to detect its loop response signal and decides whether extends the on-time or not cycle by cycle. However, the on-time still has a maximum value and can't be extended once it gets the max. Figure 3-4 shows the performance under OTE. The on-timer is extended per loop response signal and the Feedback voltage could keep near the reference point.

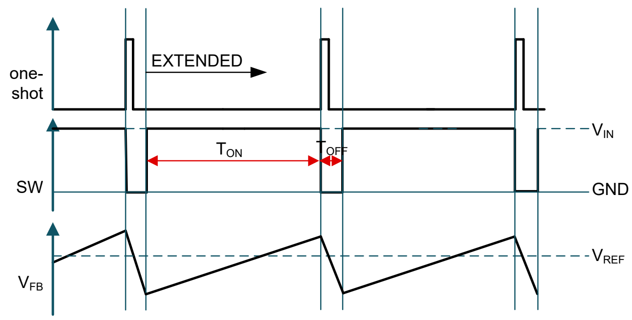


Figure 3-4. On-Time Extension of TPS56837

4 Bench Test and Comparison

The bench tests are done on the TPS56837EVM. For details, see the *TPS56837EVM evaluation module User's Guide*. The bench test setup and configuration is listed in Table 4-1.

Table 4-1. Bench Setup for TPS56837

V_{OUT}(V)	L (µH)	Cout (µF)	CFF (pF) / C15	RFF (kΩ) / R14	Rtop (kΩ) / R9	Rbot (kΩ) / R8	Mode
5	3.3	4 × 22 µF (1206, 10 V)	100	0	220	30	PSM / 500 kHz

The waveforms in Figure 4-1 to Figure 4-4 show the SW behaviors with and without the ON-time extension function triggered under different input voltage.

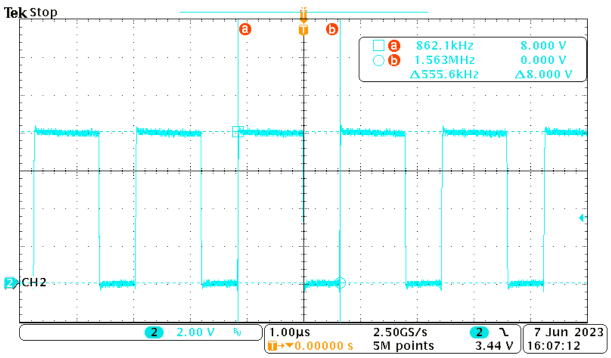


Figure 4-1. Normal Operation Without On-Time Extension (Vin=8 V)

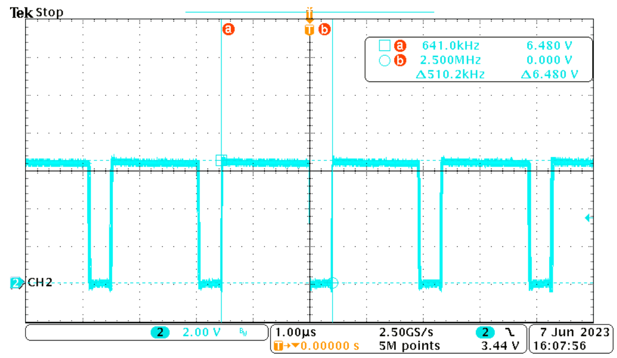


Figure 4-2. On-Time Extension (Vin=6.48 V)

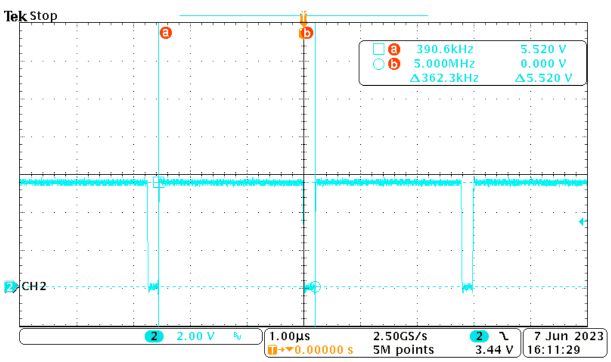


Figure 4-3. On-Time Extension (Vin=5.52 V)

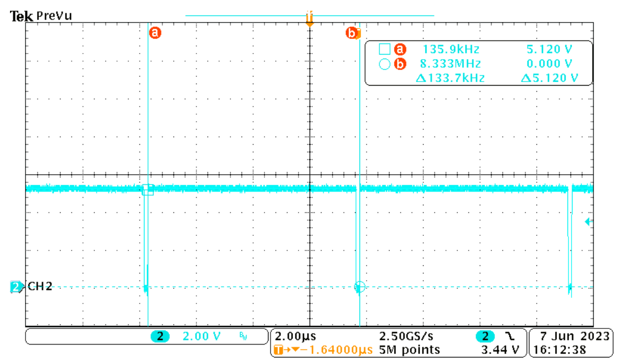


Figure 4-4. On-Time Extension (Vin=5.12 V)

4.1 Comparison Between TPS56837 and TPS56637

TPS56637 is a 6-A synchronous buck converter with D-CAP3™ control. It is pin-to-pin compatible with TPS56837 but doesn't have the large duty function.

According to the previous analysis, the maximum duty which TPS56637 can support is only decided by the frequency and minimum off-time. Thus we can get the maximum duty based on Equation 3. Considering the actual frequency is 550 kHz while the min off-time is 200 ns, we can calculate the maximum Duty is 89%. That means if the output voltage is 5 V, the input voltage would be higher than about 5÷89%=5.62 V.

Figure 4-5 and Figure 4-6 show the line dropout performance in the TPS56837EVM and TPS56637EVM. The EVM test setup is the same as with Table 4-1.

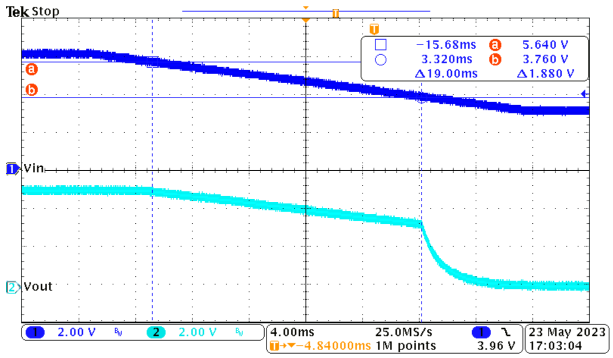


Figure 4-5. 6 V input to 4 V input of TPS56637

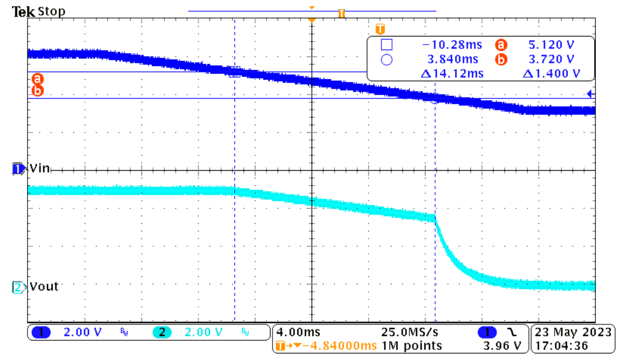


Figure 4-6. 6 V input to 4 V input of TPS56837

From the waveforms, it is obvious that TPS56837 can support 5 V output with a wider input voltage range. TPS56637 would have a output voltage drop after input is less than 5.64 V while it is 5.12 V of TPS56837. After the voltage dropped below 3.7 V, both the device shutdown due to input UVLO.

4.2 Comparison of On-Time Extension between TPS56837 and TPS568230

Both TPS568230 and TPS56837 have On-time Extension function, but their implement is different.

The OTE of TPS568230 is decided by its duty cycle. When the 1.2 < VIN/VOUT ≤ 1.6, the TON will be extended one time interval. When the VIN/VOUT ≤ 1.2, the TON will be extended two time intervals. Thus it would lead to a sudden change of frequency during OTE operation.

The OTE of TPS56837 can slow down its frequency smoothly during OTE operation, which lead to a better performance during OTE operation.

Figure 4-7 provides a frequency changes with duty cycle of both TPS568230 and TPS56837.

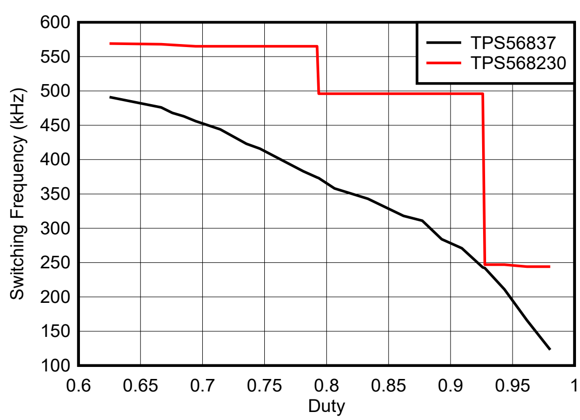


Figure 4-7. Frequency Changes with Duty Cycle

For TPS568230, due to the on-time and frequency sudden change, the output voltage would have a transient process at the boundary of its OTE condition. On the other hand, during OTE process, the frequency of TPS56837 would change smoothly and have a better line transient performance.

Figure 4-8 and Figure 4-9 shows the line transient performance under large duty condition. Obviously we can see TPS568230 has about 12mV voltage overshoot at the two boundaries while TPS56837 doesn't.

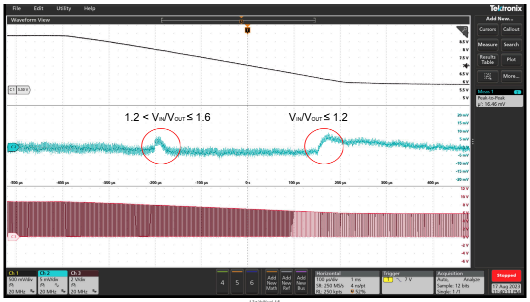


Figure 4-8. Line Transient of TPS568230 (VIN from 8 V to 6 V)

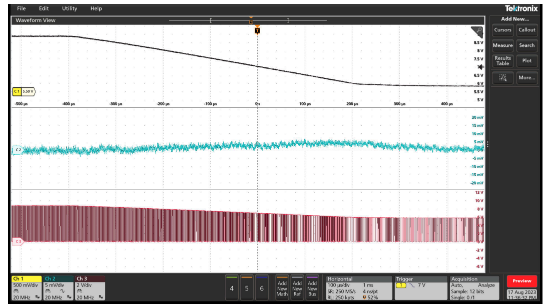
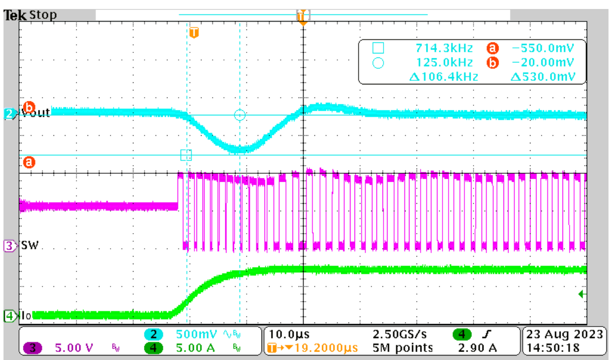


Figure 4-9. Line Transient of TPS56837 (VIN from 8 V to 6 V)

4.3 Load Transient Improvement by On-Time Extension

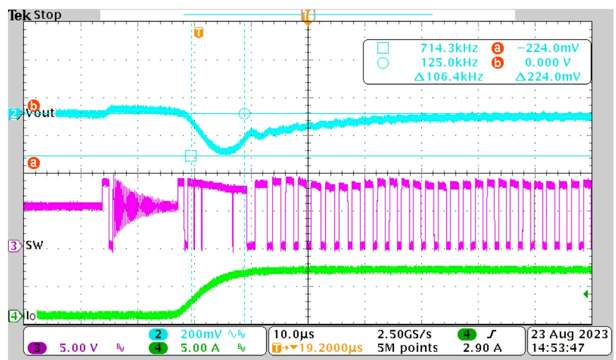
In addition to improving line dropout performance, the On-Time Extension function also improves load transient response. Figure 4-10 and Figure 4-11 indicate load transient test results of the comparison between TPS56837 and TPS56637. The setup is the same as previously indicated. The figures show the undershoot improvement during a light load to heavy load transient. The undershot for TPS56637 is 530mV while it's 224mV for TPS56837 with On-Time Extension.

When the load changes from 0 A to 8 A, the input voltage will drop about 1V, also the output voltage will drop and influence the loop response, both will allow the On-Time Extension to work. From Figure 4-11, the SW signal indicates the on-time is extended. With this longer HSFET ON, compared with non On-Time Extension in Figure 4-10, more energy is charged to the output to make the V_{OUT} voltage drop less then when the load change happens.



V_{IN} = 8 V, V_{OUT} = 5V, I_{OUT} from 0A to 6A, Slew Rate = 2.5 A/us

Figure 4-10. TPS56637 Load Transient Without On-Time Extension Triggered



V_{IN} = 8 V, V_{OUT} = 5V, I_{OUT} from 0A to 6A, Slew Rate = 2.5 A/us

Figure 4-11. TPS56837 Load Transient With On-Time Extension Triggered

5 Summary

The TPS56837 device is designed with the On-Time Extension function and can support large duty cycle operation up to 98%. With this improvement, line dropout, frequency regulation, line transient and load transient performances are also improved.

6 References

1. Texas Instruments, *TPS56837 4.5-V to 28-V Input, 8-A Synchronous Buck Converter*, data sheet.
2. Texas Instruments, *TPS56637 4.5-V to 28-V Input, 6-A Synchronous Buck Converter*, data sheet.
3. Texas Instruments, *Large Duty Cycle Operation With the TPS568230*.
4. Texas Instruments, *TPS56837 Buck Converter Evaluation Module User's Guide*.

7 Also From TI

There are several D-CAP3 converters have the same large duty cycle operation with TPS56837, including TPS566231, TPS56C231, TPS568231, TPS51383, TPS51386, TPS51385, TPS568236, TPS56x24x, TPS56x25x, TPS563203/6, TPS562203/6, TPSM86325x.