Application Note

Power Design Considerations for Sensor Transmitters in Explosive Atmospheres

Colin Chen and Xiaoying Lu

ABSTRACT

This application note presents a power supply design for a sensor transmitter system in explosive atmospheres. Based on TI's low Iq buck converter TPS629203, the design process with the desired goals is implemented. Additionally, experimental results on essential features of ripple and efficiency are conducted. The suggestion of tradeoff efficiency and voltage ripple is proposed to help designers better resolves challenges in similar applications.

Table of Contents

1 Introduction 2
2 Input and Output Ripple of Buck Converter in DCM 4
3 TPS629203 Design Consideration 6
4 Experimental Results 7
4.1 VIN and VOUT Ripple Results 7
Efficiency 9
5 Summary 11
6 References 11

List of Figures

Figure 1-1. Simplified Block Diagram 3
Figure 2-1. Current Loop of The Buck Converter in DCM 4
Figure 2-2. Input Voltage Ripple of Buck Converter in DCM 4
Figure 2-3. Output Voltage Ripple of Buck Converter in DCM 5
Figure 3-1. TPS629203 Schematic Design 6
Figure 4-1. VIN Ripple of Simulation Under I_O= 4mA 7
Figure 4-2. VIN Ripple of Simulation Under I_O= 10mA 7
Figure 4-3. VIN Ripple of Simulation Under I_O= 20mA 7
Figure 4-4. VIN Ripple of Bench Test Under I_O= 4mA 7
Figure 4-5. VIN Ripple of Bench Test Under I_O= 10mA 7
Figure 4-6. VIN Ripple of Bench Test Under I_O= 20mA 7
Figure 4-7. VOUT Ripple of Simulation Under I_O= 4mA 8
Figure 4-8. VOUT Ripple of Simulation Under I_O= 10mA 8
Figure 4-9. VOUT Ripple of Simulation Under I_O= 20mA 8
Figure 4-10. VOUT Ripple of Bench Test Under I_O= 4mA 8
Figure 4-11. VOUT Ripple of Bench Test Under I_O= 10mA 8
Figure 4-12. VOUT Ripple of Bench Test Under I_O= 20mA 8
Figure 4-13. Efficiency with a 5.6uH Inductor 9
Figure 4-14. Cycle Time in DCM 10
Figure 4-15. Efficiency with 2.2uH Inductor and 5.6uH Inductor 10

List of Tables

Table 1-1. Permitted Capacitance Corresponds To Voltage 2
Table 1-2. Typical Power Rail of Sensor Transmitter System 3
Table 4-1. Comparison of ΔV_{IN} Calculation, Simulation and Bench Test Results 9
Table 4-2. Comparison of ΔV_{OUT} Calculation, Simulation and Bench Test Results 9

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

Sensor Transmitters with HART Protocol

Sensor transmitters are widely utilized in factory automation and process control. Sensor transmitters need sensing front-ends, microcontrollers and processors. This includes a wide variety of data transmission interfaces, protocols and communication design, such as 4-20mA HART.

The HART Communication Protocol is a hybrid analog and digital industrial automation open protocol. The most notable advantage is that HART can communicate over a 4–20 mA analog current loop with a shared pair of wires. HART can support two operational modes: point-to-point and multi-drop. Point-to-point is where the 4–20 mA current and the digital signal are valid signaling protocols between the controller and measuring instrument or final control element. Multi-drop is where the analog loop current is fixed at 4mA and is possible to have more than one instrument on a signal loop. Generally, the analog signal transmits some measure of level, flow, temperature, and pressure, and so forth. The HART protocol is a backward-compatible enhancement to 4-20mA, to send command or return standardized responses which can communicate device status and diagnostics. Data can also include the device measurement digital values, and other information about the remote transmitter. Therefore, HART modifies the 4-20 mA system from only sending primary variable as a current value to adding digital communication with more functionality and flexibility. This technology is backwards compatible and can be used with existed infrastructure so is easy to adopt and cost-effective.

Safety Requirement of Explosive Atmospheres

In electrical and safety engineering, explosive atmospheres are places where fire or explosion hazards exist. Under these conditions, flammable substances in the form of gases, vapors or dust, in the mixture with air, cause combustion spread to the entire unburned mixture after ignition. Some international standards like IEC 60079 have specified the construction and testing of intrinsically safe circuits for use in an explosive atmosphere. The key feature for a power supply in such an intrinsically safe circuits is the input and output capacitance. This is because permitted capacitance needs to be strictly restricted based on the node voltage according to the standards, to limit the spark and energy generated when capacitors get failed. Table 1-1 shows the permitted capacitance corresponds to voltage based on the equipment group.

Table 1-1. Permitted Capacitance Corresponds To Voltage

Voltage, V	Permitted Capacitance, µF (for Group IIC Apparatus as an Example)	
	1 Factor of Safety	1.5 Factor of Safety
5.0		100
6.0	600	40
7.0	175	15.7
8.0	69	8.4
9.0	40	4.9
10.0	20	3
20.0	0.90	0.22
30.0	0.22	0.066

Simplified Block Diagram

Figure 1-1 shows a simplified block diagram of a sensor transmitter with HART protocol in explosive environments. The input power comes from a 4-20mA current loop. To meet the stringent capacitance requirements in Table 1-1, there is a pre-regulator that outputs 10V. A buck converter is then used to output 3.3V to power the MCU, HART, and DAC. For the 4-20mA current loop, higher power efficiency is the goal, so a low IQ buck converter operating in pulse frequency modulation (PFM) mode is an excellent choice. However, the input and output voltage ripples of the buck converter can be large due to the discontinuous conduction mode (DCM) at light loads. The HART communication protocol uses a modulation frequency to represent the digital signal, making the signal highly sensitive to large voltage ripples. These ripples cannot be reduced simply by increasing the input and output capacitance of the buck converter due to the allowed capacitance limit. Therefore, designing a power supply that considers low ripple and high efficiency is necessary.

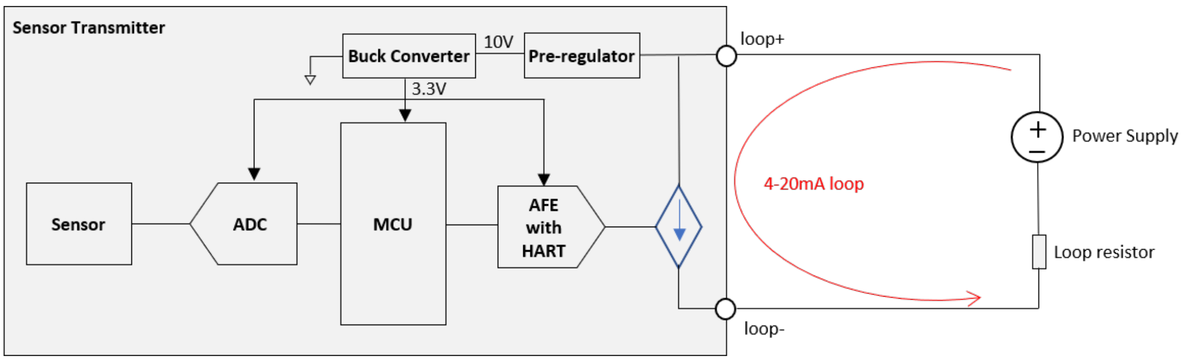

Figure 1-1. Simplified Block Diagram

This application note based on the low - IQ buck converter TPS629203, which features PFM and COT control. This design meets the requirements of a typical HART system as shown in the Table 1-2 and serves as a guide for engineers.

Table 1-2. Typical Power Rail of Sensor Transmitter System

Parameter	
Input voltage (VIN)	10V
Output voltage (VOUT)	3.3V
Rated load (I_O)	4mA-20mA
Input capacitance (CIN)	1uF
Output capacitance (COUT)	10uF
Input ripple target (ΔVIN)	0.2%· VIN
Output ripple target (ΔVOUT)	0.2%· VOUT

2 Input and Output Ripple of Buck Converter in DCM

Figure 2-1 shows the current loop of the buck converter in DCM. The high-side FET current I_{HS_FET} and the inductor current I_L are both discontinuous waves. The input current (I_{IN}) and load current (I_O) can be regarded as DC components of I_{HS_FET} and I_L respectively. Therefore, the input capacitor current I_{CIN} and the output capacitor current I_{COUT} are the AC components. Based on the charge balance, the input and output voltage ripples can be know by the charge change ΔQ on CIN and COUT in the pulse if ESR is ignored.

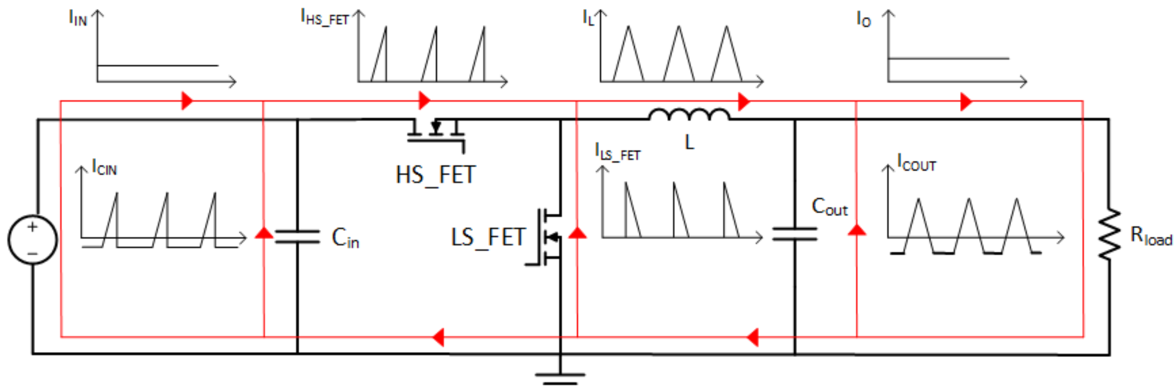

Figure 2-1. Current Loop of The Buck Converter in DCM

Input Voltage Ripple Calculation

Figure 2-1 shows the relationship of input voltage ripple ΔVIN with I_{HS_FET} and I_{IN}. The yellow area represents I_{IN} and the red line represents I_{HS_FET}. For the period when I_{IHS_FET} exceeds I_{IN}, CIN discharges into high-side FET, leading to ΔVIN decrease. The charge of ΔQ_{HS_FET} of the red area can by calculated by using Equation 1.

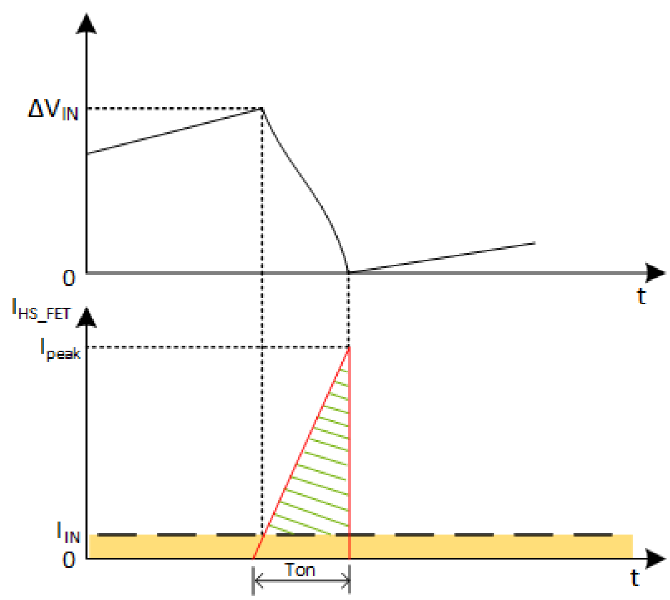

Figure 2-2. Input Voltage Ripple of Buck Converter in DCM

$$\Delta Q_{HS\_FET} = \frac{1}{2} \times I_{peak} \times \text{Ton} \tag{1}$$

According to the geometric relationship, ΔQ_{CIN} and can be calculated by using Equation 2. And ΔVIN can be calculated by using Equation 3.

$$\Delta Q_{CIN} = \Delta Q_{HS\_FET} \times \left(\frac{I_{peak} - I_{IN}}{I_{peak}}\right)^2 \quad (2)$$

$$\Delta V_{IN} = \frac{1}{2C_{IN}} \times I_{peak} \times Ton \times \left(\frac{I_{peak} - I_{IN}}{I_{peak}}\right)^2 \quad (3)$$

Output Voltage Ripple Calculation

Figure 2-3 shows the relationship ΔVOUT of with I_L and I_O in a pulse. The yellow area represents I_O and red line represents I_L. For the period when I_L exceeds I_O, COUT discharges into load, leading ΔVOUT to decrease. The charge of ΔQ_L of the red area can by calculated by using Equation 4.

$$\Delta Q_L = \frac{1}{2} \times I_{peak} \times (Ton + Toff) \quad (4)$$

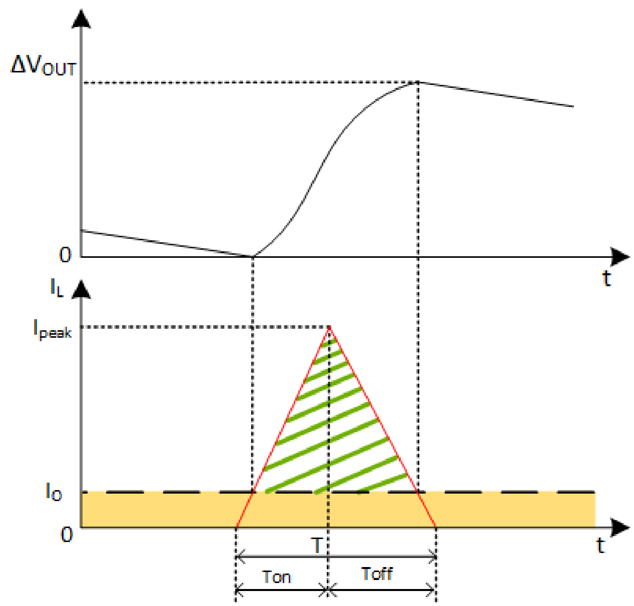

Figure 2-3. Output Voltage Ripple of Buck Converter in DCM

According to the inductor current in DCM of Equation 5**,** the charge of ΔQ_L can be further represented as Equation 6.

$$I_{peak} = \frac{V_{IN} - V_{OUT}}{L} \times Ton = \frac{V_{OUT}}{L} \times Toff \quad (5)$$

$$\Delta Q_L = \frac{1}{2} \times I_{peak} \times \frac{V_{IN}}{V_{OUT}} \times Ton \quad (6)$$

According to the geometric relationship, ΔQ_{COUT} can be calculated by Equation 7. And ΔVOUT can be calculated by Equation 8.

$$\Delta Q_{COUT} = \Delta Q_L \times \left(\frac{I_{peak} - I_{LOAD}}{I_{peak}}\right)^2 \quad (7)$$

$$\Delta V_{OUT} = \frac{I_{peak} \times Ton}{2C_{OUT}} \times \frac{V_{IN}}{V_{OUT}} \times \left(\frac{I_{peak} - I_{LOAD}}{I_{peak}}\right)^2 \quad (8)$$

3 TPS629203 Design Consideration

The TPS629203 is a DCS control (COT), high-efficiency, easy-to-use, synchronous buck converter, and the typical Iq is 4uA. In VIN = 10V and Vout = 3.3V power rail, input and output capacitor of TPS629203 are chosen as CIN=1uF (GRM21BR71E105KA99L) and COUT = 10uF (GRM21BR61E106MA73L). Considering the DC bias effect and capacitance variation of ceramic capacitor, the actual capacitance can be considered as CIN = 0.9uF, Cout = 5.8uF. From the mode description in TPS629203 300mA, 3V to 17V Low IQ Buck Converter with DCS-Control data sheet, constant Ton time with AEE function is calculated by using Equation 9.

$$\mathrm{Ton} = 100 \times \frac{V_{IN}}{V_{IN} - V_{OUT}}(\mathrm{ns}) = 150(\mathrm{ns}) \quad (9)$$

To meet the target of ripple is 0.2% of input and output voltage in Table 1-2. The inductor can be calculated as L≤ 5.6uH from Equation 3 and Equation 8. Figure 3-1 is schematic for whole design. Considering the input capacitance is low, users can encounter oscillation problems, especially when the input trace is long. Therefore, TI recommends to add a 1 ohm resistor (R3) at input trace for damping.

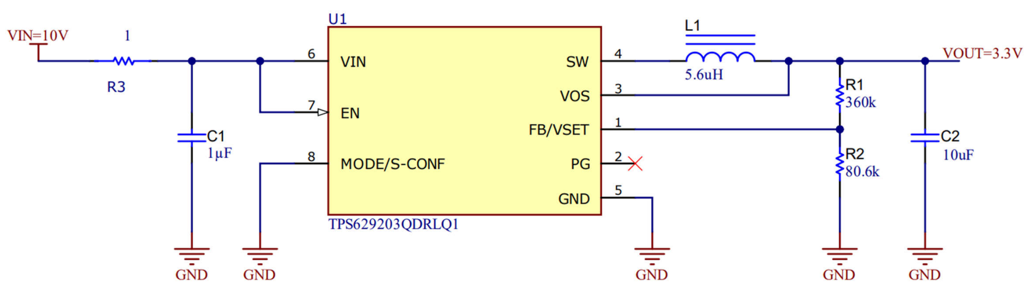

Figure 3-1. TPS629203 Schematic Design

4 Experimental Results

4.1 VIN and VOUT Ripple Results

Figure 4-1, Figure 4-2 and Figure 4-3 are the simulation results of the TPS629203 VIN ripple. Figure 4-1, Figure 4-2 and Figure 4-3 are the bench test results. The load current points are 4mA,10mA and 20mA, respectively.

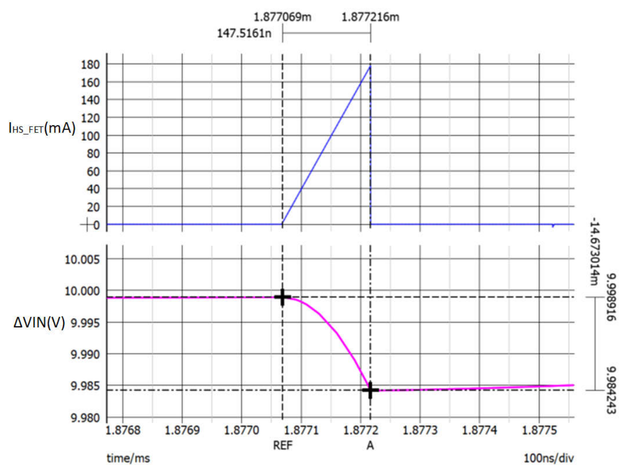

Figure 4-1. VIN Ripple of Simulation Under I_O= 4mA

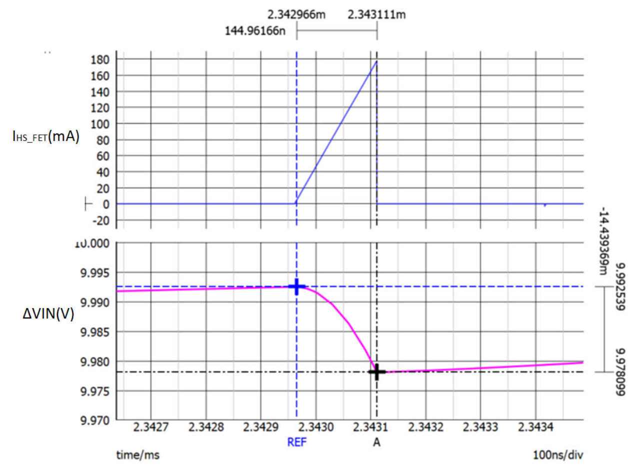

Figure 4-2. VIN Ripple of Simulation Under I_O= 10mA

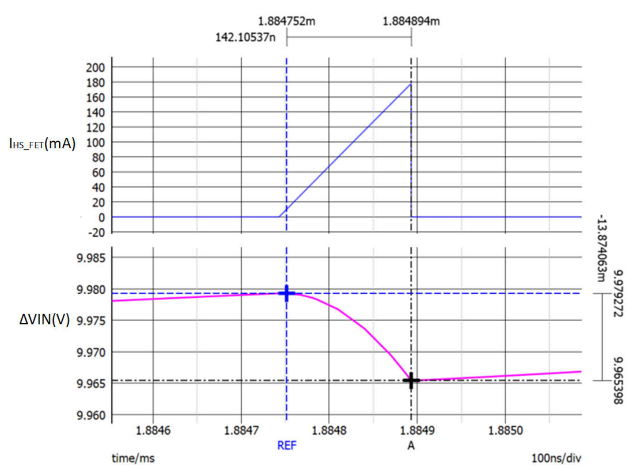

Figure 4-3. VIN Ripple of Simulation Under I_O= 20mA

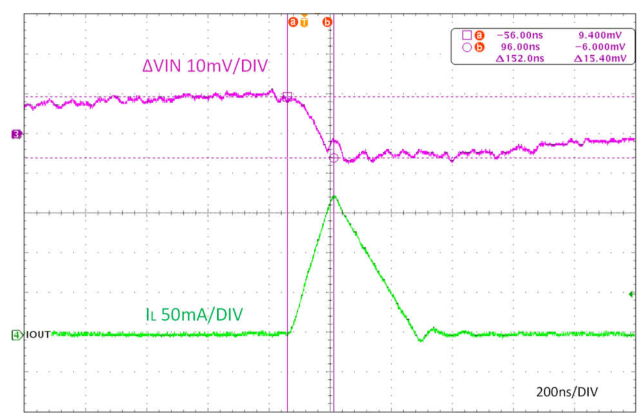

Figure 4-4. VIN Ripple of Bench Test Under I_O= 4mA

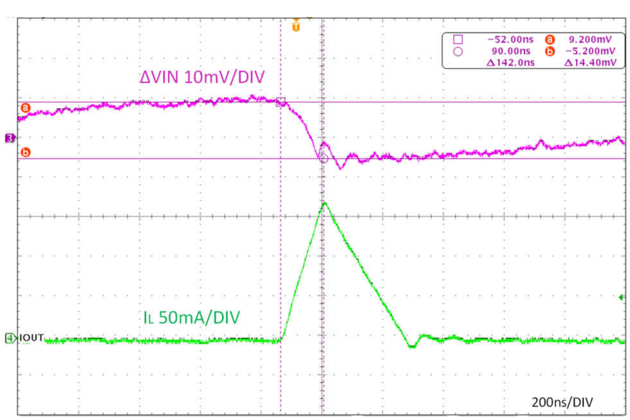

Figure 4-5. VIN Ripple of Bench Test Under I_O= 10mA

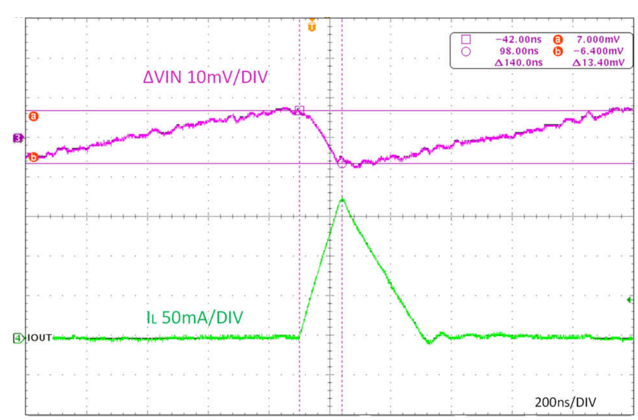

Figure 4-6. VIN Ripple of Bench Test Under I_O= 20mA

Figure 4-7, Figure 4-8 and Figure 4-9 are the simulation results of the TPS629203 VOUT ripple. Figure 4-10, Figure 4-11 and Figure 4-12 are bench test results. The load current points are 4mA,10mA and 20mA, respectively.

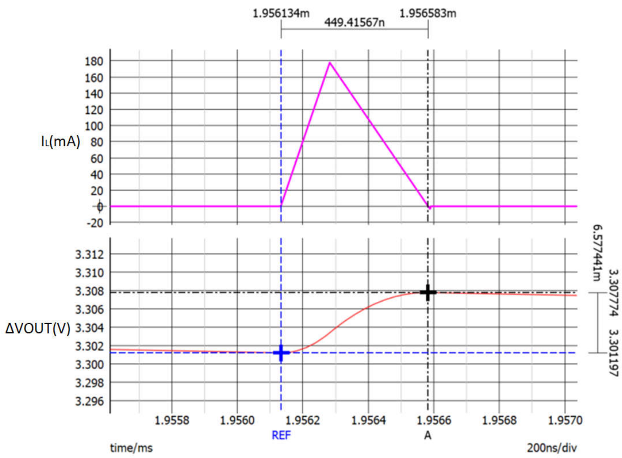

Figure 4-7. VOUT Ripple of Simulation Under I_O= 4mA

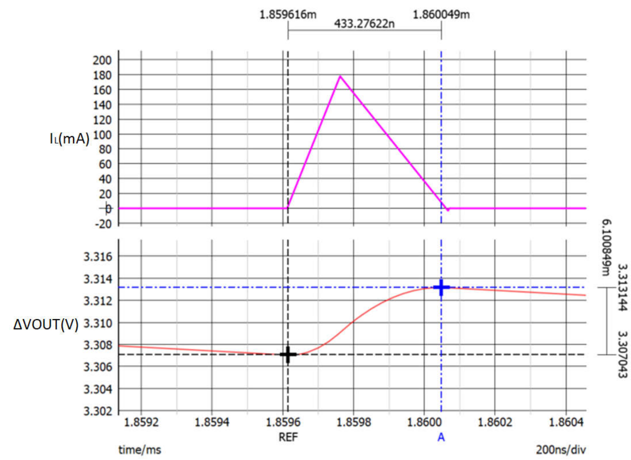

Figure 4-8. VOUT Ripple of Simulation Under I_O= 10mA

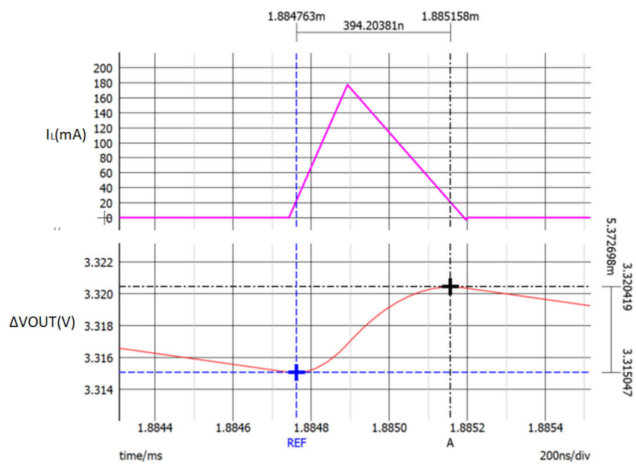

Figure 4-9. VOUT Ripple of Simulation Under I_O= 20mA

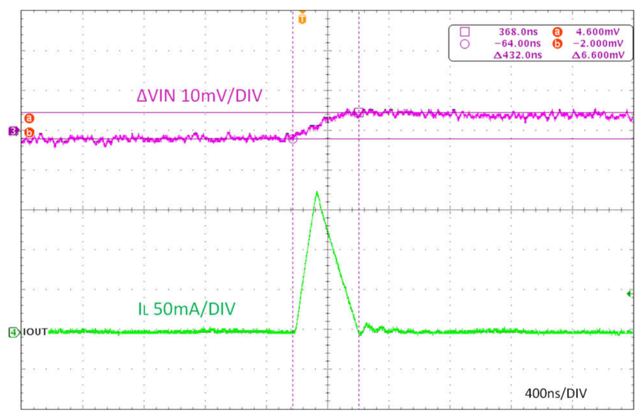

Figure 4-10. VOUT Ripple of Bench Test Under I_O= 4mA

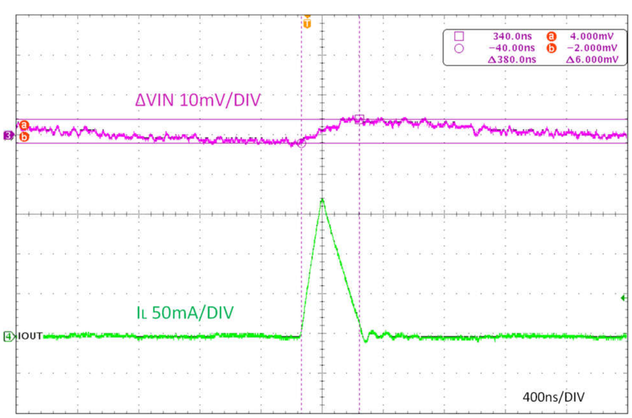

Figure 4-11. VOUT Ripple of Bench Test Under I_O= 10mA

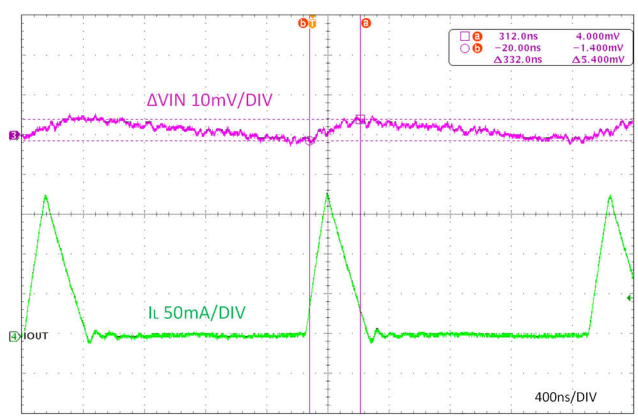

Figure 4-12. VOUT Ripple of Bench Test Under I_O= 20mA

Table 4-1 and Table 4-2 show the comparison between the calculated values and the simulation and bench test results. The error is small, which proves the correctness of the above design process and achieves the design goal.

Table 4-1. Comparison of ΔV_{IN} Calculation, Simulation and Bench Test Results

Load Current	Calculation Value (ΔV_{IN})	Simulation Value (ΔV_{IN})	Bench Test Value (ΔV_{IN})
4mA	14.6mV	14.7mV	15.4mV
10mA	14.2mV	14.4mV	14.4mV
20mA	13.4mV	13.8mV	13.4mV

Table 4-2. Comparison of ΔV_{OUT} Calculation, Simulation and Bench Test Results

Load Current	Calculation Value (ΔV_{OUT})	Simulation Value (ΔV_{OUT})	Bench Test Value (ΔV_{OUT})
4mA	6.7mV	6.6mV	6.6mV
10mA	6.1mV	6.1mV	6.0mV
20mA	5.5mV	5.4mV	5.4mV

Efficiency

Figure 4-13 shows the efficiency at 4mA and 20mA load current. Observe that the efficiency range TPS629203 is from 80.3% to 82.1%, which is a high efficiency while meeting the requirements of external capacitance.

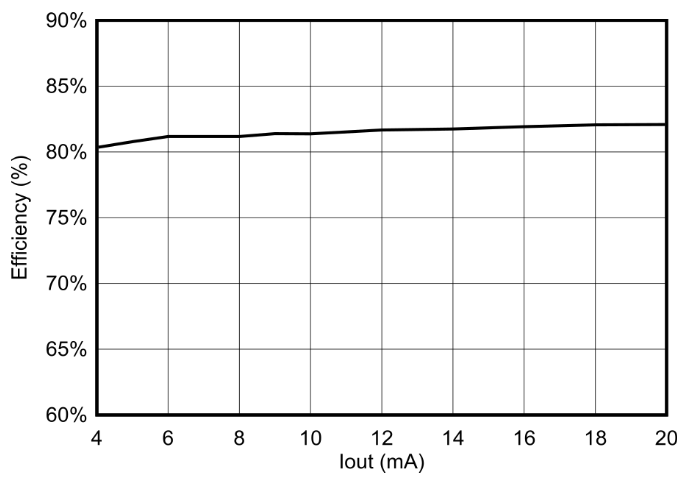

Figure 4-13. Efficiency with a 5.6uH Inductor

If the ripple limit can be relaxed, then the efficiency can be further improved. In a cycle time T_{cycle}, the charge of inductor ΔQ_L is equal to charge consumed by load in Figure 4-13. So, T_{cycle} can be calculated by using Equation 10.

$$T_{cycle} = \frac{\Delta Q_L}{I_{LOAD}} = \frac{V_{IN} - Vo}{2I_{LOAD} \times L} \times \frac{V_{IN}}{Vo} \times Ton^2 \tag{10}$$

For buck converters with constant on time, T_cycle can be increased by reducing the inductor L, which means less switching loss and higher efficiency. However, this leads to increased ripple in Equation 3 and Equation 8.

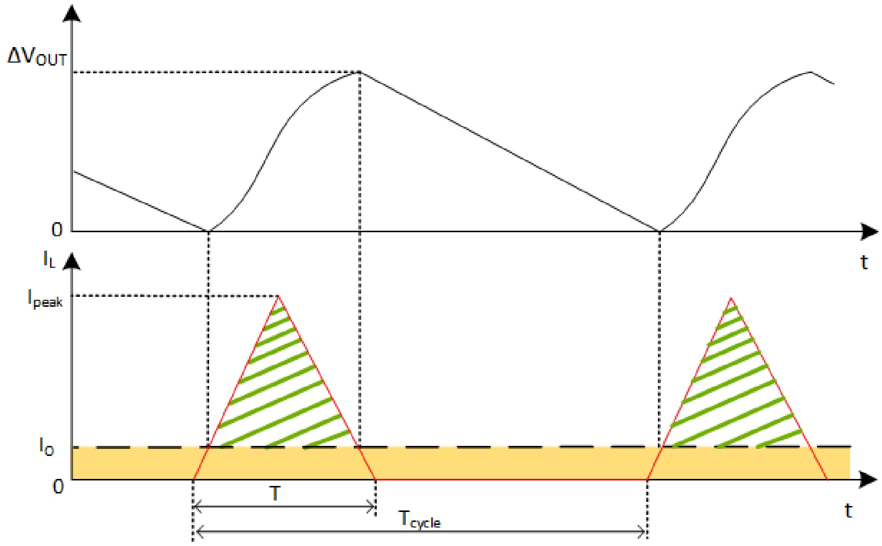

Figure 4-14. Cycle Time in DCM

Figure 4-15 shows a comparison of the efficiency of the inductor of 2.2uH (ripple is 0.5% of input and output voltage) and 5.6uH inductor (ripple is 0.2% of input and output voltage). Observe that the efficiency has increased to 86.8%-87.7%.

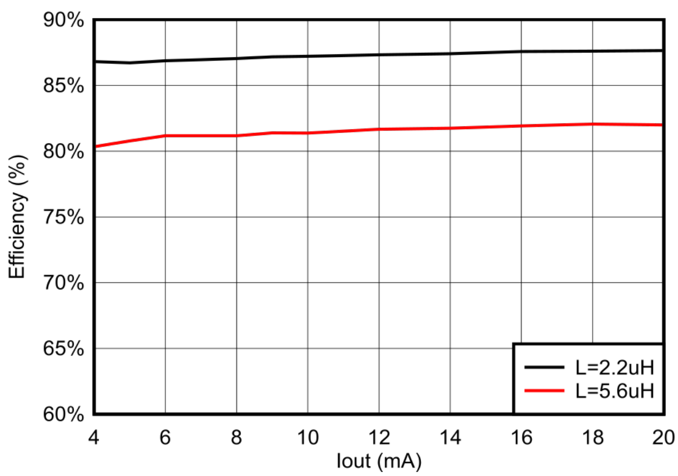

Figure 4-15. Efficiency with 2.2uH Inductor and 5.6uH Inductor

5 Summary

This document introduces the typical sensor transmitters with the HART protocol working in explosive atmospheres. Based on IEC standards, this application note covers using the device TPS629203 and related methods to design the buck converter system to satisfy input and output capacitance, ripple and efficiency. The pulse frequency modulation (PFM) and DCS control (COT) control theories are also explained to help system designers better understand the application and implement designs.

6 References

1. Texas Instruments, TPS629203 300mA, 3V to 17V Low IQ Buck Converter with DCS-Control, data sheet
2. Texas Instruments, Understanding Output Voltage Ripple in DCM Operation of D-CAP Buck Converters, application note
3. Texas Instruments, TPS629203 Buck Converter Evaluation Module, user's guide
4. IEC 60079-11, Explosive atmospheres - Part 11: Equipment protection by intrinsic safety "i", webpage
5. Texas Instruments, A Basic Guide to the HART Protocol, application note

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265