Application Note

Isolated Loop Powered 4 to 20mA Field Transmitter Designs

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ABSTRACT

This application note describes three designs of isolated low power supplies for 2-wire loop powered 4 to 20mA field transmitters or sensors, which are all based on primary side half-bridge topology and secondary side Schottky rectification. The design 1 is using a switching frequency of 50kHz and providing the best in class efficiency, which is available on ti.com as TIDA-00349. The design 2 focuses on optimizing the board space with operating switching frequency of 250kHz and using the customized low size transformer. Furthermore, the design 3 provides maximum of flexibility in terms of switching frequency up to 500kHz by using MSPM0 to generate two channels of PWM (Pulse Width Modulation) signals. This application note describes the design 3 in detail.

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Trademarks

1 Introduction

1.1 System Description

In the realm of industrial automation and control, 2-wire loop-powered 4 to 20mA field transmitters are very common for their reliable and accurate signal transmission over long distances. The current loop's ability to maintain signal integrity over several hundred meters, or even kilometers, is largely attributed to the current signal's robustness against the electrical noise that can be induced into long cable runs. The current-based signal, as opposed to voltage signal, is less susceptible to voltage drops and the interference from electromagnetic sources, making sure a stable and reliable communication pathway between sensors and control systems.

However, the very nature of industrial sites often requires sensors, such as thermocouples, to be in direct contact with grounded metallic structures, while the control systems they communicate with can reference a different ground potential. This disparity can result in ground loop currents, which, due to the extensive distances involved, can significantly degrade measurement accuracy by introducing unwanted noise and potential offsets into the signal. To mitigate these issues, electrical isolation becomes imperative.

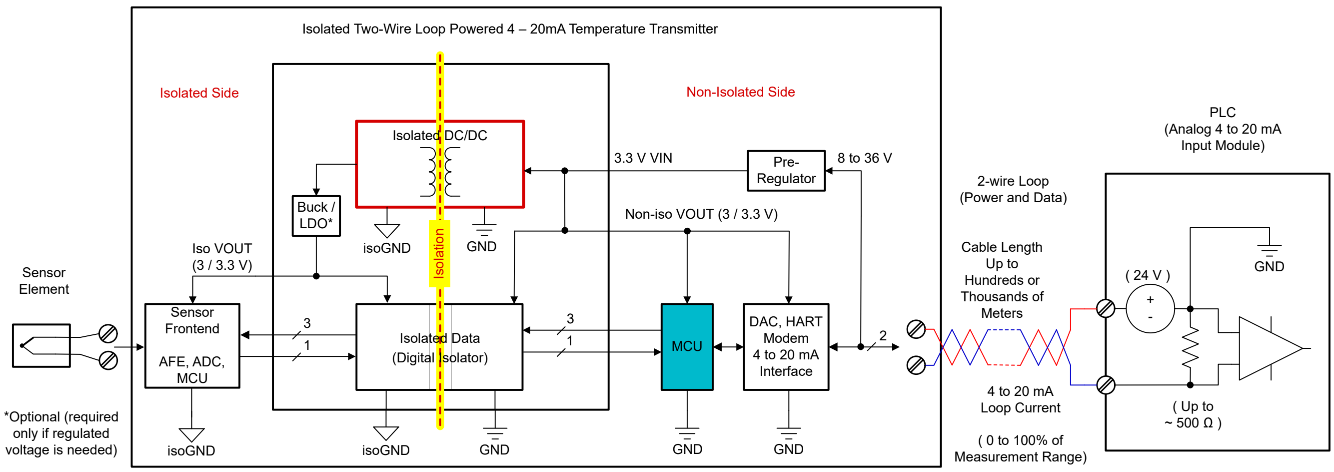

Figure 1-1. Isolated Two-Wire Loop-Powered 4 to 20mA Temperature Transmitter Control System

Figure 1-1 shows a typical block diagram of an isolated two-wire loop powered 4 to 20mA temperature transmitter system, including the current flow used for the communication bus and power for the system, which is designed to convert sensor measurements into a 4 to 20mA loop current signal. Under normal operating conditions, the total current consumption of the transmitter’s transmitter must be less than the actual loop current. Power savings achieved from any individual sub-circuit, including the isolated DC/DC, can be redistributed to other circuit blocks of the system. It allows for optimization of other functionality, ultimately leading to a more efficient end product. Due to the limited supply current budget, it is crucial that a highly efficient power design is imperative. This application note will focus on the isolated DC/DC designs which encased in the red box in Figure 1-1, and the design 3 is more suitable for situations where there is already an MCU on the non-isolated side of the system, which the location is shown in the blue box. Additionally, the flexibility of these designs also allows them to be customized for various applications that demand small size and highly efficient power conversion and isolated data transmission, especially when they must operate from power sources with restricted current availability.

1.2 Design 1: High Efficiency Design with 50kHz

Design 1 is characterized at −40°C, +25°C, and +85°C, accepts input voltages from 3V to 5.2V, and can deliver output currents up to 10mA. It uses a low power consumption charge pump to drive the transformer at 50kHz frequency. A low switching frequency helps to achieve a uniquely high efficiency even at much lower output power levels, ranging from some tens of milliwatts down into the sub-milliwatt range. This design is able to provide more than an 85% efficiency for a 5V input operation at 15mW to 50mW of output power and more than 80% efficiency for a 3.3V operation at a 3mW to 20mW power level.

1.3 Design 2: Space Optimized Design with 250kHz

Design 2 focuses on optimizing the board space by reducing the size of the transformer, Table 1-1 outlines the comparison of two transformers on different features. Design 2 and design 3 (with high switching frequency) use a customized smaller size transformer with 9.60 x 5.51 x 4.83mm^3.

Table 1-1. Comparison of Transformer Specifications

	Turns Ratio (NP:NS)	Magnetizing Inductance Lm (mH)	V-t Product (V-μs)	Isolation (V_{AC}, 1 Minute)	Dimensions (mm^3)	Operating Temperature Range (°C)	Manufacturer
Design 1	1:1.25	> 3	100	1500	9.78 × 9.14 × 10.54	–40 to 100	WURTH ELEKTRONIK
Design 2, 3	1:1.5	>0.6	10	800	9.60 x 5.51 x 4.83	–40 to 100	WURTH ELEKTRONIK

Figure 1-2 shows the detailed schematic of design 2, in order to use a smaller size transformer, the switching frequency has to be increased. This can be realized by using TPS60403 with a frequency of 250kHz. In this design, power consumption of charge pump is higher due to higher switching frequency. As a result, design 2 will be slightly less efficient than design 1. However, it can still achieve more than 80% efficiency with 3.6V input and nearly 70% efficiency with 1.8V input.

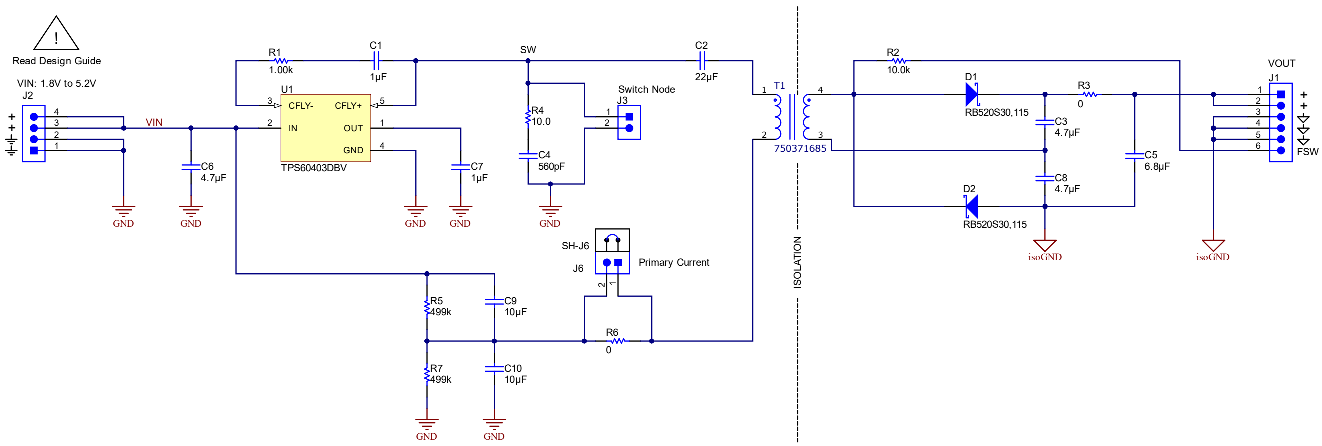

Figure 1-2. Schematic of Design 2

1.4 Design 3: MCU Driven Design with Flexible Switching Frequency

The design 3 is designed to operate with input voltages ranging from 1.62V to 3.6V, compatible with output currents up to 10mA. In terms of efficiency, design 3 can reach up to 83% with 3.6V input and 72% at 1.8V input when operating at 50kHz switching frequency. When the switching frequency is increased to 250kHz, efficiencies of up to 77% with 3.6V input and 62% with 1.8V input are attainable.

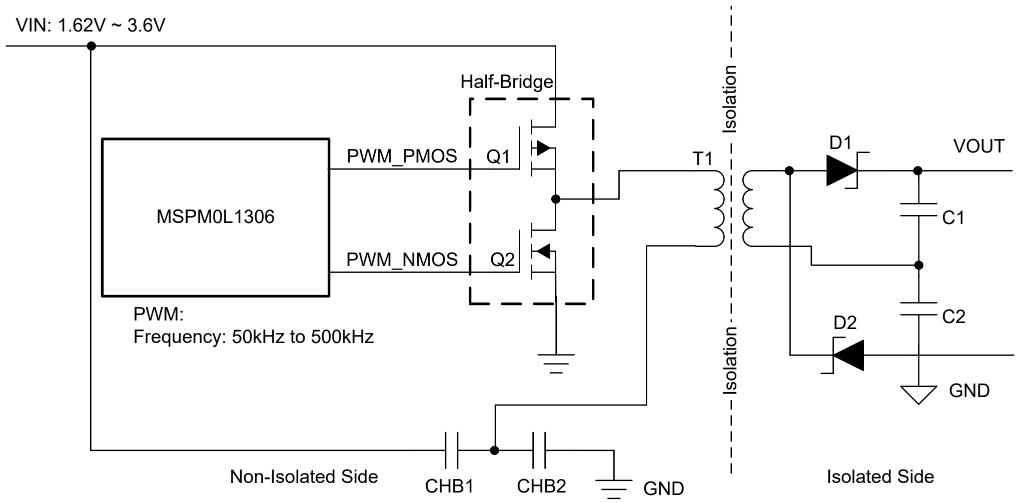

Figure 1-3. Block Diagram of Design 3

Figure 1-3 illustrates a block diagram of MCU driven design, it uses MSPM0L1306 to generate two-channel of PMW signals to control the half-bridge composed of a P-MOSFET and a N-MOSFET, which in turn drives the primary winding of the transformer on the non-isolated side and the double voltage circuit on the isolated side. The MSPM0 series MCU's versatility allows for accurate and programmable switching frequency up to 500kHz.

1.4.1 Selection of MOSFETs

To make sure the half-bridge circuit depicted in Figure 1-3 operate within safe limits, maintain efficiency, and contribute to the circuit's longevity, selecting the appropriate MOSFETs involves several considerations:

1. Voltage Rating: The MOSFETs must have a drain-to-source voltage rating (V_DS) that exceeds the maximum input voltage (3.6V) of the circuit to handle voltage spikes without breaking down.
2. R_DS (on) Value: A lower on-resistance (R_DS (on)) is preferred for reduced conduction losses, which improves efficiency and minimizes heat generation.
3. Gate Charge: Lower gate charge (Qg) allows for faster switching and lower switching losses, which is critical for high switching frequency operation.

Besides the aforementioned characteristics, it is also crucial to factor in the threshold voltage (VGS_th), switching speed, and package. Aiming for a more compact design, a comparison of various MOSFETs with ultra-small footprints is conducted, as detailed in Table 1-2 for N-MOSFETs and Table 1-3 for P-MOSFETs.

Table 1-2. Comparison of Ultra-Small Footprint N-Channel FemtoFET™ MOSFETs

	CSD13380F3	CSD13383F4	CSD13385F5	CSD15380F3	CSD17381F4
V_DS (V)	12	12	12	20	30
R_DS (on) (mΩ) at VGS = 2.5V	73	53	18	2220	110
Qg (typ) (nC)	0.91	2.0	3.9	0.216	1.04
VGS_th (typ) (V)	0.85	1.0	0.8	1.1	0.85

Table 1-3. Comparison of Ultra-Small Footprint P-Channel FemtoFET™ MOSFETs

	CSD23280F3	CSD23382F4	CSD23285F5	CSD25480F3	CSD25481F4
V_DS (V)	–12	–12	–12	–20	–20
R_DS (on) (mΩ) at VGS = -2.5 V	129	90	38	203	145
Qg (typ) (nC)	0.95	1.04	3.2	0.7	0.913
VGS_th (typ) (V)	–0.65	–0.8	–0.65	–0.95	–0.95

After comparing the specifications in the tables, the CSD13380F3 for N-Channel and CSD23382F4 for P-Channel MOSFETs have been selected. This decision is based on their lower resistance when on (R_DS(on)) and the lower charge required to switch them on and off (Qg), which means they will use less power and switch faster. Additionally, both of them the threshold voltages (V_GS(th)) are very similar, which ensures a balanced switching and reduces the risk of short through during transitions, and overall leads to a more efficient circuit operation. These features make them well-suited for high-frequency, space-conscious applications.

1.4.2 Efficiency Test

1.4.2.1 Current Consumption of PWM (Ipwm) Test

To accurately ascertain the efficiency of the MCU driven design, it is essential to know the current consumption of the MSPM0 when it generates dual-channel PWM signals. This test is conducted on the MSPM0L1306 Evaluation Module (EVM) board, with the test configuration depicted in Figure 1-4. Measuring the current consumption of the MCU when driving the half-bridge (connect the green wires), and then subtracting the current consumed by the MCU running an empty program (disconnect the green wires), yields the specific current used for generating dual-channel PWM signals.

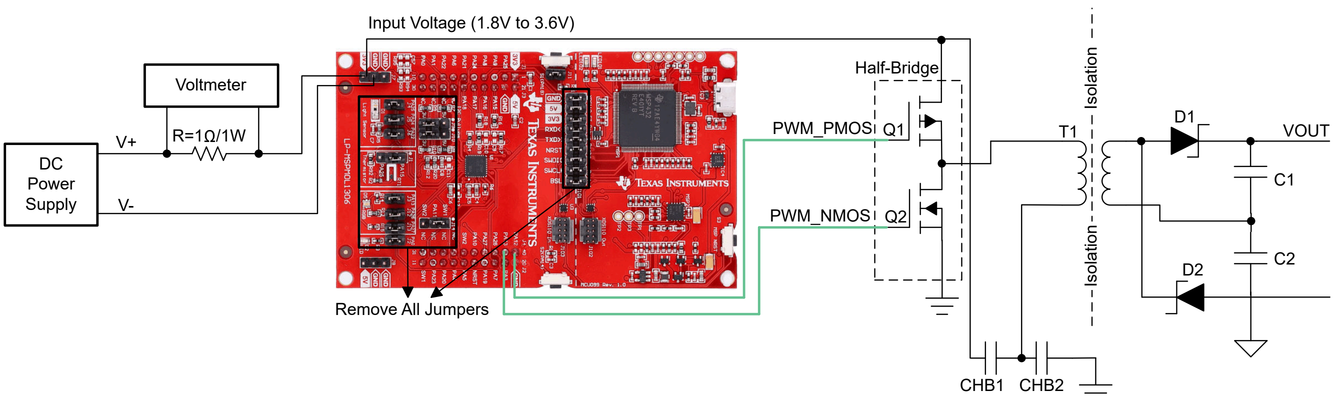

Figure 1-4. Set Up of Current Consumption Test on MSPM0L1306 EVM Board

As per the MSPM0L1306 LaunchPad Development Kit User's Guide, in Section 2.6, an external power supply is utilized instead of USB power from a PC. The MSPM0L1306 is in "Free Run" mode and disconnect programming signals between the MSPM0L1306 and the debug portion of the board (header J101).

Current measurement is facilitated by a shunt resistor, placed between the power supply's positive terminal and the 3V3 pin on the MSPM0L1306 EVM board, by measuring the voltage drop across the resistor. To prevent any extraneous current consumption that can be caused by floating I/Os, all unused GPIOs are actively set to low. Additionally, to isolate the microcontroller from any parasitic loads, all other jumpers, especially those connected to indicator LEDs, are disconnected.

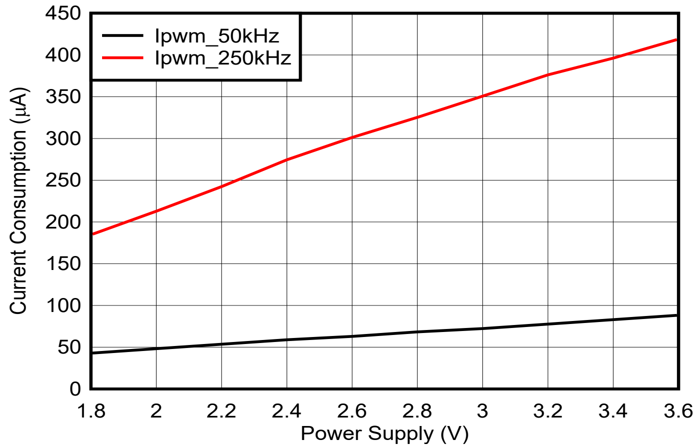

Figure 1-5. Current Consumption versus Power Supply Voltage at Different PWM Frequency of MSPM0L1306

Figure 1-5 displays the current consumption of generating PWM signals with different frequency at different power supply voltages from 1.8V to 3.6V. Red line shows the current consumption of 250kHz switching frequency with 45.3% duty cycle, black line shows the current consumption of 50kHz switching frequency with 49% duty cycle. As the power supply voltages increases, the current consumption also increases. Specifically, at a higher switching frequency of 250kHz, the current consumption is significantly greater across all power supply voltages compared to the lower frequency of 50kHz.

1.4.2.2 Efficiency Test Set Up

Efficiency of isolated DC/DC is a critical parameter for two-wire loop-powered 4 to 20mA field transmitter system, influencing both the power consumption and the reliability of the loop power supply. Figure 1-6 illustrates the setup of the MCU driven design efficiency test. The setup includes precision instruments that are connected to record the input and output voltages (Vin and Vout) and currents (Iin and Iout). Using a rotating resistor box as the load, it operates over an output current range up to 10mA to test. Digital multimeters are in place to capture voltage and current readings with high accuracy, ensuring the collected data reflects the true performance of this design. The efficiency can be calculated by using Equation 1, where Ipwm is the test results in the previous section.

$$\text{Efficiency} = \frac{Vout \times Iout}{Vin \times (Iin + Ipwm)} \quad (1)$$

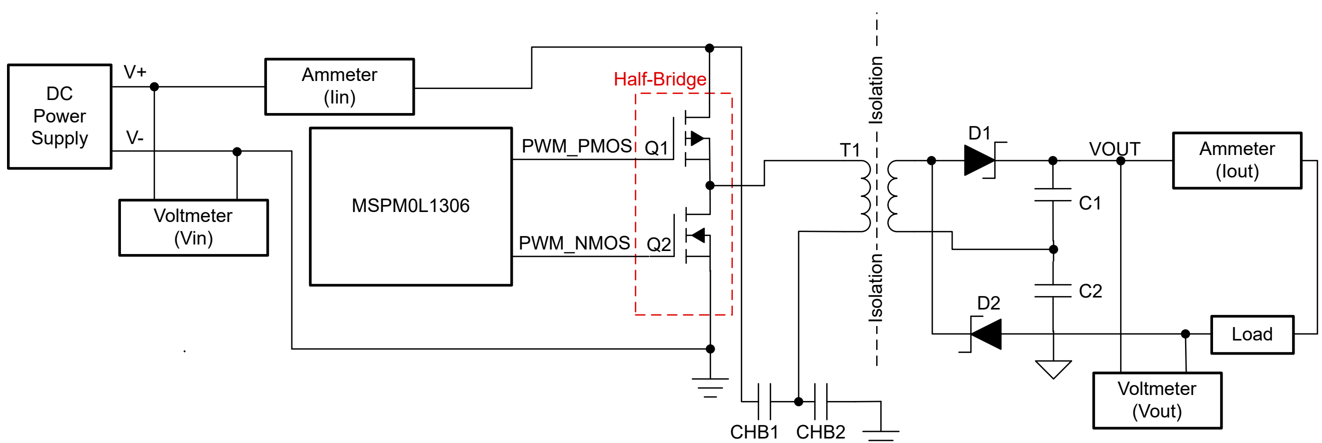

Figure 1-6. Set Up of Efficiency Test

1.4.2.3 Efficiency Test Results at 50kHz Switching Frequency

The efficiency test was conducted with input voltages set to 1.8V, 2.4V and 3.6V. Presented on Figure 1-7 are the efficiency curves versus the output current for both design 1 in solid lines and design 3 in dashed lines. In this test, design 3 runs with 50kHz switching frequency using a same transformer as design 1. At an input voltage of 3.6V, it is observed that both designs attain an efficiency more than 80%.

Figure 1-8 depicts the output voltage as a function of the output current for the two designs, where both demonstrating good linearity throughout the current range tested.

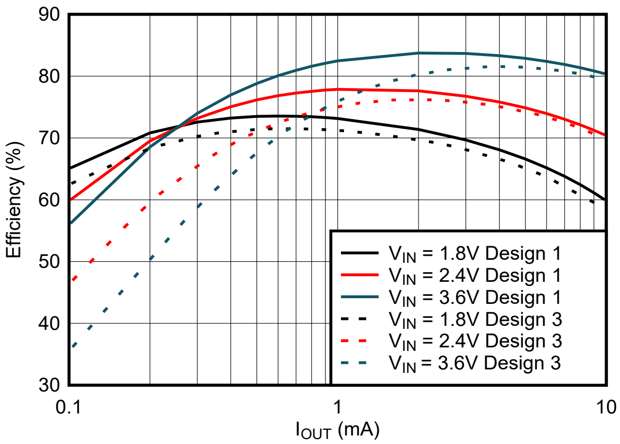

Figure 1-7. Efficiency Test Results of Design 1 and Design 3 at 50khz Switching Frequency

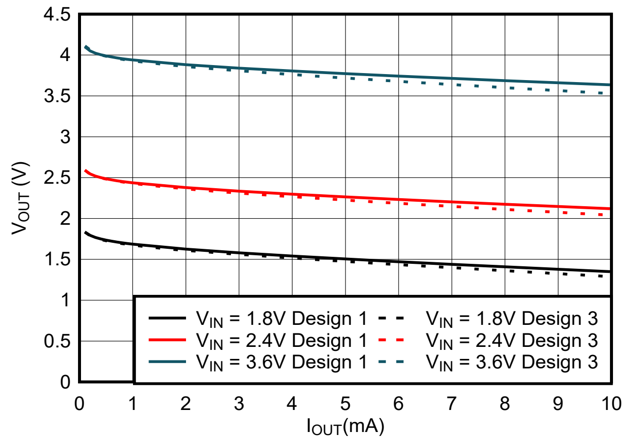

Figure 1-8. VOUT vs IOUT of Design 1 and Design 3 at 50khz Switching Frequency

1.4.2.4 Efficiency Test Results at 250kHz Switching Frequency

The efficiency test for a 250kHz switching frequency utilized the same arrangement as the 50kHz frequency test but incorporated a smaller newly designed transformer. Solid lines represent the results for design 2, while dashed lines correspond to the design 3. Figure 1-9 shows the efficiency plotted against the output current for both designs, and Figure 1-10 displays the output voltage as a function of the output current.

The tests were performed at input voltages of 1.8V, 2.4V, and 3.6V. The increasing in switching frequency to 250kHz resulted in a higher power dissipation for MSPM0L1306 generating PWM signals, as evidenced by a comparison of data from Figure 1-5. This increase in power consumption contributed to a decrease in the efficiency of design 3 comparing with design 2. Nonetheless, at an input voltage of 3.6V, design 3 also can achieve an efficiency of up to 77%.

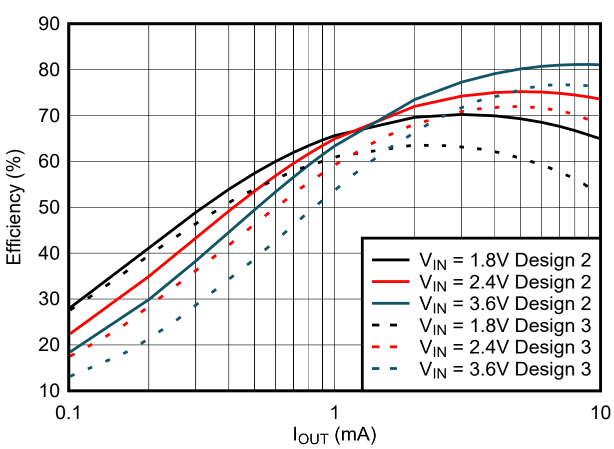

Figure 1-9. Efficiency Test Results of Design 2 and Design 3 at 250khz Switching Frequency

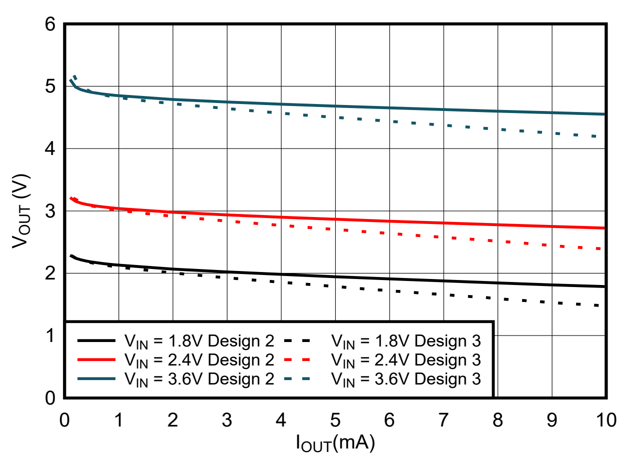

Figure 1-10. VOUT vs IOUT of Design 2 and Design 3 at 250khz Switching Frequency

2 Design File

2.1 Schematics

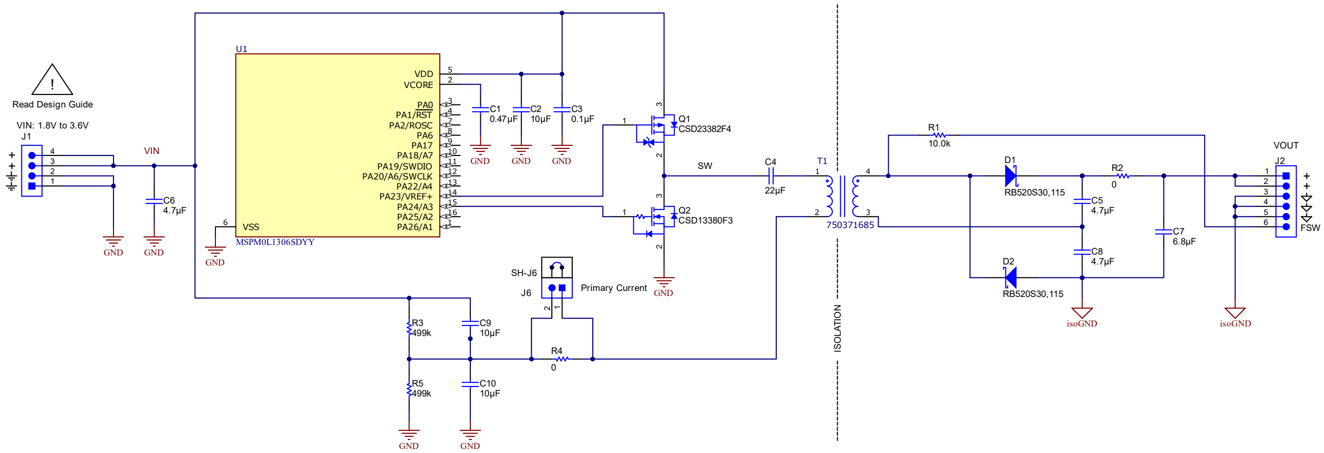

Figure 2-1. Schematic of Design 3

2.2 Bill of Materials

Table 2-1. Bill of Materials

Item #	Designator	Quantity	Part Number	Manufacturer	Description	Package Reference
1	!PCB	1		Any	Printed Circuit Board	
2	C1, C2, C3, C6	4	C0603C475K8PACTU	Kemet	CAP, CERM, 4.7uF, 10V, ±10%, X5R, 0603	0603
3	C4	1	GRM31CR61A226KE19L	MuRata	CAP, CERM, 22uF, 10V, ±10%, X5R, 1206	1206
4	C5, C8	2	CGB3B1X5R1A475K055AC	TDK	CAP, CERM, 4.7µF, 10V, ± 10%, X5R, 0603	0603
5	C7	1	C1608X5R1E685K080AC	TDK	CAP, CERM, 6.8µF, 25V, ± 10%, X5R, 0603	0603
6	C9, C10	2	GRM21BR71A106KE51L	MuRata	CAP, CERM, 10uF, 10V, ±10%, X7R, 0805	0805
7	D1, D2	2	RB520S30,115	NXP Semiconductor	Diode, Schottky, 30V, 0.2A, SOD-523	SOD-523
8	H1, H2, H3, H4	4	SJ5382	3M	Bumpon, Hemisphere, 0.25 X 0.075, Clear	75x250 mil
9	J1	1	61300411121	Wurth Elektronik eiSos	Header, 2.54mm, 4x1, Gold, TH	Header, 2.54mm, 4x1, TH
10	J2	1	61300611121	Wurth Elektronik eiSos	Header, 2.54mm, 6x1, Gold, TH	Header, 2.54mm, 6x1, TH
11	J6	1	61300211121	Wurth Elektronik eiSos	Header, 2.54mm, 2x1, Gold, TH	Header, 2.54mm, 2x1, TH
12	LBL1	1	THT-14-423-10	Brady	Thermal Transfer Printable Labels, 0.650" W x 0.200" H - 10,000 per roll	PCB Label 0.650"H x 0.200"W
13	Q1	1	CSD23382F4	Texas Instruments	MOSFET, P-CH, -12V, -3.5 A, YJC0003A (PICOSTAR-3)	YJC0003A
14	Q2	1	CSD13380F3	Texas Instruments	MOSFET, N-CH, 12V, 3.6A, YJM0003A (PICOSTAR-3)	YJM0003A
15	R1	1	CRCW040210K0FKED	Vishay-Dale	RES, 10.0 k, 1%, 0.063 W, 0402	0402

Table 2-1. Bill of Materials (continued)

Item #	Designator	Quantity	Part Number	Manufacturer	Description	Package Reference
16	R2	1	CRCW08050000Z0EAHP	Vishay-Dale	RES, 0, 5%, 0.333 W, 0805	0805
17	R3, R5	2	CRCW0402499KFKED	Vishay-Dale	RES, 499k ohm, 1%, 0.063W, 0402	0402
18	SH-J6	1	969102-0000-DA	3M	Shunt, 100mil, Gold plated, Black	Shunt
19	T1	1	750371685	Wurth Electronics	TRANSFORMER	SMT4
20	U1	1	MSPM0L1306SDYY	Texas Instruments	Mixed-Signal Microcontrollers SOT-23-THIN-16	SOT-23-THIN-6
21	FID1, FID2, FID3	0	N/A	N/A	Fiducial mark. There is nothing to buy or mount.	Fiducial
22	R4	0	CRCW08050000Z0EAHP	Vishay-Dale	RES, 0, 5%, 0.333 W, 0805	0805

3 Summary

This application note introduces three designs regarding to isolated power supply for two-wire loop-powered 4 to 20mA field transmitter system.

Design 1 runs at a fixed switching frequency of 50kHz offers the highest efficiency at 5V input voltage, reaching 86%, and maintains a higher efficiency at lower input voltages. However, it uses a larger transformer which may not be optimal for size-constrained applications.

Design 2 with 250kHz switching frequency shows a slightly reduced efficiency compared to design 1, with the best performance of 80% at 3.6V. It benefits from a smaller transformer size, which is advantageous for compact designs.

Design 3 is the most flexible with programmable frequency up to 500kHz, allowing a small transformer, and maintaining a compact form factor. Table 3-1 gives an overview of these three designs.

Table 3-1. Comparison of Three Designs

Features	Design 1 (50kHz)	Design 2 (250kHz)	Design 3 (up to 500kHz)
Switching Frequency	Fixed 50kHz (- 40%, +40%)	Fixed 250kHz (-40%, +20%)	Programmable up 500kHz
Efficiency	• 86%(5V) • 82%(3.3V)	• 80%(3.6V) • 67%(1.8V)	• 50kHz: – 83%(3.6V) – 72%(1.8V) • 250kHz: – 77%(3.6V) – 62%(1.8V)
Transformer Size (mm^3)	**Large** 9.78 x 9.50 x 10.54	**Small** 9.60 x 5.51 x 4.83	**Small** 9.60 x 5.51 x 4.83

In conclusion, the selection of an appropriate design should be based on specific application requirements, considering factors like overall board size and efficiency. The design 3 is particularly suitable for systems where an MCU is already present on the non-isolated side, offering a streamlined integration with programmable flexibility.

4 References

1. Texas Instruments, *Uniquely Efficient Isolated DC/DC Converter for Ultra-Low Power and Low-Power Applications*, design guide.
2. Texas Instruments, *Isolated Loop Powered Thermocouple Transmitter*, design guide.
3. Texas Instruments, *Isolated Power and Data Interface for Low-Power Applications*, design guide.
4. Texas Instruments, *MSPM0L1306 LaunchPad Development Kit (LP-MSPM0L1306)*, user's guide.

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